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# НАУЧНО-ТЕХНИЧЕСКИЕ ВЕДОМОСТИ

САНКТ-ПЕТЕРБУРГСКОГО ГОСУДАРСТВЕННОГО  
ПОЛИТЕХНИЧЕСКОГО УНИВЕРСИТЕТА

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Физико-математические  
науки

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**ТОМ 18, №3.2**  
**2025**

Санкт-Петербургский политехнический  
университет Петра Великого  
2025

# НАУЧНО-ТЕХНИЧЕСКИЕ ВЕДОМОСТИ САНКТ-ПЕТЕРБУРГСКОГО ГОСУДАРСТВЕННОГО ПОЛИТЕХНИЧЕСКОГО УНИВЕРСИТЕТА. ФИЗИКО-МАТЕМАТИЧЕСКИЕ НАУКИ

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## PREFACE



### **12th International School and Conference on Optoelectronics, Photonics, Engineering and Nanostructures (SPb OPEN – 2025) / 12-я Международная школа-конференция по оптоэлектронике, фотонике, инженерии и наноструктурам**

The 12th International School and Conference on Optoelectronics, Photonics, Engineering and Nanostructures (SPb OPEN 2025) was held on May 20–25, 2025. It continues the annual schools and seminars for young scientists on physics and technology of nanostructures, organized since 2009, spearheaded by Zhores Alferov, RAS Academician and winner of the 2000 Nobel Prize in Physics.

The School was organized by the St. Petersburg Higher School of Economics, Peter the Great St. Petersburg Polytechnic University, with the support of the HSE Academic Fund Programme, Photonics Russia and Special Systems Photonics LLC.

The Program Committee of the School and Conference selected 250 papers by young scientists, graduate and undergraduate students from 22 cities in Russia and Belarus. The same as last year, the average age of the attendees was under 27 years old, over 70% of the reports were presented by attendees under 30.

Presentations were given in six panels:

- Synthesis and structural properties of semiconductor materials and nanostructures,
- Lasers, solar cells, other optoelectronic devices,
- Nanophotonics, spectroscopy, microresonators, optical properties, plasmonics,
- Biophysics, nanobiotechnology, biophotonics,
- Electrical, magnetic and microwave characteristics and devices,
- Other aspects of nanotechnology.

The highest percentage of reports (23%) were given in the section "Nanophotonics...", closely followed by "Lasers..." with 22% of reports. Twenty of the best reports by young scientists were awarded with diplomas of the conference.

In addition to poster presentations from young scientists, the programme included a series of keynote speeches by prominent researchers, outlining the main advances and challenges in various fields of physics and technology. In total, 99 leading scientists participated in the conference. The keynote speakers included:

- Alexander Alodjants (ITMO University)
- Alexander Mintairov (University of Notre Dame, USA / Ioffe Institute)
- Alexey Toropov (Ioffe Institute)
- Maria Kuznetsova (St. Petersburg State University)
- Ivan Mukhin (Alferov University)
- Ivan Makhov (St. Petersburg Higher School of Economics)
- Georgiy Sapunov (Changchun Institute of Optics, Fine Mechanics and Physics, China)
- Yating Wan (King Abdullah University of Science and Technology, Saudi Arabia)
- Alexey Ustinov (Saint Petersburg Electrotechnical University "LETI")
- Maxim Vinnichenko (Peter the Great St. Petersburg Polytechnic University)

The same as last year, the peer-reviewed reports from the conference are published in St. Petersburg State Polytechnical University Journal: Physics and Mathematics. The Programme Committee of SPbOPEN-2025 hopes that the range of subjects presented at



the conference will be of interest to the journal's audience. We would like to thank the journal for giving us the opportunity to publish the proceedings, and thank the reviewers for useful recommendations and constructive criticism. We of course express our gratitude to all participants of the conference.

We invite young scientists, graduate and undergraduate students to take part in the next Saint Petersburg OPEN School and Conference in 2026! Please visit <https://spb.hse.ru/spbopen/> for more details.

**Alexey Zhukov**

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## Scanning probe lithography implementation for InGaS<sub>3</sub> optical waveguides fabrication

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**Abstract.** Integrated nanophotonics faces challenges in matching the component density of electronics, largely due to the size limitations of silicon-based photonics. High-refractive-index materials like InGaS<sub>3</sub> offer a promising solution for miniaturized visible/UV photonic circuits. This study demonstrates the fabrication of InGaS<sub>3</sub> waveguides using mechanical scanning probe lithography (m-SPL), overcoming limitations of conventional lithography techniques. Test cutting in various directions shows that m-SPL trench quality in InGaS<sub>3</sub> depends on crystallographic orientation, with zigzag-aligned force producing clean edges while jagged armchair-direction leads to fractures. The method allows to simultaneously determine crystallographic axes and optimize waveguides side walls quality. This approach establishes m-SPL as a viable route for nanostructuring unconventional materials where standard etching protocols fail, advancing high density integrated photonics.

**Keywords:** InGaS<sub>3</sub>, scanning probe lithography, waveguides

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Материалы конференции

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## Применение сканирующей зондовой литографии для создания оптических волноводов на основе InGaS<sub>3</sub>

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**Аннотация.** Интегральная нанофотоника сталкивается с трудностями в достижении высокой поверхностной плотности упаковки функциональных компонентов, сравнимой с электроникой, по причине прозрачности кремния в ИК-диапазоне, а также низкого показателя преломления SiO<sub>2</sub>, SiO<sub>x</sub>, Si<sub>3</sub>N<sub>4</sub>, SiN и т.д. Материалы с высоким показателем преломления, такие как InGaS<sub>3</sub>, предлагают перспективное решение для миниатюризированных фотонных схем в видимом/УФ-диапазоне. В данном исследовании продемонстрирована реализация InGaS<sub>3</sub>-волноводов с помощью механической сканирующей зондовой литографии (m-SPL), что позволяет преодолеть ограничения традиционных литографических методов. Тестовые разрезы в различных направлениях показали, что качество канавок, созданных методом m-SPL в InGaS<sub>3</sub>, зависит от кристаллографической ориентации: приложение силы вдоль направления «зигзаг» позволяет получить ровные чистые края, тогда как разрез по направлению «кресло» приводит к образованию трещин. Этот метод позволяет одновременно определять направления кристаллографических осей и оптимизировать качество боковых стенок волноводов. Такой подход подтверждает, что m-SPL является эффективным способом наноструктурирования новых материалов, где стандартные методы травления неприменимы, что способствует развитию оптических интегральных схем с высокой плотностью функциональных элементов.

**Ключевые слова:** InGaS<sub>3</sub>, сканирующая зондовая литография, волноводы

**Финансирование:** Работа выполнена при поддержке Российского Научного Фонда (грант № 20064-22-24).

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## Introduction

Integrated nanophotonics has become a key area of research for advancing the miniaturization of functional components. While all-dielectric photonics offers advantages such as high signal transfer speeds, negligible Joule heating, and non-interacting photon behavior, it still faces challenges in replacing electronic computing. Despite its limitations, such as quantum effects at nanoscale dimensions, charge carrier velocity constraints, thermal management issues, and leakage currents, modern electronics remains dominant due to its significantly higher functional element density (~6 orders of magnitude greater than integrated photonics). This disparity arises from the relatively large size of silicon-based photonic components. Although silicon fabrication technology is mature,



cost-effective, and compatible with planar processing, Si indirect bandgap (1.12 eV at 300 K) restricts operation to the IR range. While silicon-derived materials (e.g.,  $\text{SiO}_2$ ,  $\text{Si}_3\text{N}_4$ ) are transparent in visible and UV wavelengths, their low refractive indices ( $\sim 1.4$ ) limit the miniaturization of components below 300–400 nm and hinder dense integration. To enable higher packing densities, materials with a high refractive index and compatibility with planar fabrication techniques are essential, particularly for shorter-wavelength applications. For instance, structures based on GaP, including self-assembled nanowires grown on Si substrates, show great promise for nanophotonic integration [1, 2].

$\text{InGaS}_3$  is a wide-bandgap semiconductor (2.73 eV) with a high refractive index ( $\sim 2.5$ ). Unlike conventional van der Waals materials, it has a hexagonal layered structure with covalent inter-layer bonding. However, the in-plane bond distribution is non-uniform, and the low areal bond density facilitates layer separation through various techniques [3].

This material holds significant promise for integrated photonics, particularly for passive optical components. Similar layered semiconductors (e.g.,  $\text{MoS}_2$ ,  $\text{MoSe}_2$ ,  $\text{WS}_2$ ,  $\text{WSe}_2$ ) have already demonstrated the feasibility of precise layer exfoliation and transfer onto different substrates [4]. Thanks to its layered nature,  $\text{InGaS}_3$  can be mechanically exfoliated with monolayer precision, enabling seamless integration into planar fabrication processes and high-precision control over device geometry. Due to these properties, thin  $\text{InGaS}_3$  layers are a promising platform for developing passive light-guiding elements in integrated optical circuits.

### Materials and Methods

To fully explore  $\text{InGaS}_3$ 's light-guiding capabilities, nanoscale waveguides must be fabricated. However, conventional lithography techniques, such as electron-beam lithography, photolithography, focused ion beam (FIB) milling, nanoimprinting, and scanning probe lithography (SPL), are not yet optimized for novel materials like  $\text{InGaS}_3$ . While FIB can achieve nanoscale patterning, it often introduces a damaged surface layer (up to hundreds of nanometers thick) that requires post-processing annealing.

In contrast, SPL methods, particularly mechanical SPL (m-SPL), offer nanometer-scale precision by locally modifying surfaces using a high hardness probe. The advent of diamond-tipped probes has further expanded m-SPL's applicability, making it suitable for patterning nearly any material with the resolution required for nanophotonic devices. For fabrication, we employed an Ntegra Aura (NT-MDT) scanning probe microscope with DRP\_IN (Tipsnano) cantilevers featuring monocrystalline diamond tips (10 nm curvature radius, 250 N/m stiffness).  $\text{InGaS}_3$  flakes were transferred onto a Si/ $\text{SiO}_2$  substrate by mechanically pressing a bulk crystal onto the surface, resulting in flakes of varying thicknesses and areas. Optimal flakes were selected via atomic force microscopy (AFM) inspection.

### Results and Discussion

The edge quality of trenches fabricated by m-SPL is influenced by multiple parameters including probe tip geometry, loading force, and probe stiffness. Initial investigations involving angled line patterning at 10  $\mu\text{N}$  were performed to identify optimal conditions for smooth-edged waveguide production (Fig. 1).

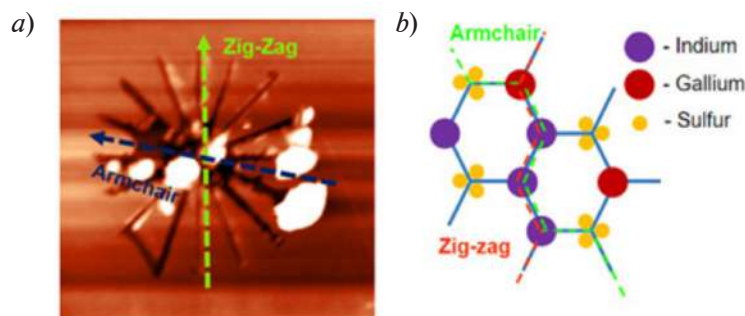


Fig. 1. AFM-scan of the cut trenches along different directions on  $\text{InGaS}_3$  flake (a); schematic of the  $\text{InGaS}_3$  crystal lattice structure with indicated 'zig-zag' and 'armchair' directions (b)

The patterning results demonstrate strong crystallographic orientation dependence: trenches exhibit sharply defined profiles in certain directions, while developing broader, irregular edges with flaking in others. This anisotropic behavior originates from the  $\text{InGaS}_3$  crystal's intrinsic mechanical properties. Like other TMDs in the  $P6_3/mmc$  space group, the material shows markedly different mechanical responses along different crystallographic axes - with armchair directions exhibiting  $1.5\text{--}2.2\times$  greater tensile strength than zigzag orientations [5]. This anisotropy leads to preferential fracture propagation along zigzag directions under mechanical stress.

Consequently, zigzag-aligned force application produces clean cleavages, while armchair-oriented loading tends to cause jagged fractures and localized delamination. The observed dependence of trench morphology on sample rotation validates this approach's dual functionality: 1) crystallographic orientation determination; 2) optimal sample alignment for side walls quality control.

To demonstrate the implementation of m-SPL technique strip waveguides were fabricated (Fig. 2). Experiment employed flakes oriented along 'zig-zag' direction, with trenches fabricated through cyclic scanning of a  $32\times 1024$ -point matrix ( $0.95\times 30\text{ }\mu\text{m}$ ) in contact mode. Using a horizontal fast-scan direction at  $230\text{ }\mu\text{m/s}$  with  $2\text{ }\mu\text{N}$  applied force achieved controlled material removal at  $10\text{ nm}$  per scan pass. Characteristic edge asymmetry emerged - the left edge maintained atomic-scale smoothness while the right edge showed pronounced material accumulation due to probe tip geometry. Edges were processed via horizontal trenches formation and surface was cleaned in contact mode ( $400\text{ nN}$ ).

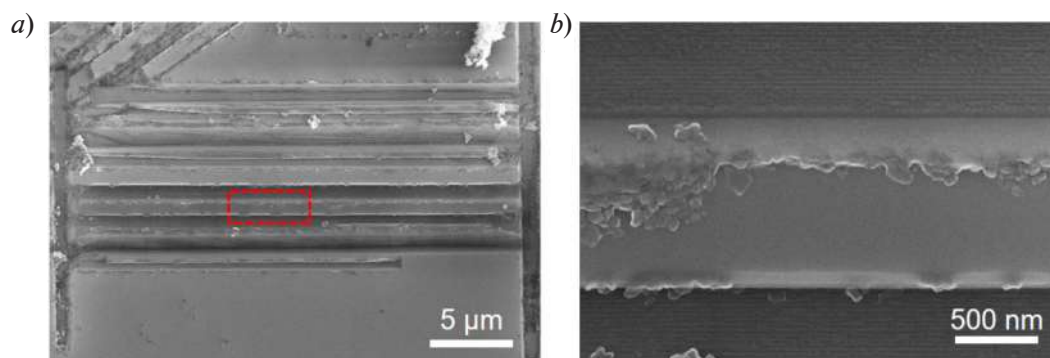


Fig. 2. SEM-images of strip waveguides fabricated via m-SPL technique on  $70\text{ nm}$  thick  $\text{InGaS}_3$  flake cutted along the 'zig-zag' direction (a); enlarged area (red dotted rectangle) demonstrating the high quality of the waveguide side-walls (b)

It is evident that m-SPL technique allows to fabricate multiple  $\sim 25$  microns long waveguides separated from each other by the value of its width. The side walls demonstrate high verticality and evenness, as it's performed in the enlarged SEM image (Fig. 2, b).

### Conclusion

To sum up the array of strip waveguides  $70\text{ nm}$  thick and  $700\text{--}900\text{ nm}$  wide were fabricated via m-SPL technique.  $\text{InGaS}_3$  mechanical anisotropy dictates the evaluation of the optimal cutting direction. It was demonstrated that the following method allows to fabricate waveguides of various design based on non-conventional novel material  $\text{InGaS}_3$  which etching protocols via standard methods are not applicable.

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### REFERENCES

1. Kuznetsov A., et al., In-Plane Directional  $\text{MoS}_2$  Emitter Employing Dielectric Nanowire Cavity, Small Structures (6.4) (2025) 2400476.
2. Kuznetsov A., et al., Elastic gallium phosphide nanowire optical waveguides – versatile subwavelength platform for integrated photonics, Small. 19 (28) (2023) 2301660.

3. Toksumakov A.N., et al., High-refractive index and mechanically cleavable non-van der Waals InGaS<sub>3</sub>, npj 2D Materials and Applications. 6 (1) (2022) 85.
4. Huo C., et al., 2D materials via liquid exfoliation: a review on fabrication and applications, Science bulletin. 60 (23) (2015) 1994–2008.
5. Falin A., et al., Mechanical properties of atomically thin tungsten dichalcogenides: WS<sub>2</sub>, WSe<sub>2</sub>, and WTe<sub>2</sub>, ACS nano. 15 (2) (2021) 2600–2610.

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## Mechanism of resistive state switching in a non-filamentary memory device made of halide perovskite

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**Abstract.** In this study, we present a comprehensive numerical investigation of the modulation of the Schottky barrier in cesium lead bromide (CsPbBr<sub>3</sub>) perovskite, focusing on the role of internal ionic charge carriers. We observe the pronounced hysteretic behavior in the current-voltage ( $I$ – $V$ ) characteristics of a metal-perovskite-metal configuration, where a 100 nm thick perovskite layer is sandwiched between chemically inert Schottky contacts. The inert nature of these contacts allows for the accumulation of mobile ions at the contact-perovskite interface without introducing secondary ion injections, thereby preventing any conducting filament formation. By implementing a one-dimensional drift-diffusion model, we simulate the dynamic evolution of mixed ionic-electronic charge carriers during  $I$ – $V$  measurements. Our findings reveal that resistive state switching (RSS) is predominantly influenced by ion accumulation at the interfaces, which effectively modulates the Schottky barrier and increases carrier tunnelling probability. Additionally, our analysis highlights the significance of polarized accumulated ions in achieving a more precise interpretation of experimental  $I$ – $V$  curves.

**Keywords:** semiconductor device simulation, numerical modelling, perovskite memristor, mobile ions in perovskite

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Материалы конференции

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## Механизм переключения сопротивления в нефиламентном запоминающем устройстве из металлгалогенидного перовскита

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**Аннотация.** В данной работе представлено комплексное исследование модуляции барьера Шоттки в перовските  $\text{CsPbBr}_3$ , где уделяется особое внимание роли ионов как носителей заряда. Здесь наблюдается выраженное гистерезисное поведение вольт-амперных характеристик (ВАХ) для мемристоров с конфигурацией металл-перовскит-металл, где слой перовскита толщиной 100 нм расположен между химически инертными контактами Шоттки. Природа этих контактов позволяет накапливать подвижные ионы на границе контакт-перовскит без инъекции вторичных ионов, тем самым предотвращая образование проводящих нитей. Реализуя одномерную модель дрейфа-диффузии, удалось провести моделирование эволюции смешанных ионно-электронных носителей заряда во время измерений ВАХ. Результаты показали, что резистивное переключение состояний в основном зависит от накопления ионов на границе перовскит - контакт, что эффективно модулирует барьер Шоттки и увеличивает вероятность туннелирования носителей. Полученный результат подчеркивает значимость поляризованных накопленных ионов для более точной интерпретации экспериментальных характеристик перовскитных мемристоров.

**Ключевые слова:** моделирование полупроводниковых приборов, численное моделирование, перовскитный мемристор, подвижные ионы в перовските

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## Introduction

Halide perovskites have emerged as a groundbreaking class of materials in the field of optoelectronics, particularly for applications in solar cells, light-emitting diodes, and photo detectors. The charge dynamics in halide perovskites are critical for understanding their performance in photovoltaic devices, as they involve processes of slow mobile ions and significantly change the current voltage ( $I-V$ ) characteristics. The presence of mobile ions in halide perovskite devices can significantly hinder their performance, prompting researchers to seek methods to minimize ion redistribution [1–2]. Conversely, the mobility of ions within perovskite materials is not solely detrimental; it can also enable innovative applications, such as memristor devices [3] and photo detectors [4].

In the context of utilizing halide perovskite materials in memristor devices, the mechanism behind resistive state switching (RSS) can be attributed to three primary physical processes [5]. The first mechanism involves filament formation, where ionic filaments are generated either



through the injection of secondary ions from reactive metallic contacts such as silver or copper, or via the migration of halide vacancies. The second mechanism pertains to RSS that occurs through interface modulation. Lastly, the third mechanism is related to charge trapping and de-trapping in defect states, which influences the overall conductivity and switching behavior of the device. In the latter mechanism, RSS is attributed to the modulation of the interface between the perovskite layer and the charge transport layer. This process is particularly influenced by dipole formation and self-doping, which arise from the accumulation of ions at the interface [6–8]. In a separate study conducted by Guan and colleagues [9], the accumulation of ions at the perovskite/ITO interface was identified as a mechanism for RSS. They inferred that the buildup of negatively charged methylammonium vacancies at the perovskite/ITO interface, triggered by the application of a positive bias to the opposing electrode, leads to an enhancement of the Schottky barrier.

In this study, we aimed to clarify the mechanism of RSS in a single perovskite crystal by utilizing numerical calculations of drift-diffusion (DD) equations. Our analysis focused on the dynamics of electronic and ionic charge carriers within a  $\text{CsPbBr}_3$  perovskite material sandwiched between two inert electrodes: a grounded boron-doped diamond (BDD) electrode and an indium tin oxide (ITO) electrode subjected to a positive bias. Our results indicate that filament formation does not occur; instead, we observed significant redistribution of internal mobile ions within the perovskite, leading to their accumulation at the perovskite/electrode interface. This ion accumulation critically alters the injection of charge carriers. By comparing our calculated I-V curve with experimental data, we demonstrated that, in addition to carrier tunneling from the electrodes, a reduction in the Schottky barrier is observed.

### Materials and methods

To analyze the  $I$ – $V$  characteristics of the BDD-perovskite-ITO system, we utilized a one-dimensional DD model for ionic and electronic transport under transient conditions. The perovskite material positioned between two electrodes, is set at a thickness of 100 nm, reflecting experimental value. Due to the inability to inject or extract mobile ions from the electrodes, these ions tend to accumulate at the interface between the perovskite and the electrodes when a voltage is applied. This accumulation can lead to significant changes in the electric potential, potentially causing numerical instability in our simulations. To mitigate this issue, we implemented the well-established Scharfetter-Gummel (SG) method for discretizing current fluxes. While it is relatively straightforward to apply SG discretization to electronic carrier current density using the Boltzmann distribution [10], we adapted a modified version of SG discretization for ionic carriers, as suggested by Koprucki et al. [11].

### System of equations

The system of transient DD equations will account for two types of carriers: ionic carrier with concentration of  $a$  for anions and  $c$  for cations, and electronics carrier with the concentrations of electrons  $n$  and holes  $p$ . The system of equations is:

$$\frac{\partial^2 V(x,t)}{\partial x^2} = -\frac{|q|}{\varepsilon \varepsilon_0} [p(x,t) - n(x,t) + c(x,t) - a(x,t) - N_A(x) + N_D(x) - N_{cat}(x) + N_{ani}(x)], \quad (1)$$

$$\frac{\partial n(x,t)}{\partial t} + \frac{1}{q} \frac{\partial j_n(x,t)}{\partial x} = U_n(x,t), \quad (2)$$

$$\frac{\partial p(x,t)}{\partial t} + \frac{1}{q} \frac{\partial j_p(x,t)}{\partial x} = U_p(x,t), \quad (3)$$

$$\frac{\partial a(x,t)}{\partial t} + \frac{1}{q} \frac{\partial j_a(x,t)}{\partial x} = 0, \quad (4)$$

$$\frac{\partial c(x,t)}{\partial t} + \frac{1}{q} \frac{\partial j_c(x,t)}{\partial x} = 0. \quad (5)$$



In Eq. (1),  $V$  is the electrical potential,  $\varepsilon_0$  is the permittivity of free space and  $\varepsilon_r$  indicates the relative permittivity of the perovskite. The terms  $N_A$  and  $N_D$  are the concentrations of acceptors and donors' impurity, respectively. Additionally, we incorporate fixed concentrations of cations  $N_{cat}$  and anions  $N_{ani}$  to effectively model Schottky defects inside the perovskite [12]. Eqs. (2)–(5) demonstrate continuity equation for each charge carrier, where  $j_i$  and  $U_i$ ,  $i = [n, p, a, c]$ , are current density and net generation associated to each charge carrier.  $q$  is the elementary charge and it is negative for electrons and anions and positive for holes and cations. Current density for electron and holes can be written in the DD form as following:

$$j_n(x, t) = q\mu_n n(x, t) \frac{\partial V(x, t)}{\partial x} - qD_n \frac{\partial n(x, t)}{\partial x}, \quad (6)$$

$$j_p(x, t) = -q\mu_p p(x, t) \frac{\partial V(x, t)}{\partial x} - qD_p \frac{\partial p(x, t)}{\partial x}. \quad (7)$$

Conversely, it is appropriate to express the ionic DD current as follows:

$$j_a(x, t) = -q\mu_a a_{lim} F[\eta_a(x, t)] \frac{\partial \phi_a(x, t)}{\partial x}, \quad (8)$$

$$j_c(x, t) = q\mu_c c_{lim} F[\eta_c(x, t)] \frac{\partial \phi_c(x, t)}{\partial x}, \quad (9)$$

where  $F$  function is Blackmore distribution function and  $\phi$  is quasi-Fermi level for ions.  $\eta_a$  and  $\eta_c$  are normalized electro-chemical potential of anions and cations, respectively, and connected to the quasi-Fermi levels as follows:

$$\eta_a(x, t) = \frac{|q|V(x, t) + \phi_a(x, t)}{kT}, \quad (10)$$

$$\eta_c(x, t) = -\frac{|q|V(x, t) + \phi_c(x, t)}{kT}. \quad (11)$$

Note that the Blackmore distribution function that describes hopping transport of ions between individual sites, is following:

$$F(\eta_i) = \frac{1}{e^{-\eta_i} + 1}. \quad (12)$$

In Eqs. (8) and (9),  $a_{lim}$  and  $c_{lim}$  represent limiting concentrations that limit the maximum accumulation of ionic carriers within the perovskite material. We implemented Schottky boundary conditions for electronic current fluxes, as will be described in the following sections, while applying zero flux conditions for ionic carriers. The main system of partial differential equations (PDEs), represented by Eqs. (1)–(5), was solved using the finite volume method. Additionally, we incorporated the WKB approximation based on method utilized by Kyoungsoon et al. [10] to account for electron tunneling from the left (BDD), and hole tunneling from the right (ITO) contacts, respectively. Moreover, we considered the lowering of the Schottky barrier due to image force charges and dipole effects. The reduction in the Schottky barrier resulting from these influences can be described by the following equation [13]:

$$\Delta\Phi(t) = q \left[ \beta \sqrt{\frac{|q|E_m(t)}{4\pi\varepsilon\varepsilon_0}} + \Gamma |E_m(t)| \right]. \quad (13)$$

In this equation,  $E_m$  represents the maximum of electric field at the surface of the electrodes.

Since there is no generation or recombination of mobile ions, the right-hand side of continuity equations for ions are zero. On the other hand, for electronic carriers we only considered trap assisted recombination. Therefore,  $U_n = -R_n$  and  $U_p = -R_p$ , where  $R_n$  and  $R_p$  are recombination rate based on well-known Shockley-Read-Hall (SRH) model. As the boundary conditions we used Schottky boundary conditions and in addition to the Schottky barrier reduction we considered charge carrier tunneling.

### Simulation geometry and parameters

The parameters used for our calculations are compiled in Table. Among the fitting parameters were the concentrations and mobilities of the ions, along with the parameters  $\beta$  and  $\Gamma$  from Eq. (13). Utilizing the simulation parameters specified in Table and applying SG discretization to solve the PDEs described by Eqs. (1)–(5), we initially established the equilibrium state for electronic carriers by presuming that ionic carriers had zero mobility. This equilibrium outcome was then used as a preliminary estimate for tackling the non-equilibrium situation, which began with ions distributed uniformly throughout the system.

Table

Simulation parameters for BDD-perovskite-ITO configuration

| Parameter     | Description                                  | Value                 | Unit                    |
|---------------|----------------------------------------------|-----------------------|-------------------------|
| $T$           | Temperature                                  | 300                   | K                       |
| $d$           | Perovskite thickness                         | 100                   | nm                      |
| $\varepsilon$ | Relative permittivity                        | 12                    | 1                       |
| $\chi$        | Electron affinity                            | -4.17                 | eV                      |
| $IP$          | Ionization potential                         | -6.48                 | eV                      |
| $N_D$         | Uniform donor concentration                  | 0                     | $\text{cm}^{-3}$        |
| $N_A$         | Uniform acceptor concentration               | $3 \cdot 10^8$        | $\text{cm}^{-3}$        |
| $N_{CB}$      | eDOS of conduction band                      | $1 \cdot 10^{19}$     | $\text{cm}^{-3}$        |
| $N_{VB}$      | eDOS of valance band                         | $1 \cdot 10^{19}$     | $\text{cm}^{-3}$        |
| $\mu_n$       | Electron mobility (Constant mobility model)  | 50                    | $\text{cm}^2/\text{Vs}$ |
| $\mu_p$       | Hole mobility (Constant mobility model)      | 50                    | $\text{cm}^2/\text{Vs}$ |
| $N_{ani}$     | Uniform fixed anion concentration            | $0.9 \cdot 10^{18}$   | $\text{cm}^{-3}$        |
| $N_{cat}$     | Uniform fixed cation concentration           | $1.3 \cdot 10^{19}$   | $\text{cm}^{-3}$        |
| $\mu_a$       | Anion mobility                               | $8.0 \cdot 10^{-9}$   | $\text{cm}^2/\text{Vs}$ |
| $\mu_c$       | Cation mobility                              | $4.0 \cdot 10^{-9}$   | $\text{cm}^2/\text{Vs}$ |
| $a_{lim}$     | Limiting anion concentration                 | $1.41 \cdot 10^{22}$  | $\text{cm}^{-3}$        |
| $c_{lim}$     | Limiting cation concentration                | $4.67 \cdot 10^{21}$  | $\text{cm}^{-3}$        |
| $\Phi_n^l$    | BDD (left) contact Schottky barrier          | 0.63                  | eV                      |
| $\Phi_n^r$    | ITO (right) contact Schottky barrier         | 1.53                  | eV                      |
| $\beta$       | Fraction of non-polarized ions               | 0.72                  | 1                       |
| $\Gamma$      | Thickness of accumulated polarized ions      | 1.25                  | nm                      |
| $w^l$         | Maximum tunneling width from the ITO contact | 10                    | nm                      |
| $w^r$         | Maximum tunneling width from the BDD contact | 10                    | nm                      |
| Area          | Contacts area                                | $2.29 \cdot 10^{-11}$ | $\text{cm}^2$           |

The device we simulated is depicted schematically in Fig. 1. This illustration shows a 100 nm thick layer of perovskite material positioned between a BDD and an ITO contact. A time-varying voltage is applied to the ITO, while the resulting calculated current is measured at the same contact.

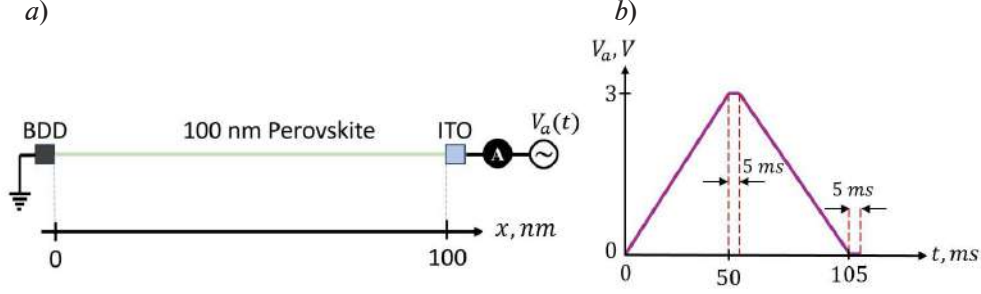


Fig. 1. Schematic of simulated device (a) and waveform of applied bias to the ITO (b)

We initialized the distribution of mobile ions to match that of the fixed ions. For solving the PDEs, we utilized a combination of the Gummel and Newton methods, leveraging the solution from the previous time step as the starting point for the current step. Given the nonlinear nature of the PDEs, we implemented a dynamic damping strategy as proposed by Amrein et al. [14].

### Results and discussion

Utilizing the parameters detailed in Table, we calculated the  $I$ – $V$  curve for the BDD–Perovskite–ITO configuration, where the BDD is grounded and a positive triangular bias is applied to the ITO. The results of this calculation are depicted in Fig. 2. In panel (Fig. 2, a), we showcase six simulation cycles in green, juxtaposed with the experimental  $I$ – $V$  characteristics represented in orange. This comparison reveals a good correlation between the simulation results and the experimental data. The pronounced increase in current observed at 3 Volts corresponds to a 5 ms retention period at the peak of applied bias. Specifically, the ITO contact experiences a triangular pulse pattern, where each cycle consists of a voltage ramping up to 3 Volts and then back down to zero over a total duration of 110 ms. Each rise and fall within the cycle are symmetric, lasting 50 ms each. A pulse of one cycle is depicted in Fig. 1, b.

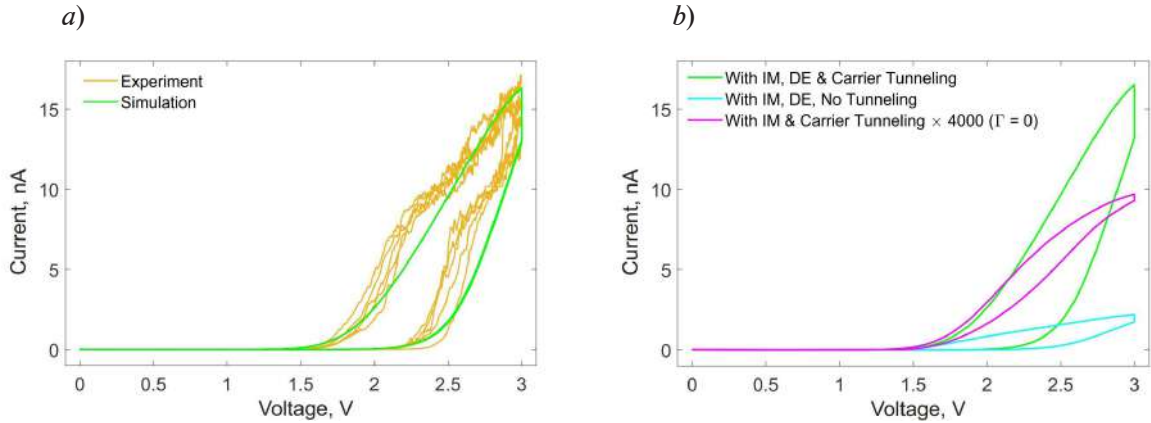


Fig. 2. Experimental (orange) and simulated (green)  $I$ – $V$  curves for 6 cycles of triangle potential pulse applied to the ITO (a); simulated  $I$ – $V$  curves illustrating the effects of varying carrier injection at the perovskite/contact interface (b). The green curve represents the scenario where both image charge force (IM) and dipole effects (DE) contribute to Schottky barrier lowering, along with carrier tunneling, the cyan curve depicts the  $I$ – $V$  characteristics without accounting for carrier tunneling but still considering Schottky barrier lowering due to IM and DE.

The magenta curve illustrates the  $I$ – $V$  response solely influenced by IM and tunneling effects, excluding dipole effects in barrier lowering

In panel of Fig. 2, *b* we present three simulated  $I$ – $V$  curves corresponding to a single cycle of a triangular pulse, each reflecting different considerations regarding carrier injection from the contacts. The green curve mirrors the scenario depicted in panel (Fig. 2, *a*), where Schottky barrier lowering is accounted for through both image charge force (IM) and dipole effect (DE), alongside electron tunneling from BDD and hole tunneling from ITO. The cyan curve represents a similar calculation but omits the effects of carrier tunneling. A comparison of these two  $I$ – $V$  curves reveals that while their shapes are comparable, they differ significantly in amplitude; specifically, the firing potential in both forward and reverse bias scans remains largely consistent, with only amplitude variations. Conversely, the magenta curve illustrates the scenario where the dipole effect on barrier lowering is excluded, although the IM effect and carrier tunneling are still considered. This corresponds to the condition  $\Gamma = 0$  in Eq. (13). To facilitate comparison with the other two curves, we have scaled this magenta curve by a factor of 4000. Notably, despite the three orders of magnitude difference in current amplitude, the firing potential in both forward and reverse bias scans remains unchanged in this case. This result diverges significantly from experimental observations, which indicate approximately a 0.8 Volt difference in firing potential between forward and backward scans. This analysis underscores the critical role of the dipole effect in Schottky barrier lowering at the perovskite/contact interface, particularly in scenarios involving significant ion accumulation.

### Conclusion

In this study, we developed a one-dimensional ionic-electronic drift-diffusion model to analyze the  $I$ – $V$  characteristics of a perovskite material situated between two chemically inert contacts. Due to the disparities in Fermi levels between the contacts and the perovskite, both contacts function as Schottky barriers. Our numerical simulations accounted for carrier tunneling and the effects of Schottky barrier reduction. Tunneling emerges as a particularly promising mechanism, driven by the pronounced band bending near the contacts caused by ion accumulation. Additionally, the enhancement of the electric field at the electrode surfaces is crucial for elucidating the observed  $I$ – $V$  curves, as it contributes to the reduction of the Schottky barrier. Beyond the conventional image charge force that facilitates barrier reduction, our calculations reveal that the dipole moment induced by the accumulated mobile ions plays a significant role in further lowering the barrier height through a dipole effect. This insight enhances our ability to accurately model the  $I$ – $V$  characteristics. Furthermore, our findings indicate that filament formation is unlikely to occur solely through internal ion redistribution in the absence of external ion injection from reactive contacts. Instead, we propose that resistive state switching should be understood primarily because of interface modulation when external ions are not introduced. These findings mark a significant advancement in our understanding of resistive state switching mechanisms in non-filamentary perovskite memristors, providing valuable insights into their operational principles.

### REFERENCES

1. Yi H., Scheiner S., Tang X., et al., Suppression of hysteresis effects in organohalide perovskite solar cells, *Advanced Materials Interfaces*. 4 (11) (2017) 1700007.
2. Satyaprasad S.P., Abdi-Jalebi M., Kamboj V.S., et al., A general approach for hysteresis-free, operationally stable metal halide perovskite field-effect transistors, *Science advances*. 6 (15) (2020) 4948.
3. Yuhang L., Li F., Cui X., et al., Multiple B-site doping suppresses ion migration in halide perovskites, *Science Advances*. 11 (11) (2025) 7054.
4. Bowen J., Chen X., Pan X., et al., Advances in Metal Halide Perovskite Memristors: A Review from a Co-Design Perspective, *Advanced Science*. 12 (2) (2025) 2409291.
5. Yan X., Shen Z., Yuan S., et al., Ion migration mediated high Seebeck effect in halide perovskites and application in infrared detection, *Chemical Engineering Journal*. (477) (2023) 147168.
6. Soumitra S., Raj K.Y., Adil Afroz M., Halide-perovskite-based memristor devices and their application in neuromorphic computing, *Physical Review Applied*. 18 (1) (2022) 017001.
7. Congyang Z., Wang B., Li W., et al., Conversion of invisible metal-organic frameworks to luminescent perovskite nanocrystals for confidential information encryption and decryption, *Nature communications*. 8 (1) (2017) 1138.
8. Sung-II K., Lee Y., Park M.-H., et al., Dimensionality dependent plasticity in halide perovskite artificial synapses for neuromorphic computing, *Advanced Electronic Materials*. 5 (9) (2019) 1900008.



9. **Xinwei G., Hu W., Azimul Haque M., et al.**, Light-responsive ion-redistribution-induced resistive switching in hybrid perovskite Schottky junctions, *Advanced Functional Materials*. 28 (3) (2018) 1704665.
10. **Mahmoodpoor A., Makarov S.**, Numerical analysis of charge carriers injection in a light emitter or detector device based on a metal-semiconductor-metal structure, *Photonics and Nanostructures-Fundamentals and Applications*. (58) (2024) 101213.
11. **Koprucki T., Gärtner K.**, Discretization scheme for drift-diffusion equations with strong diffusion enhancement, *Optical and Quantum Electronics*. (47) (2013) 791–796.
12. **Calado P., Gelmetti I., Hilton B., et al.**, Driftfusion: an open source code for simulating ordered semiconductor devices with mixed ionic-electronic conducting materials in one dimension, *Journal of Computational Electronics*. (21) (2022) 960–991.
13. **Sze S. M., Li Y., Ng K.K.**, *Physics of semiconductor devices*, John Wiley & sons. (2021).
14. **Amrein M., Wihler T.P.**, An adaptive Newton-method based on a dynamical systems approach, *Communications in Nonlinear Science and Numerical Simulation*. (19) (2014) 2958–2973.

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### **Microdisk lasers with a bridge contact pad formed by wet chemical etching**

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**Abstract.** This study presents an approach for fabricating microlasers with quantum dots on GaAs substrates, featuring a disk resonator, a bridge-type electrical contact, and a supporting mesa structure formed by wet chemical etching. The influence of under-etched ledge in the disk cavity, formed under the metal bridge, as well as the low lateral current spreading due to small electrical contact area on the cavity surface was investigated. It was found that cleaving the under-etched ledge in the disk cavity significantly reduced the threshold current leading to the possibility to continuous-wave laser operation. The low lateral current spreading associated with small metal contact on the disk surface was confirmed by the spatially resolved electroluminescence studies in the cleaved half-disk microlasers.

**Keywords:** microlasers, bridge contact, whispering gallery modes, wet chemical etching

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Материалы конференции

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### **Микродисковые лазеры с мостиковой контактной площадкой, сформированной методом мокрого химического травления**

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**Аннотация.** В работе исследованы микролазеры с квантовыми точками на подложках GaAs, состоящие из дискового резонатора, электрического контакта мостового типа



и поддерживающей мезаструктуры, сформированные жидкостным химическим травлением. Изучено влияние неотравленного выступа на краю диска, образованного под металлическим мостиком, а также слабое латеральное растекание тока из-за малой площади электрического контакта на поверхности резонатора. Обнаружено, что скалывание неотравленного выступа дискового резонатора значительно снижает пороговый ток, что приводит к возможности работы лазера в непрерывном режиме. Плохое латеральное растекание тока было подтверждено исследованиями электролюминесценции с пространственным разрешением в микролазерах полудисковой геометрии.

**Ключевые слова:** микролазеры, мостиковый контакт, мода шепчущей галереи, мокрое химическое травление

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## Introduction

Semiconductor microdisk lasers with whispering gallery modes (WGMs) and quantum dots (QDs) are promising light emitters for optoelectronic applications, ranging from optical communication systems to biomedical sensing [1]. They offer advantages such as high quality factors, low lasing thresholds, and lateral emission directionality over other microlasers [2]. Recent efforts focus on integrating these microlasers into photonic integrated circuits, requiring reliable electrical contacts. Recently, an approach of the creation of microdisk lasers supplemented with a bridge-type electrical contact and a support mesa formed by liquid chemical etching was demonstrated [3]. The bridge structure consisted of two mesas connected by a suspended gold beam, one of which is actually a microdisk resonator, and the second one serves to create an external electrical contact. The proposed method opens the way for the fabrication of small-diameter injection microlasers, since it eliminates the need to attach an electrical wire to the upper surface of the microlaser resonator. In previous experiments, relatively high threshold currents of 2 kA/cm<sup>2</sup> were measured, that was attributed to the increased losses due to the formation of under-etched ledge in the disk cavity under the bridge. In the present work we investigate the factors that affect the threshold characteristics of microdisk lasers with bridge contact.

## Materials and Methods

The laser heterostructure was synthesized using metal-organic vapor phase epitaxy on an  $n^+$ GaAs substrate. It included buffer, emitter, waveguide, and contact layers, with the active region consisting of 6 layers of InGaAs/GaAs QDs. Microlasers were fabricated using standard photolithography supplemented with explosive lithography for dielectric and metal layer formation. Etch depths was 23  $\mu\text{m}$  with laser cavity diameter of approximately 80  $\mu\text{m}$ . A TiO<sub>2</sub>-SiO<sub>2</sub> dielectric provided contact pad isolation. Ohmic contacts were made by thermal evaporation and annealing with bridge contacts formed using Cr-Au deposition and gold electroplating. The slope of the resonator wall near the active region of the heterostructure is almost vertical. The image of the formed microdisk with the gold bridge and contact pad is presented in the inset to Fig. 1, *a*. A small ledge in the disk cavity is forming under the bridge.

Aiming to investigate the influence of the ledge on the microdisk emission characteristics we cleaved a facet of the original microdisk from the bridge side in order to exclude the ledge area

(see image in the inset to Fig. 1, *b*). Moreover, one can see the metal pad on the disk surface has a small area (inset to Fig. 1, *a*), that can lead to the non-uniform electrical pumping of the cavity. In this case, we also cleaved a half-disk aiming to study the emission intensity distribution over the disk diameter. For measurements, samples were mounted on a copper heatsink. Individual electrical contact to the microlasers was made using a metal microprobe. The microlasers were pumped by current pulses of 500 ns duration with a repetition rate of 3 kHz. Electroluminescence spectra of microlasers were investigated using optical spectrum analyzer.

## Results and Discussion

Fig. 1, *a* shows the electroluminescence spectra of the original microdisk laser with bridge electrical contact obtained at the room temperature and different injection currents. At low injection currents the electroluminescence spectra correspond to the spontaneous emission of InGaAs/GaAs quantum dots. As pumping current increases a series of narrow emission lines corresponded to the WGMs appear in the long-wavelength part of the spontaneous emission band that indicated the lasing threshold. It is also confirmed with a kink on the light-current dependence for this microlaser. The threshold current for this microdisk laser is about 80 mA, which corresponds to a threshold current density of about 1.6 kA/cm<sup>2</sup>. It should also be noted, that lasing was achieved only under pulsed excitation.

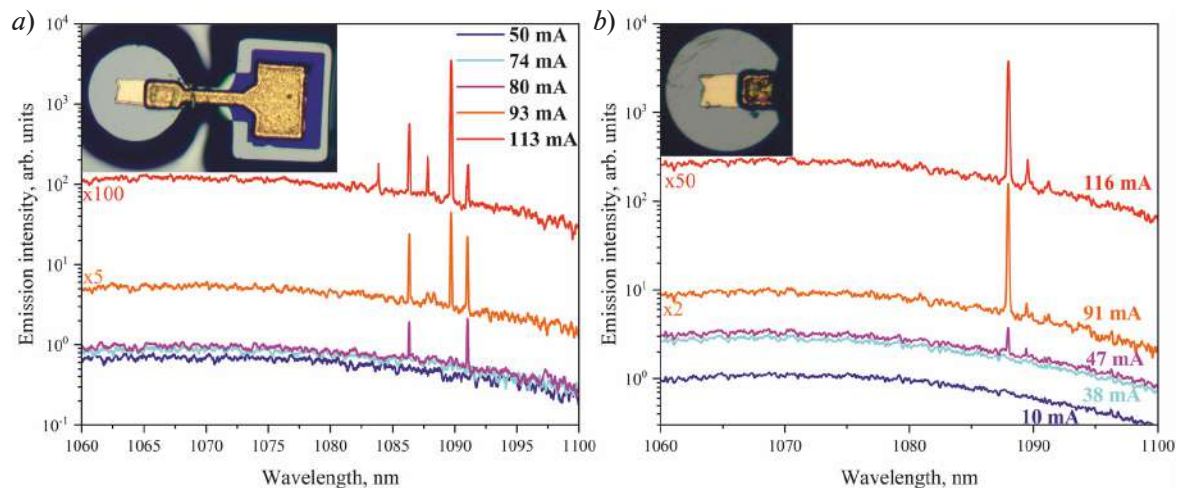


Fig. 1. Emission spectra of microlasers (initial disk (*a*), disk with cleaved facet (*b*)) measured at different injection currents  
 Insets in (*a*) and (*b*) show top view of microlasers

The room-temperature emission spectra of the microdisk laser with a removed under-etched ledge via cleaving are shown in Fig. 1, *b*. The several positive peculiarities were revealed. Firstly, the threshold current for this laser became smaller than that for the original (Fig. 1, *a*). Thus, threshold current of about 47 mA was obtained for the laser with a cleaved ledge, which is almost 2 times smaller than for the original one (Fig. 1, *a*). Secondly, the lasing spectra of the microdisk with a cleaved ledge show fewer WGMs than the original one. These results indicate that the presence of the under-etched ledge under the gold-bridge in the laser cavity actually reduces the cavity quality factor and degrades microlaser threshold characteristics. It should also be noted, that the microlaser with the cleaved ledge was able to operate in continuous-wave (CW) regime with a threshold current of about 65 mA. A higher threshold current for CW regime compared to pulsed one is attributed to the increase in laser temperature due to self-heating.

A second limitation arises from the small metal contact that covers only a fraction of the disk top surface, leading to non-uniform lateral current spreading [4]. To visualize this effect, we cleaved a microlaser through its center to form a half-disk and monitored spontaneous emission in different points of its facet. Fig. 2 compares spectra collected at the disk center (point 1) directly beneath the contact and (points 2 and 3) at two peripheral points (see inset to Fig. 2). The emission intensity decays markedly away from the electrical contact, confirming low current spreading outside the



electrical contact. Moreover, a redshift of the spontaneous emission band was also observed moving from the disk cavity center to its periphery that is associated with a lower pumping, i.e., a lower carrier concentration in the active region. Thus, an increase in the area of the metal contact should also lead to a significant decrease in the threshold characteristics as well.

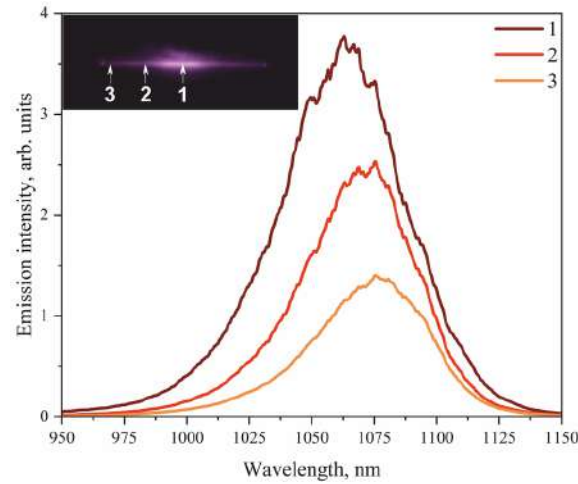


Fig. 2. Emission spectra measured at different points of the half-disk facet at the 10 mA injection current  
Inset shows the distribution of the emission intensity over the half-disk edge

### Conclusion

The QD microdisk lasers with a bridge electrical contact formed with wet chemical etching are investigated. It was found that removing the under-etched ledge in the disk cavity significantly reduced the threshold current leading to the possibility to CW laser operation. A non-uniform carrier distribution under small-area top contact was revealed. Thus, the direction of optimization of the microlaser design was determined.

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### REFERENCES

1. **Chen Y.C., Fan X.**, Biological lasers for biomedical applications, *Advanced Optical Materials*. 7 (17) (2019) 1900377.
2. **Zhukov A.E., Kryzhanovskaya N.V., Moiseev E.I., Maximov M.V.**, Quantum dot microlasers based on whispering gallery mode resonators, *Light: Science & Applications*. 10 (1) (2021) 80–91.
3. **Obratzsova A.A., Pivovarova A.A., Komarov S.D., et al.**, Bridge-contact microdisk lasers formed by wet chemical etching, *Fizika i tehnika poluprovodnikov*. 59 (1) (2025) 37–42 (in Russian).
4. **Karaborchev A.A., Makhov I.S., Shandyba N.A., et al.**, Effect of non-uniform carrier injection on two-state lasing in quantum dot microdisks with split electrical contact, *Journal of Physics D: Applied Physics*. 57 (2024) 285104.

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## **Injection edge-emitting microlasers with InGaAs/GaAs quantum dot active region**

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**Abstract.** Spectral studies of electroluminescence have been conducted on edge-emitting lasers with different cavity lengths. Mirrors were formed by focused ion beam technique and cleaving. A wide range of injection currents was used. Active region of the lasers consists of dense arrays of InGaAs/GaAs quantum dots, which enabled to obtain lasing in stripe lasers with cavities as short as 45  $\mu\text{m}$ . A noticeable blueshift of the lasing wavelength was observed with the cavity length decrease, accompanied by an increase in the threshold current density. The maximum modal gain was estimated to be at least 267  $\text{cm}^{-1}$ .

**Keywords:** microlaser, quantum dots, edge-emitter, focused ion beam

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Материалы конференции

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## **Инжекционные торцевые микролазеры с активной областью на основе InGaAs/GaAs квантовых точек**

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**Аннотация.** В работе исследованы спектры электролюминесценции торцевых микролазеров с активной областью на основе квантовых точек InGaAs/GaAs с различной длиной резонатора в широком диапазоне токов инжекции. Зеркала резонаторов



формировались травлением фокусированным ионным пучком или скалыванием по плоскостям спайности. В работе получена лазерная генерация в полосковых лазерах с длиной резонатора 45 мкм. Максимальное модальное усиление активной области оценено не менее  $267\text{ см}^{-1}$ .

**Ключевые слова:** микролазер, квантовые точки, полосковый лазер, фокусированный ионный пучок

**Финансирование:** Исследования характеристик микролазеров выполнены в рамках проекта «Зеркальные лаборатории», НИУ ВШЭ, РФ. Ионно-лучевая обработка выполнена в рамках проекта № FENW-2025-0004, ЮФУ.

**Ссылка при цитировании:** Деркач Н.Н., Махов И.С., Образцова А.А., Войтович В.И., Комаров С.Д., Фоминых Н.А., Черненко Н.Е., Шандыба Н.А., Солодовник М.С., Крыжановская Н.В., Жуков А.Е. Инжекционные торцевые микролазеры с активной областью на основе InGaAs/GaAs квантовых точек // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2025. Т. 18. № 3.2. С. 29–32. DOI: <https://doi.org/10.18721/JPM.183.204>

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## Introduction

Currently, semiconductor lasers incorporating quantum dots (QDs) have shown significant promise for optical communication systems [1]. The advantages of QD lasers include their ability to operate at high temperatures, high defect tolerance, low threshold currents, reduced linewidth, and strong resistance to parasitic optical feedback. For applications in photonic integrated circuits, minimizing the laser footprint is desirable for achieving a denser component layout and lower power consumption. Microdisk lasers utilizing whispering gallery modes feature a relatively straightforward manufacturing process, compact size, and low threshold currents [2]. However, they exhibit isotropic radiation output into free space. On the other hand, Fabry–Perot (FP) stripe lasers present an appealing alternative due to their ease of epitaxial synthesis and device fabrication processes, as well as their directional in-plane light output, which facilitates simple butt-coupling of laser radiation into waveguides. However, Stranski–Krastanow QDs, even when stacked in multiple layers, often experience low optical gain, posing challenges in reducing the length of stripe lasers to below several hundred micrometers. Another issue is fabrication of the FP laser mirrors to be compatible with the integration process technology.

In this study, we investigated FP lasers with active region based on dense arrays of InGaAs/GaAs QDs with cavity lengths as short as 50  $\mu\text{m}$ , featuring mirrors created using focused ion beam (FIB) etching technique and 45  $\mu\text{m}$ , formed by cleaving.

## Materials and Methods

A laser heterostructure was MOCVD grown on an *n*-GaAs substrate misoriented by  $6^\circ$  towards the [111] direction. The structure contained a 800 nm thick GaAs waveguide, two 1.55  $\mu\text{m}$  thick *n*- and *p*-doped  $\text{Al}_{0.39}\text{Ga}_{0.61}\text{As}$  claddings and a 350 nm thick *p*<sup>+</sup>-GaAs contact layer. The active region contained 6 QD layers formed by depositing 2 nm  $\text{In}_{0.4}\text{Ga}_{0.6}\text{As}$  and separated one from each other by 40 nm thick GaAs layers. Stripe lasers were formed by photolithography and plasma-chemical etching. To implement electrical contact a multilayer Au-based metallization was used. Short FP cavities were formed either by FIB etching (50–150  $\mu\text{m}$ ) or cleaving (45–510  $\mu\text{m}$ ).

In the experiment, the electroluminescence (EL) spectra of microlasers were studied. Electrical connection to the *p*-contact of an individual microlaser was achieved using a BeCu microprobe. To reduce the laser self-heating, a pulsed power supply mode was used (duration 500 ns, repetition rate 2 kHz). The laser radiation was collected by a microobjective and directed using fiber to the entrance slit of a grating monochromator combined with a cooled InGaAs array.



## Results and discussion

The EL spectra of edge-emitters were studied in the wide range of injection currents at the temperature of 300 K. The obtained EL spectra measured near the lasing threshold are shown in Fig. 1, *a* for FIB etched and in Fig. 1, *b* for as-cleaved lasers. The observed blue shift of the lasing wavelength with a cavity length decrease is attributed to the dependence of the gain spectral maximum on the injection current due to the presence of QD parameters dispersion [3]. The cavity length decrease also leads to an increase in threshold current density, that is associated with increased output losses in short-cavity lasers.

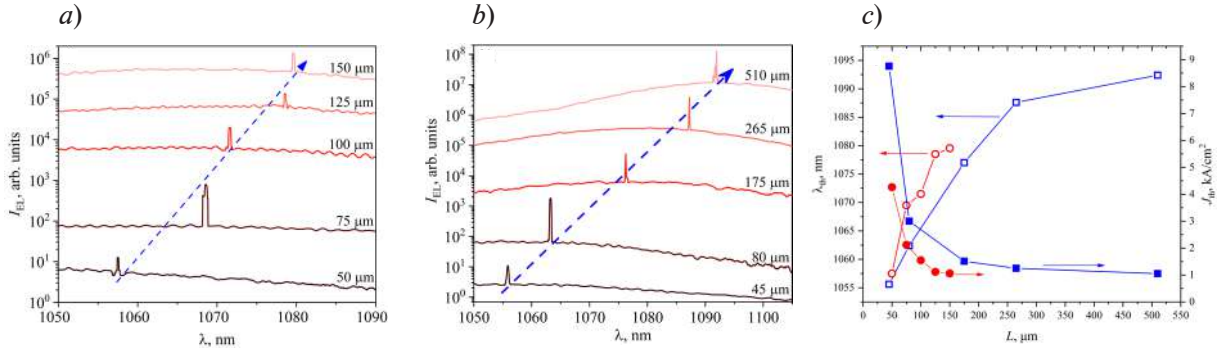


Fig. 1. EL spectra of edge-emitters with different cavity length formed by FIB (*a*) and cleaving (*b*), measured near the lasing threshold, and dependences of lasing wavelength (open symbols) and threshold current density (painted symbols) on the cavity length for FIB-etched (circles) and as-cleaved (squares) edge-emitters (*c*). Curves in (*a*) and (*b*) are vertically shifted for better clarity, blue and red lines also demonstrate shift of lasing wavelength

The obtained dependencies of the lasing wavelength and threshold current density on the cavity length are presented in Fig. 1, *c* for FIB and as-cleaved edge-emitters. One can see that these dependencies have the same tendencies for both FIB and as-cleaved lasers. A slight difference in these parameters can be attributed to a slight difference of the cavity mirrors reflectance as well as slight difference in the temperature arising due to the laser self-heating, since temperature stabilization of microlasers was not used. In the FIB-etched lasers, the threshold current reaches the minimum value of 70 mA for 125  $\mu\text{m}$  cavity length of and remains below 80 mA for 75 to 125  $\mu\text{m}$  cavities.

Since the lasing was observed in stripe lasers with FP cavity as short as 45  $\mu\text{m}$ , the mirror losses can be estimated as  $267 \text{ cm}^{-1}$ , taking into account cavity mirror reflection coefficient 0.3. Internal losses were estimated as small as  $2 \text{ cm}^{-1}$  according to the additional studies of differential quantum efficiency in long stripe lasers made of the same epitaxial wafer. As a result, total losses in 45  $\mu\text{m}$  long edge-emitter under investigation should be at least  $269 \text{ cm}^{-1}$  (note that in short stripes, internal loss is expected to be higher) that corresponds to about  $45 \text{ cm}^{-1}$  achieved modal gain per one layer of QDs at the lasing threshold. The obtained modal gain per QD layer is in good agreement with other experimental studies [4, 5].

## Conclusion

To conclude, edge-emitting lasers with InGaAs/GaAs QDs with a cavity length varied from 45  $\mu\text{m}$  to 510  $\mu\text{m}$  were investigated. The maximum optical loss, at which lasing is still possible, was determined to be not less than  $269 \text{ cm}^{-1}$ , giving an estimated modal gain of  $45 \text{ cm}^{-1}$  per one QD layer. It should be emphasized that such high gain of the QDs used makes it possible to implement very short-stripe lasers, including those with FIB-etched mirrors, as it is suitable for the microlaser integration.

## Acknowledgments

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## REFERENCES

1. Norman J.C., Mirin R.P., Bowers J.E., Quantum dot lasers – history and future prospects, Journal of Vacuum Science & Technology A. 39 (2021) 020802.
2. Zhukov A.E., Kryzhanovskaya N.V., Moiseev E.I., Maximov M.V., Quantum-dot microlasers based on whispering gallery mode resonators, Light: Science & Applications. 10 (1) (2021) 80–91.
3. Kryzhanovskaya N.V., Makhov I.S., Nadtochiy A.M., et al., Dependence of lasing wavelength on optical loss in quantum dot laser, Technical Physics Letters. 50 (11) (2024) 51–54.
4. Kharchenko A.A., Nadtochiy A.M., Mintairov S.A., et al., Study of waveguide absorption in InGaAs “quantum well-dots” heterostructures, Nano-Structures & Nano-Objects. 25 (2021) 100628.
5. Makhov I., Komarov S., Fominykh N., et al., Ultra-short stripe microlasers fabricated with a focused ion beam etching technique, Optics Letters. 50 (2) (2025) 387–390.

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### **Thin large-area graphene oxide film formation from multicomponent suspensions**

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**Abstract.** In this study, we investigate the influence of additional organic components of the graphene oxide suspension on wetting properties of PET substrates. Insufficient wettability of polymer substrates is one of the important challenges for flexible electronic devices based on graphene derivatives. In our research we showed a possibility to enhance the wettability of graphene oxide suspensions by incorporating additional organic components. Based on solubility parameters we choose N-methylpyrrolidone, dimethylacetamide, and two types of lacquer paint thinners as additional components. In all instances, we observed a successful reduction in the contact angle.

We also analyzed the drying time of multicomponent dispersions. Depending on the component ratios and the type of dispersion, the drying time can vary significantly, ranging from 3 to over 40 times, that is important for choosing the optimal deposition method. The stability of dispersions containing N-methylpyrrolidone and dimethylacetamide was confirmed for more than two months, while dispersions with lacquer paint thinners remained stable for approximately 1.5 months.

We showed possibility of formation of large-area graphene oxide films on PET substrate with the use of multicomponent graphene oxide suspensions. In case of concentrations higher than 0.9 mg/ml we observed formation of uniform films that covers the whole substrate.

**Keywords:** contact angle, dispersion medium, graphene oxide, thin films, wetting, PET

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Материалы конференции

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## Формирование тонкой пленки оксида графена большой площади из многокомпонентных суспензий

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**Аннотация.** В данной работе мы исследуем влияние дополнительных органических компонентов суспензии оксида графена на смачивающие свойства ПЭТ-подложек. Недостаточная смачиваемость полимерных подложек является одной из важных проблем для гибких электронных устройств на основе производных графена. В нашем исследовании мы показали возможность повышения смачиваемости суспензий оксида графена путем введения дополнительных органических компонентов. На основании параметров растворимости мы выбрали в качестве дополнительных компонентов N-метилпирролидон, диметилацетамид и два типа разбавителей для лакокрасочных материалов. Во всех случаях мы наблюдали успешное уменьшение контактного угла смачивания. Мы также проанализировали время высыхания многокомпонентных дисперсий. В зависимости от соотношения компонентов и типа дисперсии время высыхания может значительно варьироваться — от 3 до более чем 40 раз, что важно для выбора оптимального метода осаждения. Стабильность дисперсий, содержащих N-метилпирролидон и диметилацетамид, была подтверждена более двух месяцев, тогда как дисперсии с разбавителями лакокрасочных материалов сохраняли стабильность около 1,5 месяцев. Показана возможность формирования пленок оксида графена большой площади на ПЭТ-подложке с использованием многокомпонентных суспензий оксида графена. При концентрациях выше 0,9 мг/мл наблюдалось образование равномерных пленок, покрывающих всю подложку.

**Ключевые слова:** угол смачивания, дисперсионная среда, оксид графена, тонкие пленки, смачивание, ПЭТ

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## Introduction

One of the largest trends in the world in electronics is the development of flexible devices based on polymer substrates. However, this requires new materials which will be flexible and the conductivity of that won't be strictly dependent on the bending of substrate. Among flexible materials graphene [1] and its derivatives, graphene oxide and reduced graphene oxide [2] seem to be one of the most perspective for flexible electronics.

The first and one of the most important problems in the use of graphene derivatives for flexible electronics is formation of macrosized films on flexible substrates. In the case of graphene oxide and reduced graphene oxide wet deposition techniques including drop-casting [3], inkjet





printing [4] etc. are usually used. Another two methods that allows to deposit large area GO films are spray [5] and spin [6] coating. One of the main advantages of this method is the high film uniformity of the deposited films and the possibility of deposition of a wide range of materials, including not only graphene derivatives but also organic semiconductors, perovskite layers, etc.

Successful film formation significantly depends on the properties of the suspensions deposited. We suggest that management of the graphene oxide and reduced graphene oxide suspension properties seem to be a promising way for the formation of large-area films by spin coating. Management of suspension properties can be done by two main parameters: particle concentration and dispersion media properties, including its composition. Moreover, the effect of dispersion on the quality of GO structure hasn't been studied properly. From the literature data [7–9] we can mention that for good dispersibility dispersion media in suspension should have Hildebrand parameter ( $\delta T$ ) close or larger than of GO or rGO. Thus dimethylformamide, N-methylpyrrolidone, tetrahydrofuran, and ethylene glycol seem to be optimal candidates as additional components. We also suggest that from the point of view of size, the dye particle is very close to the graphene oxide flake, so such thinners can be used for graphene oxide dispersion. And a brand-new approach shown in this work is the use of thinners or dilutants for lacquer or enamel paints (ethylene glycol, butyl glycol, and methyl isobutyl ketone).

As a result of the use of additional components of dispersion media we showed possibility of the contact angle decrease compared to the initial aqueous suspension. We have also demonstrated that both the time of solution drying, and its concentration can affect the structural quality of GO. We showed that the use of thinner for lacquer paints is optimal for spin-coating and with the drying time close to the characteristic times of spin and spray coating. We also showed the possibility of formation of macrosized GO films and find concentration range when films are uniform and cover all the surface.

### Materials and methods

The starting component for the preparation of multi-component graphene oxide suspensions was an aqueous suspension of graphene oxide with a concentration of 3.11 mg/mL, synthesized using a modified Hummers' method (LLC "MIP Graphene," Russia Federation). The additional components used were N-methylpyrrolidone (NMP,  $\delta T = 23 \text{ MPa}^{1/2}$ , ECOS-1, Russia), dimethylacetamide (DMA,  $\delta T = 22.50 \text{ MPa}^{1/2}$ , ECOS-1, Russia), and enamel paint thinner (LT, Tamiya Ink., Japan), and an enamel paint thinner with the addition of a retarder (LTr, Tamiya Ink., Japan). Lacquer thinner is a mixture of ethylene glycol ( $\delta T = 33 \text{ MPa}^{1/2}$ ), butyl glycol ( $\delta T = 20.8 \text{ MPa}^{1/2}$ ), and methyl isobutyl ketone ( $\delta T = 17 \text{ MPa}^{1/2}$ ). The specified additional components were mixed with the initial suspension in the ratios 1:9; 2:8; 3:7; 4:6; 5:5 (equivalent GO concentrations: 0.31 mg/ml; 0.62 mg/ml; 0.93 mg/ml; 1.24 mg/ml; 1.56 mg/ml; 1.87 mg/ml). For film application, a PET film with a thickness of 125  $\mu\text{m}$  was used without any prior surface treatment. To determine the contact angle, substrates measuring  $15 \times 15 \text{ mm}$  were employed.

A custom-designed device based on a UM-301 microscope was used to study the contact angle. A mechanical pipette was used to apply droplets, with a droplet volume of 0.4  $\mu\text{L}$ . The drying time was determined by the visual disappearance of the droplet in the objective of the contact angle meter and the leveling of the PET substrate surface. The measurement of time was conducted using a timeline in the digital camera control program, with the initial point being the moment the droplet landed on the substrate and the final point being the moment the liquid disappeared from the field of view of the objective.

For GO film formation, we used the EZ4 spin-coater (LEBO Science, PRC) with the following deposition profile: 500 rpm for 30 sec and 3000 rpm for 120 sec with a further 30 min heat treatment in the low-vacuum chamber VAC-24 (Stegler, PRC) at 110  $^{\circ}\text{C}$ .

Optical images were made with M837 Series Lab Trinocular Compound Microscope (OMAX Microscope, Republic of Korea) with magnifications from 40x to 400x. SEM images of the graphene oxide film surface and EDS data were collected on the Hitachi TM-3000 scanning electron microscope (Hitachi Ltd, Japan) with a 15 kV accelerating voltage and 1200 $\times$  magnification. The thickness of the GO film was measured on NTEGRA PRIMA SPM (NT-MDT, Russian Federation) in semicontact mode with an NSG 30 cantilever: 320 kHz resonance frequency, 40 N/m force constant (Tipsnano Ob, Estonia).



Raman spectra were obtained on an InVia Raman spectrometer (Renishaw, UK). FTIR spectroscopy data for films was collected on the Nicolet iS10 (Thermo Scientific, USA) in attenuated total reflectance mode.

## Results and discussion

According to the contact angle measurements (Fig. 1) we observe a trend of increase in wetting angles with increasing GO concentration. The increase in the contact angle is associated with the peculiarities of the surface tension of the liquid containing nanoparticles near the triple line, which, in turn, changes due to the cohesive and adhesive interaction between water molecules and nanoparticles on the interfacial surfaces. That ultimately leads to an increase in the contact angle with an increasing concentration of nanoparticles reaching a peak at a certain concentration.

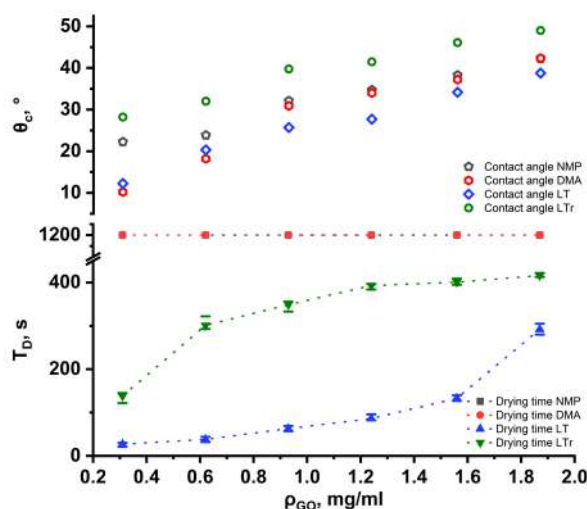


Fig. 1. Dependence of contact angle ( $\theta_c$ ) and drying time (TD) on the GO concentration ( $\rho_{GO}$ ) and composition of multicomponent suspension

In addition, a decrease in the particle size in the dispersion, according to [10], leads to an increase in the contact angle, which is apparently observed in this article because, in the case of NMP and DMA, the average contact angle at high concentrations is 3–6 degrees greater than that in the case of LT. It is assumed that in the case of NMP and DMA, better dispersibility and a smaller particle size of GO were achieved. That is indirectly confirmed by the better stability of these dispersions when settling for a considerable time.

The obtained drop drying time values demonstrate, on the one hand, a significant drying time for dispersions containing NMP and DMA as additional components, amounting to more than 20 minutes (1200 s in Fig. 1 should be understood as “more than 1200 s”). Based on the drying time values, dispersions containing LT or LTr as an additional component should be considered most suitable for the tasks of film formation by spin-coating and aerosol deposition methods because, in these cases, drying times close to those for the above processes are ensured.

The stability of multicomponent dispersions was studied by visual observation of the presence of large GO agglomerates in the dispersion. When NMP and DMA are used as additional components, no agglomerate formation is observed for more than 60 days. In the case of using LT, agglomerates appear after approximately 40–45 days, while in the case of LTr, agglomeration occurs within several hours and is obviously associated with the presence of a retarder in the dispersion. This result also indirectly indicates the correctness of determining the optimal dispersion medium for graphene oxide based on data on the values of the Hildebrand parameter.

Thus, we showed the possibility of a contact angle decrease by adding the additional organic components to the initial graphene oxide water suspension. When comparing contact angle data spread and drying time, we can say that the most promising additional component is a thinner for lacquer paints. Moreover, in the case of LT addition, drying time is close to the typical time of spray and spin coating.

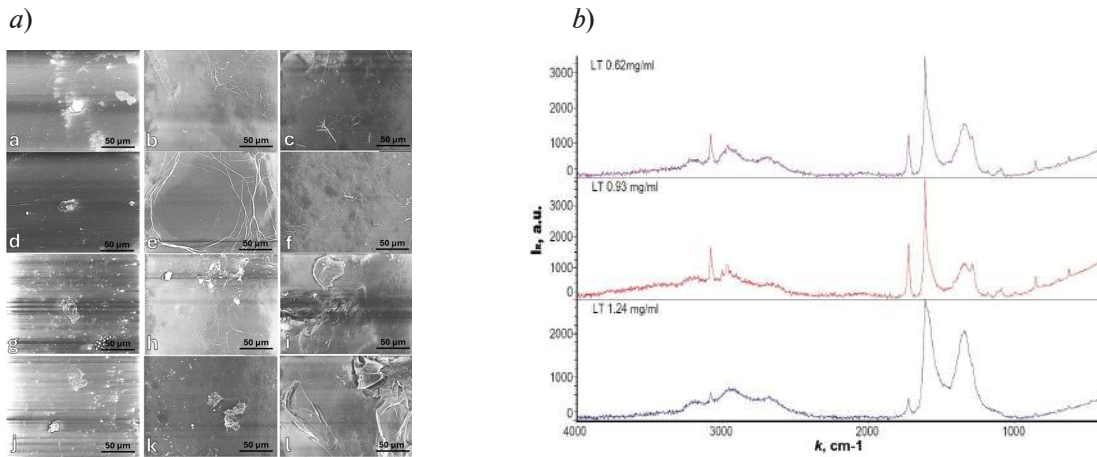


Fig. 2. SEM images of droplets of GO dispersions on a PET substrate (a) and Raman spectra of GO films deposited from multicomponent dispersion with LT ( $k$  is the wavenumber,  $I_R$  = relative Raman intensity) (b)

SEM images of a PET surface with deposited drops of multicomponent dispersions are shown in Fig. 2, a. We observed formation of island-type films in case of 0.33–0.62 mg/ml concentrations, and uniform films in other cases. Nevertheless, concentrations larger than  $\sim 1.5$  mg/ml results in large-area films but with high roughness. These films can be used for chemical and biological sensors, as well as flexible electronic devices. In the case of higher concentrations, a continuous film is formed with less pronounced folding of the upper layer. Raman spectroscopy (Fig. 2, b) also confirms the SEM imaging data. Raman spectroscopy data show the presence of spectra typical of graphene oxide with characteristic peaks in the region of 1350, 1615, and 2950  $\text{cm}^{-1}$ .

For large area film formation, we used spin-coating of the prepared multicomponent suspensions with parameters mentioned in “materials and methods” section. Optical images of the films after deposition from suspensions with different concentrations are on Fig. 3.

From Fig. 3 we see deposition of large area uniform GO films on area about  $2 \times 2$  mm. We also observe presence of some “coffee ring” effect. We also used AFM for thickness measurements. AFM visualization (Fig. 4) tells us that thickness range is from about 10 nm in case of low concentration to  $\sim 250$  nm in case of the highest concentrations. In the case of higher concentrations  $\sim 0.9$ – $1.3$  mg/ml, a continuous GO film is formed over an area of  $50 \times 50$  μm and larger.

Based on the data obtained we can mention that using multicomponent GO suspensions we can successfully form large-area films on flexible substrates with the use of spin-coating method.

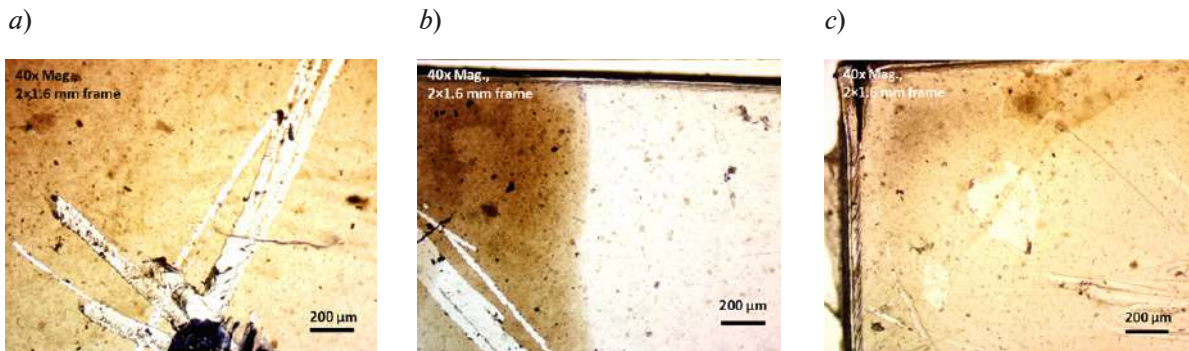


Fig. 3. Optical images of GO films spin-coated from multicomponent dispersions on a PET substrate 3:7 in LT (a); 4:6 in LT (b); 5:5 in LT (c)

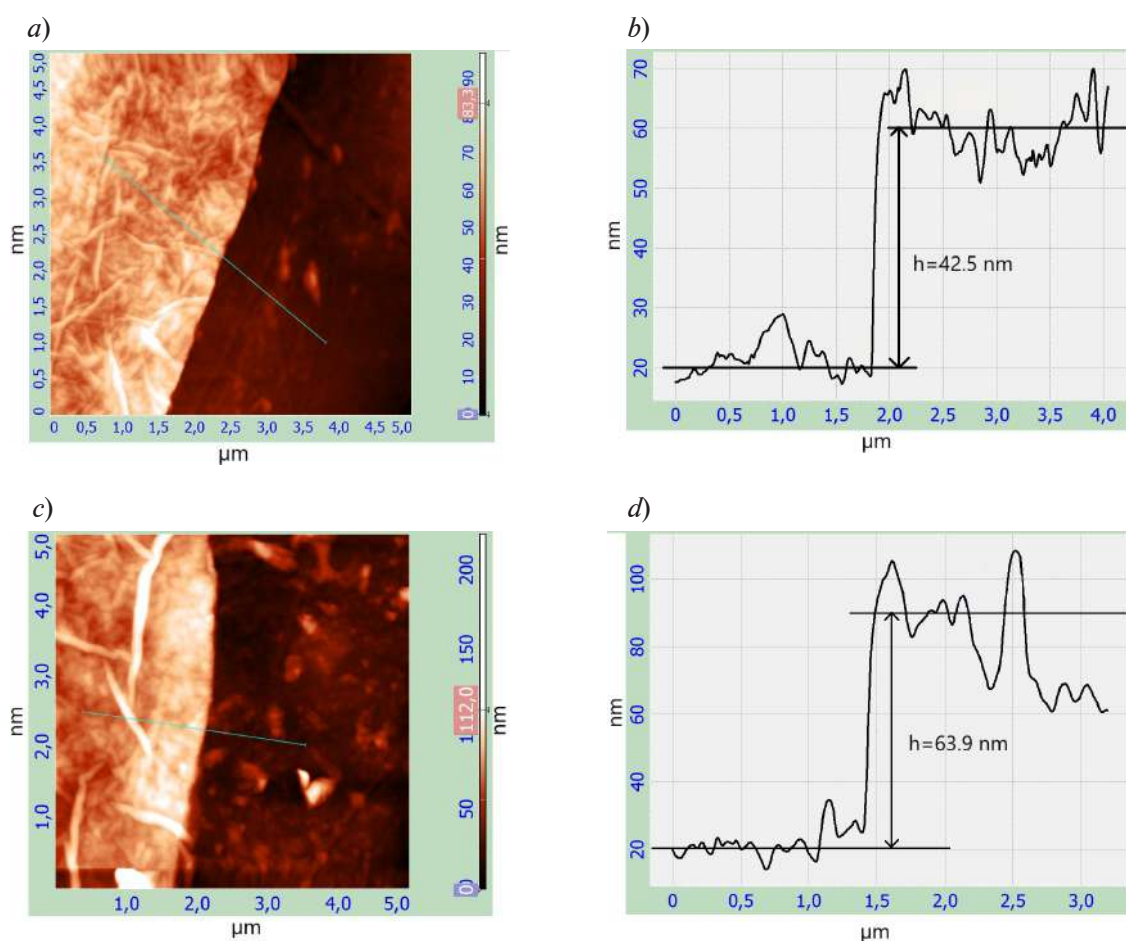


Fig. 4. AFM topography of the GO film deposited from 3:7 GO:LT (a) and cross-section (thickness of 42.51 nm (b)) and from 4:6 GO:LT (c) and cross-section (thickness of 63.90 nm (d))

### Conclusion

The work successfully demonstrated the possibility of controlling the wetting characteristics of PET substrates by adding additional organic components to a commercially available aqueous GO suspension. From the point of view of manufacturability and the possibility of forming macro-sized films, the best of the considered options for additional components is a thinner for lacquer paints. However, N-methylpyrrolidone and dimethylacetamide can also be considered as additional components if there is a heating system for the substrate or the working chamber of the application system because in the case of using N-methylpyrrolidone and dimethylacetamide, the films are slightly less defective. Based on electron microscopy data, with a component ratio from 2:8 to 4:6, or  $\sim 0.6\text{--}1.3$  mg/ml when calculated based on the concentration of graphene oxide, films of sizes sufficient for use in flexible electronics and sensor technology devices are formed. In addition, the article indirectly confirms the correctness of the concept of determining the optimal dispersion medium based on the Hildebrandt parameter.

GO dispersion with a 3:7 component ratio (GO concentration – 0.93 mg/ml) was successfully used for formation of large-area films on flexible substrates.

### REFERENCES

1. Chendake Y., et al., Graphene: A Promising Material for Flexible Electronic Devices. In: Patel SK, Taya SA, Das S, Vasu Babu K (eds) Recent Advances in Graphene Nanophotonics, Advanced Structured Materials, Springer, Cham. (2023) 83–118.
2. Chen H., Zhuo F., Zhou J., et al., Advances in graphene-based flexible and wearable strain sensors, Chemical Engineering Journal. 464 (2023) 142576.



3. **Puah P.Y., Yusoff U.H., Lee P.C., et al.**, Surface characterization, biocompatibility and osteogenic differentiation of drop-casted multilayer graphene oxide film towards human wharton's jelly derived mesenchymal stem cells, *Materials technology*. 35 (2020) 238–247.
4. **Shabanov N., Isaev A., Chiolerio A.**, Inkjet Printing of Functional Materials for Low-Temperature Electronics: A Review of Materials and Strategies, *ACS Appl. Electron. Mater.* 6 (2024) 7679–7719.
5. **Nasilowska B., Bogdanowicz Z., Hincza K., et al.**, Graphene Oxide Aerosol Deposition and its Influence on Cancer Cells. *Materials*. 13 (2020) 4464.
6. **Zhao H., Wang L., Yan M., et al.**, Photoelectric Characteristics of Reduced Graphene Oxide/Silver Nanoparticles Multilayer Films via Spin-Coating and Self-Assembly, *Materials Transactions*. 61 (2020) 1205–1209.
7. **Paredes J.I., Villar-Rodil S., Martinez-Alonso A., Tascon J.M.D.**, Graphene Oxide Dispersions in Organic Solvents, *Langmuir*. 24 (2008) 10560–10564.
8. **Khan M., Shakoar A., Khan G., Abid Zia S.**, A Study of Stable Graphene Oxide Dispersions in Various Solvents, *Journal of The Chemical Society of Pakistan*. 37 (2015) 62–67.
9. **Konios D., Stylianakis M.M., Stratakis E., Kymakis E.**, Dispersion behaviour of graphene oxide and reduced graphene oxide, *Journal of Colloid and Interface Science*. 430 (2014) 108–112.
10. **Chinnam J., Das D., Vajjha R., Satti J.**, Measurements of the contact angle of nanofluids and development of a new correlation, *International Communications in Heat and Mass Transfer* 62 (2015) 1–12.

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## **Calculation of the volume of nano- and microstructures formed on the surface of PbTe during ion-plasma treatment using machine learning**

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**Abstract.** The formation of porous Pb nano- and microstructures on the surface of PbTe films during low-energy ion-plasma treatment has been studied using scanning electron microscopy (SEM) combined with machine learning-based image analysis. PbTe epitaxial films with (111) crystallographic orientation were exposed to argon plasma at an ion energy of approximately 25 eV for varying durations (60–240 s). SEM imaging at a tilt angle of 70° enabled three-dimensional size estimation of the formed structures, which, together with automated image processing using the DLgram01 deep learning service, allowed for precise calculation of particle number, area, height, and volume. In this paper, a comparative analysis of the parameters of the Pb structure on the surface of lead telluride films with the orientation (111) and PbTe single crystals with the orientation (100) is carried out. This study demonstrates the effectiveness of machine learning for quantitative analysis of surface nanostructures after low-energy argon plasma treatment of PbTe surface.

**Keywords:** argon plasma, lead telluride, nanostructuring, volume of material

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Материалы конференции

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## **Расчет объема нано- и микроструктур, образующихся на поверхности РbТе при ионно-плазменной обработке с использованием машинного обучения**

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**Аннотация.** Формирование нано- и микроструктур на поверхности пленок РbТе при низкоэнергетической ионно-плазменной обработке изучалось с помощью сканирующей электронной микроскопии (СЭМ) в сочетании с анализом изображений на основе машинного обучения. Пленки РbТе с кристаллографической ориентацией (111) подвергались воздействию аргоновой плазмы при энергии ионов около 25 эВ при вариации времени (60–240 с). СЭМ-визуализация под углом наклона 70° позволила



провести трехмерную оценку размеров сформированных структур, что вместе с автоматизированной обработкой изображений с использованием сервиса глубокого обучения DLgram01 позволило точно рассчитать количество частиц, площадь, высоту и объем. В данной работе проведен сравнительный анализ параметров структур Pb на поверхности пленок теллурида свинца с ориентацией (111) и монокристаллов PbTe с ориентацией (100). Данное исследование демонстрирует эффективность машинного обучения для количественного анализа поверхностных наноструктур после обработки поверхности PbTe низкоэнергетической аргоновой плазмой.

**Ключевые слова:** плазма аргона, теллурид свинца, наноструктурирование, объем материала

**Финансирование:** Данная работа выполнена при поддержке Национального исследовательского центра «Курчатовский институт».

**Ссылка при цитировании:** Белов Я.Д., Амиров И.И., Зимин С.П. Расчет объема нано- и микроструктур, образующихся на поверхности PbTe при ионно-плазменной обработке с использованием машинного обучения // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2025. Т. 18. № 3.2. С. 40–44. DOI: <https://doi.org/10.18721/JPM.183.206>

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## Introduction

The study of processes forming nano- and microstructures on the surface of semiconductor materials is of significant interest both from a fundamental and applied perspective. Among promising materials for nanostructuring, lead telluride (PbTe) occupies a special place due to its unique physical properties and wide application in infrared optics and thermoelectric devices [1–2]. It is known that when PbTe is treated in argon plasma, surface sputtering occurs primarily due to the removal of lead telluride molecules, accompanied by subsequent redeposition of lead in the form of quasi-spherical nanostructures [1]. Previous studies have shown that at ion energies close to the sputtering threshold ( $\sim 25$  eV), the sizes of such structures increase with treatment duration. However, most studies were limited to analyzing morphological characteristics (shape, density, particle diameter), while a quantitative assessment of the deposited material volume—essential for understanding growth mechanisms and material redistribution—was not conducted. Such data are crucial for modeling self-organization processes and optimizing technologies for creating functional coatings.

The aim of this work was to develop a methodology for quantitatively assessing the volume of nano- and microstructures formed on the surface of PbTe films during ion-plasma treatment. To automate SEM image analysis and obtain accurate data on the number, size, and spatial distribution of structures, a machine learning approach was used with the DLgram01 service [3, 4].

## Materials and Methods

(111) PbTe films, 2  $\mu\text{m}$  thick, were grown by molecular beam epitaxy on (111)  $\text{CaF}_2/\text{Si}$  substrates. Samples were treated for durations of  $t = 60, 120, 180,$  and  $240$  seconds in a dense argon plasma reactor with high-frequency inductive discharge (13.56 MHz, 800 W, 0.15 Pa) at an ion energy of  $\sim 25$  eV [5]. To investigate the role of PbTe crystallographic orientation in sputtering processes, similar treatments were performed on the surface of (100) PbTe crystals, as described in [1]. Surface morphology after ion-plasma treatment was analyzed using a Zeiss Supra-40 scanning electron microscope. Automated SEM image processing, including determination of the number, size, and area of 2D nanostructures, was performed using machine learning [4] with the DLgram01 service [3]. This network was trained on previously obtained images, which were manually marked as a test sample. After that, a model was created on the markup data in the service to determine this type of particles. Using SEM images of nanostructures obtained at a  $70^\circ$  tilt angle, their 3D dimensions were determined, allowing for the calculation of the deposited material volume and the study of quantitative parameters of surface structures depending on treatment time and crystallographic orientation.



## Results and Discussion

Analysis of the (111) PbTe film surface after plasma treatment showed that hemispherical nanostructures formed after 60 and 120 seconds of exposure (insets in Fig. 1, *a*, *b*). At  $t = 180$  s, both hemispherical nanostructures and larger quasi-spherical structures appeared (inset in Fig. 1, *c*). Analysis of SEM images using the DLgram01 service helped determine particle sizes and densities. With increasing treatment time, the average diameter of nanostructures increased, while their density decreased (Table 1). Based on SEM images of nanostructures obtained at a  $70^\circ$  tilt angle (insets in Fig. 1), the heights of the formed nanostructures were determined, and particle size distribution histograms were constructed. Using these data, considering particle shapes, the total volume of lead particles on the surface (equal to the sum of all particle volumes over an area of  $9.35 \times 10^5 \text{ nm}^2$ ) and the corresponding equivalent film thickness (ratio of particle volume to investigation area) were calculated (Table 1).

Based on SEM image analysis, it was found that with increasing treatment time of (111) PbTe films in argon plasma, not only did the average diameter of nanostructures increase, but their shape also changed from hemispherical to teardrop-like and partially merging. This may be related to coalescence and material redistribution processes under the influence of the ion flux. These changes became especially pronounced after 180 seconds of treatment, when the active formation of large aggregates began. Analysis of the dependence of particle volume on time showed linear growth up to 180 seconds. Changes in particle shape led to a stepwise increase in volume, possibly indicating pore formation [6] or changes in the redeposition mechanism, such as increased local concentration of Pb vapor on the surface or changes in adatom mobility due to sample heating caused by prolonged argon plasma exposure.

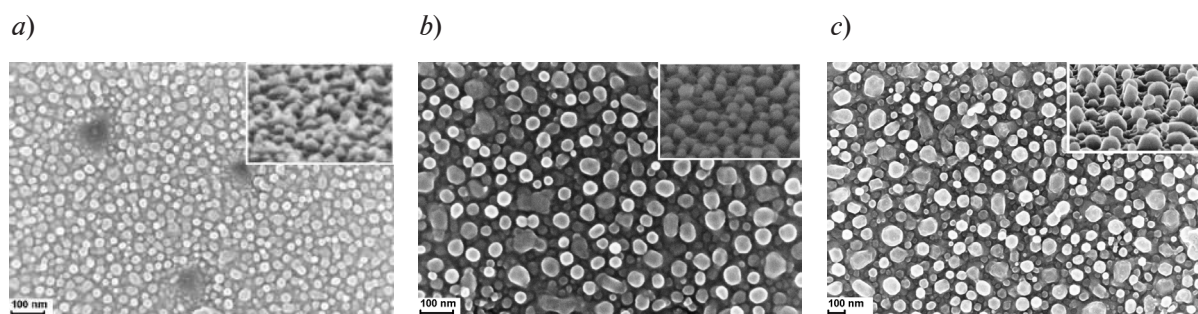


Fig. 1. Images of (111)PbTe films surface after treatment for 1-3 min (*a–c*, respectively)  
The insets show SEM images of the structures obtained at  $70^\circ$

Table 1

**Characteristics of nano- and microstructures  
after plasma treatment with different times from area  $9.35 \times 10^5 \text{ nm}^2$**

| Orientation                        | (111) PbTe               | (111) PbTe               | (111) PbTe               | (111) PbTe               | (100) PbTe               |
|------------------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| Plasma treatment time, s           | 60                       | 120                      | 180                      | 240                      | 240                      |
| Particle density, $\text{cm}^{-2}$ | $9.6 \cdot 10^{10}$      | $4.4 \cdot 10^{10}$      | $3.1 \cdot 10^{10}$      | $1.1 \cdot 10^{10}$      | $7 \cdot 10^9$           |
| Diameter, nm                       | 15-25                    | 20-35                    | 25-50                    | 50-75                    | 65-85                    |
| Average particle height, nm        | $20 \pm 2$               | $25 \pm 3$               | $40 \pm 4$               | $60 \pm 6$               | $78 \pm 8$               |
| Volume of particles, $\text{nm}^3$ | $2.3 \pm 0.2 \cdot 10^6$ | $7.0 \pm 0.6 \cdot 10^6$ | $1.1 \pm 0.1 \cdot 10^7$ | $2.1 \pm 0.2 \cdot 10^7$ | $2.7 \pm 0.3 \cdot 10^7$ |
| Equivalent Pb thickness, nm        | $2.5 \pm 0.4$            | $7.5 \pm 1.1$            | $12.2 \pm 1.7$           | $22.5 \pm 3.2$           | $28 \pm 3.9$             |

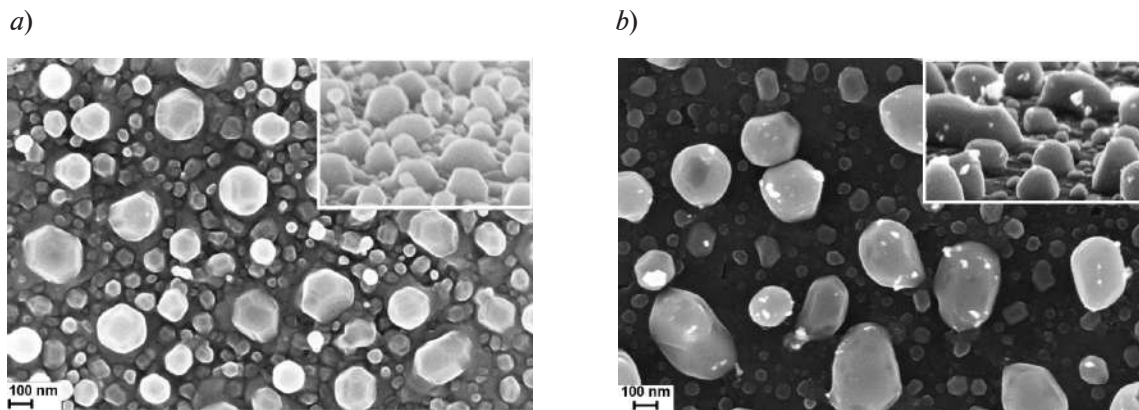


Fig. 2. Comparison of PbTe surface morphology after 240 s treatment for (111) (a) and (100) (b) orientations

Surface analysis of PbTe after 240 seconds of argon plasma treatment revealed significant differences in the nature of nano- and microstructure formation depending on the crystallographic orientation of the sample. Fig. 2 shows the surface morphology for single-crystal PbTe samples with (111) and (100) orientations. For (100) PbTe (Fig. 2, *b*), redeposition occurred more actively, and structure sizes increased. As seen from SEM images (Fig. 2), well-formed, predominantly hemispherical structures uniformly distributed across the surface were observed on the (111) film. In contrast, on the (100) film, larger and more heterogeneous formations appeared, including individual teardrop-like structures and their aggregates. At higher magnifications, pores were visible on the surface of such structures.

According to Table 1, the average structure diameter on the (111) film was 50–75 nm, while on the (100) film, it increased to 65–85 nm. A more significant difference was observed in particle height: the average height for the (100) orientation reached 78 nm compared to 60 nm for (111). The difference in volumes was minor since the density for (100) was 1.7 times lower: the particle volume on the (100) crystal was  $\sim 2.7 \times 10^7 \text{ nm}^3$  over an area of  $9.35 \times 10^5 \text{ nm}^2$ , which was 20% higher than for the (111) film ( $\sim 2.1 \times 10^7 \text{ nm}^3$ ).

The equivalent lead layer thickness for the (100) orientation was 28 nm, compared to 22.5 nm for (111). This is because the sizes of large aggregates on (100) were much larger than on (111), although their density was 1.7 times lower.

The obtained data indicate that the crystallographic orientation of lead telluride plays an important role in the formation of morphology and structure volume during ion-plasma treatment, which should be considered when purposefully creating nanostructured surfaces.

### Conclusion

The particle volume calculation method, based on automated SEM image processing using machine learning with the DLgram01 service, demonstrated high accuracy for analyzing structures formed on single-crystal PbTe surfaces during ion-plasma treatment. Changes in the size, shape, and structure of lead particles on the PbTe surface at constant ion energy, process duration, and crystallographic orientation are associated with varying sputtering rates, surface temperature, and the formation of lead particles on the treated surface.

### REFERENCES

1. Zimin S.P., Amirov I.I., Mazaletskiy L.A., et al., Sputtering Yields for Single Crystal Samples of PbX (X= S, Se, Te) with Different Crystallographic Orientations, *Journal of Surface Investigation: X-ray, Synchrotron and Neutron Techniques*. 18 (6) (2024) 1326–1332.
2. Wang B., Zhao H., Zhang B., et al., Enhanced thermoelectric performance of *n*-type PbTe via carrier concentration optimization over a broad temperature range, *ACS Applied Materials & Interfaces*. (2023) 15 (11) 14424–14432.

3. **Matveev A.V., Nartova A.V., Sankova N.N., Okunev A.G.**, DLgram cloud service for deep-learning analysis of microscopy images, *Microscopy Research and Technique*. 87 (5) (2024) 991–998.

4. **Okunev A.G., Mashukov M.Y., Nartova A.V., Matveev A.V.**, Nanoparticle recognition on scanning probe microscopy images using computer vision and deep learning, *Nanomaterials*. 10. I. 7. 1285. (2020) 16.

5. **Zimin S.P., Amirov I.I., Naumov V.V., et al.**, Modification of the Surface of Lead-Tin Telluride Films by Low-Energy Argon Ions, *Journal of Surface Investigation: X-ray, Synchrotron and Neutron Techniques*. 16 (5) (2022) 876–883.

6. **Zimin S.P., Amirov I.I., Naumov V.V., Guseva K.E.**, The Formation of Hollow Lead Structures on the Surface of PbSe Films Treated in Argon Plasma, *Technical Physics Letters*. 44 (6) (2018) 518–521.

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## Effect of rapid thermal annealing on the properties of GaPN(As)-based heterostructures grown on silicon substrates

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**Abstract.** The unique properties of dilute nitrides, such as GaPN(As), make them highly promising for use in solar cells and optoelectronic devices. In this work we report on the investigation of the effects of rapid thermal annealing on the structural and optical properties of GaPN(As) solid solutions. The GaPN(As)-based heterostructures were grown on a silicon substrates by plasma assisted molecular beam epitaxy. The effect of rapid thermal annealing on the properties of these materials was studied using photoluminescence spectroscopy and X-ray diffraction analysis.

**Keywords:** dilute nitride semiconductors, GaPN(As), rapid thermal annealing, photoluminescence, X-ray diffraction

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Материалы конференции

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## Влияние быстрого термического отжига на свойства структур GaPN(As), выращенных на кремниевых подложках

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**Аннотация.** Уникальные свойства разбавленных нитридов, таких как GaPN(As), делают их перспективными для использования в солнечных элементах и оптоэлектронных приборах. В данной работе мы исследуем влияние быстрого термического отжига на структурные и оптические свойства твердых растворов GaPN(As). Гетероструктуры GaPN(As) были выращены на кремниевых подложках методом молекулярно-пучковой эпитаксии с плазменной активацией. Влияние быстрого термического отжига на свойства этих материалов было изучено с помощью фотолюминесцентной спектроскопии и рентгеноструктурного анализа.

**Ключевые слова:** разбавленные нитриды, GaPN(As), быстрый термический отжиг, фотолюминесценция, рентгеновская дифракция

**Финансирование:** Исследование выполнено за счет гранта Российского научного фонда № 23-79-00032.

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## Introduction

Dilute nitrides are a class of III-V semiconductors in which a small fraction of the group V atoms is replaced by nitrogen. Low-nitrogen solid solutions, such as GaPN(As), show unique properties, including direct and variable bandgap on the condition of lattice matching with silicon substrates [1]. Thus, these materials have the potential for creating efficient light-emitting devices for integrated silicon photonics.

It is known that heteroepitaxy on Si substrates leads to the formation of many defects in GaPN(As)-based structures [2]. This in turn leads to degradation in their optical properties. At the same time, many studies have shown that the optical properties of GaPN(As) alloys can be improved if the density of defects is reduced. It can be achieved by optimizing the growth conditions or by performing post-growth rapid thermal annealing [2–5].

## Materials and methods

In this study, a heterostructures with bulk GaPN(As) layer were grown by plasma assisted molecular beam epitaxy on a silicon substrate with a (001) orientation misoriented by 4°. We investigated three samples: 1, GaP<sub>0.98</sub>N<sub>0.02</sub>/Si with a bulk layer thickness of 300 nm; 2, GaP<sub>0.98</sub>N<sub>0.02</sub>/Si with a bulk layer thickness of 600 nm; 3, GaP<sub>0.88</sub>N<sub>0.02</sub>As<sub>0.1</sub>/Si with a bulk layer thickness of 1200 nm.

After growth, the samples were annealed at temperatures of 830, 850 and 870 °C for 30 seconds on a Jipelec JetFirst 100 setup in a nitrogen atmosphere. The optical properties of heterostructures before and after annealing were studied by photoluminescence (PL) spectroscopy in the range of 550–700 nm at room temperature. The structural properties were assessed by X-ray diffraction analysis using an X-ray diffractometer DRON-8 (with the copper anode with radiation type Kα1 ( $\lambda = 1.5405 \text{ \AA}$ )).

## Results and discussion

The PL spectra of the first and second samples before and after rapid thermal annealing (RTA) are presented in Fig. 1, *a, c*. The peak PL intensity of the sample 1 after annealing increases about two times at temperatures of 830 and 850 °C and has not changed at 870 °C. The peak PL intensity of the sample 2 after annealing increases about two times at temperatures of 830 and 870 °C and about three times at 850 °C. So, the maximum PL intensity was obtained at a temperature of 830 °C for sample 1 and 850 °C for sample 2. In addition to the intensity increase, a shift of the peak wavelength to the short-wave region of the spectrum (blueshift) was observed with increasing annealing temperature. More details of the changes in the photoluminescence peak for sample 1 and 2 are shown in Fig. 1, *b, d*.

The increase in PL intensity may be due to the density of N-related point defects is reduced by RTA [3]. The blueshift could be caused by the increase in injected carriers due to the decrease of defects and the improvement of the uniformity of the nitrogen compositions after annealing [6]. At annealing temperatures of 850 and 870 °C peaks corresponding to different composition of GaPN appear. This indicates splitting of homogeneous composition of GaPN into regions with different concentration of nitrogen.

The third sample's intensity doubled after annealing at 830 °C and increased by one and a half times after annealing at 850 and 870 °C (Fig. 2, *a*). For the last two temperatures extra bends of the PL curve appear, as it was in the case of the second sample, indicating the presence of different nitrogen clusters.



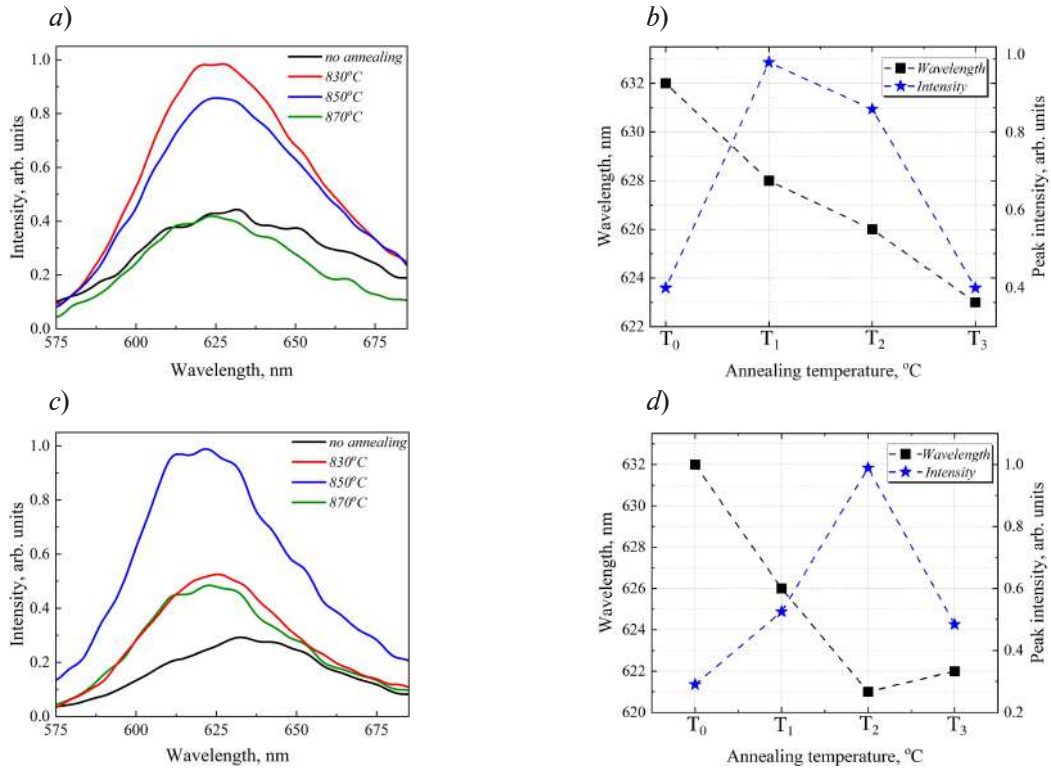


Fig. 1. PL spectrum of samples 1 (a) and 2 (c) without annealing and after RTA at different temperatures; dependence of peak PL intensity on annealing temperature (blue stars) and wavelength on annealing temperature (black squares) of samples 1 (b) and 2 (d), where  $T_0$  corresponds to no annealing,  $T_1$ ,  $T_2$ ,  $T_3$  to 830, 850, 870 °C, respectively

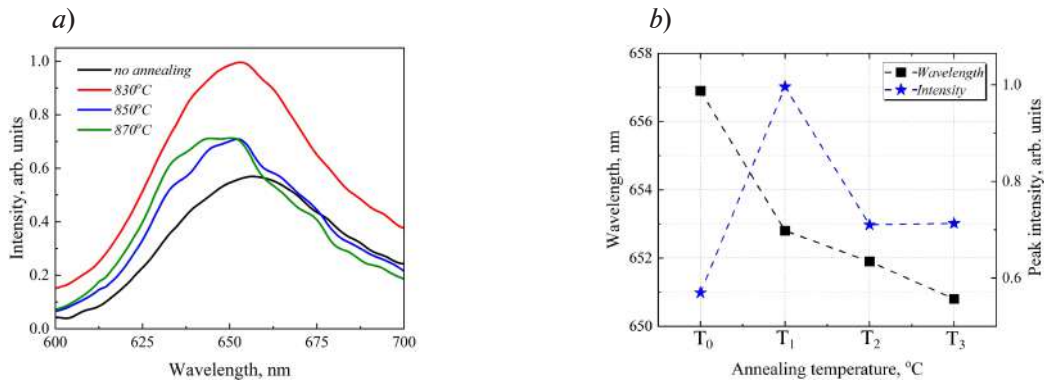


Fig. 2. PL spectrum of the sample 3 without annealing and after RTA at different temperatures (a); dependence of peak PL intensity on annealing temperature (blue stars) and wavelength on annealing temperature (black squares), where  $T_0$  corresponds to no annealing,  $T_1$ ,  $T_2$ ,  $T_3$  to 830, 850, 870 °C, respectively (b)

At the same time, the X-ray diffraction pattern shows that the crystal structure of the bulk layer remained unchanged, that is the XRD curve shape does not depend on the annealing temperature (Fig. 3).

A slight shift in the peak of the buffer layer is also observed. Shift to the right is due to stress relaxation in the buffer layer, since number of defects decreases after annealing.

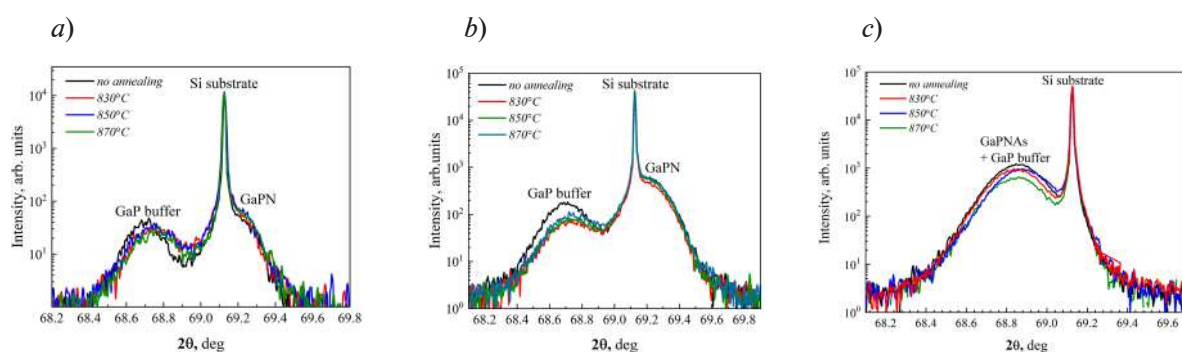


Fig. 3. XRD curves without annealing and at different annealing temperatures of sample 1 (a); sample 2 (b); sample 3 (c)

### Conclusion

We have studied the effects of rapid thermal annealing on the optical and structural properties of GaPN(As) layers grown on a silicon substrate by plasma assisted molecular beam epitaxy. It was shown that the rapid thermal annealing process at 830–870 °C for 30 s in  $N_2$  atmosphere successfully improves, as expected, the PL intensity of the GaPN layers about two and three times and the GaPNAs layer about two times. In addition, the optimal annealing temperature of samples was found (830 and 850 °C). At the same time, a decrease in the density of defects was observed and no changes in the structural properties of the bulk layers GaPN(As) were observed after RTA.

### REFERENCES

1. Mohamed Henini, Dilute Nitride Semiconductors, 1st Edition, Elsevier Science. (2004).
2. Ben Saddik K., et al., Growth modes and chemical-phase separation in  $GaP_{1-x}N_x$  layers grown by chemical beam epitaxy on GaP/Si (001), J. Appl. Phys. 134 (2023) 175703.
3. Balanta M.A.G., et al., Effects of nitrogen incorporation and thermal annealing on the optical and spin properties of GaPN dilute nitride alloys, Journal of Alloys and Compounds. 814 (2020) 152233.
4. Lazarenko A.A., Shubina K.Yu., Nikitina E.V., et al., Influence of rapid thermal annealing on the distribution of nitrogen atoms in GaAsN/GaAs, Ioffe Institute Journal: Physics and technique of semiconductors. 55 (11) (2021) 1080–1077.
5. Sakuntam Sanorpima et al., Growth and post-growth rapid thermal annealing of InGaPN on GaP grown by metalorganic vapor phase epitaxy, Journal of Crystal Growth. 298 (2007) 150–153.
6. Utsumi A., et al., Increase in luminescence efficiency of GaPN layers by thermal annealing, Physica Status Solidi. 7 (2003) 2741–2744.

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## Electrostatic control of correlated phases in spatially inhomogeneous two-dimensional moiré structures

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**Abstract.** Two-dimensional moiré structures are a promising platform for quantum simulations. In 2D van der Waals twisted bilayers, a moiré superlattice acts as a periodic potential for capturing interlayer excitons, which opens new possibilities for constructing quantum correlated phases. In addition, precise control of electronic states in such structures is possible via electrostatic doping and application of out-of-plane electric fields. However, effects related to spatial inhomogeneity, which is often present in experimental samples of van der Waals heterostructures, are currently not well studied. Here we experimentally investigate correlated phases in a spatially inhomogeneous twisted WSe<sub>2</sub>/WS<sub>2</sub> bilayer with electrostatically controlled free charge carrier density. Using photoluminescence (PL) spectroscopy, we locally detect multiple correlated phases and demonstrate continuous tuning of their energies via electric bias. Our results contribute towards the development of quantum simulators based on correlated phases in twisted van der Waals heterostructures.

**Keywords:** moiré superlattice, 2D semiconductors, strongly correlated electronic states

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## Электростатическое управление коррелированными фазами в пространственно неоднородной двумерной муаровой структуре

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**Аннотация.** Двумерные муаровые структуры являются многообещающей платформой для создания квантовых симуляторов. В двумерных Ван-дер-Ваальсовых скрученных бислоях муаровая сверхрешетка действует как периодический потенциал для захвата межслоевых экситонов, что открывает новые возможности для формирования квантово-коррелированных фаз. Кроме того, точный контроль электронных состояний в таких структурах возможен с помощью электростатического допирования и приложения внеплоскостных электрических полей. Однако эффекты, связанные с пространственной неоднородностью, которая часто присутствует в экспериментальных образцах Ван-дер-Ваальсовых гетероструктур, в настоящее время изучены недостаточно. В данной работе мы экспериментально исследуем коррелированные фазы в пространственно неоднородном скрученном бислое  $\text{WSe}_2/\text{WS}_2$  с электростатически контролируемой плотностью свободных носителей заряда. Используя фотолюминесцентную спектроскопию (ФЛ), мы локально обнаруживаем множество коррелированных фаз и демонстрируем непрерывную перестройку их энергий с помощью электрического смещения. Наши результаты важны для разработки квантовых симуляторов на основе коррелированных фаз в скрученных Ван-дер-Ваальсовых гетероструктурах.

**Ключевые слова:** муаровая сверхрешетка, двумерные полупроводники, сильно коррелированные электронные состояния

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## Introduction

Moiré structures are a powerful platform for studying solid state physics, with prospective applications for developing novel quantum simulators. Heterostructures based on two-dimensional materials make it possible to create moiré superlattices and control electronic states with unique degrees of freedom such as the twist angle, lattice mismatch, deformation, doping by charge carriers, as well as external electric and magnetic fields. This makes it possible to implement and study various fundamental multiparticle quantum models of condensed matter physics [1]. In addition, the strong optical response of excitons in such structures allows straightforward optical



readout [2]. By now, correlated electronic phases have been observed in  $\text{WSe}_2/\text{WS}_2$  heterostructures, and corresponding exciton dynamics have been studied [3]. Here we study the behavior of strongly correlated phases in a spatially heterogeneous structure.

### Results and discussion

We investigate a moiré superlattice device based on  $\text{WSe}_2$  and  $\text{WS}_2$  monolayers in R stacking and with contact, top and bottom gates (Fig. 1, *a*). We can apply voltages  $V_{\text{lg}}$  and  $V_{\text{bg}}$  to the top and bottom gates for independent control of the free carrier density and displacement electric field. The contacts and gates are made of atomically thin graphite and gold electrodes fabricated by electron beam lithography. The interlayer exciton (IX) is generated by optical excitation, while the impurity electron and hole are in different monolayers (Fig. 1, *b*).

PL spectra are measured at 8 K with 633 nm laser excitation, revealing a complex dependence on gate voltage. We observe an interlayer exciton at 1.38–1.42 eV and a shift in its energy near the electron filling factor  $n = 1$  of the moiré superlattice. In the range between the filling factors  $n = 0$  and  $n = 1$ ,

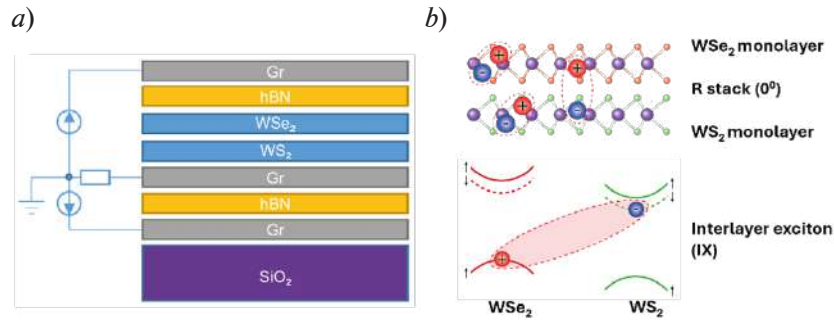


Fig. 1. Scheme of the sample (*a*), showing two monolayers in an R stack (top) and interlayer exciton formation in  $\text{WSe}_2/\text{WS}_2$  heterostructure (bottom) (*b*)

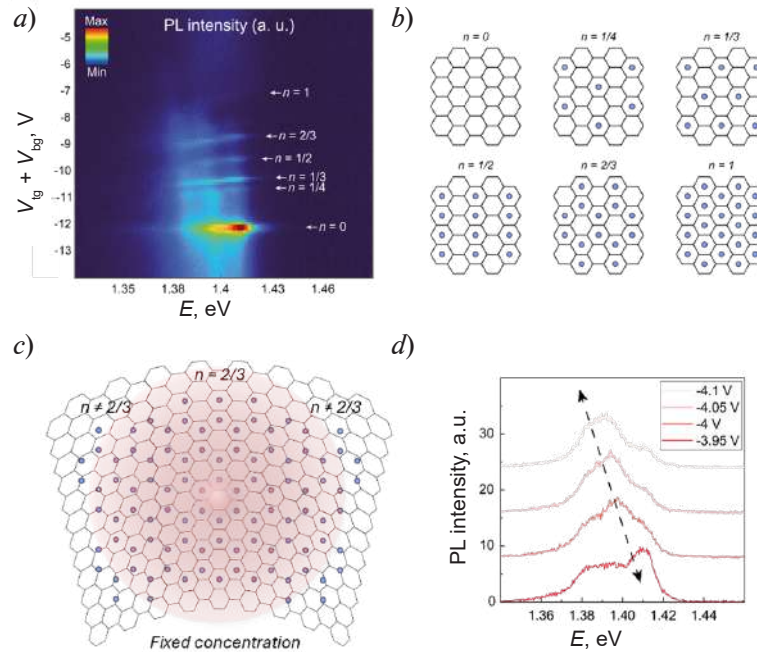


Fig. 2. Dependence of the photoluminescence spectrum of a  $\text{WSe}_2/\text{WS}_2$  structure on gate voltage (*a*); localization of free electron charge carriers in a moiré superlattice (*b*); schematic illustration of a spatial distribution of both energy IX and the filling factor due to heterogeneity in the sample (*c*), the red-colored area indicates the laser spot; shift of the filling factor  $n = 2/3$  with the applied voltage (the dotted line schematically shows the shift of the PL maximum) (*d*)



we clearly observe a number of maxima in the PL spectra, corresponding to fractional filling factors of the moiré superlattice [4, 5] (Fig. 2, *a*). The integer and fractional filling factors correspond to the state of the generalized Wigner crystal. In this case, the free charge carriers form an ordered periodic lattice and are localized at the points of symmetry of the moiré superlattice (Fig. 2, *b*). Interestingly, we also observe a continuous energy shift of the local photoluminescence maxima with voltage. This is attributed to the spatial inhomogeneity of the twist angle between semiconductor monolayers, where twist angle gradient within the excitation laser spot creates certain spatial distributions of both the IX energy and filling factor (Fig. 2, *c*). In addition, local tensile or compressive strain can also contribute to the observed effect. We note that the presence of such inhomogeneity in the heterostructure in principle allows us to manipulate the spatial position of the desired correlated state in the heterostructure within the excitation laser spot. In this case, the region of the structure with a certain filling factor shifts inside the laser spot when the concentration of charge carriers changes, which leads to a change in the energy of the interlayer exciton. Fig. 2, *d* shows such shift of the PL peak corresponding to the filling factor  $n = 2/3$ . Further studies of exciton dynamics in such structures will provide better understanding of the processes occurring in moiré superlattices for the development of 2D quantum simulators.

### Conclusions

In this work, we fabricated and characterized moiré structures based on twisted WSe<sub>2</sub> and WS<sub>2</sub> monolayers. We observed a continuous energy shift of the PL peaks corresponding to certain filling factors, which is attributed to the spatial inhomogeneity of the twist angle and local strain of the heterostructure. This will allow for future research on Hubbard physics in spatially inhomogeneous structures. Our results are important for the development of quantum technologies using two-dimensional materials.

### REFERENCES

1. Wu F., et al., Hubbard model physics in transition metal dichalcogenide moiré bands, *Physical Review Letters*. 121 (2) (2018) 026402.
2. Jin C., et al., Observation of moiré excitons in WSe<sub>2</sub>/WS<sub>2</sub> heterostructure superlattices, *Nature*. 576 (7746) (2019) 76–80.
3. Tang Y. et al., Simulation of Hubbard model physics in WSe<sub>2</sub>/WS<sub>2</sub> moiré superlattices, *Nature*. 579 (7799) (2020) 353–358.
4. Lian Z. et al., Valley-polarized excitonic Mott insulator in WS<sub>2</sub>/WSe<sub>2</sub> moiré superlattice, *Nature Physics*. 20 (1) (2024) 34–39.
5. Zhang Z. et al., Correlated interlayer exciton insulator in heterostructures of monolayer WSe<sub>2</sub> and moiré WS<sub>2</sub>/WSe<sub>2</sub>, *Nature physics*. 18 (10) (2022) 1214–1220.

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## Effect of Al concentration on the pyroelectric properties of AlGaInP<sub>2</sub> alloys

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**Abstract.** CuPt<sub>B</sub> ordered AlGaInP<sub>2</sub> alloys grown on GaAs by MOVCD epitaxy were studied by structural (X-ray diffraction, electron microscopy), optical (photoluminescence) and Kelvin probe microscopy methods. A strong dependence of the layer surface potential on the alloy composition was found. The effect of martensitic transition in the ordered AlGaInP<sub>2</sub> layers was found to be in connection with the alloy composition: higher Al concentrations lead to an increase of the piezoelectric field changes and shorter recovery time (relaxation) of the layers after mechanical effect (cleavage).

**Keywords:** AlGaInP, martensitic transition, pyroelectric properties

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Материалы конференции

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## Влияние концентрации Al на пьезоэлектрические свойства твердых растворов AlGaInP<sub>2</sub>

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**Аннотация.** Методами кельвин-зонд, а также структурного и оптического анализов были изучены CuPt<sub>B</sub> спонтанно-упорядоченные твердые растворы AlGaInP<sub>2</sub>, выращенные на подложках из GaAs методом МОС-гидридной эпитаксии. Была найдена сильная зависимость значения поверхностного потенциала и эффекта мартенситного перехода от состава образцов: повышение концентрации Al ведет к увеличению напряженности встроенного поля и сокращению времени восстановления (релаксации) после механического воздействия (скола).

**Ключевые слова:** AlGaInP, мартенситный переход, пироэлектрические свойства

**Финансирование:** Работа выполнена при поддержке гранта РНФ № 00375-29-24.

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## Introduction

Ternary GaInP<sub>2</sub> and quaternary AlGaInP<sub>2</sub> alloys lattice matched to GaAs substrates are used in many modern optoelectronic devices: LEDs, lasers, photovoltaic converters. GaInP<sub>2</sub> grown on [001] GaAs reveals CuPt<sub>B</sub>-type spontaneous ordering, which corresponds to a rhombohedral monolayer superlattice GaP<sub>1</sub>/InP<sub>1</sub> oriented along [111]<sub>B</sub> diagonals [1]. Mixing of Al to the Ga sublattice allows to vary the bandgap in the range of 1.9–2.3 eV preserving the lattice parameter. These quaternary alloys also reveal a tendency to CuPt<sub>B</sub> ordering. This type of ordering is followed by changes in the electronic structure (narrowing of the bandgap and splitting of the valence band), and by the uprising of a built-in electric field, i.e., the material shows pyroelectric properties [2, 3]. Here we demonstrate the effect of aluminum concentration on the pyroelectric properties of AlGaInP<sub>2</sub> epi-layers.

## Materials and Methods

Samples with different Al compositions, referred to as GaInP<sub>2</sub>, AlInP<sub>2</sub> and AlGaInP<sub>2</sub>, were grown by metalorganic vapor phase epitaxy (MOVPE) on an Aixtron AIX-200/4 unit at the growth temperature of 690°C and V/III fluxes ratio of 150. Exactly oriented (100) GaAs substrates were used to ensure the high ordering degree. The samples were not intentionally doped and possessed  $n < 10^{17}$  cm<sup>-3</sup> conductivity.

The alloy composition was obtained on a Carl Zeiss SUPRA 25 scanning electron microscope equipped with energy dispersive X-ray spectroscopy unit (EDX). X-ray diffraction (XRD) was measured on a DRON-8 diffractometer. Since the EDX method accuracy is poor and reveals high deviations up to several per cents, XRD data was used for In composition estimation and further correction of the EDX data by linear extrapolation having in mind that GaAs lattice matched compositions are Ga<sub>0.51</sub>In<sub>0.49</sub>P and Al<sub>0.52</sub>In<sub>0.48</sub>P. Also EDX data was corrected assuming stoichiometry of the alloy (i.e. 50% of the Phosphorous composition).

Photoluminescence spectra were measured on a micro photoluminescence research unit (μ-PL) (50x objective) at temperatures from 5 to 300°K. The value of the ordering induced bandgap narrowing was estimated by a quadratic formula [1], disordered alloy band gap was estimated using the obtained composition and the corresponding bowing parameters [4]. All samples revealed high ordering degree ( $\eta > 0.45$ ). Ordering degree of AlInP<sub>2</sub> was not estimated due to its indirect bandgap, but assumed to be high, since the growth conditions did not change.

Kelvin probe microscopy (KPM) technique was used to measure surface potential distribution and to determine magnitude of built-in electric field of the ordered layers. NT-MDT Integra Aura atomic force microscope was used. The value of the built-in electric field caused by pyroelectric effect was estimated from the layer thickness and potential difference between ordered and disordered samples.

## Results and Discussion

Fig.1, *a–c* shows the initial state growth plane surface potential map  $U^{001}$  of Al<sub>x</sub>Ga<sub>1-x</sub>InP<sub>2</sub> samples with  $d = 0.5$  μm and different compositions. All samples exhibit uniform distribution of the surface potential with average deviations of  $\pm 20$  mV. It should be noted that average surface potential values strongly depend on the alloy composition. Sample with  $x = 18\%$  reveals

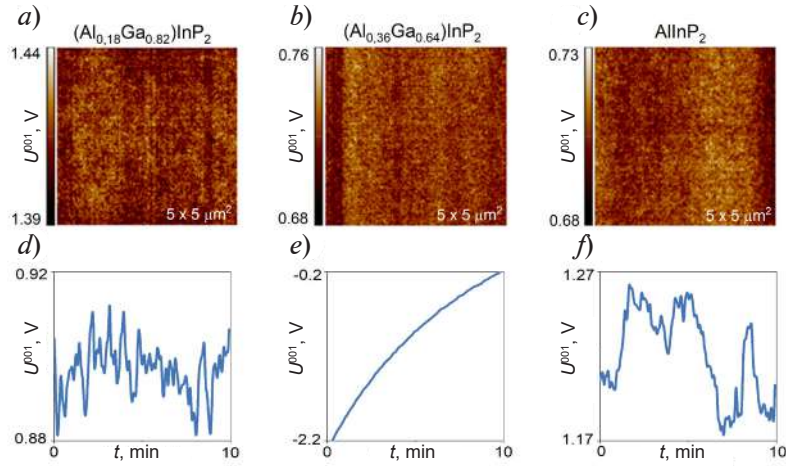


Fig. 1. Examples of growth plane surface potentials before (a, b, c) and changes of  $U^{001}$  over the time after the cleavage (d, e, f) of samples at different  $x$

$U^{001} = 1.42$  V, which is quite close to the ternary  $\text{GaInP}_2$  alloy [5], while samples with higher Al concentrations ( $x = 0.36, 1.0$ ) possess much lower surface potential  $U^{001} = 0.7\text{--}0.72$  V. Also  $\text{AlGaInP}_2$  samples behaved as  $n$ -type, while  $\text{AlInP}_2$  samples behaved as  $p$ -type. In KPM measurements the conductivity type is determined by the sign of the built-in electric field of the surface space charge region: positive changes in surface potential are characteristic for  $n$ -type semiconductor, when illumination is applied, negative are characteristic for  $p$ -type. In case of a pyroelectric material or material with charged states (e.g. non-stoichiometric dielectrics) KPM signal also reacts to the surface charge indicating on the built-in electric field.

After the cleavage procedure, surface potential is measured at one point and we can see the changes occurring during a certain period of time (Fig.1, d–f). These changes take place due to the martensitic transition of the crystal lattice from relaxed to stressed state [5]. The stress between the substrate and the layer is local and occurs due to the  $\text{CuPt}_B$ -type atomic ordering in the  $\text{AlGaInP}_2$  alloy. Ordered alloy structure has a trigonal  $C^{3v}$  lattice symmetry with rhombohedral elementary unit, which is distorted in the  $[111]$  direction due to the substrate-to-layer interaction.

The behavior of the surface potential differs greatly depending on the Al composition.  $\text{Al}_{0.36}\text{Ga}_{0.64}\text{InP}_2$  sample reveals the highest drop in the  $U^{001}$  value, changing from 0.72 to almost -2.2 V. However, the new state is unstable, and we can observe fast relaxation that takes place during the measurement. Samples with  $x = 0.18$  reveal smaller changes of the surface potential and it seem to be quasi-stable with  $U^{001} = 0.9\text{V}$  and average noise of 20 mV. Same behavior was observed in ternary  $\text{GaInP}_2$  samples [5]. Surface potential of  $\text{AlInP}_2$  sample on the contrary increases to  $\sim 1.2$  V.

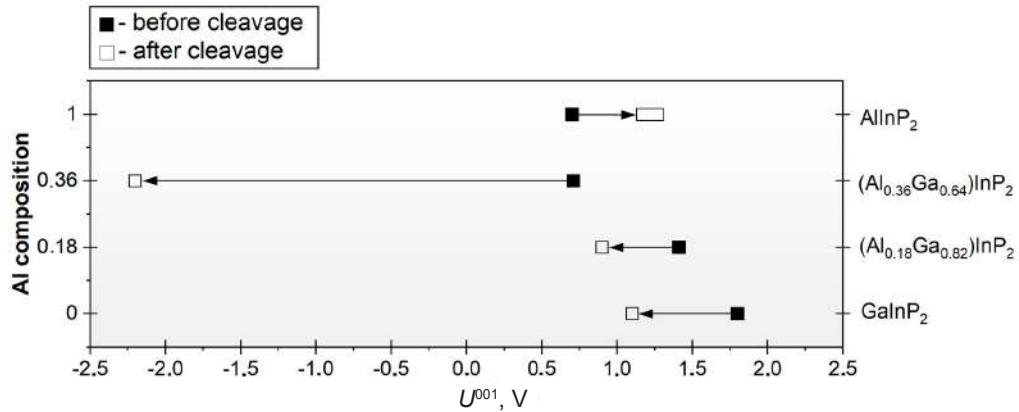


Fig. 2. Surface potential changes induced by martensitic transition in  $\text{GaInP}_2$  [5] and  $\text{AlGaInP}_2$  layers with different Al compositions

Instead of relaxation (as  $\text{Al}_{0.36}\text{Ga}_{0.64}\text{InP}_2$ ) or quasi-stable state ( $\text{GaInP}_2$ ) this sample reveal rapid switching between some quasi-stable states. Also, it can be noticed that after the cleavage the dark-to-illuminated surface potential change its sign indicating n-type conductivity. Change in conductivity type behavior is a strong indication that they originate from the pyroelectric effect.

Fig. 2 summarizes the observed changes of the pyroelectric effect caused by the martensitic transition.

### Conclusion

It has been shown that the pyroelectric properties of the  $\text{CuPt}_B$  ordered  $\text{AlGaInP}_2$  alloy depend on the Al composition. Among all studied samples,  $\text{Al}_{0.36}\text{Ga}_{0.64}\text{InP}_2$  epi-layers seem to have a fast relaxing state with the highest changes of surface potential. At the same time  $\text{AlInP}_2$  and  $\text{Al}_{0.18}\text{Ga}_{0.82}\text{InP}_2$  reveal smaller surface potential changes. Layer with Al concentration of  $x = 0.18$  reveals quasi-stable behavior similar to the previously observed ternary  $\text{GaInP}_2$ .  $\text{AlInP}_2$  reveals rapid switching between some quasi-stable states and changed its Kelvin-probe detected conductivity from p-type to n-type after the cleavage.

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### REFERENCES

1. **Mascarenhas A.**, Spontaneous Ordering in Semiconductor Alloys, Springer Science + Business Media LLC, New York, (2002) 474.
2. **Balunov P.A., Ankudinov A.V., Breev I.D., et al.** Local piezoelectric doping of monolayer  $\text{WSe}_2$ , Appl. Phys. Lett., 122 (2023) 222102.
3. **Alonso R.G., Mascarenhas A., Homer G.S., et al.** Evidence for pyroelectricity in single variant spontaneously ordered  $\text{GaInP}_2$ , Solid State Communications, 5 (88) (1993) 341–344.
4. **Kish F.A., Fletcher R.M.**, Chapter 5:  $\text{AlGaInP}$  Light-Emitting Diodes, Semiconductors and semimetals, (48)149–226.
5. **Ankudinov A.V., Bert N.A., Dunaevskiy M.S., et al.** Piezoelectric fields and martensitic transition in spontaneously ordered  $\text{GaInP}_2/\text{GaAs}$  epi-layers, Appl. Phys. Lett. (124) (2024) 052101.

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### Localized Ga droplets formation on nanopatterned silicon substrates

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**Abstract.** In this work, the effect of the modes of processing SiO<sub>2</sub>/Si substrates with a focused ion beam on the subsequent epitaxial growth of Ga droplets was investigated. It was shown that an increase in beam passes and ion dose led to a broadening of the pyramidal cavities and also affects the localization of Ga droplets. It was found that the use of additional preliminary processing of substrates in a hydrogen fluoride has a positive effect on the formation of gallium droplets inside the holes. The maximum degree of filling was observed at a hole size of about 350 nm.

**Keywords:** wet chemical etching, silicon, monolithic integration, focused ion beam, nanopatterning, molecular beam epitaxy, droplet epitaxy

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### Локализованное формирование капель Ga на нанопрофилированных подложках кремния

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**Аннотация.** В работе представлены результаты исследований влияния режимов обработки подложек SiO<sub>2</sub>/Si сфокусированным ионным пучком на последующее получение наноструктур Ga методом капельной эпитаксии. Показано, что увеличение проходов пучка и дозы приводит к расширению пирамидальных углублений, а также влияет на локализацию капель Ga. Установлено, что использование дополнительной предварительной обработки подложек в плавиковой кислоте положительным образом влияет на локализацию капельных структур Ga в пирамидальных углублениях. Максимальная степень заполнения наблюдалась при размере углублений приблизительно равных 350 нм.

**Ключевые слова:** жидкостное травление, кремний, монокристаллическая интеграция, сфокусированные ионные пучки, нанопрофилирование, молекулярно-лучевая эпитаксия, капельная эпитаксия

**Финансирование:** Работа выполнена при финансовой поддержке Министерства науки и высшего образования Российской Федерации; проект № FENW-2025-0004.

**Ссылка при цитировании:** Ерёменко М.М., Шандыба Н.А., Черненко Н.Е., Кириченко Д.В., Балакирев С.В., Солодовник М.С. Локализованное формирование капель Ga на нанопрофилированных подложках кремния // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2025. Т. 18. № 3.2. С. 57–59. DOI: <https://doi.org/10.18721/JPM.183.210>

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## Introduction

Today, direct monolithic integration of III-V semiconductors on silicon faces problems mainly associated with the difference in lattice constants and thermal expansion coefficients, which in turn significantly affects the defect density of the grown structures [1–3]. In this regard, local integration has proven to be a promising method both for reducing defects and localizing grown structures and for better compatibility with CMOS technology [4]. However, modern substrate nano- or micropatterning technique with traditional lithography to achieve local integration of III-V semiconductors on silicon is not only a labor-intensive but also an expensive process. Therefore, the search for new approaches to creating a pattern on the surface of semiconductor wafers and subsequent epitaxial growth of nanostructure arrays is one of many urgent tasks.

In this paper, we propose to use focused ion beams to form arrays of modified nanoscale holes on the SiO<sub>2</sub>/Si surface. Subsequent treatment in KOH allowed us to form pyramidal cavities, the shape of which helps localize the structures and reduce their defect level during epitaxial growth of III-V semiconductors [5–7]. For study the initial stage of the epitaxial growth processes on such FIB-modified substrates, we used droplet epitaxy technique [8] as a first stage of GaAs nano- and microcrystal growth. At the final stage, the effect of pregrowth treatment on the formation and localization of Ga metal droplets was studied.

## Materials and Methods

In this work we used Si(001) substrates coated with a SiO<sub>2</sub> layer. The FIB modification of the samples was performed by processing square areas of  $l = 0.25 \times 0.25$  and  $0.5 \times 0.5 \mu\text{m}$  with pitches between etched points of ( $0.5 \mu\text{m}$ ). The number of beam passes  $N$  varied from 450 to 1500. After that, the samples were etched in 30% KOH solution to form pyramidal cavities. Then the samples were placed in a growth chamber and annealed for 2 hours at a temperature of about 950 °C. After annealing, the samples were cooled to the growth temperature ( $T = 750^\circ\text{C}$ ) and gallium was deposited with a thickness  $H$  of 200 ML at a rate of  $\nu = 0.1 \text{ ML/s}$  (the deposition rate was previously calibrated using the RHEED pattern on the GaAs substrate).

## Results and Discussion

Fig. 1 shows SEM images of silicon samples with FIB-modified areas after Ga droplet formation. It is shown that gallium droplet nucleation mostly occurs on the faces of pyramidal cavities (Fig. 1, *a*). This may be due to the fact that the surface after etching is quickly covered with a layer of native oxide, which does not allow Ga droplets to form in the center. Therefore, with other parameters remaining unchanged, for the next samples, additional pre-treatment of the samples was carried out in a 2% hydrogen fluoride solution. As can be seen from the Figures 1, *b* and 1c, this allowed us to improve the localization of droplet structures and ensure their formation in the centers of the pyramidal cavities.

Analysis of the sample morphology showed that an increase in the number of ion beam passes led to a decrease in the localization of the formed gallium droplets in the center and stimulated their formation in the cavity corners. Apparently, such behavior is associated with an increase in the size of the etched cavities during wet chemical etching in KOH due to an increase in the depth of the initial holes during FIB-modification [9]. Thus, an increase in the hole size

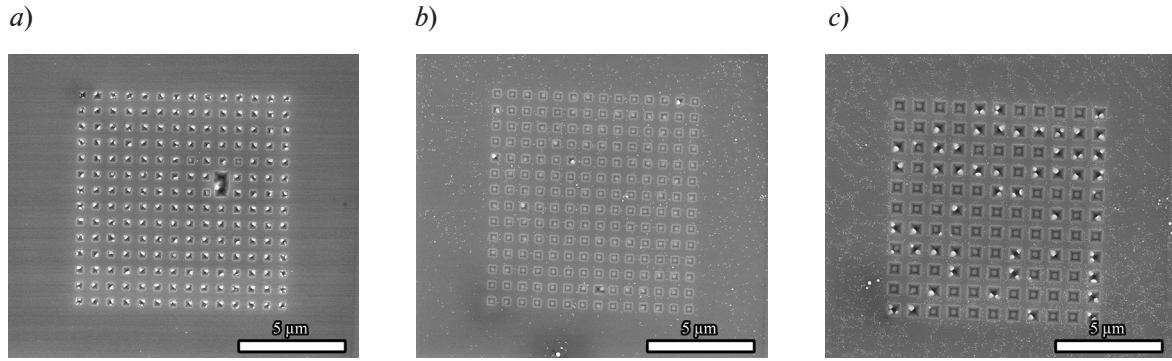


Fig. 1. SEM-images of FIB-modified  $\text{SiO}_2/\text{Si}$  areas with gallium droplets inside etching pits before (a) and after (b, c) growth procedure optimization

affected a decrease in the probability of the gallium droplets nucleation in the center of the cavities (Fig. 1, c). Changing the initial size of the FIB-modified areas from  $0.25 \times 0.25$  to  $0.5 \times 0.5 \mu\text{m}$  led to a similar effect (Fig. 1, b, c).

It was found that the maximum filling with Ga droplets (the degree of filling was calculated as the ratio of the number of Ga droplets localized in the center of the cavities to their total number) is observed when the width of the pyramidal cavities is minimal ( $\sim 350 \text{ nm}$ ). An increase in the number of passes led to a decrease in the percentage of droplet localization in the center for the initial  $0.25 \times 0.25 \mu\text{m}$  areas, while for the initial  $0.5 \times 0.5 \mu\text{m}$  areas the results obtained are ambiguous. On the one hand, increasing the number of passes increases the etching depth and, accordingly, the width of the pyramidal cavities, which should reduce the localization of droplets, but, on the other hand, processing in 2% hydrogen fluoride solution led to thinning of the native oxide and the emergence of the possibility of surface diffusion, as well as etching of the overhanging oxide above the cavities, which, in theory, increased the localization of droplets in the center to a certain level. An increase in the degree of filling with an increase in the number of passes for the initial  $0.5 \times 0.5 \mu\text{m}$  areas is associated with a decrease in the distance between the cavities.

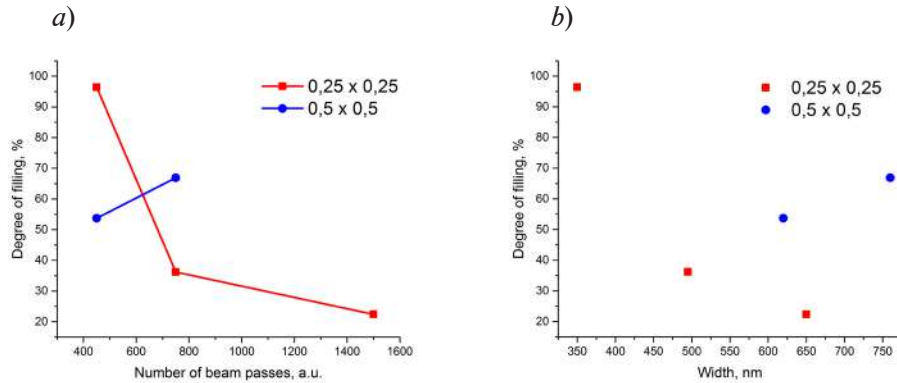


Fig. 2. Influence of the number of beam passes (a) and the size of the pyramidal cavities (b) on their degree of filling

### Conclusion

In this work, the possibility of achieving high selectivity of epitaxial growth on silicon samples with preliminary FIB treatment and wet chemical etching was demonstrated. The results presented also suggest that the gallium ion beam not only has a masking effect when processing silicon, but can also act as a method for creating a template on the surface for epitaxial processes.

## REFERENCES

1. Tiwari P., Trivico N.V., Schmid H., Moselund K.E., Review: III–V infrared emitters on Si: fabrication concepts, device architectures and down-scaling with a focus on template-assisted selective epitaxy, *Semiconductor Science and Technology*. 38 (2023) 053001.
2. Supplie O., Romanyuk O., Koppka C., et al., Metalorganic vapor phase epitaxy of III–V-on-silicon: Experiment and theory, *Progress in Crystal Growth and Characterization of Materials*. 64 (4) (2018) 103–132.
3. Eremenko M.M., Shandyba N.A., Chernenko N.E., et al., Study of the initial stage of GaAs growth on FIB-modified silicon substrates, *Journal of Physics: Conference Series*. 2086 (2021) 012007.
4. Dushaq G., Nayfeh A., Rasras M.A., Complementary metal oxide semiconductor (CMOS) compatible gallium arsenide metal-semiconductor-metal photodetectors (GaAs MSMs) on silicon using ultra-thin germanium buffer layer for visible photonic applications, *Journal of Applied Physics*. 126 (2019) 193106.
5. Wan Y., Li Q., Geng Y., et al., InAs/GaAs quantum dots on GaAs-on-V-grooved-Si substrate with high optical quality in the 1.3  $\mu\text{m}$  band, *Applied Physics Letters*. 107 (2015) 081106.
6. Paladugu M., Merckling C., Loo R., et al., Site Selective Integration of III–V Materials on Si for Nanoscale Logic and Photonic Devices, *Crystal Growth & Design*. 12 (2012) 4696–4702.
7. Li Q., Ng K.W., Lau K.M., Growing antiphase-domain-free GaAs thin films out of highly ordered planar nanowire arrays on exact (001) silicon, *Applied Physics Letters*. 106 (2015) 072105.
8. Balakirev S.V., Kirichenko D.V., Chernenko N.E., et al., Low-density arrays of ultra-small InAs nanostructures obtained by two-stage arsenic exposure during droplet epitaxy, *Applied Surface Science*. 578 (2022) 152023.
9. Eremenko M.M., Shandyba N.A., Chernenko N.E., et al., Combined approach of patterning on  $\text{SiO}_2/\text{Si}$  substrate using ion beam and chemical wet etching, *St. Petersburg State Polytechnical University Journal. Physics and Mathematics*. 17 (3.1) (2024) 75–78.

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## Graphene photodetector integrated on an optical waveguide

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**Abstract.** In this paper we report on our progress on fabrication of graphene-based photodetectors integrated on an optical waveguide. Graphene is a unique material for detecting radiation due to its record low electron heat capacity and weak electron-phonon coupling. The obtained experimental data can be used to optimize modern graphene photodetectors and develop new ones.

**Keywords:** graphene, photodetectors, waveguides

**Funding:** The research was supported by RSF project No. 23-72-00014 (bandwidth measurements) and by Academic Fund Program at HSE University grant No 24-00-035 “Photodetectors for photonic integrated circuits based on new two-dimensional materials” (responsivity measurements).

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Материалы конференции

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## Графеновый фотодетектор, интегрированный на оптический волновод

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**Аннотация.** В этой статье мы описываем наши последние достижения в создании фотодетекторов на основе графена, интегрированных на оптический волновод. Графен является уникальным материалом для детектирования излучения благодаря своей рекордно низкой электронной теплоемкости и слабой электрон-фононной связи. Полученные экспериментальные данные могут быть использованы для оптимизации современных графеновых фотоприемников и разработки новых.

**Ключевые слова:** графен, фотодетекторы, оптические волноводы



**Финансирование:** Исследование проводилось при поддержке проекта РФФ № 23-72-00014 (измерение полосы пропускания) и гранта Программы «Научный фонд Национального исследовательского университета «Высшая школа экономики» (НИУ ВШЭ) № 24-00-035 «Фотодетекторы для фотонных интегральных» (измерение чувствительности).

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## Introduction

The rapid advancement of technology has led to an exponential increase in information consumption, necessitating the development of efficient detection systems. The quest for fast and cost-effective detectors has been a longstanding priority in the field. While several photodetector types are currently available, each presents distinct limitations [1–4].

The integration of graphene-based photodetectors with optical waveguides represents a promising solution for high-speed optoelectronic applications [5]. Graphene's exceptional optoelectronic properties, including broadband absorption and high carrier mobility [6], enable the development of compact, high-throughput photodetectors on integrated photonic platforms. Recent research has demonstrated waveguide-coupled graphene photodetectors with bandwidths exceeding 100 GHz and sensitivity comparable to traditional photodiodes [7].

This study focuses on the fabrication of a 1550 nm wavelength photodetector. Special attention is devoted to device architecture, performance characteristics, and challenges related to achieving high sensitivity and speed. The combination of graphene with optical waveguides enhances light-matter interaction while maintaining compatibility with existing photonic platforms. This paper explores the design and operation principles of graphene-based photodetectors integrated on optical waveguides, along with future prospects.

## Device fabrication and characterization

A silicon substrate with a 450 nm thick silicon nitride upper layer served as the foundation for waveguide structures. Electron beam lithography utilizing a negative electron-beam resist was employed to fabricate the waveguides. To create the final structure, the silicon nitride is then chemically etched in  $\text{CHF}_3$  plasma. Our devices are equipped with focusing gratings couplers for coupling light into the chip. The technology for manufacturing waveguides, as well as focusing gratings couplers is described in detail in [8]. Following waveguide creation, graphene channel fabrication commenced. Graphene was synthesized via chemical vapor deposition (CVD) and transferred onto the silicon substrate [9]. The transferred graphene was a single layer, as confirmed by Raman spectroscopy. Positive electron beam lithography and plasma chemical etching in  $\text{O}_2$  were used to form graphene channel. Formation of contact electrodes to graphene required the application of positive electron beam lithography and electron beam evaporation of V-Au contacts. The contact electrodes are located at different distances  $L_1 = 700$  nm and  $L_2 = 300$  nm from the waveguide to create an asymmetric structure. This asymmetry results in a photovoltage signal due to a combination of thermoelectric and photovoltaic effects at zero bias [10]. Fig. 1 shows optical image of fabricated device (Fig. 1, *a*) as well schematical representation of device cross section (Fig. 1, *b*).

Before the photoresponse measurements, we measured the transmission spectrum of the fabricated waveguides. The total input and output losses were about 30 dB and were then taken into account to calculate the internal responsivity of the photodetector. Next, we measure photoresponse of fabricated devices. The modulated radiation from a single-mode, continuous-wave laser operating at 1550 nm was directed through the polarization controller via the optical fiber

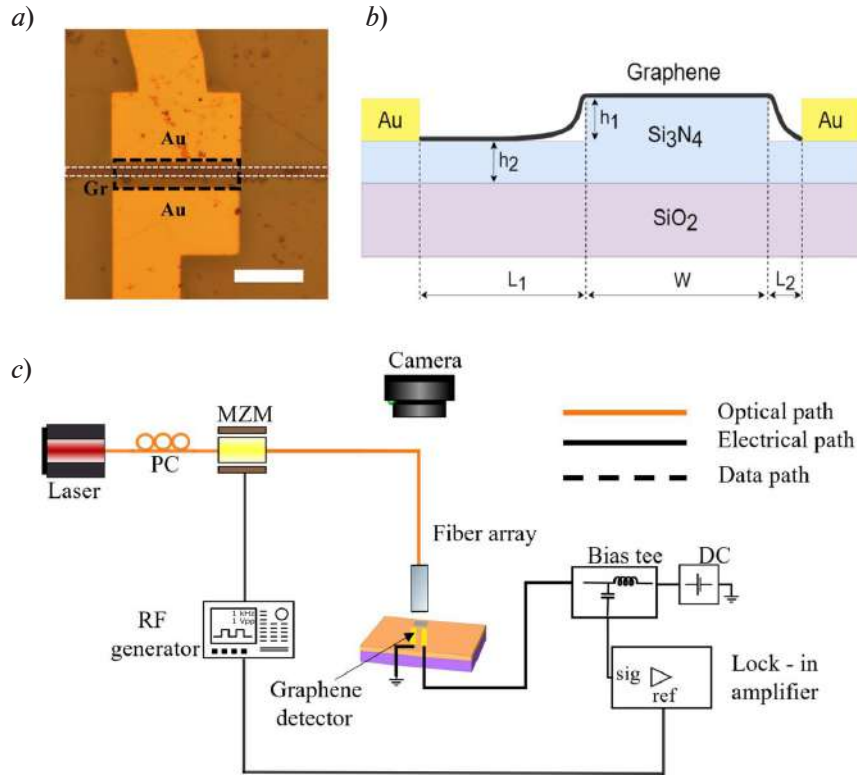


Fig. 1. Optical photograph of a graphene detector integrated onto a waveguide with gold contacts, black dashed rectangle indicates the graphene region, and the white dashed rectangle denotes the waveguide, scale bar: 10  $\mu\text{m}$  (a); cross-sectional schematic of the graphene detector integrated onto the waveguide, where  $w$  represents the waveguide width,  $L_1=700$  nm and  $L_2=300$  nm denote the distances from the waveguide to each gold contact,  $h_1=225$  nm is the waveguide height, and  $h_2=225$  nm is the thickness of the  $\text{Si}_3\text{N}_4$  layer (b); schematic of the sensitivity measurement setup for the graphene detector integrated onto the waveguide (c), sample is placed on a probe station connected to a fiber array and electrical contacts for signal readout, laser radiation is directed through a polarization controller (PC) to the fiber array, the modulating signal is generated by a radio-frequency (RF) generator and synchronized with a lock-in amplifier. DC bias is applied via a bias tee

to the input of the optical chip (Fig. 1, c). The laser light was coupled into and out of the planar  $\text{Si}_3\text{N}_4$  waveguide using focusing grating couplers. The input optical power was 1 mW, and the total input and output coupling losses were about 30 dB, which were taken into account to calculate the internal responsivity of the photodetector. The radiation was detected due to the absorption of the evanescent mode by graphene, which exited the waveguide. The measured electrical signal was fed through the bias adapter to the lock-in amplifier. The bias adapter was used to measure the photovoltage signal from the bias current. The internal responsivity of the photodetector was determined as the ratio of the photovoltage to the power absorbed by graphene and was 0.1 V/W. Given the measured graphene channel resistance of approximately 1 k $\Omega$ , this corresponds to a current responsivity of about 0.1 mA/W.

The primary mechanism for detecting radiation in our photodetector is the photothermoelectric effect in graphene [11, 12], which arises from the ununiform heating of graphene electrons due to its asymmetric location on the waveguide. In this case, the intrinsic response time of the photodetector is determined by the energy relaxation time of hot electrons [3]. At room temperature, the primary energy relaxation mechanism is the interaction of electrons with acoustic phonons [13]. The intrinsic response time is determined by the electron-phonon time. This time is independent of the excitation radiation frequency at the same power level. Therefore, to evaluate the potential of our graphene for fast detection, we used a standard heterodyne detection method at sub-THz frequencies.

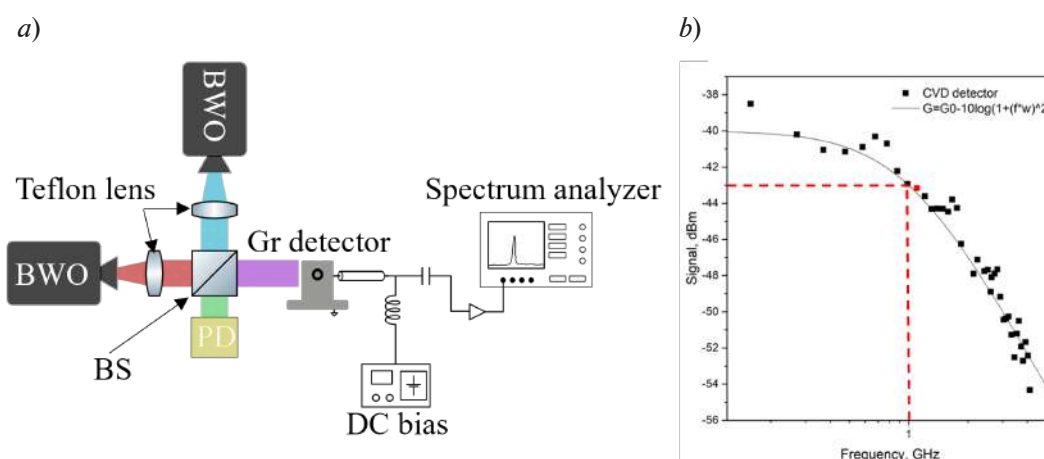


Fig. 2. Heterodyne detection scheme for a graphene detector integrated onto a silicon lens. Two backward-wave oscillator (BWO) operating at frequencies of 129–131 GHz were used for the measurements. The radiation was focused using teflon lenses and directed onto the graphene detector through a beam splitter (BS). Electrical readout was performed via a bias tee, with the high-frequency signal amplified by a cascade of amplifiers and measured using a spectrum analyzer (a); signal power from the graphene detector as a function of intermediate frequency, with the red dashed line indicating the 3 dB roll-off (b)

To evaluate the potential for high-speed operation of the photodetectors, we fabricated devices based on the same quality CVD graphene integrated into a THz antenna [14]. Next, we used a standard heterodyne mixing technique to measure the detector's bandwidth (Fig. 2, a). The heterodyne mixing principle involves feeding two similar-frequency signals from a generator to the detector. This produces sum and difference frequency signals at the mixer output, with the sum frequency filtered to yield an intermediate frequency (IF) signal. Terahertz radiation were provided by two tunable backward-wave oscillators. Each oscillator was equipped with a waveguide adapter fitted with a Teflon lens to produce plane-parallel terahertz radiation. This radiation passed through a beam splitter to the detector. The result of the dependence of the power at IF on the frequency is shown in Fig. 2, b. The bandwidth of our detector is 1 GHz and was limited by the setup.

### Conclusion

Device characterization revealed promising photoresponse with responsivity and potential for high-speed operation exceeding 1 GHz bandwidth. The total response time of the photodetector is determined by a combination of the device's intrinsic response time and the bandwidth of the signal acquisition line (parasitic capacitances and inductances). The response time of 1 GHz we measured corresponds to the bandwidth of 1 cm of the aluminum lead wires and is not determined by the quality of the graphene. Improving the read out line should result in increased speed. Graphene-based waveguide-integrated photodetectors represent a significant advancement in ultrafast optoelectronics. Their compatibility with existing photonic platforms, combined with exceptional speed and broadband performance, positions them as key components for future high-speed communication and quantum photonic systems.

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## REFERENCES

1. Thomson D., et al., Roadmap on silicon photonics. J. Opt. 18 (2016) 073003.
2. Chrostowski L., et al., Silicon Photonics Design: From Devices to Systems, Cambridge University Press. (2015).
3. Arafin S., et al., Advanced InP photonic integrated circuits for communication and sensing. IEEE J. Sel. Top. Quantum Electron. 24 (2018) 1–12.
4. Nagarajan R., et al., InP photonic integrated circuits. IEEE J. Sel. Top. Quantum Electron. 16 (2010) 1113–1125.
5. Romagnoli M., et al., Graphene-based integrated photonics for next-generation datacom and telecom. Nature Reviews Materials. 3 (10) (2018) 392–414.
6. Gabor Nathaniel M., et al., Hot carrier–assisted intrinsic photoresponse in graphene, Science. 334 (6056) (2011) 648–652.
7. Ding Y., et al., Ultra-compact integrated graphene plasmonic photodetector with bandwidth above 110 GHz, Nanophotonics. 9 (2) (2020) 317–325.
8. An P.P., et al., High-speed optical-waveguide integrated single-walled carbon nanotube bolometer, Applied Physics Letters. 125 (20) (2024).
9. Gayduchenko I.A., et al., Manifestation of plasmonic response in the detection of sub-terahertz radiation by graphene-based devices, Nanotechnology. 29 (24) (2018) 245204.
10. Schall D., et al., 50 GBit/s Photodetectors Based on Wafer-Scale Graphene for Integrated Silicon Photonic Communication Systems, ACS Publications. Collection. (2015).
11. Xu Xiaodong, et al., Photo-thermoelectric effect at a graphene interface junction, Nano letters. 10 (2) (2010) 562–566.
12. Castilla Sebastián, et al., Fast and sensitive terahertz detection using an antenna-integrated graphene pn junction, Nano letters. 19 (5) (2019) 2765–2773.
13. Massicotte Mathieu, et al., Hot carriers in graphene—fundamentals and applications, Nanoscale. 13 (18) (2021) 8376–8411.
14. Gazaliev A.S., et al., Graphene two terminal detector as THz mixer, In Journal of Physics: Conference Series IOP Publishing. 2086 (1) (2021) 012054.
15. Rogalski A.M., et al., Two-dimensional infrared and terahertz detectors: Outlook and status, Applied Physics Reviews. (2019).

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### **Influence of electrode geometry on growth of horizontally aligned carbon nanotubes**

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**Abstract.** This work investigates the influence of electrode geometrical parameters on the electric-field-strength distribution required for the directed growth of horizontally aligned carbon nanotubes by plasma-enhanced chemical vapor deposition. Optimal electrode parameters that provide maximal electric field strength and high efficiency of aligned nanotube growth have been determined. The influence of electrode shape (rectangular, semicircular, and triangular) on the field-strength distribution and nanotube alignment is demonstrated. The results contribute to optimizing the growth process of horizontally aligned carbon nanotubes for applications in sensors and nanopiezotronic devices.

**Keywords:** carbon nanotubes, horizontal growth, PECVD, electric field, electrode, modelling, directed growth

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### **Влияние геометрии электрода на рост горизонтально ориентированных углеродных нанотрубок**

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**Аннотация.** В данной работе исследуется влияние геометрических параметров электродов на распределение напряженности электрического поля, необходимого для направленного роста горизонтально ориентированных углеродных нанотрубок методом плазменно-химического осаждения из газовой фазы. Определены оптимальные параметры электродов, обеспечивающие максимальную напряженность электрического поля и высокую эффективность ориентированного роста нанотрубок. Показано, влияние формы электродов (прямоугольных, полукруглых и треугольных) на распределение напряженности поля и ориентацию нанотрубок. Результаты работы способствуют оптимизации процесса роста горизонтально ориентированных углеродных нанотрубок для применения в сенсорах и устройствах нанопьезотроники.





**Ключевые слова:** углеродные нанотрубки, горизонтальный рост, PECVD, электрическое поле, электрод, моделирование, направленный рост

**Финансирование:** Грант Российского научного фонда «Разработка пьезоэлектрических наногенераторов на основе вертикально ориентированных углеродных нанотрубок, допированных азотом» в Южном федеральном университете [22-79–10163].

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## Introduction

Carbon nanotubes (CNTs) are among the most promising materials for a wide range of applications due to their exceptional electrical, mechanical, and thermal properties [1–3]. These unique characteristics make CNTs ideal candidates for use in fields such as microelectronics, sensors, energy, and high-strength materials [4–6]. Special attention is given to horizontally aligned carbon nanotubes (HCNTs), which are particularly useful in microelectronic and sensor technologies, as they can be integrated into microelectronic circuits with high controllability and reproducibility [3]. The unique properties of HCNTs make them ideal for applications in energy converters, supercapacitors, flexible electronics, and gas sensors [7–11].

The ability to control the orientation of carbon nanotubes during their growth is critical for their practical applications. Horizontal growth is especially sought after, as it allows CNTs to be integrated into electronic devices and systems with uniform orientation, which significantly impacts their conductivity and other properties, enabling their effective use in high-performance devices [12]. The electric field intensity (EFI), created by electrodes on the substrate, is one of the key factors determining the directionality of CNT growth. The electric field vector influences the orientation of the nanotubes due to their high polarizability along their longitudinal axis [3].

Directed growth of HCNTs involves manipulating the electric field to control the orientation and structure of the nanotubes during their formation. Recent studies have shown that optimizing the geometry of the electrodes can enhance the electric field intensity and, consequently, improve the alignment of the nanotubes. However, achieving stable and high-quality horizontal growth remains a challenging task due to factors such as the electrode shape, their size, and the gap between them.

The aim of this study is to investigate the influence of electrode geometry on the distribution of the electric field that affects the directed growth of horizontally aligned carbon nanotubes using the plasma-enhanced chemical vapor deposition (PECVD) method.

## Materials and methods

The study was carried out using numerical modelling in the COMSOL Multiphysics software package, which provides the necessary tools for calculating electric-field distributions. For these purposes, the “Electrostatics” module, intended for analyzing electrostatic fields in specified regions, was used. Modelling was performed for a silicon substrate with various electrode geometries to evaluate their influence on the electric-field distribution in the gap between them.

The modelled structure included a Si substrate measuring  $5 \times 5$  mm and 100  $\mu\text{m}$  thick, coated with a 250 nm  $\text{SiO}_2$  layer. The electrodes, made of Mo, were 100 nm thick. The voltage between the electrodes was 1 V. The gap between the electrodes varied from 100  $\mu\text{m}$  to 1  $\mu\text{m}$ , which made it possible to conduct the study for different gap values.

Within the first investigation, the influence of electrode shape on the electric-field distribution in the gap was studied. Three electrode shapes were selected for this purpose: rectangular, semi-circular, and triangular. The geometry of the rectangular electrodes was as follows: length 4 mm,

width 2 mm. The semicircular electrodes had a base length of 4 mm and a radius of 1.95 mm. The triangular electrodes had a height of 1.95 mm and a base of 3.9 mm, with the apex angle fixed at 90°. The gap between the electrodes was set at 100  $\mu\text{m}$  and remained constant for this experiment. Modelling was carried out with a constant voltage of 1 V applied between the electrodes.

The next stage of the study considered the influence of the geometric parameters of the electrodes on the electric-field distribution. For the semicircular electrodes, the circle radius remained constant at 1.95 mm. Electrode parameters were changed by shifting the lower base by 0.25 mm, which reduced the electrode height from 1.95 mm to 0.45 mm. For the triangular electrodes, the angle ( $\alpha$ ) opposite the base of the triangle was varied. The angle ranged as follows:  $\alpha = 15^\circ, 30^\circ, 40^\circ, 60^\circ, 75^\circ, 90^\circ$ , with corresponding base lengths of 0.5134 mm, 1.045 mm, 1.419 mm, 2.252 mm, 2.458 mm, 3.9 mm. For the rectangular electrodes, length and width were not changed, since theoretical studies showed that altering these parameters would not significantly affect the distribution of electric-field intensity. All changes were made with a constant gap between the electrodes, which was maintained at 100  $\mu\text{m}$ .

The final stage of the study was devoted to analysing the influence of the gap size between the electrodes on the distribution of electric-field intensity. The gap between the electrodes was varied from 1  $\mu\text{m}$  to 100  $\mu\text{m}$  with intermediate values of 10, 25, 50, and 75  $\mu\text{m}$ . The geometric parameters of the electrodes remained unchanged: the rectangular electrodes had a length of 4 mm and a width of 2 mm, the semicircular electrodes had a base length of 4 mm and a radius of 1.95 mm, and the triangular electrodes had a height of 1.95 mm and a base of 3.9 mm with an apex angle of 90°.

## Results and discussion

**Electric-field distribution versus electrode shape.** Fig. 1 illustrates how the geometry of 100-nm-thick Mo electrodes separated by a 100  $\mu\text{m}$  gap governs the magnitude of the electric field ( $E$ ) in the inter-electrode region. In the rectangular configuration a broad plateau of elevated field is formed;  $E$  reaches  $\approx 0.0063 \text{ V}/\mu\text{m}$  and remains nearly constant across about 60 % of the gap width, a condition favorable for simultaneous nucleation of CNT seeds over large catalyst areas. In the model with triangular electrodes, the electric field magnitude reached  $E \approx 0.0055 \text{ V}/\mu\text{m}$ , and the field lines converged toward the sharp electrode vertices. Along the base the magnitude decreases to roughly 85 % of the peak, producing a pronounced guiding component that aligned growing CNTs parallel to the gap axis at the cost of a more localized high-field zone. The semicircular geometry gives the lowest amplitude ( $E \approx 0.0046 \text{ V}/\mu\text{m}$ ) and a smooth gradient; the absence of corners suppresses field concentration and displaces the high-field zone away from the catalyst surface, which complicates electrostatic control of the growth front.

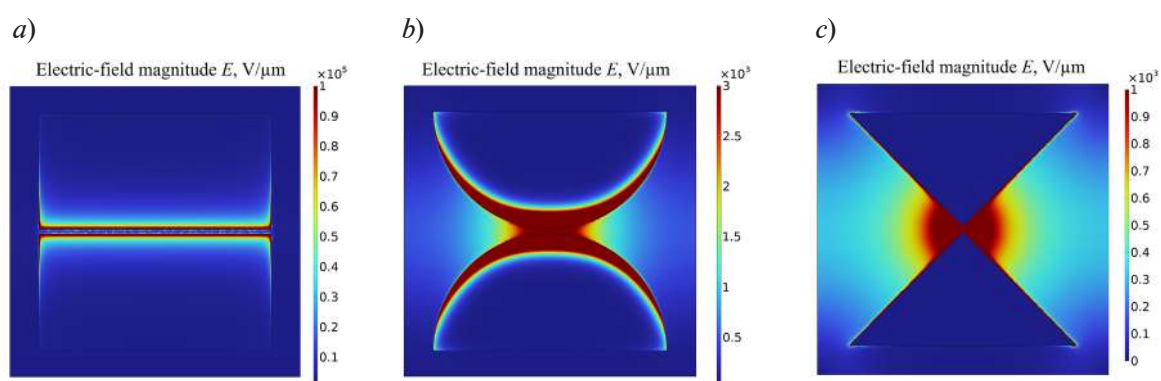


Fig. 1. Surface map of electric-field magnitude  $E$  for Mo electrodes with triangular (a), semicircular (b) and rectangular (c) shapes at a gap of 100  $\mu\text{m}$

Rectangular and triangular electrodes therefore deliver the highest attainable field, whereas semicircular ones are intrinsically limited. The choice between the former two is a trade-off between the area of uniform field (rectangular) and the degree of local enhancement (triangular); this balance must be considered in subsequent optimization of size and gap.



**Effect of electrode dimensions.** For semicircular electrodes the radius was fixed at 1.95 mm while the height  $h$  was reduced from 1.95 to 0.45 mm. Lowering  $h$  increases  $E$  by only  $\approx 6\%$ ; the maximum  $0.0046 \text{ V}/\mu\text{m}$  occurs at  $h \approx 1.5 \text{ mm}$ , after which the curve saturates. Field lines remain nearly parallel and the high-field area broadens symmetrically, indicating weak sensitivity of the distribution to height at constant radius.

In the triangular case the apex angle  $\alpha$  (and thus the base length  $L$ ) was varied between  $15^\circ$  ( $L = 0.51 \text{ mm}$ ) and  $90^\circ$  ( $L = 3.9 \text{ mm}$ ). At  $\alpha = 90^\circ$  the field rises to  $E = 0.0055 \text{ V}/\mu\text{m}$ . Decreasing the angle to  $75^\circ$  and further to  $40^\circ$  induces an almost linear decline, losing up to  $35\%$  of the maximum at  $\alpha = 40^\circ$ . Equipotential maps reveal progressive smearing of the field peak along the base, whereas at  $\alpha = 90^\circ$  the potential gradient is tightly focused near the apex.

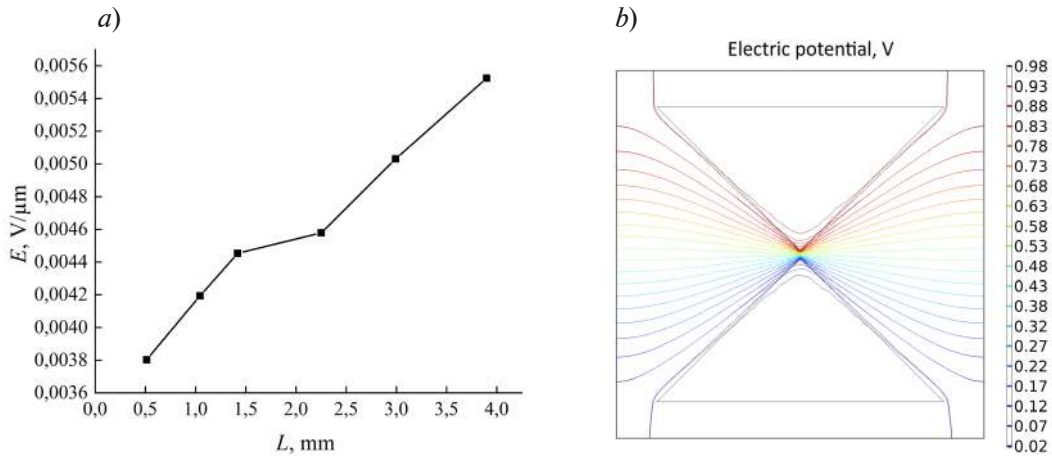


Fig. 2. Dependence of electric-field magnitude  $E$  on base length  $L$  for triangular electrodes (a); equipotential contours for  $\alpha = 90^\circ$  (b)

Height variations thus have a secondary effect for semicircular electrodes, whereas the apex angle is the dominant parameter for triangular ones, governing both magnitude and spatial localisation of the field. These trends provide design rules when a high  $E$  must be combined with a predictable action zone.

**Gap-size dependence.** Reducing the inter-electrode spacing  $d$  is the most effective route to elevate  $E$  in all three geometries. For rectangular electrodes the distribution remains nearly flat:  $E$  increases from  $0.0063 \text{ V}/\mu\text{m}$  at  $d = 100 \mu\text{m}$  to  $0.26 \text{ V}/\mu\text{m}$  at  $d = 1 \mu\text{m}$  without pronounced local peaks. Semicircular electrodes respond less linearly: for  $d > 25 \mu\text{m}$  the rise is moderate,

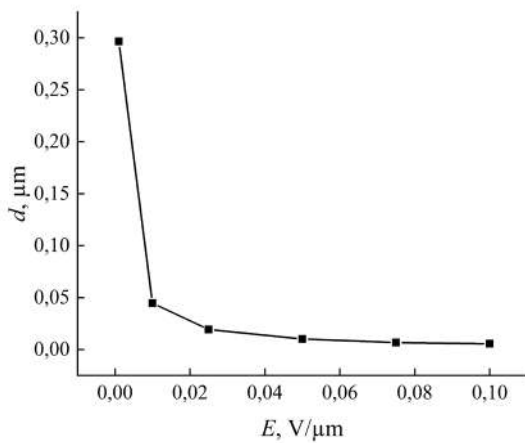


Fig. 3. Dependence of electric-field magnitude  $E$  on gap  $d$  for triangular electrodes ( $\alpha = 90^\circ$ ,  $h = 1.95 \text{ mm}$ ,  $L = 3.9 \text{ mm}$ )

but at  $d \leq 10 \mu\text{m}$  stronger gradients emerge; the maximum is limited to  $0.12 \text{ V}/\mu\text{m}$  and the high-field zone shifts toward the arc, shrinking the useful region.

The triangular profile exhibits the steepest dependence. Shrinking  $d$  from 100 to  $1 \mu\text{m}$  boosts  $E$  from  $0.0055 \text{ V}/\mu\text{m}$  to  $0.30 \text{ V}/\mu\text{m}$ . Simultaneously, the equipotential lines move toward the apex, concentrating the field in a narrow corridor and imposing a strong directional component that aligns CNTs along the gap.

At  $d = 1 \mu\text{m}$  the triangular design ( $\alpha = 90^\circ$ ,  $h = 1.95 \text{ mm}$ ,  $L = 3.9 \text{ mm}$ ) yields the highest field,  $0.30 \text{ V}/\mu\text{m}$ , outperforming the rectangular ( $0.26 \text{ V}/\mu\text{m}$ ) and semicircular ( $0.12 \text{ V}/\mu\text{m}$ ) counterparts.

Local enhancement of the electric field is governed by electrode shape and the presence of sharp vertices that concentrate field lines;

without gap reduction the gains remain modest. Dimensional scaling is critical only for triangular geometry: extending  $L$  beyond  $\approx 3$  mm offers no additional benefit, enabling compact arrays. The gap remains the primary tuning parameter: a tenfold reduction increases  $E$  by nearly two orders of magnitude, providing a means to steer horizontal CNT growth at lower anode biases.

The optimal triangular configuration with a lithographically defined 1  $\mu\text{m}$  gap can be integrated on standard-thickness silicon substrates without complicating the process flow. The present findings have been used to design a photomask for an experimental sample featuring the specified triangular electrodes, on which the efficiency of horizontal PECVD growth of carbon nanotubes will be evaluated.

### Conclusion

The numerical analysis carried out in COMSOL Multiphysics has provided a comprehensive assessment of how the shape and dimensions of Mo electrodes patterned on a silicon substrate, together with the electrode gap, govern the electric-field distribution that is critical for horizontal PECVD growth of carbon nanotubes (CNTs). Rectangular and, in particular, triangular electrodes generate the highest field strength, while semicircular geometry performs less efficiently because its rounded profile smooths the potential gradient. For triangular electrodes the apex angle is decisive: at  $\alpha = 90^\circ$  and a base length of 3.9 mm a strongly localised field enhancement is achieved that can align CNTs along the gap axis. By contrast, varying the height of semicircular electrodes at constant radius has a negligible effect on the field pattern.

The study has shown that the gap width  $d$  exerts the greatest influence on the field magnitude. Reducing  $d$  from 100 to 1  $\mu\text{m}$  increases the field strength by almost two orders of magnitude; in the optimal triangular configuration the value reaches  $E \approx 0.30$  V/ $\mu\text{m}$ , sufficient to direct catalyst nanoparticles at reduced anode bias.

The results provide a solid platform for precise control of CNT orientation in micro- and nanoelectronic applications ranging from sensors to interconnects in flexible electronics. Future work will focus on experimental verification of the simulations, exploration of sub-micrometre gaps ( $d < 1$   $\mu\text{m}$ ) and optimization of plasma-timing parameters to further enhance the structural integrity and uniformity of CNT arrays.

### REFERENCES

1. Gupta S.K., Gupta N., Kunzru D., Vapor grown carbon fibers from pyrolysis of hydrocarbons: Modeling of filament growth and poisoning, *Journal of Analytical and Applied Pyrolysis*. 26 (3) (1993) 131–144.
2. Pan Z., Ren J., Guan G., et al., Synthesizing nitrogen-doped core–sheath carbon nanotube films for flexible lithium-ion batteries, *Advanced Energy Materials*. 6 (11) (2016) 1600271.
3. Simon P., Gogotsi Y., Materials for electrochemical capacitors, *Nature Materials*. 7 (11) (2008) 845–854.
4. Shin Y.C., Lee J.B., Kim D.-H., et al., Development of a shape-memory tube to prevent vascular stenosis, *Advanced Materials*. 31 (41) (2019) 1904476.
5. Zhang R., Zhang Y., Wei F., Horizontally aligned carbon nanotube arrays: Growth mechanism, controlled synthesis, characterization, properties and applications, *Chemical Society Reviews*. 46 (12) (2017) 3661–3715.
6. Zhang X., Lu W., Zhou G., Li Q., Understanding the mechanical and conductive properties of carbon nanotube fibers for smart electronics, *Advanced Materials*. 32 (5) (2020) 1902028.
7. Lin Q., Yang X., Wang P., et al., High-resolution TEM observations of isolated rhombohedral crystallites in graphite blocks, *Carbon*. 50 (6) (2012) 2369–2371.
8. Zhang Y., Chang A., Cao J., et al., Electric-field-directed growth of aligned single-walled carbon nanotubes, *Applied Physics Letters*. 79 (19) (2001) 3155–3157.
9. Zhu W., Chen X., Cao A., Wang Z., Synthesis of hermetically sealed graphite-encapsulated metallic cobalt (alloy) core/shell nanostructures, *Carbon*. 49 (4) (2011) 1462–1472.
10. Zhou W., Chen S., Luo Z., Wang C., Copper catalyzing growth of single-walled carbon nanotubes on substrates, *Nano Letters*. 6 (12) (2006) 2987–2990.
11. Zhang B., Hong G., Peng B., et al., Grow single-walled carbon nanotubes cross-bar in one batch, *Journal of Physical Chemistry C*. 113 (14) (2009) 5341–5344.
12. Eatemadi A., Daraee H., Karimkhanloo H., et al., Carbon nanotubes: Properties, synthesis, purification, and medical applications, *Nanoscale Research Letters*. 9 (1) (2014) 1–13.



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Conference materials

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## First-principles calculation of copper impurity diffusion in hexagonal ruthenium

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**Abstract.** Ruthenium is a promising material for use in microelectronic devices as a diffusion barrier layer to prevent copper diffusion. However, there are few data on quantitative assessments of the diffusion coefficients of any impurities in hexagonal bulk Ru, which is the stable structural phase of Ru. In this work, we performed a density functional theory study of Cu impurity diffusion in bulk hexagonal Ru. Impurity diffusion coefficients are computed as a function of temperature using the ‘8-frequency model’, which provides the relevant impurity and solvent jump frequencies and correlation factors. The effect of temperature-dependent expansion of the ruthenium lattice volume is taken into account within the quasi-harmonic approximation. The Arrhenius equation for the diffusion coefficient is  $D_{\parallel} = 6.12 \cdot 10^{-5} \exp(-5.01 \text{ eV}/kT) \text{ m}^2\text{s}^{-1}$  for diffusion within the basal plane and  $D_{\perp} = 2.18 \cdot 10^{-4} \exp(-5.11 \text{ eV}/kT) \text{ m}^2\text{s}^{-1}$  for diffusion between adjacent basal planes in the lattice. Our calculations serve as a foundation for a more accurate understanding of experimental data.

**Keywords:** impurity diffusion, diffusion coefficient, density functional theory, quasi-harmonic approximation, ruthenium, copper

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Материалы конференции

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## Моделирование диффузии примеси меди в гексагональном рутении из первых принципов

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**Аннотация.** Рутений является перспективным материалом для применения в микроэлектронике в качестве диффузионного барьерного слоя, предотвращающего диффузию меди. Однако диффузия каких-либо примесей в объеме гексагонального рутения теоретически мало изучена, и соответствующие коэффициенты диффузии отсутствуют в литературе. В данной работе проводится исследование из первых принципов диффузии примеси меди в объеме гексагонального рутения.

**Ключевые слова:** диффузия примеси, коэффициент диффузии, теория функционала плотности, квазигармоническое приближение, рутений, медь



**Ссылка при цитировании:** Горохов С.А., Резник А.А., Резванов А.А. Моделирование диффузии примеси меди в гексагональном рутении из первых принципов // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2025. Т. 18. № 3.2. С. 72–75. DOI: <https://doi.org/10.18721/JPM.183.213>

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### Introduction

One of the main trends in the modern semiconductor microelectronics industry is the continuous scaling down of minimum feature sizes [1]. Specifically, due to the narrowing of the width of copper conductors in the metallization system and reduction in the distance between them, there is active screening of new materials as diffusion barriers and adhesive layers for Cu. Metal ruthenium and its compounds are considered as potential materials for this application. Ru combines both high barrier properties, preventing Cu diffusion, and good adhesion to Cu [2].

In recent years, a substantial amount of research has been conducted on the development of diffusion barriers based on Ru. However, the methods of deposition used make it possible to obtain only polycrystalline films of Ru, in which Cu is expected to diffuse along the grain boundaries [3]. Consequently, such experimental studies do not provide information about the rate of diffusion of Cu in hexagonal (hcp) Ru. In this research, we perform a study of Cu impurity diffusion in bulk hcp Ru using the density functional theory (DFT) approach.

### Methodology

For the calculation of vacancy-mediated diffusion coefficients of Cu in hcp Ru as a function of temperature the "8-frequency model" of Ghate was applied [4]. According to this approach, there are eight different jump frequencies corresponding to exchanges in the positions of impurity and nearest-neighbor solvent atoms with adjacent vacancies. Each of these eight jump frequencies was calculated based on the extended Eyring's equation [5] as

$$w = \frac{kT}{h} \exp\left(-\frac{G_{TS}^* - G_{IS}}{kT}\right), \quad (1)$$

where  $G_{TS}^*$  is the free energy of the transition state, which is a saddle point on the diffusion path, after excluding the contribution from its single imaginary phonon frequency,  $G_{IS}$  is the free energy of the initial state,  $h$  is Planck's constant,  $k$  is Boltzman's constant and  $T$  is absolute temperature. The resulting set of jump frequencies allows then to compute the correlation factor  $f$  and get diffusion coefficients

$$D_{\parallel} = \frac{3}{4} C_2 c^2 f_{Az} w_A, \quad (2)$$

$$D_{\perp} = \frac{1}{2} C_2 a^2 (3f_{Bx} w_B + f_{Ax} w_A). \quad (3)$$

Here,  $C_2$  is the vacancy adjacent to the impurity concentration defining through calculation of corresponding free energies,  $a$  and  $c$  are the lattice parameters of the hcp Ru,  $w_A$  and  $w_B$  are the jump frequencies of impurity and vacancy exchanges between adjacent basal planes and within a basal plane, respectively. In order to take into account the effect of thermal lattice expansion of ruthenium, a quasi-harmonic approximation (QHA) was applied preliminarily. Based on these results, four lattice parameters were obtained corresponding to temperatures of 300, 600, 900, and 1200 K for which diffusion coefficients were calculated according to equations (2) and (3).

### Computational details

All calculations were performed within the framework of DFT as implemented in the Quantum ESPRESSO package [6]. For exchange-correlation energy, we employ a generalized gradient approximation using the Wu-Cohen (WC) parametrization [7]. A plane-wave energy cutoff was set to 50 Ry. For all calculations we used a  $3 \times 3 \times 2$  supercell of Ru, consisting of 36 atoms in the defect-free cell. In order to find the transition state and the migration energy barrier for the each saddle point structure the climbing image nudged elastic band method (CI-NEB) was applied [8]. The preliminary QHA calculation was provided using thermo\_pw package [9] which utilize the density functional perturbation theory (DFPT) framework for phonon frequencies computing. Then vibrational properties for all energies required were obtained with the finite displacement method as realized in the Phonopy program package [10].

### Results and discussion

The values of diffusion coefficients obtained for different temperatures were treated using a linear fit of  $\ln(D)$  as a function of  $1/T$  to obtain the effective prefactor  $D_0$  and diffusion activation energy  $Q$  parameters of an Arrhenius plot

$$D = D_0 \exp(-Q/kT). \quad (4)$$

Fig. 1 shows the linear Arrhenius plots of vacancy-mediated Cu diffusion coefficients in hcp Ru within a basal plane and parallel (between adjacent basal planes) to the  $c$ -axis together with available experimental data [11]. One can see the diffusion rate within a basal plane is slightly higher than between adjacent basal planes in the high temperature range and becomes lower with decreasing temperature. In fact, diffusion of Cu in hcp Ru appears to be slower than in bulk TiN [12, 13] or TaN [14], which are currently used as diffusion barrier layers. Large deviation in the obtained values from available experimental data are probably explained by grain boundary diffusion, observed in this research, due to the polycrystalline nature of the Ru film.

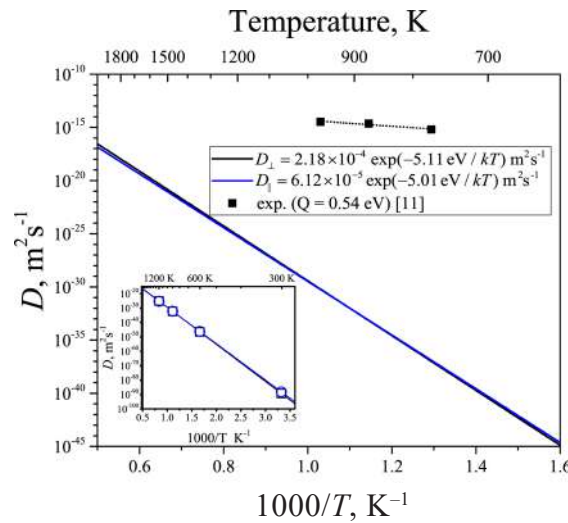


Fig. 1. Arrhenius plots of the calculated Cu diffusion coefficients in hcp Ru within a basal plane and between adjacent basal planes and experimental data corresponding to grain boundary diffusion [11]

### Conclusion

We have performed a first-principles study of Cu impurity diffusion in hcp Ru. Arrhenius plots were obtained for vacancy-mediated diffusion within a basal plane and between adjacent basal planes. Our results confirm the excellent barrier properties of Ru against Cu diffusion, and the possibility of using Ru as a promising candidate to replace current state-of-the-art diffusion barrier technologies.

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## REFERENCES

1. Krasnikov G.Ya., Orlov O.M., Distinctive features and problems of CMOS technology for decrease in the node size to 0.18  $\mu\text{m}$  or less, Nanotechnologies in Russia. 3 (7-8) (2008) 502–506.
2. Valeev A.S., Krasnikov G.Ya., Manufacturing technology of intra- and interchip interconnects for modern ULSIs: review and concepts of development, Russian Microelectronics. 44 (3) (2015) 154–172.
3. Bernasconi R., Magagnin L., Ruthenium as diffusion barrier layer in electronic interconnects: current literature with a focus on electrochemical deposition methods, Journal of the electrochemical society. 166 (1) (2018) D3219–D3225.
4. Ghate P.B., Screened interaction model for impurity diffusion in zinc, Physical Review. 133 (4A) (1964) A1167–A1175.
5. Glasstone S., Laidler K.J., Eyring H., The Theory of rate processes, Vol. 547, McGraw-Hill Book Company, Inc., Columbus. (1941).
6. Giannozzi P., et al., Advanced capabilities for materials modelling with Quantum ESPRESSO, Journal of physics: Condensed matter. 29 (46) (2017) 465901.
7. Wu Z., Cohen R.E., More accurate generalized gradient approximation for solids, Physical Review B—Condensed Matter and Materials Physics. 73 (23) (2006) 235116.
8. Henkelman G., Uberuaga B.P., Jynsson H., A climbing image nudged elastic band method for finding saddle points and minimum energy paths, The Journal of chemical physics. 113 (22) (2000) 9901–9904.
9. Palumbo M., Dal Corso A., Lattice dynamics and thermophysical properties of hcp Os and Ru from the quasi-harmonic approximation, Journal of Physics: Condensed Matter. 29 (39) (2017) 395401.
10. Togo A., Tanaka I., First principles phonon calculations in materials science, Scripta Materialia. 108 (2015) 1–5.
11. Chen C.W., Jeng J.S., Chen J.S., Comparative study of Cu diffusion in Ru and Ru-C films for Cu metallization, Journal of The Electrochemical Society. 157 (11) (2010) H997.
12. Bochkarev A.S., et al., Ab initio study of Cu impurity diffusion in bulk TiN, Physical Review B. 94 (10) (2016) 104303.
13. Gorokhov S.A., Rezvanov A.A., Reznik A.A., Energy barriers of point defects migration in TiN from first principles, Electronic engineering. Series 3: Microelectronics. 3 (191) (2023) 5–13.
14. Zhao Y., Lu G., First-principles simulations of copper diffusion in tantalum and tantalum nitride, Physical Review B—Condensed Matter and Materials Physics. 79 (21) (2009) 214104.

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## Numerical modeling of optical transmittance of 2×2 directional couplers based on GaP nanowires

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**Abstract.** In this paper, the optical properties of the GaP nanowires-based directional X-coupler are investigated for the design and further fabrication of a passive nanophotonic device. Results of numerical calculations demonstrate how the coupling length, nanowires diameter, and the gap between them influence the spectral composition of the output signals. By optimizing these geometric parameters, efficient subwavelength directional X-couplers based on GaP nanowires can be fabricated for light control in photonic circuits.

**Keywords:** photonics, passive optical device, directional coupler, nanowires

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## Численное моделирование оптического пропускания направляющих 2×2-разветвителей на основе нитевидных нанокристаллов GaP

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**Аннотация.** В работе исследуются оптические свойства направляющих 2×2-разветвителей на основе нитевидных нанокристаллов (ННК) GaP с целью изготовления пассивного нанофотонного устройства. Результаты численного расчета показывают, как длина оптической связи, диаметр ННК и зазор между ними влияют на спектральный состав выходных сигналов. Оптимизируя эти геометрические параметры, можно изготовить эффективные субволновые направляющие 2×2-разветвители на основе ННК GaP для управления светом в фотонных интегральных цепях.

**Ключевые слова:** фотоника, пассивные оптические элементы, направляющие разветвители, нитевидные нанокристаллы

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## Introduction

Optical  $2\times 2$  or X-couplers are fundamental components of integrated photonic systems. They can serve as passive optical elements for light manipulation, acting as spectral filters or power splitters. Silicon is the primary material for such devices [1]. Despite its well-studied nature and technological maturity, this material has significant drawbacks, including difficulties in obtaining emitters and visible range opacity, which hinder its miniaturization and application. Gallium phosphide (GaP) meets the requirement of transparency in the visible range. Additionally, it exhibits a high refractive index [2] and nonlinear properties in this spectral region [3]. GaP is also an indirect-bandgap semiconductor with a bandgap of 2.26 eV at room temperature [4]. Due to this property and the ability to grow crystals with low sidewall roughness [5], GaP-based nanostructures demonstrate low absorption and scattering losses for visible light propagation and can be used as efficient waveguides [6]. Furthermore, GaP structure growth methods show great potential for compatibility with silicon technologies [7]. Additionally, there is a possibility of implementing emitters within a single GaP-based structure through chemical composition modification [8]. All these factors demonstrate GaP's significant promise for fabricating miniature elements of integrated nanophotonics, particularly  $2\times 2$ -directional couplers. GaP structures in the form of nanowires (NWs) possess favorable elastic mechanical properties, and owing to their high refractive index, NWs can be bent while preserving waveguide properties [9]. This work investigates the optical properties of a  $2\times 2$ -directional coupler based on GaP NWs, aiming to develop a full-fledged nanophotonic device and enable further optimization of its characteristics.

## Materials and methods

The analysis of a structure was performed using numerical simulations in Ansys Lumerical software. The simulations involved solving Maxwell's equations using the Finite-Difference Frequency-Domain (FDFD) method according to the Yee algorithm [10]. The model schematic is shown in Fig. 1, *a*. The directional coupler was set from two NWs placed parallel and converging at the center, forming the optical coupling region. The coupler sections had a length of 5  $\mu\text{m}$ , except for the bends and the optical coupling regions.  $\text{SiO}_2$  was chosen as the substrate material. The following parameters were used in the simulation: the GaP nanowire diameter  $D = 200$  nm, the gap distance  $g = 50$  nm between the NWs within the optical coupling region, and the parameter  $L_s = 5$  and 10  $\mu\text{m}$  – the length of the straight section in the optical coupling region. It is important to note that a symmetric structure was modeled, and the nanowire diameter remained constant along length. For comparison, 2D calculations of device cross-section in the optical coupling region were performed using the finite element method eigenmode solver implemented in COMSOL Multiphysics software.

## Results and discussion

For the presented  $2\times 2$ -directional coupler geometry, it is sufficient to consider the fundamental TE-like mode responsible for optical coupling. For a comprehensive analysis, we should also consider higher-order waveguide modes that have a lower effective refractive index than the fundamental mode. This leads to electric field spreads more widely outside the waveguide resulting in stronger interaction between adjacent nanowires. However, this low effective index also makes higher-order modes highly susceptible to attenuation. In devices with bends, a portion of their energy radiates away, leading to significant losses. Consequently, by the time they reach the

optical coupling zone, their power is extremely low, making their contribution to energy redistribution negligible in most practical calculations.

The main results of the 3D-calculation are the transmission spectra evaluated at the output ports. Typical spectra are presented in Fig. 1, *b*. They are featured by the presence of transmission bands at the output ports, with transmittance maxima alternating between these ports as the wavelength changes. The negligibly small transmittance at shorter wavelengths is associated with material absorption in GaP. The absence of transmittance at longer wavelengths is associated with optical losses due to field leakage into the substrate.

Another distinctive feature is the pattern of electromagnetic wave propagation within the structure. To demonstrate this, stationary electric field distributions in the optical coupling region were calculated (Fig. 1, *c*, *d*, *e*). The field distributions reveal EM field energy exchange between the coupler arms, where the number of exchange cycles increases as operating wavelength increases, owing to the greater possibility of interference.

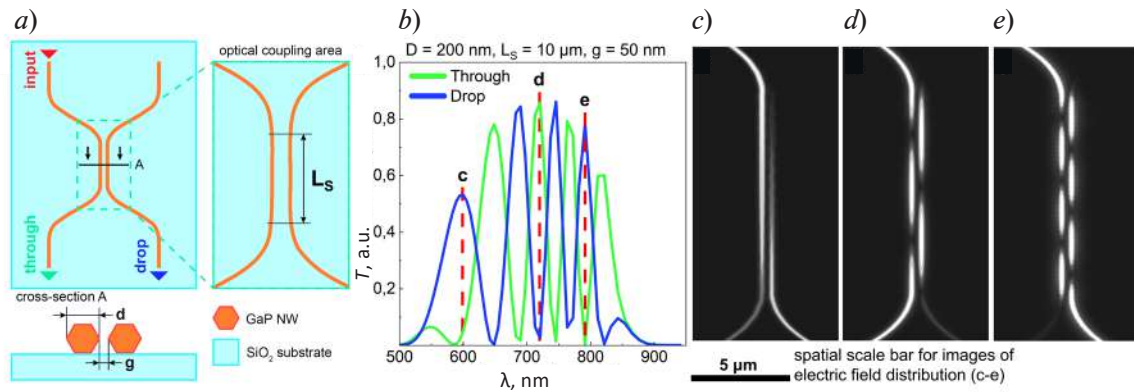


Fig. 1. GaP-based directional coupler 3D-simulations:

Device model to simulate in Ansys Lumerical (*a*), calculated transmittance spectra for geometrical parameters  $D = 200$  nm,  $L_s = 10$   $\mu$ m,  $g = 50$  nm (*b*); electric field intensity distributions in the optical coupling region for alternating transmittance maxima of both ports 550 nm (*c*), 600 nm (*d*), 648 nm (*e*), 690 nm (*f*), 720 nm (*g*), 746 nm (*h*), 768 nm (*i*), 791 nm (*j*)

The numerical calculation presented above provides the most comprehensive characterization of the structure's optical properties, as it accounts for the geometric parameters. However, such calculations are extremely resource-intensive, making them difficult to use for designing devices with optimized parameters. Computational costs can be significantly reduced by considering a 2D problem. Region of the optical phenomena of interest lies within the optical coupling region, so it is enough to simulate the cross-section of this region (Fig. 2, *a*). Since sufficiently small distances between the NWs are considered, waveguide modes overlap and interaction occurs, leading to the phenomenon of cross-talk. The cross-talk induces optical coupling and energy transfer from one nanowire to the other and leads to the formation of two supermodes: symmetric (even) and anti-symmetric (odd). They are characterized by propagation constants  $\beta_+$  and  $\beta_-$ , determined for each wavelength via the corresponding effective refractive indices:  $\beta_{\pm} = 2\pi n_{\pm}/\lambda$ , where  $\lambda$  is the light wavelength in vacuum. The field of the modes propagating in this system follows an exponential law  $E \sim \exp[-\beta \cdot L]$ . It is necessary to consider the distance  $L$  over which the modes effectively interact with each other, as the coupling length ( $L_c$ ). Previously, to characterize the couplers, the length of the straight section within the optical coupling region ( $L_s$ ) was introduced. This distance is merely a geometric parameter and cannot fully characterize the optical coupling region because field interaction occurs not only on the straight sections but also within the bend regions. The signal intensities distribution at the output ports depends on the linear combination of the fields propagating along the coupling length  $L_c$ , specific expressions are given in Fig. 2, *a*. Values of  $n_+$  and  $n_-$  were obtained via COMSOL Multiphysics simulations.

As a result, spectral maps of the output signal intensity distributions depending on geometric parameters were obtained. The transmittance dependence on coupling length  $L_c$  for different ports is shown in Fig. 2, *b*. An increase in the coupling length  $L_c$  leads to an increase in the number of



transmittance bands, a decrease in their width, and a transmittance maxima blue shift. The maps also demonstrate the alternation of signal intensities at the output ports, except in loss-prone regions. In particular, material losses dominate in the short-wavelength region; it is evident how these losses increase with the coupler length, leading to significant signal attenuation. Fig. 2, *d* presents a map of the through-port spectrum dependence on the gap width  $g$  between the NWs. As  $g$  increases, the number of transmission bands decreases, and their width increases due to the weakening of interference effects. Furthermore, increasing  $g$  causes a transmittance maxima red shift (shift towards longer wavelengths). A stronger influence on the maxima position is exerted by changing the nanowire diameter  $D$  (Fig. 2, *e*). However, varying  $D$  practically does not affect the number of transmission bands. Figures 2, *d*, *e* clearly show the waveguide mode cutoff spectral position. At wavelengths below this point, the structure functionalizes as a directional coupler.

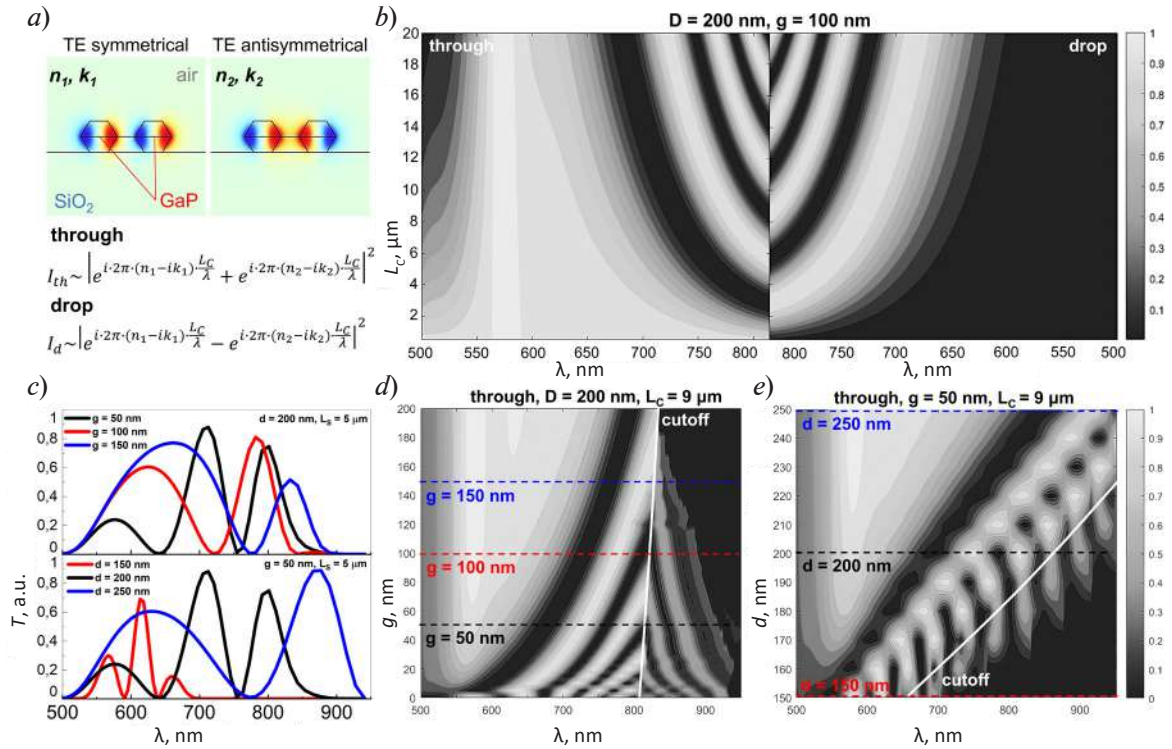


Fig. 2. GaP-based directional coupler 2D-calculations: even and odd modes and analytical formulas used to calculate the intensity at the optical coupling zone outputs (a), spectral maps of signal intensity distribution at through and drop ports depending on optical coupling length for fixed  $D = 200 \text{ nm}$  and  $g = 100 \text{ nm}$  (b), transmittance spectra obtained in the 3D-simulations for several sets of parameters (c), given for comparison with the spectral maps of signal intensity distribution at through port depending on gap between NWs for fixed  $D = 200 \text{ nm}$  and  $L_c = 9 \mu\text{m}$  (d), spectral maps of signal intensity distribution at through port depending on NWs diameter for fixed  $g = 50 \text{ nm}$  and  $L_c = 9 \mu\text{m}$  obtained in 2D-calculations (e)

Although the 2D calculation requires significantly fewer computational resources, it does not account for all geometric features of GaP-nanowire-based directional couplers. However, the coupling length  $L_c$  serves as an effective parameter and with the correct choice of  $L_c$ , the 2D model can adequately characterize the 3D system. To demonstrate this, a part of the 3D through-port simulation results for the structure with  $L_s = 5 \mu\text{m}$  (Fig. 2, c) were sorted to compare with 2D calculation results. For the maps in Figures 2, *d*, *e*, the  $L_c$  value was chosen as  $9 \mu\text{m}$ , and the parameters  $D$  or  $g$  were fixed at values corresponding to the 3D calculation. Examining intensity maps cross-sections along the remaining varied parameter, it is evident that the transmittance spectra obtained from the 2D model fully match the spectra calculated in 3D.

## Conclusion

In summary, this work demonstrates that GaP NWs-based 2×2 directional couplers can effectively control visible light at nanoscale. By determining the effective parameter of  $L_C$ , significant optimization of the design process can be achieved by replacing resource-intensive 3D modeling with 2D calculation. Optimizing the structure's geometric parameters leads to precise tuning of the device's spectral characteristics. This tunability enables multiple operational modes, from optical switching to power splitting, making these GaP NW couplers versatile components for integrated photonic systems.

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## REFERENCES

1. Thomson D., Zilkie A., Bowers J. E., et al., Roadmap on silicon photonics, Journal of Optics. 18 (7) (2016) 073003.
2. Bond W.L., Measurement of the refractive indices of several crystals, Journal of Applied Physics. 36 (5) (1965) 1674–1677.
3. Singh S., Srivastava P., Optical properties of gallium phosphide (GaP) nanowires, Applied Nanoscience. 3 (2013) 89–94.
4. Lorenz M.R., Pettit G.D., Taylor R.C., Band gap of gallium phosphide from 0 to 900 K and light emission from diodes at high temperatures, Physical Review. 171 (3) (1968) 876.
5. Fedorov V.V., Bolshakov A.D., Sergaeva O., et al., Gallium phosphide nanowires in a free-standing, flexible, and semitransparent membrane for large-scale infrared-to-visible light conversion, ACS nano. 14 (8) (2020) 10624–32.
6. Kuznetsov A., Anikina M.A., Toksumakov A.N., et al., In-Plane Directional MoS<sub>2</sub> Emitter Employing Dielectric Nanowire Cavity, Small Structures. 6 (4) (2025) 2400476.
7. Beyer A., Ohlmann J., Liebich S., et al., GaP heteroepitaxy on Si (001): Correlation of Si-surface structure, GaP growth conditions, and Si-III/V interface structure, Journal of Applied Physics. 111 (8) (2012).
8. Kuznetsov A., Roy P., Kondratev V.M., et al., Anisotropic Radiation in Heterostructured “Emitter in a Cavity” Nanowire, Nanomaterials. 12 (2) (2022) 241.
9. Kuznetsov A., Moiseev E., Abramov A.N., et al., Elastic Gallium Phosphide Nanowire Optical Waveguides – Versatile Subwavelength Platform for Integrated Photonics, Small. (2023) 2301660.
10. Taflove A., Hagness S. C., Piket-May M., in The Electrical Engineering Handbook (Ed.: W.-K. Chen), Academic Press, Cambridge, MA. (2005) 629–670.

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## Evaluation of the impact of atmospheric refraction on the bit error rate in the space-Earth optical communication channel

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**Abstract.** Classical optical communication allows the design of a high-speed data transmission channel between the spacecraft and the ground station. Its advantages are high interference resistance, high energy efficiency, low detectability, and significant potential for speed enhancement compared to radio communication. However, optical communication has a few technological limitations. This study investigates the contribution of atmospheric refraction to the value of bit error rate (BER). Preliminary results show a decrease in the signal-to-noise ratio as a function of the spacecraft's elevation angle, resulting in increased bit errors in data communication.

**Keywords:** free-space optical communication, space-Earth communication, atmospheric refraction, laser physics

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Материалы конференции

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## Оценка влияния атмосферной рефракции на величину битовой ошибки в оптическом канале связи космос-Земля

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**Аннотация.** Классическая оптическая связь позволяет организовать канал по высокоскоростной передачи данных с космических аппаратов на Землю. Среди ее преимуществ высокая помехозащищенность, высокая энергоэффективность, малозаметность и высокий потенциал увеличения скорости, в сравнении с радиосвязью. В этом исследовании изучается вклад явления астрономической рефракции в потенциальное значение величины битовой ошибки. Предварительные результаты



показывают уменьшение соотношения сигнала к шуму в линиях связи между спутником и наземным приемником в зависимости от угла возвышения космического аппарата, что в свою очередь приводит к увеличению битовой ошибки при передаче данных.

**Ключевые слова:** оптическая связь в свободном пространстве, связь космос-Земля, атмосферная рефракция, лазерная физика

**Ссылка при цитировании:** Бахшалиев Р.М., Хмелев А.В., Дуплинский А.В., Барбышев К.А., Мерзлинкин В.Е., Левашов С.Д. Оценка влияния атмосферной рефракции на величину битовой ошибки в оптическом канале связи космос-Земля // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2025. Т. 18. № 3.2. С. 81–85. DOI: <https://doi.org/10.18721/JPM.183.215>

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## Introduction

Space-ground optical communication requires an acquisition, pointing, and tracking system on both sides with a closed feedback loop consisting of a fast-steering mirror and a camera [1, 2]. However, during the operation of the guidance and stabilization system, the beacon laser signal transmitted from the Earth [3] and the telecommunication signal sent from the spacecraft experience different optical paths as they traverse the atmospheric layers. This results in an increased guidance error, which reduces the signal-to-noise ratio and leads to an increase in BER due to the Gaussian distribution of the beam intensity. In 2023, the Vector [4] payload was developed and successfully launched into orbit to demonstrate classical laser communication between satellite and ground station, and also to test some technical solutions and service systems.

## Methods and results

From a structural perspective, the Earth's atmosphere can be represented as layers of a specified height, each possessing its own average temperature and pressure values. The refractive index of air can be calculated as [5]:

$$n = N \cdot 10^{-6} + 1, \quad (1)$$

where  $N$  is the reduced refractive index.

The reduced refractive index can be calculated as follows:

$$N = N_0 \cdot \frac{P \cdot T_0}{T \cdot P_0}, \quad (2)$$

where  $N_0$  is an initial reduced refractive index,  $T_0$  and  $P_0$  represent the initial temperature and pressure in the layer with the refractive index  $N_0$ , respectively,  $T$  and  $P$  are the temperature and pressure in the layer with the refractive index  $N$ . For dry air, at a temperature of 273.15 K and a pressure of 760 mm Hg, the refractive index can be calculated as [6]:

$$N_0 = \left( 103.38 + \frac{0.5854}{\lambda^4} \right) \frac{P}{T}, \quad (3)$$

where  $\lambda$  is the wavelength of radiation.

To estimate the divergence of the optical beam arriving on Earth from the spacecraft, the length must be determined while taking air refraction and the observation location into account. This quantity can be calculated based on the laws of geometric optics (see Fig. 1).

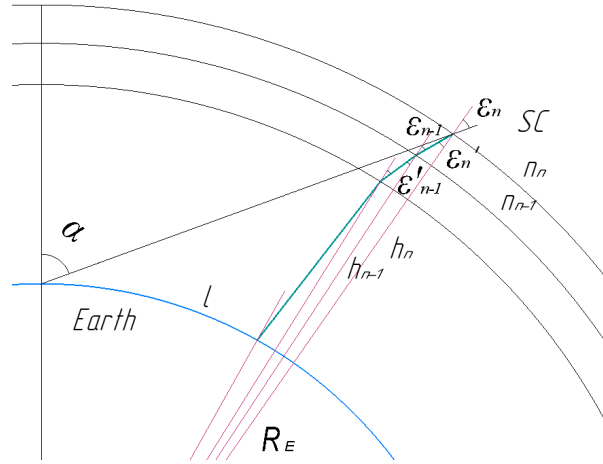


Fig. 1. Methodology for calculating atmospheric refraction:  $\epsilon_n, \epsilon'_n, \epsilon_{n-1}, \epsilon'_{n-1}$ , are the angles of incidence and refraction,  $h_n, h_{n-1}$  are the heights from the Earth to layers with refractive indices  $n_n, n_{n-1}$ ,  $R_E$  is the radius of the Earth,  $\alpha$  is the elevation angle of spacecraft,  $l$  is the length between the observation point and the deflected ray on the surface of the Earth

The signal-to-noise ratio (SNR) influences the BER, which is also impacted by the type of signal modulation used. The satellite Vector employs pulse position modulation (PPM), and the function of the BER is defined as [7]:

$$\text{SNR}_2 = \text{SNR}_1 \cdot e^{\left(\frac{l^2}{2\sigma^2}\right)}, \quad (4)$$

where  $L$  is the number of time intervals (with  $L = 4$  for PPM-4 encoding). Since the spot formed on Earth by the spacecraft exhibits a Gaussian distribution of energy  $E$ , the SNR at the center of this spot is expressed as:

$$\text{SNR}_1 = E \cdot \frac{1}{\sigma\sqrt{2\pi} \cdot \text{Noise}}, \quad (5)$$

where  $\sigma$  is the standard deviation of the Gaussian distribution.

At a point offset by  $l$  from the center of the spot due to atmospheric refraction, the SNR can be expressed as:

$$\text{SNR}_1 = \text{SNR}_2 \cdot e^{\left(\frac{l^2}{2\sigma^2}\right)}. \quad (6)$$

By assigning values to the channel parameters, one can obtain the BER for two different values of SNR ( $\text{BER}_2 / \text{BER}_1$ ), serving as an indicator that characterizes the quality of the channel.

The SNR value is determined by the satellite beam energy and the Gaussian beam profile, as shown in Eq. (5), which are defined by the design of the spacecraft. We calculate the  $\text{BER}_2/\text{BER}_1$  value for the CubeSat Impulse-1 with the payload Vector in low Earth orbit. Let us the  $\text{SNR}_1$  value to be at least 13 dB at the at the maximum elevation  $\alpha = 85^\circ$ , so that the BER is not more than  $10^{-6}$ , according to Eq. (4) (see Fig. 2).

The divergence parameter of a diffraction-limited optical system  $\sigma$  is set to 5 in the zenith position ( $\alpha = 0^\circ$ ), which is typical for optics that can be installed on a spacecraft of such a form factor as CubeSat. Note that the SNR value changes due to the varying distance between the

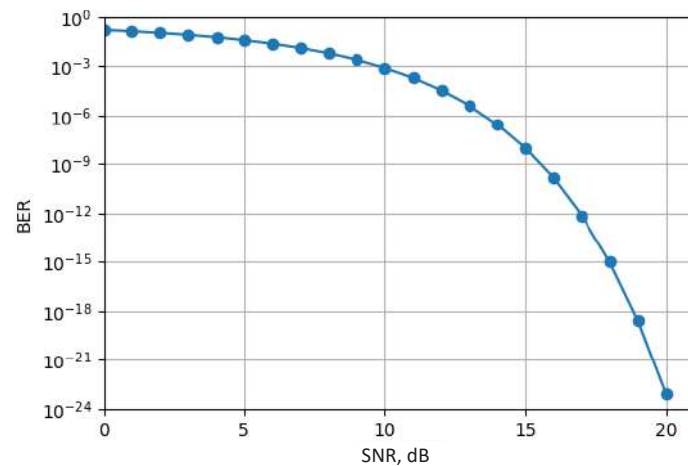


Fig. 2. Bit error rate vs signal-to-noise ratio for PPM coding

satellite and the ground station, and the divergence parameter also changes as the diameter of the Gaussian beam spot on Earth changes. The values can be determined and calculated based on the parameters of the orbit. Fig. 3 illustrates the dependence of the bit error ratio ( $BER_2/BER_1$ ) on atmospheric refraction, specifically in relation to elevation angle of the satellite along its trajectory.

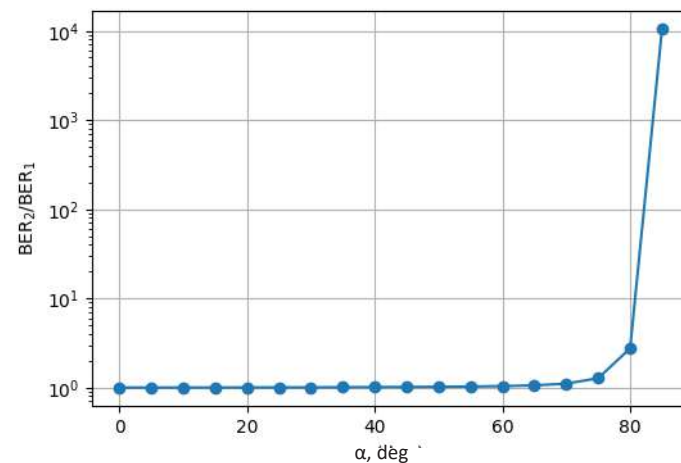


Fig. 3. Bit error ratio ( $BER_2/BER_1$ ) vs elevation angle for PPM coding

Starting from the elevation angles of more than 60°, the influence of atmospheric refraction on the deterioration of the bit error ratio is emerged. At elevation angles of more than 80°, there is a sharp increase in bit errors by more than 10 dB, which cannot provide the required level of errors. As a result, we should consider atmospheric refraction to optimize the use of the communication channel and maximize the duration of the communication session.

### Conclusion

We have conducted the calculations of the increase in the BER as a function of the elevation angle of the spacecraft, taking into account the phenomenon of atmospheric refraction. The changes in the BER due to the contribution of the refraction phenomenon in the atmosphere allow us to assess the quality of the channel in the classical optical communication link between the spacecraft and the Earth. The results of the calculations show that at zenith angles of more than 80 degrees and up to 90 degrees, there is a sharp increase in BER from one to several orders of magnitude, which requires compensation.



## REFERENCES

1. Liao S.K., Cai W.Q., Liu W.Y., et al., Satellite-to-ground quantum key distribution, *Nature*. 549 (2017) 43–47.
2. Li Y., Cai W.-Q., Ren J.-G., et al., Microsatellite-based real-time quantum key distribution, *Nature*. 640 (2025) 47–54.
3. Khmelev A., Duplinsky A., Bakhshaliev R., et al., Eurasian-scale experimental satellite-based quantum key distribution with detector efficiency mismatch analysis, *Opt. Express*. 32 (2024) 11964–11978.
4. Miller A.V., Pismeniuk L.V., Bakhshaliev R.M., Vector—towards quantum key distribution with small satellites, *EPJ Quantum Technology*. 10 (1) (2023) 52.
5. Zuyev V.Ye., Rasprostraneniye lazernogo izlucheniya v atmosphere, *Radio i svyaz*. (1981) 288.
6. Kushtin I.F., Refraktsiya svetovykh luchey v atmosphere, *Nedra*. (1971) 251.
7. Elganimi T.Y., Performance comparison between OOK, PPM and pam modulation schemes for free space optical (FSO) communication systems: analytical study, *International Journal of Computer Applications*. 79 (11) 2013.

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### **Simulation of light propagation in waveguides coupled to hexagonal microcavities formed in the GaAs-based photonic crystal**

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**Abstract.** This paper presents the results of numerical simulation of the light-matter interaction in the GaAs-based photonic crystal (PhC). The study focuses on the coupled configurations of waveguides and hexagonal microcavities operating at a wavelength of 1.3  $\mu\text{m}$ . A systematic investigation is conducted into the influence of the diameter of microcavity, its distance from the waveguide and the defect configuration on the distribution of the electric field strength within the PhC structure. It is shown that a spacing of 2 rows between the waveguide and 1.65- $\mu\text{m}$ -diameter cavity allows achieving maximum electric field strength within the cavity. An introduction of a defect into the waveguide leads to a further increase in the electric field strength in the cavity, with an optimal radius of 209 nm.

**Keywords:** photonic crystal, waveguide, microcavity, GaAs

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Материалы конференции

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### **Моделирование распространения света в волноводах, связанных с гексагональными микрополостями, сформированными в фотонном кристалле на основе GaAs**

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**Аннотация.** В данной работе представлены результаты численного моделирования взаимодействия света с веществом в фотонном кристалле (ФК) на основе GaAs. Исследование посвящено связанным конфигурациям волноводов и гексагональных микрополостей, функционирующих на длине волны 1,3 мкм. Проводится систематическое исследование влияния диаметра микрополости, ее расстояния от волновода и конфигурации дефекта на распределение напряженности электрического поля в пределах структуры ФК. Показано, что расстояние в 2 ряда между волноводом и полостью с диаметром 1,65 мкм позволяет достичь максимальной напряженности





электрического поля в пределах полости. Внедрение дефекта в волновод приводит к дальнейшему увеличению напряженности электрического поля в полости при оптимальном радиусе 209 нм.

**Ключевые слова:** фотонный кристалл, волновод, микрополость, GaAs

**Финансирование:** Исследование выполнено за счет гранта Российского научного фонда № 23-79-10313, <https://rscf.ru/project/23-79-10313/>, в Южном федеральном университете и при финансовой поддержке проекта № FENW-2025-0004.

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## Introduction

Photonic crystals (PhCs) are a class of optical materials characterized by a periodic modulation of the permittivity in space. When the period of this modulation is comparable to the wavelength of light, it leads to the formation of a complete or partial photonic bandgap (PBG) in the spectrum of electromagnetic states of the material [1]. Due to these unique optical properties, PhCs are considered a promising platform for the development of large-scale optical integrated circuits.

PhCs offer a wide range of potential applications in both fundamental research and applied fields [2–5]. In particular, there are a number of works devoted to the application of waveguide-cavity configurations, such as a pressure sensor based on two-dimensional (2D) PhC structures, which operates by detecting the shift in the resonant wavelength in response to applied pressure [6]. Another work is also of interest, where the novel design of a microring resonator based on a subwavelength grating was presented. The sensitivity acquired in this paper is the highest compared to the previously reported values in the literature [7]. Although the above papers confirm the relevance of PhCs in modern photonics, specific configurations of the waveguide-microcavity systems are yet to be optimized.

In the present study, simulation of light-matter interaction in PhCs containing coupling configurations of waveguides and hexagonal microcavities is carried out. The target wavelength is chosen to be 1.3  $\mu\text{m}$ , which is dictated by its location within the second transparency window of optical fiber, characterized by low attenuation and zero dispersion [8].

## Materials and methods

This study focuses on a 2D PhC formed by a hexagonal lattice of air holes embedded within a GaAs matrix. The geometric parameters of the structure were optimized for a wavelength of 1.3  $\mu\text{m}$ : the radius of the air holes and the lattice period were set to 209 and 520 nm, respectively. This selection of parameters ensured that the radiation fell within the complete photonic bandgap of the PhC, applicable to both transverse electric (TE) and transverse magnetic modes. Repositioning of holes within the PhC structure allowed for the design of diverse configurations, including hexagonal cavities coupled to waveguides.

The simulation was carried out in the Comsol Multiphysics 6.1 software package. For the analysis of TE-wave propagation through the PhC, a scalar equation for the transverse component of the electric field (EF) was employed:

$$-\nabla \cdot \nabla E_z - n^2 k_0^2 E_z = 0, \quad (1)$$

where  $n$  is the refractive index and  $k_0$  is the free-space wave number.

## Results and discussion

Fig. 1 presents the results of numerical simulations of a structure comprising a waveguide and a hexagonal cavity with a diameter ( $d$ ) of  $1.65 \mu\text{m}$  and discretely varying separation between them ( $L$ ). The distance between the waveguide and the cavity varies in increments corresponding to one row of air holes of the PhC.

While Fig. 1, *a*, *b* demonstrates blurred patterns of the EF strength distribution within the cavity, pronounced hexapole modes are observed in Fig. 1, *c*, implying that this waveguide-microcavity configuration is optimal for  $d = 1.65 \mu\text{m}$ . A dip (for the waveguide) and a peak (for the cavity) in the dependences in Fig. 2, *a*, *b* indicate that a significant portion of the radiation from the waveguide is transferred to the microcavity, which is also seen in Fig. 1, *c*. The optimal values of the PhC parameters are marked with green circles in figure 2. Therefore, the waveguide must be positioned two rows from the microcavity to achieve maximum efficiency of the system.

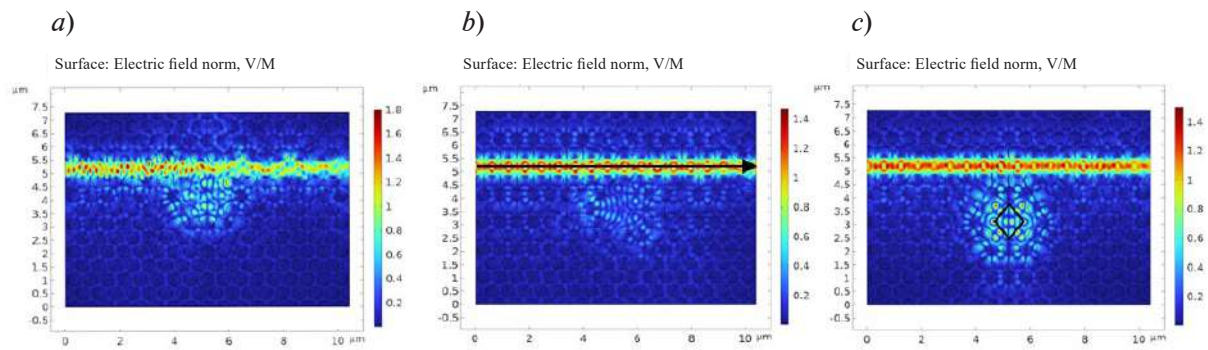


Fig. 1. Distribution of the EF strength in the PhC with a different separation between the waveguide and the cavity ( $d = 1.65 \mu\text{m}$ ): (a)  $L = 0$ ; (b)  $L = 1$ ; (c)  $L = 2$ . The arrow in Fig. 1, *b* and the rhombus in Fig. 1, *c* indicate a line along which the integrated EF strength was measured

It should be noted that the structure with a microcavity located without a spacing from the waveguide (Fig. 1, *a*) has an even lower integrated EF strength along the waveguide. However, this configuration cannot be considered optimal because increased losses in such a microcavity can lead to a decrease in the quality factor of the hexagonal resonator. Fig. 2, *a* also demonstrates that the structures with  $d = 2.69 \mu\text{m}$  are optimal when the microcavity is located 1 row from the waveguide. In this case, hexapole modes are also observed in the microcavity, implying that it can operate as a high-quality resonator.

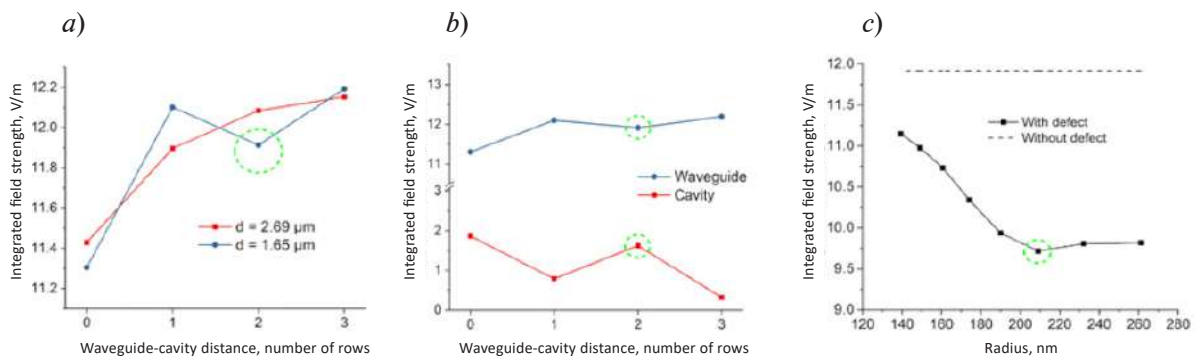


Fig. 2. Dependences of the integrated EF strength along the waveguide (*a*) and within the cavity with a diameter  $d$  (*b*) on the number of rows of air holes  $L$  and along the waveguide on the radius of defect in the waveguide (*c*)

In order to improve the penetration of radiation from the waveguide into the hexagonal cavity, a defect was introduced at a distance of  $5.2 \mu\text{m}$  from the left edge of the waveguide (light input). Fig. 3 presents the results of numerical simulations of a structure comprising the hexagonal

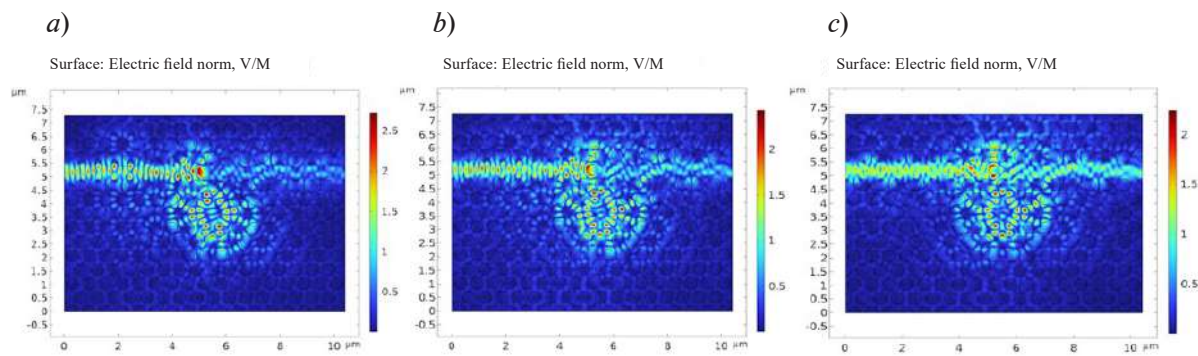


Fig. 3. Distribution of the EF strength in the waveguide-microcavity structure with a defect radius of 232 nm (a), 209 nm (b) and 174 nm (c) obtained as a result of the simulation

cavity located at  $L = 1$  from the waveguide with a defect with different radii. Fig. 2, *c* demonstrates a dependence of the integrated EF strength along the waveguide on the defect radius. The results presented suggest that the introduction of the defect allows a reduction of the integrated EF strength along the waveguide. As the defect radius increases, the integrated EF strength along the waveguide decreases until the radius reaches a value of 209 nm. A further increase in the defect radius leads to an increase in the EF strength. This effect indicates that at a defect radius of 209 nm (equal to the pillar radius in the periodic PhC structure), the maximum portion of light from the waveguide is introduced into the hexagonal cavity, which corresponds to Fig. 3, *b*.

### Conclusion

The presented work is dedicated to the numerical simulation of the interaction of light with GaAs-based PhCs containing a hexagonal microcavity coupled to a waveguide and operating at a wavelength of 1.3  $\mu\text{m}$ . It is shown that the optimal configuration providing efficient input of light into the hexagonal microcavity is a structure with a 1.65- and 2.69- $\mu\text{m}$ -diameter cavity located 2 and 1 row of air holes from the waveguide, respectively. A structure with a defect having a radius of 209 nm allows further enhancing of the PhC characteristics. The results obtained can be applied in the development of compact optical devices such as optical modulators and switches.

### REFERENCES

1. Dyachenko P.N., Miklyaev Y.V., Dmitrienko V.E., Three-dimensional photonic quasicrystal with a complete band gap, JETP Lett. 86 (4) (2007) 240–243.
2. Tamer A. Moniem., All-optical XNOR gate based on 2D photonic-crystal ring resonators, Quantum Electronics. 47 (2) (2017) 169–172.
3. Xiong Y., Photonic Crystal Circular Defect (CirD) Laser, Photonics. 6 (2) (2019) 54.
4. Syrov M.D., Substantiation Study of Using Immobilized Cytostatics in Management of Tumors with Peritoneal Canceromatosis, Vestn. Exp. Clin. Surg. 8 (1) (2015) 82–86.
5. Hassan S., Chack D., Pavesi L., High extinction ratio thermo-optic based reconfigurable optical logic gates for programmable PICs, AIP Adv. 12 (5) (2022) 055304
6. Dinodiya S., Bhargava A., A Comparative Analysis of Pressure Sensing Parameters for Two Dimensional Photonic Crystal Sensors Based on Si and GaAs, Silicon. 14 (9) (2022) 4611–4618.
7. Butt M.A., Khonina S.N., Kazanskiy N.L., A highly sensitive design of subwavelength grating double-slot waveguide microring resonator, Laser Phys. Lett. 17 (7) (2020) 076201.
8. Brus C.-S., Torre A.D., Grassani D., et al. Supercontinuum in integrated photonics: generation, applications, challenges, and perspectives, Nanophotonics. 12 (7) (2023) 1199–1244.

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## **Determination of the length of the $2\times N$ superstructure during the synthesis of Ge on Si(001) at different temperatures**

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**Abstract.** The article is devoted to the study of the length of the  $2\times N$  superstructure during epitaxial growth of Ge on Si(001) at different synthesis temperatures in the range from 200 °C to 750 °C. The analysis took place during the growth process by reflection high-energy electron diffraction in the direction of [110]. The work makes it possible to evaluate the effectiveness of elastic stress relief due to  $2\times N$  at the initial stages of growth over a wide temperature range.

**Keywords:** molecular beam epitaxy, reflection high-energy electron diffraction, relaxation of elastic stresses,  $2\times N$  superstructure, heteroepitaxy

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Материалы конференции

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## **Определение длины сверхструктуры $2\times N$ при синтезе Ge на Si(001) при разных температурах**

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**Аннотация.** Статья посвящена исследованию длины сверхструктуры  $2\times N$  при эпитаксиальном росте Ge на Si(001) при разных температурах синтеза в диапазоне от 200 °C до 750 °C. Анализ происходил в процессе роста методом дифракции быстрых электронов в направлении [110]. Работа позволяет дать оценку эффективности снятия упругих напряжений за счет образования сверхструктуры  $2\times N$  на начальных стадиях роста в широком температурном диапазоне.

**Ключевые слова:** молекулярно-пучковая эпитаксия, дифракция быстрых электронов, релаксация упругих напряжений, сверхструктура  $2\times N$ , гетероэпитаксия

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## Introduction

In the world of constantly evolving technologies, increasingly stringent requirements are put forward for electronic components. Despite their miniature size, they must be efficient enough to perform the necessary tasks. The transition to nanoscale structures has opened up the possibility of creating small and, due to the effect of dimensional quantization, efficient components for microelectronics, optoelectronics and many other areas [1, 2]. The main requirements for such structures are their purity, precise size compliance and sharpness of heteroboundaries. The molecular beam epitaxy (MBE) method is well suited for such parameters, allowing the creation of structures of a given thickness with sharp heteroboundaries and a minimum number of defects [3]. The silicon–germanium material system is considered well studied and quite successful. Silicon, due to its availability, has an extensive technological base. Germanium, due to its compatibility with silicon and better electronic properties, is able to significantly improve the characteristics of electronic components created on the basis of Ge–Si [4]. Despite the active development and study of Ge growth processes on Si, there are significant gaps in knowledge that are becoming increasingly noticeable given modern requirements for the quality of nanostructures. One of them is the relaxation of elastic stresses of the germanium layer on silicon. Relaxation of elastic stresses due to a change in the surface morphology occurs during the epitaxial growth of Ge on Si due to a 4.2% lattice mismatch. The relaxation mechanism at the initial stages of growth is the formation of  $2 \times N$  and  $M \times N$  superstructures, and after the formation of the wetting layer is complete, the transition from two-dimensional to three-dimensional growth occurs [5]. This process can be tracked during growth without stopping it using the reflection high-energy electron diffraction (RHEED) method [6]. Epitaxial processes that depend on the growth parameters determine the geometric and electrophysical properties of nanostructures. Therefore, increasing the control of epitaxial synthesis processes will lead to the creation of nanostructures of the required sizes and properties. Based on this, the aim of the work is to determine the length of the  $2 \times N$  superstructure at different temperatures during epitaxial growth of Ge on Si(001) using RHEED patterns.

## Materials and methods

The experiments were carried out at the “Katun–100” MBE installation. Commercially available Si(001) substrates with a misorientation angle of  $0.1^\circ$  were used. Ge synthesis occurred after pre-epitaxial cleaning of the substrate and application of a 75 nm buffer layer. The germanium deposition rate was the same for all experiments and amounted to 0.02 ML/s.

During the experiment, the surface morphology was determined by the reflection high-energy electron diffraction method. The initial stage of Ge formation on Si(001) is the emergence of the  $2 \times N$  superstructure. On the surface, long dimer rows of Si are replaced by short rows of Ge. This mechanism of elastic stress relaxation at the initial stage of growth is the most advantageous for this material system [7]. The length of the superstructure can be determined by the  $(1/N)$  reflections that appear in the diffraction patterns (Fig. 1) [8].

Fig. 1, *a* shows the diffraction pattern from the Si(001) surface, and Fig. 1, *b* shows the diffraction pattern from the Ge/Si(001) surface. As can be seen, Fig. 1, *b* has additional  $1/N$  reflections. The superstructure length was determined as follows. The distance between the (00) and (01) reflections was divided by the distance  $(1/N)$  and (01). Thus, taking into account the inversion of scales in reciprocal space, it was determined how many times the new superstructure is larger than the crystal lattice parameter.

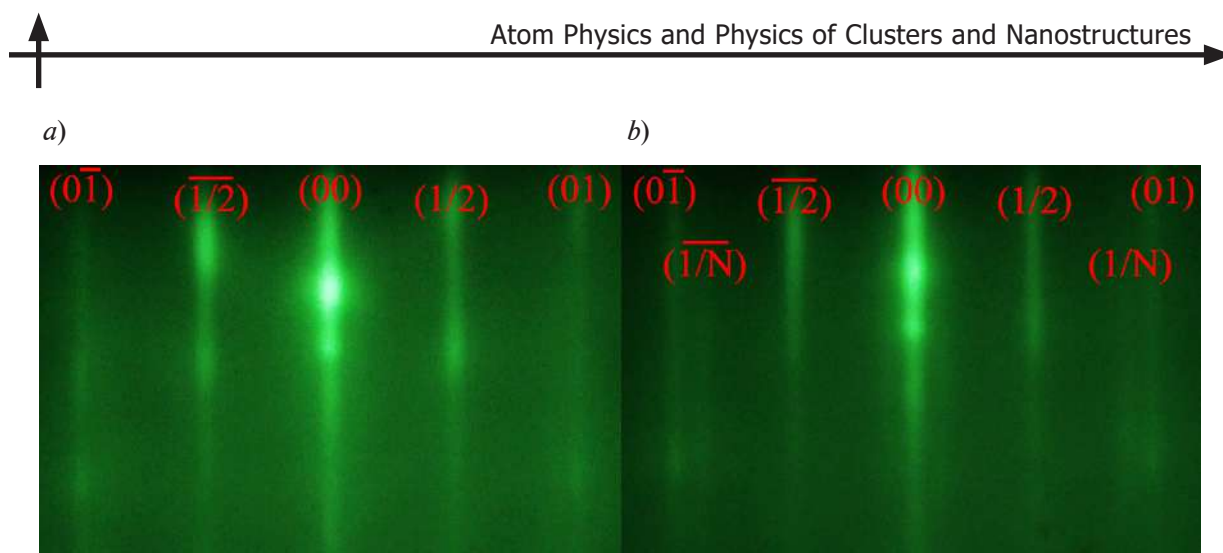


Fig. 1. RHEED patterns from pure Si(001) (a) and from Ge/Si(001) (b)

Elastic stresses caused by lattice mismatch, at a certain thickness of the two-dimensional germanium layer, can no longer be relieved by the formation of superstructures. At this stage, a stronger relaxation mechanism is activated – three-dimensional growth [9]. The start time of 3D growth is determined by the change in the intensity of the reflex (01) of the RHEED pattern [10]. Fig. 2 shows, as an example, the dependence of intensity ( $I$ ) on amount of material ( $n$ ) during the deposition of Ge on Si (001) at a temperature of 400 °C. Fig. 2 also shows RHEED patterns characteristic of a two-dimensional layer (on the left) and a three-dimensional structure (on the right).

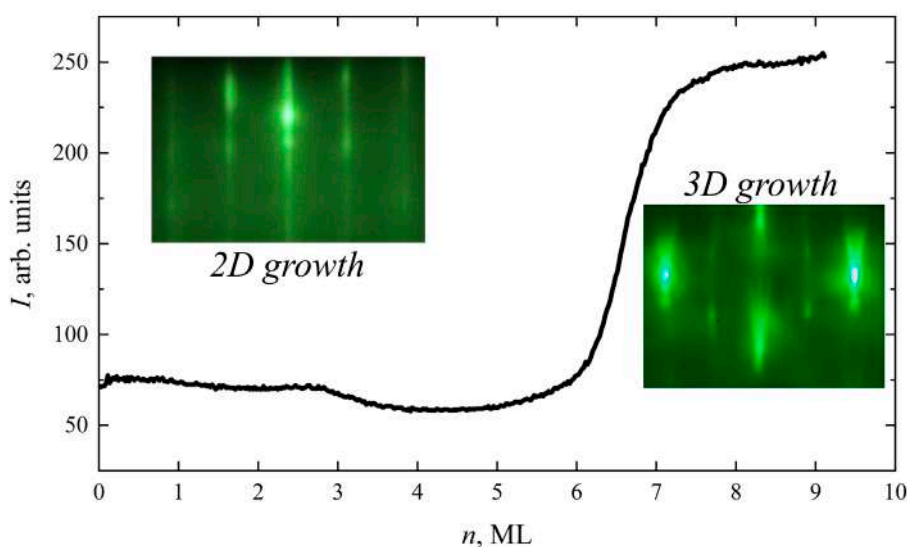


Fig. 2. Dependence of intensity of reflex (01) of RHEED pattern

Knowing the growth rate and the time of transition from two-dimensional to three-dimensional growth, it is possible to determine the thickness of the wetting layer, i.e. the critical thickness, above which germanium grows on silicon with the formation of three-dimensional islands.

### Results and discussion

Based on the results of the analysis of experiments on the deposition of Ge on Si(001), carried out at different substrate temperatures in the range from 200 °C to 750 °C, the dependence of the superstructure length ( $N$ ) on the synthesis temperature (Fig. 3, a) and the dependence of the critical thickness ( $n_{\text{critical}}$ ) of the wetting layer on the growth temperature (Fig. 3, b) were constructed.

The dependence of the length  $N$  on temperature in Fig. 3, a can be divided into three temperature ranges. In the first range of 200–350 °C, a decrease in the number  $N$  is observed. This can

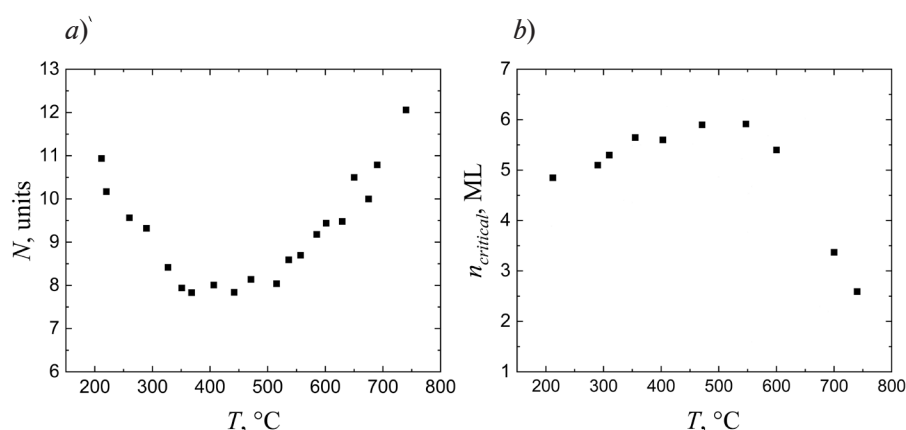


Fig. 3. Dependence of  $2 \times N$  superstructure length (a) and critical thickness of the wetting layer (b) on growth temperature

be explained by the destruction of dimer chains due to the intensification of thermal vibrations of atoms. A decrease in the number  $N$ , in turn, indicates that with an increase in temperature, a more complete relaxation of elastic stresses in the system occurs due to the appearance of a larger number of dimer vacancies. In the second range of 350–500 °C, the length of the superstructure  $2 \times N$  remains constant. This can occur because the highest degree of relaxation accessible to this mechanism (the formation of dimer vacancies) has been achieved, or such a number of vacancies ( $N = 8$ ) completely removes all stresses at these temperatures. In the third range of 500–750 °C, the length of the dimer rows begins to grow. This character of the dependence is explained by a set of processes. A more effective mechanism for the relaxation of elastic stresses is now the formation of  $M \times N$  superstructures [11, 12] and the transition to 3D growth, as evidenced by a decrease in the critical thickness of the wetting layer (Fig. 3, b). An increase in temperature increases the rate of diffusion into the bulk of the substrate, thereby reducing the Ge concentration on the surface, which reduces the stresses in the system and leads to an increase in the length of the dimer rows [13, 14].

### Conclusion

In this work, the reflection high-energy electron diffraction method was used to obtain a detailed dependence of the average size of the  $2 \times N$  superstructure on temperature in the range of 200–750 °C, which allows us to judge the mechanisms of elastic stress relaxation at the initial stages of Ge synthesis on Si(001). At growth temperatures from 200 °C to 350 °C, the efficiency of stress relaxation in the system is determined by the diffusion length of adatoms. At temperatures of 350–500 °C, maximum stress relaxation occurs, which is achieved by the formation of a  $2 \times 8$  superstructure. In the temperature range from 500 °C to 750 °C, the length of the dimer series begins to be affected by factors associated with the emergence of  $M \times N$  superstructures, accelerated transition to 3D growth, and diffusion of Ge atoms into the Si(001) substrate.

### REFERENCES

1. Porret C., Hikavy A., Granados J. G., et al., Very low temperature epitaxy of group-IV semiconductors for use in FinFET, stacked nanowires and monolithic 3D integration, ECS Journal of Solid State Science and Technology. 8 (2019) P392–P399.
2. Mitchell C.J., Hu T., Sun S., et al., Mid-infrared silicon photonics: From benchtop to real-world applications, APL Photonics. 9 (8) (2024) 080901-1–080901-15.
3. Shen C., Zhan W., Li M., et al., Development of in situ characterization techniques in molecular beam epitaxy, Journal of Semiconductors. 45 (3) (2024) 031301-1–031301-24.
4. Lozovoy K.A., Douhan R.M.H., Dirko V.V., et al., Silicon-based avalanche photodiodes: Advancements and applications in medical imaging, Nanomaterials. 13 (23) (2023) 3078-1–3078-24.
5. Voigtländer B., Fundamental processes in Si/Si and Ge/Si epitaxy studied by scanning tunneling microscopy during growth, Surface Science Reports. 43 (5–8) (2001) 127–254.

6. Hafez M.A., Zayed M.K., Elsayed-Ali H.E., Geometric interpretation of reflection and transmission RHEED patterns, *Micron*. 159 (2022) 103286-1–103286-21.
7. Dirko V.V., Lozovoy K.A., Kokhanenko A.P., et al., Thickness-dependent elastic strain in Stranski–Krastanow growth, *Physical chemistry chemical physics*. 22 (4) (2020) 19318–19325.
8. Taniguchi T., Ishibe T., Naruse N., et al., High thermoelectric power factor realization in Si-rich SiGe/Si superlattices by super-controlled interfaces, *ACS Applied Materials & Interfaces*. 12 (22) (2020) 25428–25434.
9. Dvurechenskii A.V., Yakimov A.I. Silicon-based nanoheterostructures with quantum dots, *Advances in semiconductor nanostructures*. (2017) 59–99.
10. Nikiforov A.I., Ulyanov V.V., Timofeev V.A., et al., Wetting layer formation in superlattices with Ge quantum dots on Si (1 0 0), *Microelectronics journal*. 40 (4–5) (2009) 782–784.
11. Arapkina L.V., Chizh K.V., Dubkov V.P., et al., Evolution of Ge wetting layers growing on smooth and rough Si (001) surfaces: Isolated {105} facets as a kinetic factor of stress relaxation, *Applied Surface Science*. 608 (2023) 155094.
12. Arapkina L.V., Yuryev V.A., Classification of Ge hut clusters in arrays formed by molecular beam epitaxy at low temperatures on the Si(001) surface, *Physics-Uspekhi*. 53 (3) (2010) 289–302.
13. Nikiforov A.I., Timofeev V.A., Teys S.A., et al., Initial stage growth of  $\text{Ge}_x\text{Si}_{1-x}$  layers and Ge quantum dot formation on  $\text{Ge}_x\text{Si}_{1-x}$  surface by MBE, *Nanoscale research letters*. 7 (1) (2012) 561.
14. Rastelli A., Stoffel M., Malachias A., et al., Three-dimensional composition profiles of single quantum dots determined by scanning-probe-microscopy-based nanotomography, *Nano letters*. 8 (5) (2008) 1404–1409.

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## STM visualization of local density of optical states of gold nanoantennas with sub-diffraction resolution

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**Abstract.** Simultaneous recording of luminescence induced by inelastic electron tunneling together with topography in scanning tunneling microscopy (STM-L) is a powerful tool in the study of local optical properties of nanostructures. In this study, we use the STM-L technique to visualize the local density of optical states (LDOS) by detecting the optical signal generated in the tunnel junction between a tungsten STM probe and a hollow hemispherical gold nanoantenna ( $d = 500$  nm,  $h = 300$  nm) fabricated by femtosecond laser printing. The light emission from the tunnel gap is caused by the process of inelastic tunneling of electrons. The intensity of photon signal directly dependent on LDOS — a key parameter in the design of light emitting inelastic tunneling-based nanoscale photon sources. We demonstrate that the STM-L method can provide information on the LDOS features of individual nanoantenna with sub-diffraction spatial resolution, as well as reveal smooth LDOS variations in periodic arrays of nanoantennas. These results highlight the unique capability of STM-L to reveal nanoscale optical patterns inaccessible to conventional diffraction-limited microscopy, highlighting its potential for advanced optical characterization at the nanoscale.

**Keywords:** gold nanoantenna, inelastic tunneling of electrons, local density of optical states, sub-diffraction imaging, femtosecond laser printing, scanning tunneling microscopy

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Материалы конференции

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## Визуализация локальной плотности оптических состояний золотых наноантенн с субдифракционным разрешением в сканирующем туннельном микроскопе

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**Аннотация.** Мультиканальная регистрация люминесценции, возбуждаемой зондом сканирующего туннельного микроскопа (СТМ-Л), и туннельная спектроскопия с регистрацией оптического сигнала (СТС-Л) доказали свою эффективность в качестве мощных инструментов для одновременного исследования оптических и электрических свойств источников фотонов. В данном исследовании мы используем технику СТМ-Л для визуализации локальной плотности оптических состояний (ЛПОС) путем регистрации оптического сигнала, генерируемого в туннельном переходе между вольфрамовым зондом СТМ и полый полусферической золотой наноантенной ( $d = 500$  нм,  $h = 300$  нм), изготовленной с помощью фемтосекундной лазерной печати. Световое излучение из туннельного зазора вызвано процессом неупругого туннелирования электронов (НТЭ), а его интенсивность напрямую зависит от ЛПОС — ключевого параметра в разработке наноразмерных источников фотонов. Мы демонстрируем, что СТМ-Л позволяет получать информацию о тонких пространственных особенностях ЛПОС как на уровне отдельных наноструктур с разрешением ниже дифракционного, так и выявлять плавные изменения ЛПОС в периодических массивах наноантенн. Эти результаты подчеркивают уникальные возможности СТМ-Л для продвинутых исследований оптических и электрических свойств наноразмерных источников фотонов, недоступных для традиционной оптической микроскопии с дифракционным ограничением.

**Ключевые слова:** золотая наноантенна, неупругое туннелирование электронов, локальная плотность оптических состояний, субдифракционные оптические измерения, фемтосекундная лазерная печать, сканирующая туннельная микроскопия

**Финансирование:** Работа выполнена при поддержке Российского научного фонда (грант № 25-19-00666).

**Ссылка при цитировании:** Соломонов Н.А., Лебедев Д.В., Павлов Д.В., Кучмижак А.А., Голубок А.О., Мухин И.С. Визуализация локальной плотности оптических состояний золотых наноантенн с субдифракционным разрешением в сканирующем туннельном микроскопе // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2025. Т. 18. № 3.2. С. 96–100. DOI: <https://doi.org/10.18721/JPM.183.218>

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### Introduction

The development of nanoscale light sources control by electrical signals remains a key challenge in modern optoelectronics and integrated photonics. Among the various approaches to implement such device, light emission via inelastic tunneling of electrons in metal–insulator–metal (MIM) and metal–insulator–semiconductor (MIS) tunnel junctions have attracted significant attention

as a promising platform for electrically-driven photon generation at the nanoscale [1–3]. In such MIM and MIS systems, electrons can tunnel through a sub-nanometer insulating layer (tunnel gap) losing part of their energy through the excitation of various states across a broad energy spectrum. This includes electron–hole pairs, molecular vibration transitions, localized plasmon modes (gap plasmon), propagating surface plasmons, and other states near the sample surface. Some of these excitations may decay radiatively, resulting in photon emission that can be detected using an external optical system [4]. However, only a small part of the tunneling electrons participates in the inelastic process, which leads to a low external quantum efficiency of the LEIT process. This fact significantly limits the application of LEIT for nanoscale light source technologies.

One of the strategies to enhance photon yield is to introduce resonant nanostructures, such as plasmonic nanoantennas, which create a strong enhancement of the local electromagnetic field into the tunneling region [5, 6]. These structures can significantly enhance the local density of optical states (LDOS), thereby increasing the probability of photon emission during inelastic tunneling process. As a result, properly designed nanoantennas can significantly improve the radiation efficiency of tunneling transitions and facilitate the development of compact nanoscale electrically-driven light sources.

In this work, we employ multichannel registration of luminescence excited by a scanning tunnelling microscope probe (STM-L) to visualize subtle spatial features in the LDOS of hollow hemispherical gold nanoantennas fabricated via femtosecond laser printing. We observe distinct LDOS patterns at the individual nanoantenna level associated with the excitation of intrinsic plasmonic modes, as well as smoothly varying LDOS distributions across periodic antenna arrays arising from propagating surface plasmon waves and their subsequent scattering into photons within the visible spectral range.

### Materials and methods

The investigated sample consisted of a 50 nm thick gold film deposited on an optically smooth glass substrate using electron beam evaporation without any adhesion layer. Hollow arrays of hemispherical gold nanoantennas with a base diameter of 500 nm and a height of 300 nm were fabricated on the gold surface via direct femtosecond laser printing [7]. The fabrication was performed using a pulsed Ti:sapphire laser system ( $\lambda = 800$  nm, pulse duration  $\sim 100$  fs, repetition rate of 80 MHz) focused onto the metal film through a high-numerical-aperture objective.

Tunnel junction was formed between the fabricated nanostructures and an electrochemically etched tungsten STM tip in an ultrahigh vacuum scanning tunneling microscope (Omicron VT STM/AFM). Photon emission from the tunnel gap was recorded using an IDQuantique ID120 (350–1000 nm) single-photon counting module synchronized with the acquisition of topographic data in the STM.

### Results and Discussion

Fig. 1 shows the typical STM topography maps and corresponding maps of the spatial distribution of the recorded optical signal (STM-L) for a single hollow gold nanoantenna and a periodic array of nanoantennas. The STM measurements were carried out with scan resolutions of  $200 \times 200$  points over a  $1 \times 1$   $\mu\text{m}$  area for the single nanoantenna, and  $150 \times 150$  points over a  $4 \times 4$   $\mu\text{m}$  area for their array. The tunneling parameters were fixed at a bias voltage of 2.5 V and a tunneling current of 1 nA. All measurements were performed at room temperature under ultrahigh vacuum conditions ( $\sim 10^{-10}$  mbar).

In the case of a single nanoantenna (Fig. 1, *a*, *b*), the photon emission observed in the STM-L map exhibits a distinct spatial pattern, with increased intensity both at the edges and center of the antenna. This reflects an inhomogeneous distribution of the local density of the nanoantenna LDOS, which can be attributed to the excitation of intrinsic plasmonic modes of nanoantenna.

For a periodic array of nanoantennas (Fig. 1, *c*, *d*), the STM-L signal shows both localized emission from individual antennas and smoothly varying background component. The gradual variation in the emission intensity, observed when the STM probe is positioned between the nanoantennas, can be attributed to the excitation of propagating surface plasmon waves launched by inelastic electron tunneling. These waves subsequently interfere and scatter by the periodic nanoantenna structure, resulting in the emission of photons in the visible frequency range, which are registered by the optical detection system.

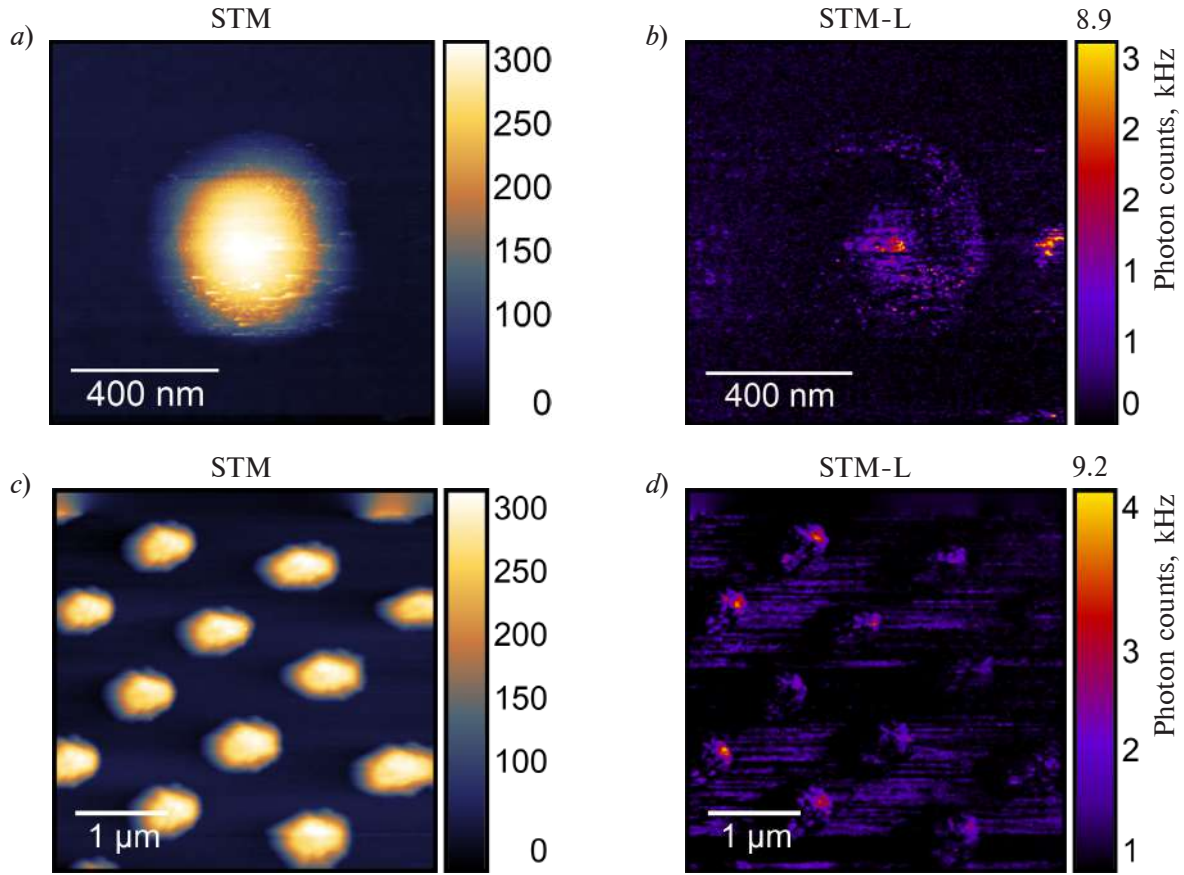


Fig. 1. STM-L measurement of the studied systems: single nanoantenna (*a, b*) and periodic nanoantenna array (*c, d*): (*a, c*) STM topography (*b, d*) spatial distribution of the recorded optical signal (STM-L)

### Conclusion

This study demonstrates the potential of STM-L to resolve fine spatial variations of LDOS in plasmonic nanostructures. We have observed characteristic LDOS distributions in single hollow gold nanoantennas, including patterns corresponding to the excitation of intrinsic plasmonic modes caused by inelastic electron tunnelling. Smoothly varying intensities (or LDOS) of the recorded radiation were found in periodic arrays, explained by the excitation and scattering of propagating surface plasmon waves with emission of photons in the visible range.

The results confirm the potential of STM-L as a power tool for studying light-matter interactions with sub-diffraction resolution at the level of individual nano-objects.

### REFERENCES

1. Lebedev D.V., Solomonov N.A., et al., Femtosecond Laser-Printed Gold Nanoantennas for Electrically Driven and Bias-Tuned Nanoscale Light Sources Operating in Visible and Infrared Spectral Ranges, *The Journal of Physical Chemistry Letters* 14 (22) (2023) 5134–5140.
2. Lebedev D.V., Solomonov N.A., et al., Electrically-Driven Light Source Embedded in a GaP Nanowaveguide for Visible-Range Photonics on Chip, *Advanced Optical Materials*. 12 (25) (2024) 2400581.
3. Solomonov N.A., Lebedev D.V., et al., Luminescence enhancement in inelastic tunnelling of electrons by changing the geometry of the tunnelling contact, *St. Petersburg State Polytechnical University Journal. Physics and Mathematics*. 17 (3.2) (2024) 236–240.
4. Lebedev D.V., et al., Indirect Detection of the Light Emission in the Local Tunnel Junction, *Physica status solidi (RRL)—Rapid Research Letters*. 14 (3) (2020) 1900607.

5. **Lebedev D.V., et al.**, Nanoscale electrically driven light source based on hybrid semiconductor/metal nanoantenna, *The Journal of Physical Chemistry Letters*. 13 (20) (2022) 4612–4620.
6. **Kern J., et al.**, Electrically driven optical antennas, *Nature Photonics*. 9 (9) (2015) 582–586.
7. **Pavlov D.V., et al.**, Third-Harmonic Generation in Plasmonic Metasurfaces Fabricated by Direct Femtosecond Laser Printing, *JETP Letters*. 119 (10) (2024) 763–767.

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## Optical properties of nanostructured nickel thin films obtained by oblique angle deposition

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**Abstract.** The article presents a study of the optical properties of nickel nanospirals obtained by glancing angle deposition in order to identify and analyze circular dichroism (CD), a phenomenon in which a material exhibits different light absorption with left- and right- circular polarization. It has been experimentally established that the chiral geometry of nanospirals, formed due to the effect of shading and the speed of rotation of the substrate during deposition, is the cause of a pronounced optical response. The use of scanning electron microscopy (SEM) confirmed the formation of a series of spiral samples with varying pitch and diameter, which connects these morphological parameters with their spectral characteristics. Spectroscopic measurements in the visible range revealed circular dichroism. It is shown that the specific chiral geometry of nanostructures, formed due to sputtering conditions, leads to differential absorption of left- and right-circularly polarized light in the visible range. The results demonstrate the dependence of the optical response on the morphology of nanospirals, which opens up opportunities for designing metamaterials with specified parameters. The discovered circular dichroism makes such structures promising for use in nanophotonics, the creation of polarization filters, etc. The application of a magnetic field has little effect on the optical properties of the studied samples.

**Keywords:** chiral metasurfaces, circular dichroism, nanospirals, oblique angle deposition

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## **Оптические свойства наноструктурированных пленок никеля, полученных методом наклонного напыления**

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**Аннотация.** Представлены результаты экспериментальных исследований киральных пленочных структур на основе массивов наноспиралей никеля, полученных методом наклонного осаждения. Показано, что в условиях испарения электронным пучком на вращающейся наклонной подложке формируется массив наноспиралей, закрученных в одном направлении. Полученные таким образом киральные тонкопленочные метаматериалы обладают выраженным круговым дихроизмом, который может быть использован для создания поляризаторов и оптических фильтров.

**Ключевые слова:** киральные метаповерхности, циркулярный дихроизм, наноспирали, наклонное напыление

**Финансирование:** Работа выполнена в рамках государственного задания НИЦ «Курчатовский институт» с использованием оборудования Центра коллективного пользования «Диагностика микро- и наноструктур». Данное исследование было проведено при финансовой поддержке Правительства Ярославской области, проект № 12NP/2024.

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## **Introduction**

The possibility of creating artificial chiral materials with unique optical characteristics allows to study the fundamental mechanisms of the interaction of light with matter and opens up broad prospects for their practical application [1]. Chirality is manifested in optical phenomena in the form of different types of interaction of such a material with right- and left- circularly polarized light [2]. These phenomena can be used for practical applications in the creation of optical filters, polarizers and sensors of various types.

## **Materials and Methods**

In this work, the method of glancing angle deposition (GLAD) was used for nanostructuring the film. Within the framework of this method, nanospiral arrays are formed under conditions of electron beam evaporation onto an inclined substrate due to the shading effect. This effect consists in the fact that crystallites, which have received a random advantage in grow that the initial stages of deposition, further shade their neighbors, suppressing their growth. As a result, pores



form in the growing film and an array of individual nanofibers is formed. Turning on the rotation of the substrate around the normal to its surface during growth leads to a gradual displacement of the shadow region and the formation of nanospirals from nanofibers [1, 2]. Spirals are twisted fibers in the same direction, which is determined by the direction of rotation of the sample.

Experiments on glancing angle deposition of thin films were carried out at the Oratoriya-9 electron beam evaporation facility. During spraying, the angle of inclination of the sample to the source was  $85^\circ$ . Base vacuum is equal to  $4 \cdot 10^{-6}$  Torr. The morphology and structure of the resulting films were studied by scanning electron microscopy (SUPRA-40). Optical characteristics were measured on a Jasco J-1500 circular dichroism spectrometer in the transmission mode. To study the effect of the magnetic field on optical properties, measurements were repeated with the induction of an external magnetic field of 2100 Oe along the optical axis.

### Results and discussion

Fig. 1 shows the results of studies for samples obtained at different speeds of rotation of the substrate from 0.1 to 0.3 rpm: SEM images of the side view of films are shown on the left panel, and the corresponding top view are shown on the right panel. Table 1 shows the average geometric parameters of the resulting nanostructures. The pitch of a spiral is the height of one complete spiral turn, measured parallel to the axis of the spiral. The external diameter of the spiral is the maximum diameter of the spiral coil, measured from the outermost point of the coil to its center. The fiber diameter is the diameter of the circle, which is the cross-section of the fiber from which the spiral is twisted.

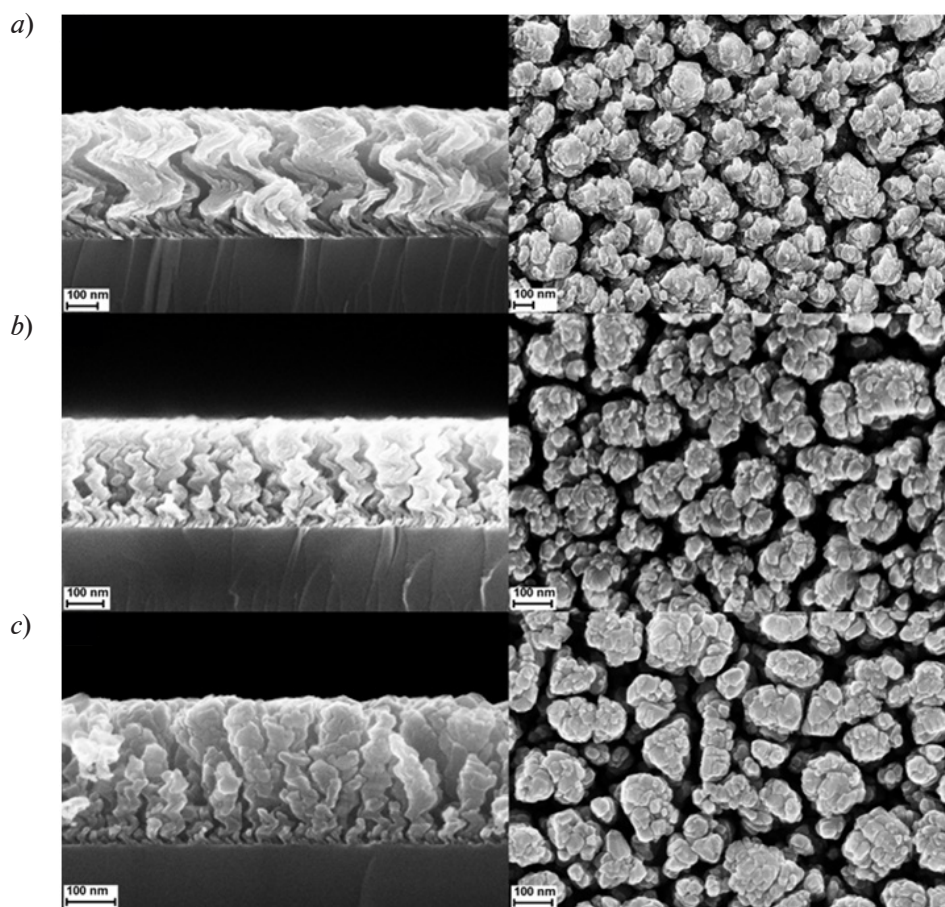


Fig. 1. Microscopic images of nanostructured Ni films (left panel on the side, right panel on the top) obtained at a growth rate of 0.3nm/s and at a rotation speed: 0.1 rpm (a), 0.2 rpm (b), 0.3 rpm (c)

Table 1

Geometric parameters of nanospirals

| Rotation speed, rpm | Height, nm | Pitch, nm | External diameter of spiral, nm | Fiber diameter, nm |
|---------------------|------------|-----------|---------------------------------|--------------------|
| 0.1                 | 403±16     | 203±8     | 162±36                          | 27±3               |
| 0.2                 | 287±69     | 75±5      | 70±31                           | 25±2               |
| 0.3                 | 277±75     | 53±8      | 40±17                           | 23±2               |

The results of measurements of the circular dichroism effect are shown in Fig. 2. The circular dichroism spectra for samples obtained at different speeds of rotation of the substrate are shown: from 0.1 to 0.3 rpm. An analysis of the above data shows that the films obtained demonstrate a pronounced effect of circular dichroism of up to several degrees. At the same time, the obtained spectra significantly depend on the geometric dimensions of the nanospirals (pitch of the spirals) [3, 4]. As the rotation speed of the substrate increases, the pitch of the spiral decreases and, accordingly, the minimum and maximum on the spectrum shift to the region of shorter wavelengths [4, 5]. The inclusion of an external magnetic field slightly changes the optical characteristics. The intensity of CD is related to the quality of the resulting nanostructures. When the nanospiral shape approaches the geometric perfection of the spiral, that is, their proximity to the model of a regular spiral with constant pitch, diameter and smooth curvature, the intensity of maximum and minimum, that is, the difference in absorption of left- and right-circularly polarized light increases in amplitude.

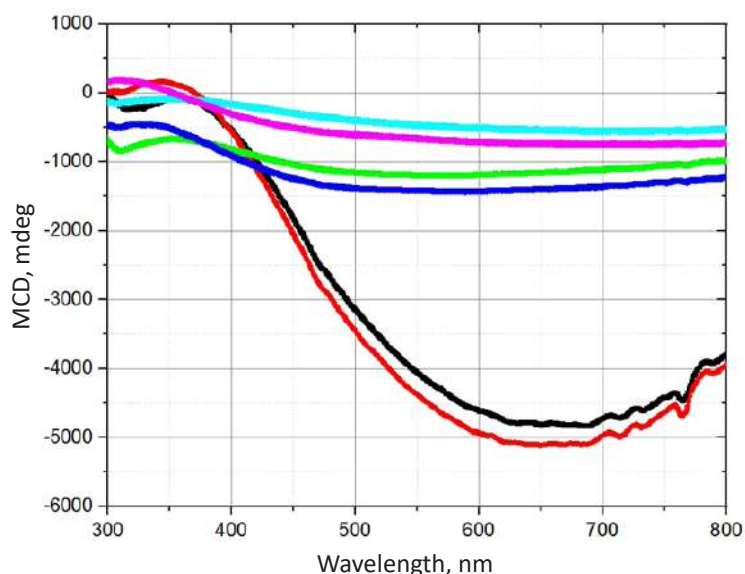


Fig. 2. Magnetic circular dichroism spectra for a series of samples with different rotational speeds:  
0.1 rpm at  $H = 0$  Oe (black line) and at  $H = 2100$  Oe (red line),  
0.2 rpm at  $H = 0$  Oe (green line) and at  $H = 2100$  Oe (blue line),  
0.3 rpm at  $H = 0$  Oe (light blue line) and at  $H = 2100$  Oe (pink line)

### Conclusion

To sum up, the experimental studies have shown that thin nanostructured nickel films obtained by the method of GLAD with the rotation of the substrate are arrays of nanospirals twisted in the same direction. By changing the speed of rotation of the substrate during deposition, it is possible to directionally change the geometric dimensions of the nanospirals, thereby changing the optical characteristics of the resulting films. The addition of an external magnetic field slightly increases the value of circular dichroism, that is the difference in absorption of left- and right- circularly polarized light.



## REFERENCES

1. **Barranco A., Borrás A., Gonzalez-Elise A., Palmero A.**, Perspectives on oblique angle deposition of thin films: From fundamentals to devices, *Progress in Materials science*. 76 (2016) 59–153.
2. **Trushin O.S., Fattakhov I.S., Popov A.A., et al.**, Tailoring magnetic anisotropy and optical characteristics of nanostructural Co Films by oblique angle deposition, *Physics of the Solid State*. 6 (2023) 953.
3. **Hawkeye M., Taschuk M., Brett M.**, *Glancing Angle Deposition of Thin Films*, UK:John Wiley & Sons Ltd. (2014) 1–299.
4. **Schaferling M.**, *Chiral Nanophotonics*. Springer series in Optical Sciences 205. Springer International Publishing Switzerland. (2017).
5. **Collins J.T., Kuppe C., Hooper D., et al.**, Chirality and Chiroptical Effects in Metal Nanostructures: Fundamentals and Current Trends, *Advanced Optical Materials*. 5 (16) (2017).

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## Magnetic properties of iron nanowires in a porous aluminum oxide matrix

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**Abstract.** This paper is devoted to the study of magnetic properties of iron nanowire arrays synthesized using a porous  $\text{Al}_2\text{O}_3$  template. Samples of porous aluminum oxide were obtained by double electrochemical anodization of the prepared foil in 0.5 M oxalic acid at a voltage of 60 V and a temperature of 25 °C and studied by scanning electron microscopy. The pore diameter is about 85 nm. Nanowires were electrodeposited in a three-electrode setup in the prepared matrices in a pulsed mode. The surfaces of porous membranes and the geometry of nanowires were studied using a scanning electron microscope. The magnetic properties of nanowire arrays were studied using a vibration magnetometer and micromagnetic modeling.

**Keywords:** anodizing, aluminum oxide matrices, nanowires, electrochemical deposition, vibrating magnetometry, micromagnetic modeling

**Funding:** The work was performed within the framework of the state assignment of the Kurchatov Institute Research Center using the equipment of the Center for Collective Use «Diagnostics of micro- and nanostructures»; The reported study was funded by Government of the Yaroslavl region, project 21NP/2024.

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## Магнитные свойства железных нанопроволок в пористой матрице оксида алюминия

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**Аннотация.** Настоящая работа посвящена исследованию магнитных свойств массивов железных нанопроволок, синтезированных с использованием пористого шаблона  $\text{Al}_2\text{O}_3$ . Образцы пористого оксида алюминия были получены путем двойного электрохимического анодирования подготовленной фольги в 0,5 М щавелевой кислоте при напряжении 60 В и температуре 25 °C и исследованы методом сканирующей электронной микроскопии.





Электроосаждение нанопроволок проводилось в трехэлектродной установке в подготовленные матрицы в импульсном режиме. Магнитные свойства массивов нанопроволок изучались с помощью вибрационного магнитометра и микромагнитного моделирования.

**Ключевые слова:** анодирование, матрицы оксида алюминия, нанопроволоки, электрохимическое осаждение, вибрационная магнитометрия, микромагнитное моделирование

**Финансирование:** Работа проведена в рамках государственного задания НИЦ «Курчатовский институт»; Исследование выполнено при финансовой поддержке Правительства Ярославской области в рамках научного проекта № 21НП/2024.

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## Introduction

One of the best and most extensive methods for ensuring repeatability and high quality of the resulting nanostructures is the use of porous anodic aluminium oxide (PAAO) templates [1–3], in particular arrays for the growth of controlled, self-organizing, as well as highly ordered structures, including nanorods, nanowires, nanotubes, nanocomposite materials with strict adherence to product dimensions at a packing density of  $10^9$ – $10^{11}$  units/cm<sup>2</sup> [4]. It is known that one of the most common method obtaining such nanowires (NW) is a matrix (template) synthesis – filling required material in narrow channels in a porous matrix. The unique properties of porous anodic aluminum oxide (PAAO) membranes make this material potentially the best template for electrochemical deposition of Fe nanowires [5]. Such nanowires are relevant as potential structures for 3D magnetic memory of the “racetrack memory” type [6].

## Materials and Methods

To produce porous matrices of aluminum oxide, we used 2×2 cm Al (99, 9% purity) plates with a 0.5 mm thickness. To obtain a smooth surface, the samples were electropolished, resulting in a mirror-like surface. Anodizing was carried out using 0.5 M oxalic acid with the temperature about 25 °C in a potentiostatic mode at 60 V. The duration of the first anodization was  $\tau = 30$  minutes, after which the oxide layer was removed in CrO<sub>3</sub> (1.8%) + H<sub>3</sub>PO<sub>4</sub> (6%) at  $T = 80$  °C for 10 minutes. Second anodization for the sample was carried out for 3 hours. Then, selective etching of aluminum was performed from the back side of the matrix in a solution of HCl + CuCl<sub>2</sub>. After that, the barrier layer was removed in CrO<sub>3</sub> (1.8%) + H<sub>3</sub>PO<sub>4</sub> (6%) at  $T = 80$  °C for 2 minutes. To create a contact for further electrochemical anodizing, a Ti/Ag/Cu structure was created on the back side of the matrix by magnetron sputtering. The deposition of Fe into the pores was carried by the electrochemical method from FeSO<sub>4</sub> + K<sub>2</sub>SO<sub>4</sub> + H<sub>3</sub>BO<sub>3</sub> + ascorbic acid. The deposition was performed by the pulse method in a 3-electrode cell with an Ag/Cl reference electrode.

## Results and Discussion

Fig. 1 shows an SEM image of the PAAO template before deposition, which shows that highly porous PAAO templates were successfully fabricated by two-step anodizing of the Al substrate. The SEM image of PAAO was further analyzed using ImageJ software, and pore diameter ( $D_p$ ) =  $85 \pm 2.2$  nm, pore distance ( $D_c$ ) =  $116 \pm 5$  nm.

Iron nanowires were formed by the electrochemical deposition method. Fig. 2, *a* shows a general plan of a sample of a porous matrix filled with nanowires. The length of the nanowires and the aspect ratio of the nanowires were 25  $\mu$ m and 300, respectively. Fig. 2, *b* shows a SEM image of the sample on a smaller scale. Nanowires are continuous columns of a ferromagnet, the degree of filling is close to 100%.

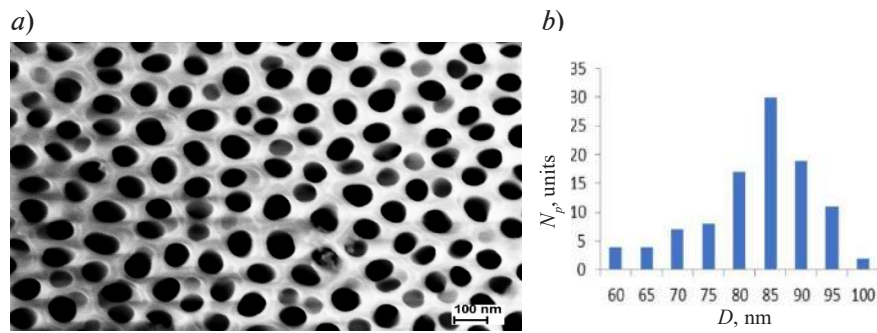


Fig. 1. SEM image of the PAAO template before deposition (a) and pores distribution (b)

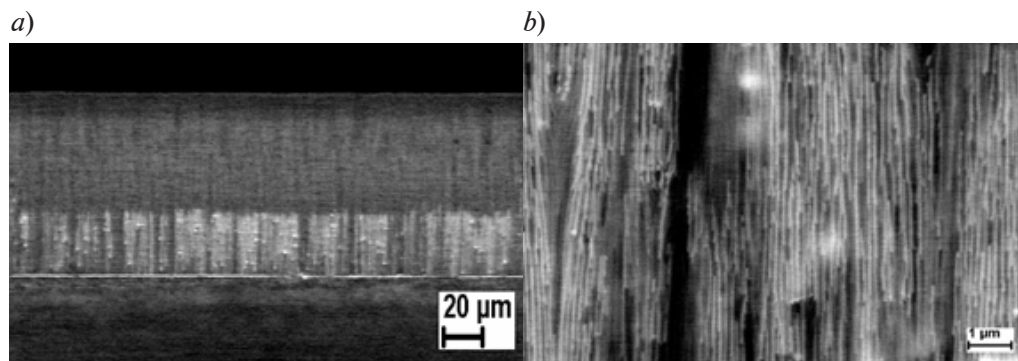


Fig. 2. Obtained Fe nanowires: chip profile of a PAO sample filled with iron nanowires (light tone of the sample below) (a), localized section of iron nanowires in an enlarged format (b)

Based on the obtained shape and ordering of the sample, micromagnetic modeling of the iron nanowire array was performed in the UberMag software package. The model is an array of 7 nanowires ordered in the form of a hexagon with one central thread. The distance between the centers, the length and the diameter of the nanowires were 120 nm, 500 nm and 85 nm, respectively. Each nanowire has the same parameters  $A = 21 \cdot 10^{-12} \text{ J} \cdot \text{m}^{-1}$ ,  $M_s = 1.7 \cdot 10^6 \text{ A} \cdot \text{m}^{-1}$ ,  $K_1 = 48 \cdot 10^3 \text{ J/m}^3$ . Fig. 3, a shows the resulting hysteresis loop for such an array. The coercive force was 340 Oe. The steps on the loop can be explained by the mechanism of magnetization reversal of such an array, where nanowires change the direction of magnetization alternately. The steps are formed due to the fact that the nanowires are remagnetized not in isolation, but in an ensemble. When one wire switches, it changes the local field acting on its neighbors. Micromagnetic modeling is based on the solution of the Landau-Lifshitz-Gilbert (LLG) equation on a discrete grid. Modeling records the energy of the system at discrete moments of time in the interval of specified discrete values of the field strength. A sharp change in  $m_z$  for one integration step or a step in the field strength appears as a step.

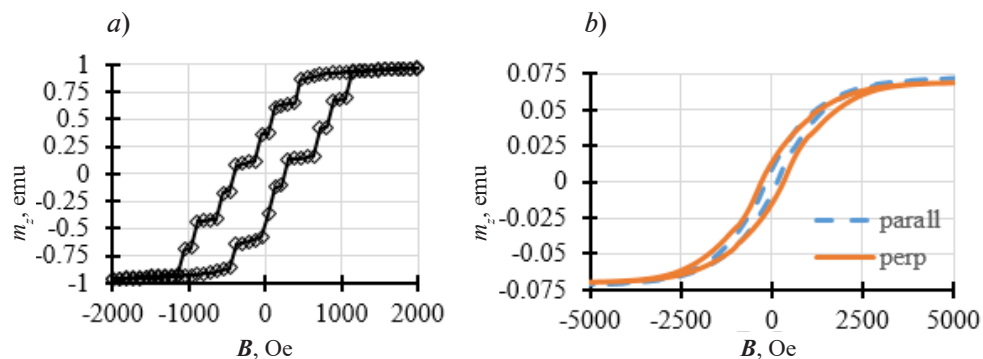


Fig. 3. Micromagnetic modeling of the hysteresis loop of the ensemble of iron nanowires (a), experimental loop for iron nanowires with parallel and perpendicular applied magnetic field (b)

Fig. 3, *b* shows the hysteresis loop of a real sample measured using a LakeShore 7407 vibration magnetometer. The measurements were carried out at room temperature from  $-16$  kOe to  $16$  kOe with the magnetic field directed parallel and perpendicular to the sample surface. The dashed hysteresis loop is for the parallel orientation of the external magnetic field, and the solid one is for the perpendicular one. The coercivity was  $310$  Oe. Loops for the parallel and perpendicular directions of the external magnetic field are very similar, although with such sample parameters the loop for the parallel direction should have a larger slope and a smaller width. This fact can be explained by partial oxidation of iron, since it weakens the shape anisotropy by reducing the effective diameter of the ferromagnetic core. Greatly increases the coercivity in all directions due to pinning at the boundary with the oxide layer and possible exchange bias. As a result, even at high aspect ratios, demagnetizing fields can compensate for shape anisotropy, making hysteresis loops more similar.

However, comparing the simulation results, it can be seen that the coercive force for a perpendicular external magnetic field differs slightly and can be explained by the imperfect structure of the real sample. The absence of steps on Fig. 3, *b* is explained by the fact that in the real sample there are  $10^9$ – $10^{11}$  units/cm<sup>2</sup> and the steps are strongly smoothed.

### Conclusion

In conclusion, can be noted that iron nanowires with an aspect ratio of  $300$  were obtained. A single iron nanowire in UberMag package was also simulated. The correspondence of the calculated and experimental data is confirmed. The coercive force for the model and experiment has a slight difference and is  $340$  Oe and  $310$  Oe, respectively. It can be concluded that shape anisotropy really exists for such samples, allowing them to be used as magnetic memory.

### Acknowledgments

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### REFERENCES

1. Masuda H., Yamada H., Satoh M., Highly-ordered nanochannel-array architecture in anodic alumina, Appl. Phys. Lett. 71 (1997) 2770.
2. Muratova E.N., Artificially and naturally ordered micro- and nanoscale capillary membranes based on anodic aluminum oxide: Ph.D. Thesis, St. Petersburg: ETU “LETI”. (2014).
3. Vorobeva A.I., Utkina E.A., Komar O.M., Homogeneous deposition of nickel in the pore of ordered thin aluminum oxide, Russian Microelectronics. 42 (2013) 79–88.
4. Hao Q., Huang H., Fan X., Assembly of gold nanoparticles into aluminum nanobowl array, Nanotechnology. 28 (105301) (2017).
5. Varvaro G., Casoli F., Ultrahigh-density magnetic recording storage materials and media designs. Stanford: Pan Stanford Publishing. (2016).
6. Parkin S., Hayashi M., Thomas L., Magnetic Domain-Wall Racetrack Memory, Science. 320 (2008) 190–194.

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## **HOT surface illuminated photodiodes based on $n$ -InAsSbP/InAs/ $p$ -InAsSbP heterostructures**

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**Abstract.** Photodetectors operating in the mid-infrared (IR) wavelength range ( $3 - 4 \mu\text{m}$ ) are widely used in gas analysis instruments and low-temperature pyrometry, such as methane and natural gas sensors, alcohol detectors, fire safety sensors, and fast-response pyrometers. This study investigates the causes of the decrease in current sensitivity with rising temperature in surface-illuminated photodiodes (PDs) based on  $n$ -InAsSbP/InAs/ $p$ -InAsSbP double heterostructures (DHS), sensitive in the spectral range of  $\lambda = 2 - 4 \mu\text{m}$  at temperatures of 200–500 K. Proposed design improvements for the PD chip resulted in a weaker temperature dependence of the parameters, enabling reliable operation at 500 K with a current sensitivity of  $S_i = 0.1 \text{ A/W}$ .

**Keywords:** InAsSb solid solution, InAs heterostructures, MWIR photodiode, HOT PD, PD mid infrared, FSI infrared photodiodes, surface illuminated PDs

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Материалы конференции

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## **Поверхностно освещаемые высокотемпературные фотодиоды на основе гетероструктур $n$ -InAsSbP/InAs/ $p$ -InAsSbP**

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**Аннотация.** Представлены результаты разработки и исследования фотодиодов на основе гетероструктуры  $n$ -InAsSbP/InAs/ $p$ -InAsSbP в интервале температур 125 – 500 К. Обсуждаются конструктивные особенности эпитаксиальной структуры и чипа фотоприемника, которые обеспечили значения токовой чувствительности и обнаружительной способности  $S_i = 1.6 \text{ A/W}$  и  $D^* = 1.5 \cdot 10^{10} \text{ см} \cdot \text{Гц}^{1/2} \cdot \text{Вт}^{-1}$  при комнатной температуре и  $S_i > 0,1 \text{ A/W}$  при  $T = 500 \text{ K}$ .

**Ключевые слова:** средневолновый фотодиод, фотодиод InAs, фотодиоды InAsSb, высокотемпературные фотодиоды, гетероструктура InAsSbP/InAs, FSI фотодиод



**Ссылка при цитировании:** Климов А.А., Кунков Р.Э., Лухмырина Т.С., Матвеев Б.А., Ременный М.А., Карандашев С.А. Поверхностно освещаемые высокотемпературные фотодиоды на основе гетероструктур  $n$ -InAsSbP/InAs/ $p$ -InAsSbP // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2025. Т. 3.2 № 18. С. 110–114. DOI: <https://doi.org/10.18721/JPM.183.221>

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## Introduction

Photodetectors operating in the mid-wave infrared (MWIR) range ( $\lambda = 2.5\text{--}6\ \mu\text{m}$ ) are widely used in gas analysis and low-temperature pyrometry instruments, such as methane and natural gas infrared sensors, breathalyzers, alcohol interlocks, fire safety detectors, and fast-response low-temperature pyrometers. The ongoing development of these devices is accompanied by a trend toward reducing the size, weight, and power consumption of photodetector modules (SWaP minimization – Scale, Weight, and Power). This creates a demand for photodetectors with sufficiently high performance to eliminate the need for cooling or thermal stabilization systems.

This demand has led to the emergence of the term ‘high-operating-temperature (HOT) infrared photodetectors’ [1], referring to detectors that operate at near-room temperature or above [2], as well as detectors achieving background-limited performance (BLIP mode) at  $T \geq 150\ \text{K}$ .

Previously, we reported on the development and investigation of  $n$ -InAsSbP/InAs/ $p$ -InAsSbP double heterostructure (DHS) photodiodes with front-side illumination (FSI geometry), grown by liquid-phase epitaxy (LPE) on  $n^+$ -InAs (100) substrates. These photodiodes exhibited sensitivity in the spectral range  $\lambda = 2\text{--}4\ \mu\text{m}$  and operated within a temperature range of 200–500 K [3, 4]. In those studies, a detectivity of  $D^* = 1.5 \cdot 10^{10}\ \text{cm} \cdot \text{Hz}^{1/2} \cdot \text{W}^{-1}$  (300 K) was achieved, representing one of the best results among published data. However, the fabricated photodiodes showed a sharp decline in current responsivity at temperatures above 300 K (down to  $S_i = 0.01\ \text{A/W}$  at  $T = 500\ \text{K}$ ), limiting their potential for use in uncooled infrared sensors operating at elevated temperatures.

This work focuses on the development of  $n$ -InAsSbP/InAs/ $p$ -InAsSbP DHS photodetectors with illumination through the  $p$ -InAsSbP layer, operating in the  $\lambda = 2\text{--}4\ \mu\text{m}$  range. The proposed chip design modifications result in a weaker temperature dependence of photodiode parameters compared to previous versions, enabling operation at  $T = 500\ \text{K}$  with a responsivity of  $S_i > 0.1\ \text{A/W}$ .

## Results and discussion

The  $n$ -InAsSbP/InAs/ $p$ -InAsSbP heterostructures investigated in this work were grown by LPE on  $n^+$ -InAs (100) substrates, following a methodology analogous to that described in references [3, 4]. Post-growth processing employed standard photolithographic techniques to fabricate single-element photodiode chips utilizing FSI through the wide-bandgap  $p$ -InAsSbP layer. The resulting chips featured a photosensitive area of  $390 \times 390\ \mu\text{m}$  with a thickness of approximately  $40\ \mu\text{m}$ . Ohmic contacts were implemented as follows: a solid contact to the  $n^+$ -InAs substrate and a branched contact to the  $p$ -InAsSbP layer. Final device packaging was performed using TO-18 housings with intermediate subcarrier board mounting.

Photoluminescence (PL) characterization at 77 K (Fig. 1) revealed distinct spectral features when comparing the studied heterostructures with reference samples from [5] and undoped  $n$ -InAs substrates ( $n = 1 \cdot 10^{16}\ \text{cm}^{-3}$ ). The PL spectra exhibited two characteristic bands: a lower-energy emission at  $\sim 410\ \text{meV}$  corresponding to the InAs photosensitive region, and a higher-energy band at 470–490 meV originating from the  $p$ -InAsSbP layer. Comparative analysis with prior work [5] suggests two significant structural differences: reduced donor doping concentration in the InAs photosensitive region, as evidenced by spectral alignment with undoped InAs, and increased bandgap in the  $p$ -InAsSbP layer. These modifications are anticipated to yield improved dark current characteristics, as subsequently confirmed by the experimental data presented in Fig. 4.



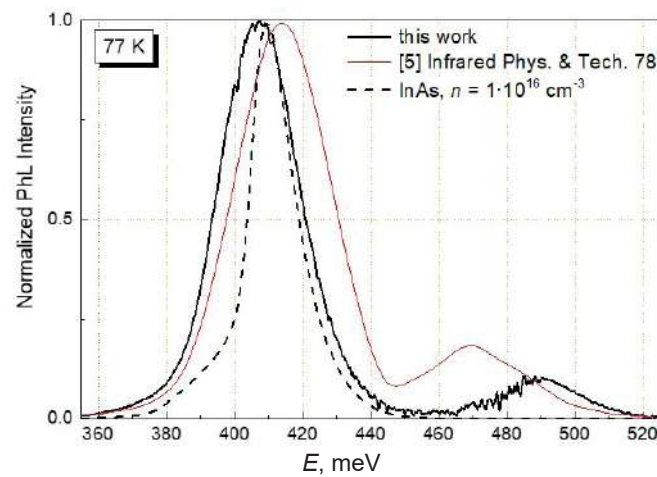


Fig. 1. Photoluminescence spectra of the  $n$ -InAsSbP/InAs/ $p$ -InAsSbP heterostructure from this work, reference [5], and undoped  $n$ -InAs substrate ( $n_0 = 1 \cdot 10^{16} \text{ cm}^{-3}$ ) at 77 K

Temperature-dependent spectral responsivity measurements (Fig. 2) demonstrated distinct behavior across different thermal regimes. In the 125–300 K range (Fig. 2, *a*), the responsivity spectra displayed a pronounced maximum attributed to multipass optical absorption within the photosensitive region, enhanced by reflection from the mirror-like substrate contact. This effect diminished at elevated temperatures due to reduced substrate transparency. The responsivity degradation observed above 300 K (Fig. 2, *b*) correlates with decreasing charge collection efficiency as the  $p$ – $n$  junction's dark resistance approaches the series resistance between the depletion region and anode contact [6]. This mechanism similarly explains the comparatively lower responsivity of point-contact photodiodes reported in references [3, 4].

Comparative analysis of FSI and back-side illuminated (BSI) geometries (Fig. 3, *a*) revealed superior temperature stability in BSI devices, attributable to their reduced substrate thickness and implementation of solid anode contacts that minimize current crowding effects. The observed behavior suggests that FSI devices in the current study experience noticeable current crowding above 400 K. Temperature-dependent  $R_0 \cdot A$  product analysis (Fig. 3, *b*) confirmed diffusion-dominated transport mechanisms across the 175–500 K range, with activation energies approximating the InAs bandgap. Deviations at higher temperatures correlate with current crowding phenomena in devices employing non-solid anode contacts, further supporting the proposed responsivity degradation mechanism.

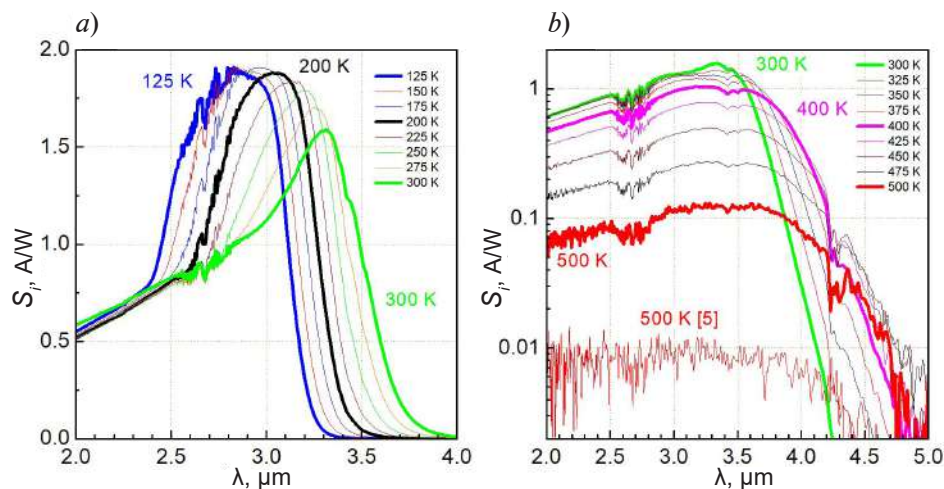


Fig. 2. Spectral responsivity of photodiodes at temperatures of 125–300 K (*a*), 300–500 K (*b*), and reference sample [4] at  $T = 500 \text{ K}$  (*b*)

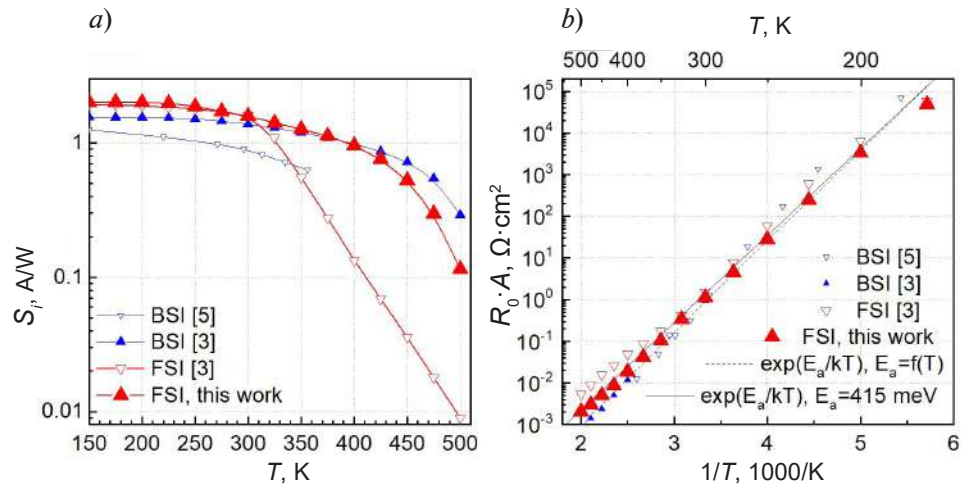


Fig. 3. Temperature dependences of peak responsivity  $S_p$  (a) and  $R_0 \cdot A$  product (b) for photodiodes with InAs photosensitive region in back-side illuminated (BSI) and front-side illuminated (FSI) configurations

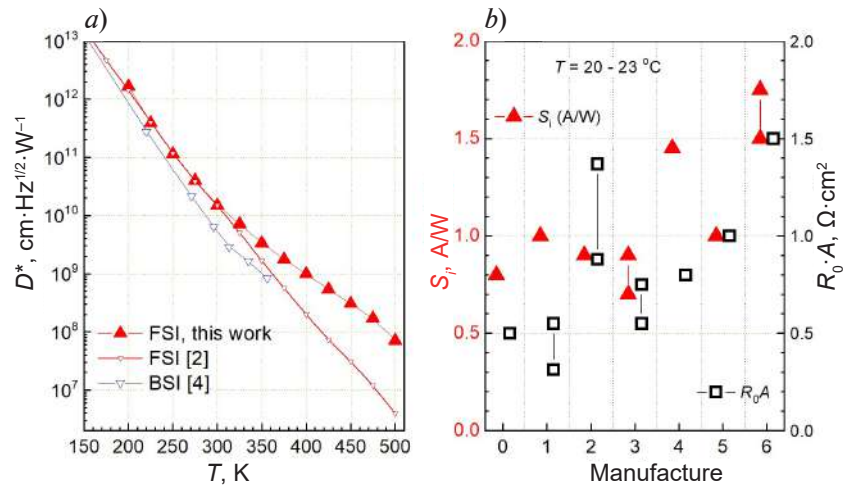


Fig. 4. Temperature-dependent detectivity compared with prior works (a); benchmarking of responsivity and  $R_0 \cdot A$  values against alternative technologies (b). Numbers on the X-axis correspond to developers listed in Table

Table

**Performance comparison with alternative technologies**

| Manufacturer                 | $S_p$ , current sensitivity, A/W | $R_0 \cdot A$ , $\Omega \cdot \text{cm}^2$ | Detectivity $D^*$ , $\text{cm} \cdot \text{Hz}^{1/2} \cdot \text{W}^{-1}$        |
|------------------------------|----------------------------------|--------------------------------------------|----------------------------------------------------------------------------------|
| 0. Vigo System SA            | 0.8                              | 0.5                                        | $7 \cdot 10^9$                                                                   |
| 1. Hamamatsu                 | 1                                | 0.314–0.55                                 | $(3\text{--}4.5) \cdot 10^9$                                                     |
| 2. Laser Components          | 0.9                              | 0.88–1.37                                  | $1 \cdot 10^{10}$                                                                |
| 3. Vigo System SA            | 0.7–0.9                          | 0.55–0.75                                  | $(5\text{--}7) \cdot 10^9$                                                       |
| 4. Reference sample from [7] | 1.45                             | 0.8                                        | $1.6 \cdot 10^{10}$ , $1 \cdot 10^{10}$<br>(From value $S_p$ and $R_0 \cdot A$ ) |
| 5. Reference sample from [8] | 1                                | 1                                          | $8 \cdot 10^9$                                                                   |
| 6. This work                 | 1.5–1.75                         | 1.5                                        | $1.5 \cdot 10^{10}$                                                              |

The enhanced detectivity ( $D^*$ ) demonstrated in Fig. 4, *a* stems from two key improvements: (1) increased dark resistance through epitaxial structure optimization relative to Ref. [5], and (2) improved responsivity in branched-anode devices compared to prior designs [3]. Benchmarking against state-of-the-art alternatives (Fig. 4, *b*, Table) confirms the competitive performance of the developed  $n$ -InAsSbP/InAs/ $p$ -InAsSbP photodiodes, particularly when compared to both InAs-based and HgCdTe detectors operating in the 2–4  $\mu\text{m}$  spectral range. These results substantiate the potential of branched-anode architectures for uncooled mid-wave infrared photodetection applications.

### Conclusion

The photoelectric properties of experimental FSI photodiode samples fabricated from  $n$ -InAs/ $n$ -InAsSbP/ $n$ -InAs/ $p$ -InAsSbP double heterostructures with branched anode contacts were investigated over the temperature range of 125–500 K. Through optimized epitaxial structure design and chip architecture, the devices demonstrated remarkable performance characteristics, achieving a current responsivity of  $S_i = 1.6 \text{ A/W}$  and specific detectivity of  $D^* = 1.5 \cdot 10^{10} \text{ cm} \cdot \text{Hz}^{1/2} \cdot \text{W}^{-1}$  at room temperature. Notably, the photodiodes maintained a responsivity exceeding  $S_i > 0.1 \text{ A/W}$  even at elevated temperatures up to 500 K.

### REFERENCES

1. Piotrowski J., Rogalski A., High-Operating-Temperature Infrared Photodetectors, SPIE Press: Bellingham, WA, USA. (2007).
2. Sotnikova G.Yu., Aleksandrov S.A., Gavrillov G.A., Advances in applied physics. 10 (4) (2022) 389–403.
3. Remennyi M.A., Klimov A.A., Kunkov R.E., et al., Proceedings of the XXVII International Scientific and Technical Conference on Photoelectronics and Night Vision Devices, Moscow. (2024) 76.
4. Klimov A.A., Kunkov R.E., Lukhmyrina T.S., et al., Abstracts of the Physica.SPb Conference, St. Petersburg. (2024) 188.
5. Brunkov P.N., Il'inskaya N.D., Karandashev S.A., et al., Infrared Physics & Technology. 78 (2016) 249–253.
6. Il'inskaya N.D., Zakgeim A.L., Karandashev S.A., et al., Fizika i Tekhnika Poluprovodnikov. 46 (5) (2012) 708–713.
7. Lin H., Xie H., Sun Y., Hu S., Dai N., Journal of Crystal Growth. 617 (2023) 127293.
8. Brunkov P.N., Il'inskaya N.D., Karandashev S.A., et al., Semiconductors. 48 (10) (2014) 1359–1362.

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### **Formation of site-controlled InAs quantum dots on nanopatterned GaAs(111)B surfaces**

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**Abstract.** We study the processes of site-controlled growth of InAs quantum dots (QDs) on GaAs(111)B surfaces patterned by focused ion beams (FIB). The QDs tend to occupy vertexes of the pyramidal holes formed after annealing of the FIB-treated surfaces. The average degree of localization of QDs is found to strongly depend on the number of FIB passes and has a maximum value of 0.84, 0.7 and 0.92 for arrays with a distance of 2, 1 and 0.5  $\mu\text{m}$  between holes, respectively. The average size and surface density of QDs also depends on the number of FIB passes, mainly with a non-monotonic nature. Photoluminescence emission of InAs QDs grown on the GaAs(111)B surface is observed in the spectral range of 950–1150 nm at a measurement temperature of 77 K.

**Keywords:** GaAs(111)B, focused ion beams, molecular beam epitaxy, quantum dots

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Материалы конференции

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### **Формирование упорядоченных квантовых точек InAs на структурированных поверхностях GaAs(111)B**

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**Аннотация.** Проведено исследование процессов селективно-позиционированного роста квантовых точек (КТ) InAs на поверхностях GaAs(111)B, структурированных методом фокусированных ионных пучков (ФИП). Установлено, что КТ стремятся зарождаться в вершинах пирамидальных углублений, образующихся после отжига ФИП-модифицированных поверхностей. Средняя степень локализации КТ в значительной степени зависит от числа проходов ФИП и имеет максимальное значение 0,84, 0,7 и 0,92

для массивов с расстояниями между углублениями 2, 1 и 0,5 мкм соответственно. Средний размер и поверхностная плотность КТ также зависят от числа проходов ФИП, имея преимущественно немонотонный характер. Показано, что фотолюминесцентное излучение КТ InAs, выращенных на поверхности GaAs(111)B, находится в спектральном диапазоне 950–1150 нм при температуре измерения 77 К.

**Ключевые слова:** GaAs(111)B, фокусированные ионные пучки, молекулярно-лучевая эпитаксия, квантовые точки

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## Introduction

Quantum computing and communications are taking an increasingly firm place in the modern scientific and technical environment, providing the potential for the implementation of quantum internet [1]. For this purpose, photonic systems emerge as a particularly promising solution owing to their ability to propagate quantum states over long distances, exploit multiple degrees of freedom and maintain compatibility with traditional photonic infrastructure [2]. InAs/GaAs quantum dots (QDs) are regarded as one of the most advanced quantum emitters, offering key advantages such as telecom-wavelength operation, broad spectral tunability, on-demand photon generation, high indistinguishability and exceptional single-photon purity [3]. QDs grown on GaAs(111) patterned substrates exhibit enhanced properties due to their inherent  $C_{3v}$  symmetry enabling vanishing fine structure splitting – a critical requirement for high-fidelity quantum entanglement [4, 5]. Additionally, the formation of pyramidal holes on GaAs(111) surfaces facilitates the precise localization of triple QDs, making them highly suitable for applications in cellular automata, spin blockade devices, magnetoconductance studies, spin buses and related quantum phenomena [6].

In this paper, we investigate the epitaxial growth of InAs QDs on GaAs(111)B surfaces patterned with pyramidal holes. A systematic analysis of the QD size, surface density and spatial localization within nucleation centers is conducted to optimize the substrate patterning parameters and subsequent epitaxial growth conditions.

## Materials and Methods

The GaAs(111)B surfaces were patterned by a focused ion beam (FIB) on a FEI Nova NanoLab 600 scanning electron microscope (SEM) equipped with a  $Ga^+$  FIB column. FIB treatment point arrays of  $5 \times 5 \mu m$  in size with 0.5, 1 and  $2 \mu m$  spacing between the points ( $L$ ) and the number of ion beam passes ( $N$ ) from 1 to 60 were used. Then, the substrates were placed in a SemiTEq STE 35 MBE equipment for annealing and transformation of rounded nanoholes into pyramidal ones. In the next step, InAs QDs were deposited on the surface with a thickness of 2.5 monolayers at a temperature of 500 °C. The samples obtained were examined using a FEI Nova NanoLab 600 SEM and an NT-MDT Ntegra atomic force microscope in a semi-contact mode.

## Results and Discussion

SEM images of the FIB-treated arrays demonstrate that the FIB points transform into tetrahedral holes with three (111) facets for various spacings and number of passes (Fig. 1). Depending



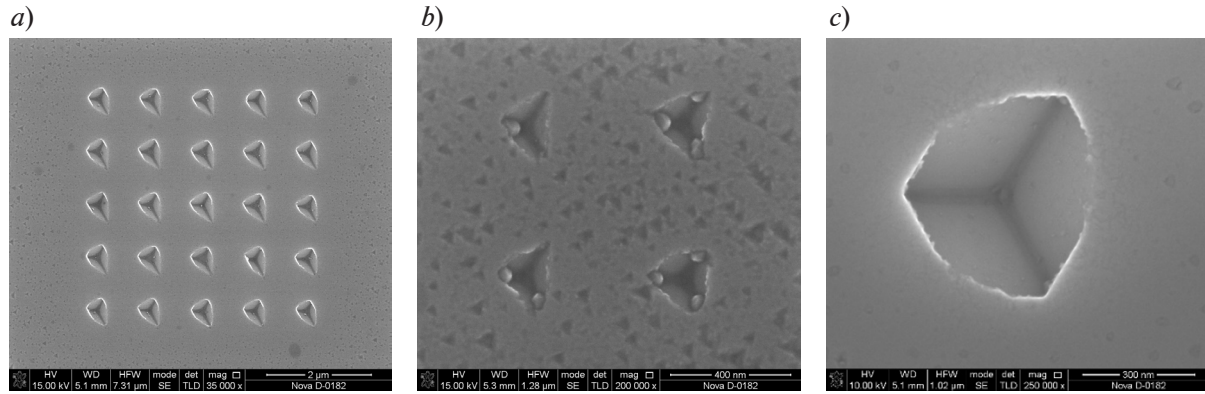


Fig. 1. SEM images of the hole arrays with InAs QDs:  $L = 1 \mu\text{m}$ ,  $N = 60$  (a),  $L = 0.5 \mu\text{m}$ ,  $N = 5$  (b),  $L = 2 \mu\text{m}$ ,  $N = 40$  (c)

on the treatment conditions, the surface between the holes can be smooth (Fig. 1, a, c) or rough (Fig. 1, b), which is governed by the intensity of ion resputtering. However, in both cases, InAs QDs are preferably localized within the pyramidal holes rather than outside the treated areas. When the period between holes is  $1 \mu\text{m}$ , the holes contain approximately 1 QD located near the hole center (Fig. 1, a). In the case of a period reduced to  $0.5 \mu\text{m}$ , QDs tend to occupy vertexes of the lateral triangle of the hole (triangular vertexes) (Fig. 1, b). An increase in the treatment period leads to the formation of large holes which have pronounced surface edges overhanging the hole walls (Fig. 1, c). In this case, QDs tend to occupy all vertexes of the hole pyramid.

An analysis of the degree of localization of QDs over the triangular vertexes of the  $1\text{-}\mu\text{m}$  array shows that QDs are formed randomly in different holes within the same array with the localization varying from 0 (no QDs in required positions) to 1 (exactly 3 QDs in 3 vertexes) (Fig. 2, a). The average degree of localization depends on the initial parameters of the FIB treatment and has a maximum of 0.7 for  $L = 1 \mu\text{m}$  and  $N = 5$  with decreasing to 0.26 at  $N = 60$  (Fig. 2, b). The average size of QDs decreases from 42 to 23 nm with increasing  $N$  from 1 to 30 and then rises to 30 nm at  $N = 60$ .

A similar investigation for the  $2\text{-}\mu\text{m}$  array of holes demonstrates that the average localization of QDs has a value ranging from 0.55 to 0.61 at 1–30 FIB passes and reaches 0.84 at 60 passes. However, the surface density of QDs monotonically decreases from  $1.5$  ( $1$  pass) to  $0.6 \mu\text{m}^{-2}$  (60 passes) in this case. A maximum average degree of localization of QDs is reached for the  $0.5\text{-}\mu\text{m}$  array of holes and has a value of 0.92 for 20 FIB passes, with a 81% fraction of holes containing exactly three QDs at triangular vertexes.

It should be noted that the average localization of QDs changes non-monotonically with increasing  $N$  for all three interhole distances ( $L$ ). This behavior may be associated with the complicated dynamics of the hole formation during annealing of samples after the FIB treatment.

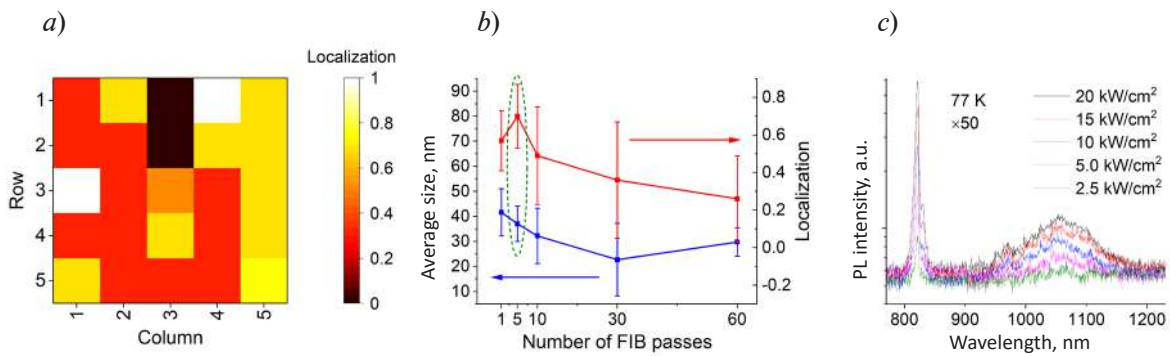


Fig. 2. Map of localization of QDs over the hole arrays with  $L = 1 \mu\text{m}$  and  $N = 10$  (a), average size and degree of localization of QDs vs. number of FIB passes for  $L = 1 \mu\text{m}$  (b), PL spectra of InAs QDs formed on the GaAs(111)B surface (c)

Depending on the ion dose, the complex oxide above the FIB points can be in a more or less stable phase, inducing various intensities of the local droplet etching [7]. As a result, the holes have a wide size and shape distribution and serve as centers with various nucleation probability.

The photoluminescence (PL) spectra of InAs QDs grown on the GaAs(111)B were also measured at 77 K. It was found that they emit in a range of 950–1150 nm (Fig. 2, *c*), implying that they have a wide size distribution. However, the positive side of these spectra is that the emission wavelength of such QDs can be tuned over a wide range. Therefore, they have a great potential of a further use in site-controlled quantum emitters.

### Conclusion

Thus, InAs QDs tend to occupy vertexes of the pyramidal holes obtained after FIB treatment of the GaAs(111)B surfaces. The average degree of localization of QDs for the 1- $\mu$ m array has a maximum of 0.7 at 5 FIB passes, whereas their average size has a minimum of 23 nm at 30 FIB passes. For the 2- $\mu$ m array, the localization of QDs reaches 0.84 at 60 FIB passes. A maximum localization of 0.92 is observed for the 0.5- $\mu$ m array of holes at 20 FIB passes.

### REFERENCES

1. Ramakrishnan R.K., Ravichandran A.B., Kaushik I., et al., The Quantum Internet: A Hardware Review, Journal of the Indian Institute of Science. 103 (2023) 547–567.
2. Luo W., Cao L., Shi Y., et al., Recent progress in quantum photonic chips for quantum communication and internet, Light Science & Applications. 12 (2023) 175.
3. Katsumi R., Ota Ya., Benyousef M., Telecom-band QDs compatible with Si photonics for photonic quantum applications, Advanced Quantum Technologies. 8 (2) (2025) 2300423.
4. Tuktamyshev A., Fedorov A., Bietti S., et al., Telecom-wavelength InAs QDs with low fine structure splitting grown by droplet epitaxy on GaAs(111)A vicinal substrates, Applied Physics Letters. 118 (13) (2021).
5. Mano T., Ohtake A., Kuroda T., Lattice-Mismatched Epitaxy of InAs on (111)A-Oriented Substrate: Metamorphic Layer Growth and Self-Assembly of Quantum Dots, Physica Status Solidi. (2024) 2300767.
6. Gaudreau L., Kam A., Granger G., et al., A tunable few electron triple quantum dot, Applied Physics Letters. 95 (2009) 193101.
7. Balakirev S.V., Chernenko N.E., Lakhina E.A., et al., Influence of local droplet etching modes on the transformation of nanoholes formed by focused ion beams on a GaAs(111) surface, Nanobiotechnology Reports. 19 (S1) (2024) S37.

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### **Metrological aspect of oxide coatings growth on products with an aluminum substrate**

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**Abstract.** The article presents the study results of the influence of process mode parameters on the thickness of the oxide coating of aluminum-based products. Ceramic-like coatings were formed by the microarc oxidation method on AD31 alloy using a capacitor process installation with a sinusoidal current at a constant current density of 15 A/dm<sup>2</sup> in the anodic-cathode mode. The study of oxide film growth was performed using a B7-517 thickness gauge. It is shown that for approximating the dependence of the oxide film thickness on the processing time of products, it is advisable to use piecewise approximation by mathematical functions of different types: exponential and linear. The use of such an approach is due to the influence of diffusion and chemical processes that dominate at the stages of spark and microarc discharges of the microarc oxidation process. However, this approach is not applicable for the purpose of analyzing the dependence of the film thickness on the concentration of sodium hydroxide and the ratio of the anodic and cathodic current components. In this case, the approximation is made by a quadratic function, due to the influence of nonlinear factors-impacts of the technological process. The results of the metrological analysis confirmed that the error in the adequacy of these models does not exceed 5%. It is advisable to use the obtained results when producing coatings with the required functional characteristics by the microarc oxidation method.

**Keywords:** microarc oxidation, digital twin, thickness, processing time, concentration, ratio of current components

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## Метрологический аспект роста оксидных покрытий на изделиях с алюминиевой подложкой

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**Аннотация.** Исследованы корреляционные зависимости, позволяющие оценить характер влияния параметров технологических режимов (время оксидирования, соотношение анодного и катодного составляющих тока, концентрация гидроксида натрия) на динамику формирования толщины микродугового оксидного покрытия на изделиях с алюминиевой основой. Керамикоподобные покрытия формировались на сплаве марки АД31 с использованием конденсаторной технологической установки процесса микродугового оксидирования на синусоидальном токе при постоянном значении плотности тока 15 А/дм<sup>2</sup> в анодно-катодном режиме. Непосредственное исследование роста оксидной пленки проводилось толщиномером В517-7. Аналитические выражения зависимости кинетики роста микродугового оксидного покрытия на изделиях с алюминиевой основой получены с использованием программной среды MatLAB. Показано, что для аппроксимации зависимости роста толщины оксидной пленки от времени обработки изделий, необходимо применять комбинированный подход, заключающийся в частичной аппроксимации математическими функциями разного вида: экспоненциальными и линейными. Использование такого подхода обусловлено влиянием диффузионных и химических процессов, доминирующих на стадиях искровых и микродуговых разрядов процесса микродугового оксидирования. Однако, такой подход не применим с целью анализа зависимости толщины пленки от концентрации гидроксида натрия и соотношения анодного и катодного составляющих тока. В этом случае аппроксимация производится квадратичной функцией, в следствии проявления нелинейных факторов-воздействий на технологический процесс. Метрологический анализ выражений показал, что погрешность адекватности этих моделей составляет не более 5%. Полученные результаты применимы как для определения погрешностей измерений параметров-воздействий процесса микродугового оксидирования, так и для получения покрытий с требуемыми функциональными характеристиками.

**Ключевые слова:** микродуговое оксидирование, цифровой двойник, толщина, время обработки, концентрация, соотношение составляющих тока

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### Introduction

The growth of oxide coatings formed by the microarc oxidation (MAO) method is characterized by an increase in thickness, the formation of a porous structure [1]. It should be noted that the coating itself grows not only over the metal base, but also penetrates into the substrate structure, modifying it. Based on studies of the dependence of the MAO coating thickness on the factors-impacts, it is possible to identify new analytical mathematical models. For example, in [2], it is shown that the coating thickness increases with processing time and has an exponential dependence. In [3], at the spark discharge stage, the dependence of the MAO coating thickness on the processing time is described by an exponential function, and at the micro-arc discharge stage, by a linear function. With an increase in the NaOH concentration in the silicate-alkaline electrolyte, the oxide film thickness decreases [4]. In connection with the introduction of digital twins of various technological processes into production cycles, the task of metrological analysis and control of the coatings, properties formed in real time and predicted during the digital twin operation is relevant [5]. The solution to this problem will improve the MAO coatings quality, the accuracy of reproducible performance characteristics, and technical and economic indicators when developing new technological modes.

### Materials and methods

For the purpose of metrological analysis of the growth process of microarc oxide coatings on products with an aluminum substrate, 20 samples with a microarc coating were obtained. The test samples have a rectangular shape with dimensions of  $20 \times 15 \times 2$  mm and a treated surface area of  $S = 0.05971$  dm<sup>2</sup>. The main material of the sample substrate is AD31 alloy - aluminum alloyed with manganese, silicon, titanium. Before MAO treatment, the test samples were milled and then polished. After, the samples that had passed the preparation stage were placed in a galvanic bath

Table 1

**Parameters of the process modes for studying the influence of processing time, ratio of current components and NaOH concentration on the formation of coating thickness**

| Sample No. | $t$ , s | $j$ , A/dm <sup>2</sup> | $C_N$ , g/l | $I_A/I_C$ |
|------------|---------|-------------------------|-------------|-----------|
| 1          | 100     | 15                      | 0.5         | 1.00      |
| 2          | 200     | 15                      | 0.5         | 1.00      |
| 3          | 300     | 15                      | 0.5         | 1.00      |
| 4          | 600     | 15                      | 0.5         | 1.00      |
| 5          | 900     | 15                      | 0.5         | 1.00      |
| 6          | 1200    | 15                      | 0.5         | 1.00      |
| 7          | 1500    | 15                      | 0.5         | 1.00      |
| 8          | 1800    | 15                      | 0.5         | 1.00      |
| 9          | 1800    | 15                      | 0.5         | 0.25      |
| 10         | 1800    | 15                      | 0.5         | 0.50      |
| 11         | 1800    | 15                      | 0.5         | 1.00      |
| 12         | 1800    | 15                      | 0.5         | 1.25      |
| 13         | 1800    | 15                      | 0.5         | 1.50      |
| 14         | 1800    | 15                      | 0.5         | 1.75      |
| 15         | 1800    | 15                      | 0.5         | 1.00      |
| 16         | 1800    | 15                      | 1.0         | 1.00      |
| 17         | 1800    | 15                      | 1.5         | 1.00      |
| 18         | 1800    | 15                      | 2.0         | 1.00      |
| 19         | 1800    | 15                      | 2.5         | 1.00      |
| 20         | 1800    | 15                      | 3.0         | 1.00      |

Notations:  $t$  is the oxidation time, s;  $j$  is the current density, A/dm<sup>2</sup>;  $C_N$  is the concentration of sodium hydroxide, g/l;  $I_A/I_C$  is the ratio of the anodic and cathodic current components.



of a microarc oxidation installation with electrolyte containing  $C_{NaSi}$  80 g/l  $Na_2SiO_3$  and  $C_N$  0.5, 1, 1.5, 2, 2.5 and 3 g/l NaOH. The current density  $j$  in the anodic-cathode mode was constant and amounted to 15 A/dm<sup>2</sup>. The ratio of the anodic and cathodic current components  $I_A/I_C$  varied in the range from 0.25 to 1.5 (in increments of 0.25). The duration of sample treatment  $t$  was 100, 200, 300, 600, 900, 1200, 1500 and 1800 s. The thickness of the obtained oxide coatings was measured using a B7-517 thickness gauge. Using the MatLAB software environment, expressions for the dependences of the coating thickness on the factors affecting the structure of the coating itself were obtained, and graphs of the obtained dependences were constructed. Errors in indirect measurements of the thickness of the formed oxide coating were calculated.

Table 1 shows the parameters of the process modes under which the influence of the duration of product processing (samples 1–8), the ratio of current components (samples 9–14) and the concentration of NaOH (samples 15–20) on the coating thickness was studied.

### Results and discussion

Table 2 presents the results of measuring the thickness of the coatings obtained under different process modes, respectively, the graphs of the influence of process parameters on the coating thickness are shown in Fig. 1.

Table 2

Results of measuring the thickness of the formed MAO coatings

| Sample No. | $t$ , s | $h(t)$ , $\mu\text{m}$ | Sample No. | $I_C/I_A$ | $h(I_A/I_C)$ , $\mu\text{m}$ | Sample No. | $C_N$ , g/l | $h(C_N)$ , $\mu\text{m}$ |
|------------|---------|------------------------|------------|-----------|------------------------------|------------|-------------|--------------------------|
| 1          | 100     | 0.68                   | 9          | 0.25      | 29.53                        | 15         | 0.5         | 28.64                    |
| 2          | 200     | 2.07                   | 10         | 0.50      | 19.11                        | 16         | 1.0         | 29.32                    |
| 3          | 300     | 6.68                   | 11         | 0.75      | 12.37                        | 17         | 1.5         | 28.27                    |
| 4          | 600     | 8.98                   | 12         | 1.00      | 7.99                         | 18         | 2.0         | 27.76                    |
| 5          | 900     | 12.17                  | 13         | 1.25      | 5.18                         | 19         | 2.5         | 27.39                    |
| 6          | 1200    | 16.15                  | 14         | 1.50      | 3.99                         | 20         | 3.0         | 26.75                    |
| 7          | 1500    | 22.28                  |            |           |                              |            |             |                          |
| 8          | 1800    | 29.98                  |            |           |                              |            |             |                          |

Notations:  $h(t)$  is the coating thickness from the oxidation time,  $\mu\text{m}$ ;  $h(I_A/I_C)$  is the coating thickness from the ratio of the current components,  $\mu\text{m}$ ;  $h(C_N)$  is the coating thickness from the concentration of NaOH,  $\mu\text{m}$ .

As a result of processing the measurements results of the obtained MAO coatings thickness by the least squares method, analytical mathematical models of the studied dependencies of the oxide coating thickness on the oxidation time (1), the ratio of the anodic and cathodic current components (2) and the concentration of sodium hydroxide (3), respectively, were identified. The obtained mathematical expressions are given below:

$$h(t) = \begin{cases} e^{0.0058 \cdot t} - 1; & 0 < t \leq 300, \\ 0.0022 \cdot t + 3.4747; & 300 \leq t \leq 1800, \end{cases} \quad (1)$$

$$h(I_A/I_C) = 21.243 \cdot (I_A/I_C)^2 - 59.0496 \cdot I_A/I_C + 43.9807, \quad (2)$$

$$h(C_N) = -0.2643 \cdot C_N^2 + 0.0107 \cdot C_N + 28.95. \quad (3)$$

The graphs of the corresponding functions are shown in Fig. 1, *a–c*.

The study of the graphs (Fig. 1, *a–c*) showed that the dependence of the formed oxide film thickness on the oxidation time is advisable to approximate piecewise by mathematical functions of different types: exponential and linear according to expression (1). The use of this approach is due to the influence of diffusion and chemical processes dominating at the stages of spark and microarc discharges of the microarc oxidation process, which is confirmed by other studies [3].

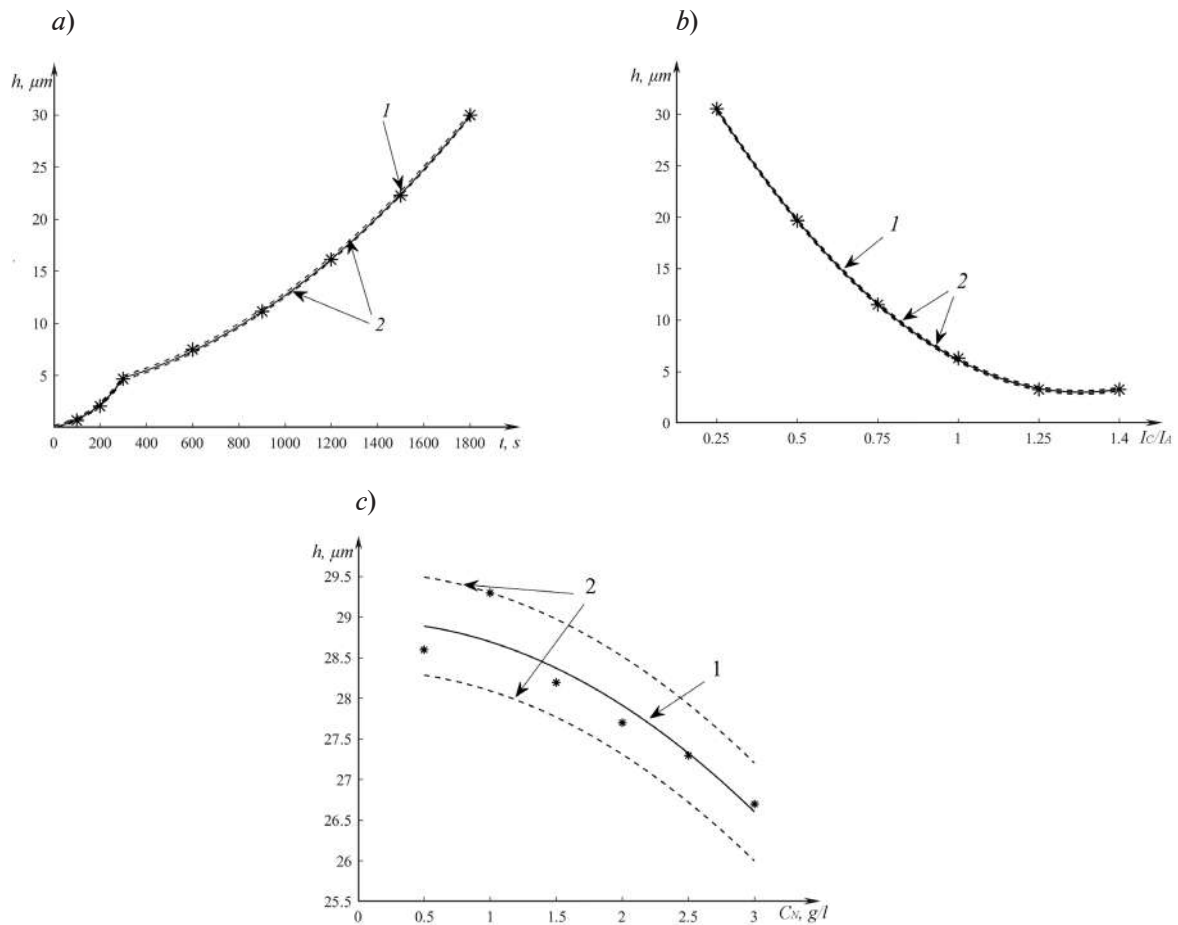


Fig. 1. Dependences of the coating thickness on the processing time  $t$  (a), on the ratio of the anodic and cathodic current components  $I_c/I_a$  (b) and on the NaOH concentration  $C_N$  (c): 1 is the approximating curve; 2 is the upper and lower error limits that form the uncertainty region; experimental data works in dots

However, such an approach is not applicable for the purpose of analyzing the dependence of the film thickness on the concentration of sodium hydroxide and the ratio of the anodic and cathodic components of the current. In this case, the approximation is made by a quadratic function due to the manifestation of nonlinear factors-impacts on the technological process.

A metrological analysis of the dynamics of a microarc oxide coating formation on products with an aluminum substrate was carried out. The error in the adequacy of the obtained mathematical expressions does not exceed  $\pm 5\%$ , which is confirmed by the lower and upper boundaries of the uncertainty regions shown in Fig. 1. It is advisable to use the obtained results when obtaining coatings with the required functional characteristics by the microarc oxidation method.

### Conclusion

The results of the metrological analysis of the MAO coatings growth and the identified mathematical models should be used in developing a digital twin of the MAO process. The obtained analytical expressions are described by different mathematical functions due to the presence of both diffusion and chemical processes dominating at the stages of arc and microarc discharges, and the nonlinearity of the factors influencing the technological process. The dependence of the thickness growth of the ceramic-like coating on the duration of processing of a product made of valve metal or alloy is described by exponential and linear functions, and the dependence of the thickness on the ratio of the current components and the concentration of sodium hydroxide is described by quadratic functions. The error in the adequacy of the obtained models does not exceed 5%.

## REFERENCES

1. **Pecherskaya E.A., Kononov S.V., Golubkov P.E., et al.**, Study of optical characteristics of microdischarges in the micro-arc oxidation process, *Vacuum*. 229 (2024) 113558.
2. **Ashutosh J., Kumar S., Blawert C.**, Evolution of PEO coatings on AM50 magnesium alloy using phosphate-based electrolyte with and without glycerol and its electrochemical characterization, *Jour. of Mag. and All.* 8 (2020) 692–715.
3. **Wang X., Zhang F.**, Influence of anions in phosphate and tetraborate electrolytes on growth kinetics of microarc oxidation coatings on  $Ti_6Al_4V$  alloy, *Trans. Nonferrous Met. Soc. China*. 32 (2022) 2243–2252.
4. **Sun Ch., Wang Y.**, Influence of Electrolyte Parameters on the Properties of the Ceramic Coatings Deposited on Aluminum Alloy by Plasma Electrolytic Oxidation, *Powder Metall Met Ceram.* 54 (2015) 101–105.
5. **Golubkov P.E., Pecherskaya E.A., Gurin S.A., et al.**, Influence of process parameters on the properties of microarc oxide coatings, *St. Petersburg State Polytechnical University Journal. Physics and Mathematics*. 16 (3.1) (2023) 368–373.

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## Method for optimizing fiber optic interferometer for quantum systems

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**Abstract.** A method for optimizing the parameters of a two-arm fiber-optic interferometer is proposed. To increase the OSNR at the interferometer output, a step-by-step method for aligning the lengths of the interferometer arms using a time delay meter is proposed. A high (83%) contrast of the interference pattern is achieved, which increases the sensitivity of the system and allows recording optical signals in a large dynamic range.

**Keywords:** fiber-optic communication system, interferometer, optical fiber, laser

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Материалы конференции

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## Метод оптимизации волоконно-оптического интерферометра для квантовых систем

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**Аннотация.** Предложен метод оптимизации параметров двухплечевого волоконно-оптического интерферометра. Для повышения OSNR на выходе интерферометра предложен пошаговый метод выравнивания длин плеч интерферометра с помощью измерителя временной задержки и последующего включения линии задержки. Достигнут высокий (83%) контраст интерференционной картины, что повышает чувствительность системы и позволяет регистрировать оптические сигналы в большом динамическом диапазоне.

**Ключевые слова:** волоконно-оптические телекоммуникационные системы, интерферометр, оптическое волокно, лазер

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## Introduction

Fiber-optic systems have wide applications in different areas: telecommunications, aerospace, astronomy, security, and scientific research.

Fiber-optic communication systems (FOCS) using quantum technologies provide a high degree of protection of transmitted data from unauthorized access. However, these technologies impose special specifications for their components: lasers, photoreceivers, optical fibers, and others. One of the components of quantum systems is an interferometer used to register a quantum key. For reliable registration of the quantum key at high speed, it is necessary to ensure equality of the lengths of the interferometer arms, the state of polarization of the transmitted signal, and minimal losses.

## Experimental results and discussion

Coherent high-speed DWDM fiber-optic systems are characterized by a low optical signal detection threshold. A key feature of coherent systems is the interference superposition of optical signals at the photodetector input. This technology places increased demands on the polarization characteristics of all data transmission system components.

The proposed method for aligning the optical travel time of signals along different arms of the interferometer is characterized by simplicity of implementation, visibility of control, high accuracy (up to 20 ps), and the possibility of use with a high bit rate (up to 50–100 GBit/s).

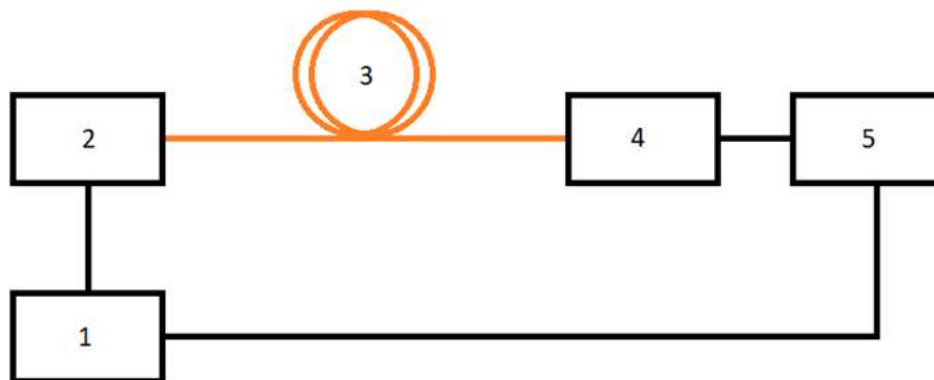


Fig. 1. Block diagram of experimental setup for measuring the delay in optical fiber: pulse generator 1, laser 2, optical fiber 3, photodetector 4, time interval meter 5



Fig. 2. Measuring the delay between the first and second pulses using an Agilent 53230A frequency counter





The experimental study was conducted using typical DWDM telecommunications equipment. The block diagram of the experimental setup is shown in Fig. 1. The signal from a narrowband laser source was modulated by a rectangular pulse generator. A sequence of optical pulses at a wavelength of  $\lambda = 1550$  nm of nanosecond duration was introduced into a 1:2 coupler and then into two single-mode optical fibers. Optical signals at the ends of the fibers were recorded using photodetectors and fed to the inputs of an Agilent Technologies 53230A dual-channel frequency counter and an Agilent Technologies MSO-X-3052A oscilloscope. This Agilent Technologies 53230A frequency counter was used as a time interval meter (Fig. 2). To increase the contrast of the interference pattern, the delay between pulses should be minimal.

The envelope shape and pulse duration were monitored using an Agilent Technologies MSO-X-3052A oscilloscope (Fig. 3). These parameters depend on the laser type, parameters, and length of the optical fiber.

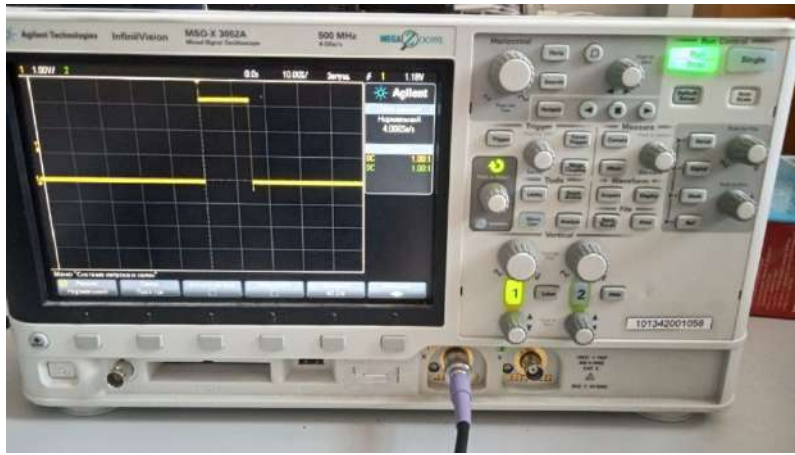


Fig. 3. Optical pulse at the end of optical cable at Agilent oscilloscope

To check the accuracy of the interferometer adjustment, a modulator was included in one of the interferometer arms. The contrast depth of the interference pattern at the interferometer output reached 83%, which indicates that the time delay of the optical signal passing through the optical fibers included in the interferometer arms is equal.

The polarization state was also monitored during the experiment by a polarimeter THORLABS PAX1000 (Fig. 4). The result of measuring the state of the optical pulse polarization using the polarimeter is shown in Fig. 5.

The achieved interference pattern contrast of 83% with an interferometer arm length of about 5 m made it possible to measure the optical signal in a dynamic range of more than 80 dB.

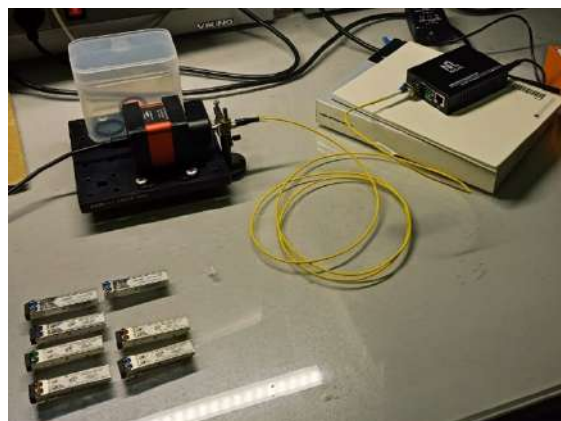


Fig. 4. Experimental stand for the polarization state monitoring

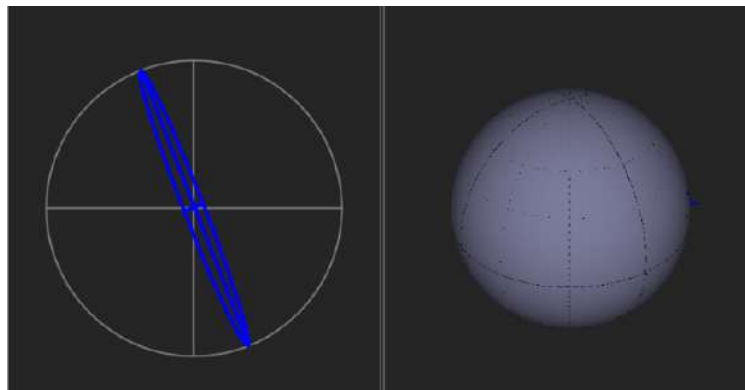


Fig. 5. Result of measuring the state of the optical pulse polarization using a polarimeter

### Conclusion

Thus, the method of equalizing the lengths of the interferometer arms using a time-delay meter between pulses passing through different arms of the interferometer has been experimentally confirmed. The possibility of controlling the delay time to 20 ps and less has been demonstrated. Aligning the lengths of the interferometer arms (up to 5 mm) increases the sensitivity of the interferometer and allows recording signals in a large (80 dB) range.

### REFERENCES

1. **Agrawal G.**, Fiber-Optics Communication Systems 5th Edition, New York. (2021).
2. **Agrawal G.** Nonlinear Fiber Optics 6th Edition, Elsevier. (2019).
3. **Yakovlev N.V., Bykov A.V., Andreeva E.I.**, Effect of the FWM and SRS on the fiber optics wavelength multiplexing system parameters, Saint Petersburg OPEN 2021, 8th International School and Conference on Optoelectronics, Photonics, Engineering and Nanostructures St. Petersburg, Russia, May 25 – 28. (2021).
4. **Ferreira M.** Nonlinear Effects in Optical Fibers. John Wiley & Sons, Inc., Hoboken, New Jersey, USA. 2011.
5. **Andreeva E.I.**, Properties of Temporary Optical Solitons in Optical Fibers and the Possibility of their Use in Telecommunications Proceedings of Telecommunication Universities. 4 (1) (2018) 5–12.

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## **Study of low temperature reactive magnetron sputtering NbN films for fabrication of an ultra-high sensitive detector**

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**Abstract.** This paper focuses on the study of reactive magnetron sputtering thin NbN films for sensitization of hot electron bolometers. HEB will be utilized in the Millimetron space observatory. The main principle of operation is a superconductivity that is experimentally observed when NbN film is cooled to the temperature of a liquid helium. At a critical temperature of superconductive transition a resistance of the film falls to zero and film becomes sensitive to light radiation of infrared and millimeter wavelength range. It is important to note that a thickness of film greatly affects on the sensitivity of film. When the thickness of film is decreased, the heat capacity decreases and with it the sensitivity of detectors based on superconductive film increases. In this research dependencies of the critical temperature from various parameters of fabrication technology were identified. Subsequently, parameters of reactive magnetron sputtering with the highest critical temperature at the lowest thickness of film were discovered.

**Keywords:** NbN films, critical temperature, superconductive transition, HEB, reactive magnetron sputtering, thin films, superconductivity, atomic force microscope

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## **Изучение низкотемпературного реактивного магнетронного распыления пленок NbN для изготовления детектора с высокой чувствительностью**

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**Аннотация.** Сверхпроводящие пленки NbN, изготовленные методом реактивного магнетронного распыления, являются чувствительным элементом болометров на эффекте

электронного разогрева НЕВ. Основной принцип НЕВ устройств основан на свойстве сверхпроводимости, которое проявляется при понижении температуры детектора до температуры жидкого гелия. В таком состоянии детектор очень чувствителен к инфракрасному и миллиметровому диапазону волн, характерному для излучения многих элементов в нашей вселенной. Данная работа посвящена повышению чувствительности болометров на эффекте электронного разогрева благодаря уменьшению толщины пленки NbN при сохранении максимально возможной температуры сверхпроводящего перехода.

**Ключевые слова:** пленки нитрида ниобия, критическая температура, сверхпроводящий переход, болометр на эффекте электронного разогрева, реактивное магнетронное распыление, тонкие пленки, сверхпроводимость, атомно-силовой микроскоп

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## Introduction

Astro Space Center of P.N. Lebedev Physics Institute is working on the scientific program of the Millimetron space observatory [1]. The main goal of this program is observation of H<sub>2</sub>O molecules for studying the evolution of life in the Universe. The equipment of space observatories with broadband and sensitive receivers makes it possible to study many water emission lines. Therefore, such space observatories, including Millimetron, make it possible to study water abundances and the entire chain of water transformations in the interstellar medium. The High Resolution Spectrometer incorporates heterodyne array receivers, one of which will be based on niobium nitride hot electron bolometers (NbN HEB) [2]. The sensitive element of NbN HEB is a superconductive niobium nitride film (NbN films on Si) produced by using the reactive magnetron sputtering [3].

NbN is a well-known material with comparatively high critical temperature from 14 to 16 K in bulk material [4]. The critical temperature depends on the proportion of niobium Nb to nitrogen N<sub>2</sub> [5–7]. NbN films on Si are fabricated with different sputtering technologies such as reactive magnetron sputtering [8], pulsed laser deposition [9], high-temperature chemical vapor deposition [10] and etc. Due to the existing technology and the high potential of reactive magnetron sputtering, this method of deposition of NbN films was chosen. The key parameters for evaluating film quality is critical temperature  $T_c$ , thickness.  $T_c$  is temperature at which a resistance of the film drops to zero.

The technology of superconducting NbN film deposition remains relevant, with numerous research groups regularly publish new research findings, for example,  $T_c$  is 9.6 K for 50 nm film [8] and  $T_c$  is 13 K for 100 nm [11]. The thicknesses of these films are very high and sensitivity is very low. Increasing the sensitivity of film is possible via reduction of film thickness, for instance, for 5.5 nm NbN on Si  $T_c$  is 7.8 K [12]. This work is devoted to optimisation of reactive magnetron sputtering process to achieve the most thin film with the highest possible critical temperature  $T_c$ .

## Materials and Methods

The magnetron sputtering system Leybold Z400 was implemented for deposition of superconductive NbN films, the scheme of set up is depicted in Fig. 1. The vacuum chamber was pumped out to  $2 \cdot 10^{-6}$  mbar using a two-stage pumping system. The inert gas Ar intrudes in the vacuum chamber. Then the voltage is applied to the magnetron with the Nb target in constant current mode, and N<sub>2</sub> is intruded. N<sub>2</sub> gas reacts with the Nb target, and NbN film deposition occurs [13]. In this work several parameters of the reactive magnetron sputtering are changed, such as current on glow discharge  $I$ , nitrogen gas pressure  $P_{N_2}$ , sputtering time  $\tau$ .

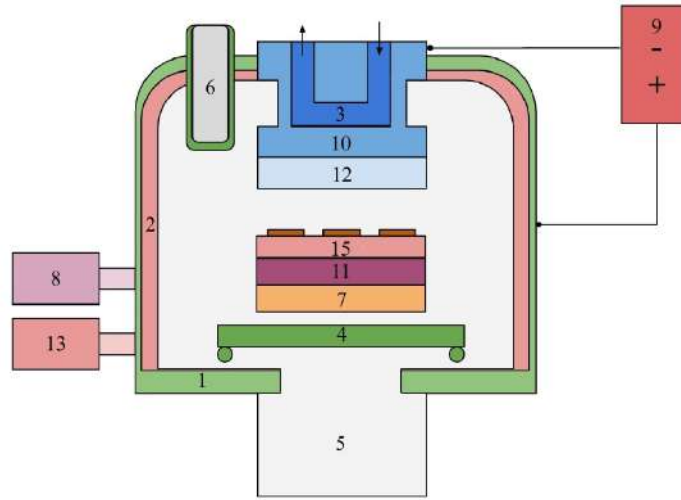


Fig. 1. Scheme of the magnetron sputtering system: vacuum chamber (1); heat jacket (2); cooling water (3); high vacuum valve (4); two-stage pumping system (5); nitrogen trap (6); heater of substrate holder (7); Ar gas intruder (8); sputtering power supply (9); magnetron (10); substrate holder (11); Nb target (12); N<sub>2</sub> gas intruder (13)

Several parameters of the fabricated film were investigated including critical temperature  $T_c$ , surface resistance  $R_s$  and the thickness film  $d$ . NbN film is cooled in Dewar with liquid helium and at  $T_c$  [14].  $R_s$  and  $d$  are measured with Four-point method and atomic force microscope in half-contact regime, respectively.

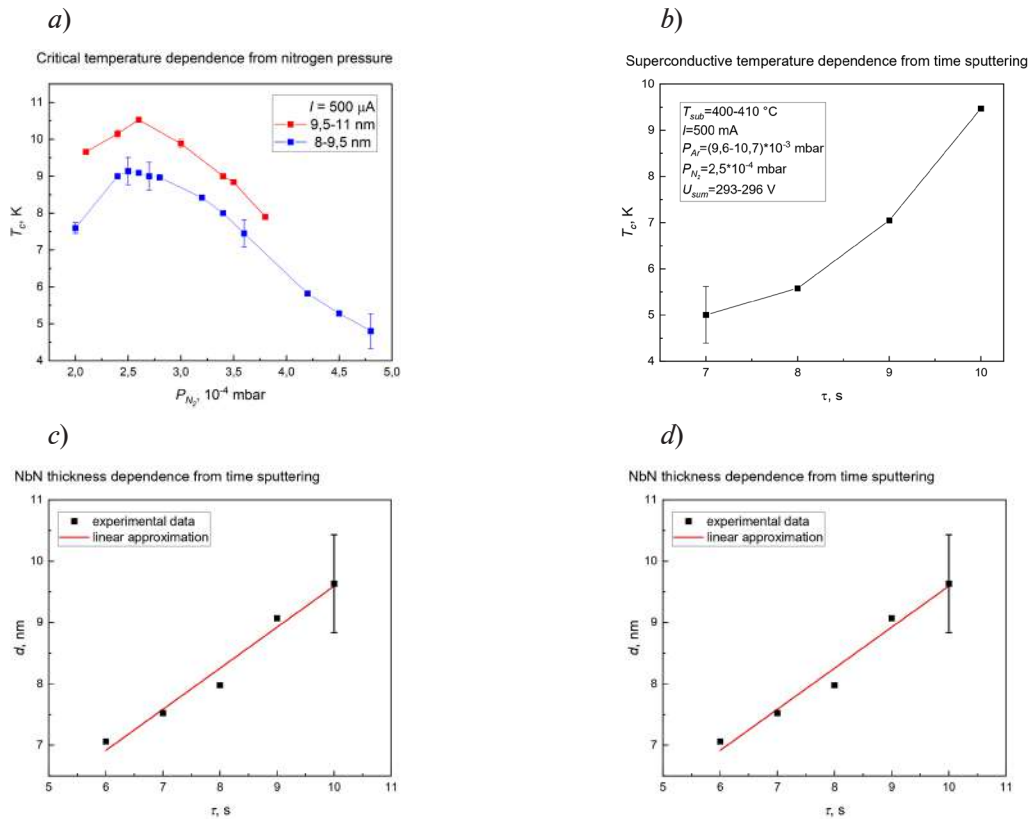


Fig. 2. Main dependences of the reactive magnetron sputtering technology:  $T_c$  on nitrogen pressure (a);  $T_c$  (b) and film thickness on sputtering time, respectively (c); surface resistance on film thickness (d)



## Results and discussion

During this work, several dependencies were revealed (Fig. 2). The key parameter in this work is the nitrogen pressure. The final critical temperature depends on the ratio of nitrogen to niobium in the film. The highest superconducting transition temperature,  $T_c$ , was achieved at  $P_{N_2} = 2.5 \cdot 10^{-4}$  mbar (Fig. 2, *a*).

After raising the critical temperature, it was necessary to reduce the film thickness to increase sensitivity. From Fig. 2, *b*, the minimum sputtering time is  $\tau = 7$  s. At lower values of  $\tau$ , the surface resistance  $R_s$  sharply increases, which leads to increased film islanding and drastically reduces  $T_c$ .

Therefore, it was important to understand the dependence of the film thickness on the specific sputtering time, as demonstrated in Fig. 2, *c*. A sputtering time of 7 s corresponds to a 7 nm film. The final parameter is the surface resistance of the film, which determines the final geometry of NbN-based devices. The dependence of  $R_s$  on thickness was determined (Fig. 2, *d*).

All the final properties of the superconducting film were obtained to characterize the specific magnetron sputtering system that will be used for future work.

## Conclusion

In this work the reactive magnetron sputtering technology was optimized for superconductive 7 nm NbN film with  $T_c = 7-8$  K.

## Acknowledgments

Work was conducted in Moscow State Pedagogical University.

## REFERENCES

1. Tretyakov I.V., Khudchenko A.V., Rudakov K.I., et al., Development of Mixers for the High-Resolution Spectrometer of the Millimetron Space Observatory, IEEE Transactions on Terahertz Science and Technology. 15 (2) (2025).
2. Semenov A.D., Goltsman G.N., Sobolewski R., Hot-electron effect in superconductors and its applications for radiation sensors, Supercond. Sci. Technol. 15 (4) (2002) R1.
3. Minakov V.I., Kogan M.Z., Production of thin-film microcircuits, Energia. Leningrad Branch. (1973).
4. Matthias B.T., Geballe T.H., Compton V.B., Superconductivity, Rev. Mod. Phys. 35 (2) (1963) 414.
5. Rogener H., Physik Z., Zur Supraleitung des Niobnitrids, Springer Nature. 132 (446) (1952) 446–467.
6. Matthias B.T., Hulm J.K., A Search for New Superconducting Compounds, Phys. Rev. 87 (5) (1952) 799.
7. Ziegler W.T., Young R.A., Studies of Compounds for Superconductivity, Phys. Rev. 90 (1) (1953) 115.
8. Marquardt R., Cipo J., Schlichting F., et al., Correlation between properties of direct current magnetron sputtered thin niobium nitride films and plasma parameters, Thin Solid Films. 742 (2022) 139046.
9. Treece R.E., Horwitz J.S., Claassen J.H., Chrisey D.B., Pulsed laser deposition of high-quality NbN thin films, Appl. Phys. Lett. 65 (22) (1994) 2860–2862.
10. Hazra D., Tsavdaris N., Jebari S., et al., Superconducting properties of very high quality NbN thin films grown by high temperature chemical vapor deposition, Supercond. Sci. Technol. 29 (10) (2016) 105011.
11. Kosutova T., Yao Y., Fernandes D., et al., Ion-assisted sputter-deposition of superconducting NbN thin films on silicon, Supercond. Sci. Technol. 38 (9) (2025) 095010.
12. Sidorova M., Semenov A., Hübbers H.-W., et al., Electron energy relaxation in disordered superconducting NbN films, Mariia Sidorova, Phys. Rev. B. 102 (5) (2020) 054501.
13. Leybold. Technical documentation. Cathode sputtering Process. General information. UC 533/29.3.88
14. Tinkham M., Introduction to superconductivity. McGraw-Hill, IncM. (1996).



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Conference materials

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## On the reconstruction of multiplet antennas from basic resonators

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**Abstract.** In this paper, we consider the possibility of reconstructing the geometry of an unknown multiplet antenna from the geometries of elementary radiators by combining their spatial far-field spectra when decomposed into spherical harmonics. We propose a simple step-by-step algorithm that allows us to combine a set of basic resonators for implementing a non-trivial radiation pattern.

**Keywords:** antenna, telecommunications, multipolar decomposition, radiation pattern, beam forming, computational electrodynamics

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Материалы конференции

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## О восстановлении многомодовых антенн из базисных резонаторов

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**Аннотация.** В данной работе рассматривается возможность восстановления геометрии неизвестной многомодовой антенны из геометрий элементарных излучателей путем совмещения их пространственных спектров дальнего поля при разложении на сферические гармоники. Представлена простая последовательность действий, позволяющую получить набор простейших антенных элементов для реализации нетривиальной диаграммы направленности.

**Ключевые слова:** антенна, телекоммуникации, мультипольное разложение, диаграмма направленности, формирование луча, вычислительная электродинамика

**Финансирование:** Данная работа выполнена при поддержке Российского Научного Фонда по проекту № 24-19-00269.

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## Introduction

One of the most important tasks in modern telecommunication systems is to create a selective radiation pattern [1, 2]. Such diagrams may have slits, punctured points, and other features and singularities predetermined by the purpose of the communication channel (radar, satellite communications, smart beam control). To achieve this goal (enabling a controlled feature), in an arbitrary radiation pattern, in the general case, an antenna we modify must have a permitted harmonic of such an order that is capable of forming an electromagnetic field of similar dimension [3]. For example, a punctured point in the diagram can be provided by turning on a convenient dipole antenna with a fundamental minimum in the plane of the vibrator. In this paper, we consider an algorithm that can be used to accurately build a multiplet antenna with specified characteristics. The potential development of such a method may make it possible to improve existing beam control methods such as metasurfaces [4, 5] and antenna arrays [6, 7].

## Discussion

At the first stage, the requirements are imposed on the radiation pattern of the multiplet antenna being reconstructed: its polarization and energy characteristics. The resulting electric field is then converted into a spectrum of multipolar contribution coefficients of spherical harmonics [8, 9]. Let us call this spectrum the required vector state of the reconstructed antenna.

Having performed the decomposition procedure for various trivial antennas, which we will call basic (e.g. electric dipole with pure electric response, split ring with both electric and magnetic responses, omega particles with coupled magnetoelectric response), one can obtain linearly independent non-orthogonal non-unit vector-states in which the system exist whenever the corresponding basic antenna is turned on at some normalized frequency  $f_n$ . It is assumed that by linear combination of such basic state vectors, it is possible to obtain, among other things, the required vector state of the reconstructed antenna.

Naturally, this decomposition still does not take into account the relative position and rotation of several antenna elements, so that we have only been able to decompose spectra of the same symmetry as the basic antennas. To introduce rotations into the algorithm, one has to recall that the modified spherical functions which coefficients we study generate the basis for irreducible representations of the  $SO(3)$  symmetry group. Introducing the antenna rotation  $R(\lambda, \beta, \gamma)$  in Cartesian system of coordinates  $\{x \rightarrow x', y \rightarrow y', z \rightarrow z'\}$  through Euler angles  $\{\lambda, \beta, \gamma\}$  in  $ZYZ$  order, for the spherical harmonic  $Y^m(x', y', z')$  of order  $l, m$  one can obtain [10]:

$$Y_l^m(x', y', z') = \sum_{k=-l}^{+l} [D_l^{mk}(R(\alpha, \beta, \gamma))]^* Y_l^k(x, y, z), \quad (1)$$

where  $D_l^{mk}(R(\alpha, \beta, \gamma))$  stands for the element of Wigner D-matrix. Based on this, the corresponding multipolar (either electric or magnetic) coefficient of the rotated antenna can be calculated as:

$$A_l^m(\alpha, \beta, \gamma) = \sum_{k=-l}^{+l} e^{im\alpha} e^{ik\gamma} \sqrt{(l+m)!(l-m)!(l+k)!(l-k)!} \times \\ \times \sum_{s=\max\{0, k-m\}}^{s=\min\{l+k, l-k\}} \frac{(-1)^{m-k+s} \cos^{2l+k-m-2s}(\beta/2) \cdot \sin^{m-k+2s}(\beta/2)}{(l+k-s)!s!(m-k+s)!(l-k-s)!} \cdot A_l^m(0, 0, 0). \quad (2)$$

The corresponding examples of the rotation of the basic harmonics are shown in Fig. 1. Here the basic electric dipole antenna oriented along the  $Z$  axis was rotated 90 degrees so that the  $Y$  axis coincided with the  $Z$  axis and the  $Z'$  axis coincided with the  $-Y$  axis.

With using this calculation it is possible to obtain a complete space of vector states of the basic antennas, which makes up the resulting multiplet structure. After this stage, it is necessary to set up an iterative search by iterating according to the following algorithm: (i) the most unbalanced

multipole contribution is selected, i.e. the one that gives the largest amplitude to the required vector state, (ii) the base vector states being iterated are phased and normalized relative to the selected unbalanced contribution, (iii) the normalized one is subtracted from the required vector state. and a phased vector, which leaves behind a smaller difference, (iv) the steps (ii) and (iii) are repeated until the required convergence is achieved.

Finally, after achieving convergence, the sets of subtracted vector states, along with amplitudes, phases, and Eulerian rotation angles, can be compared with real prototypes of basic antennas and configured into a multiplet antenna.

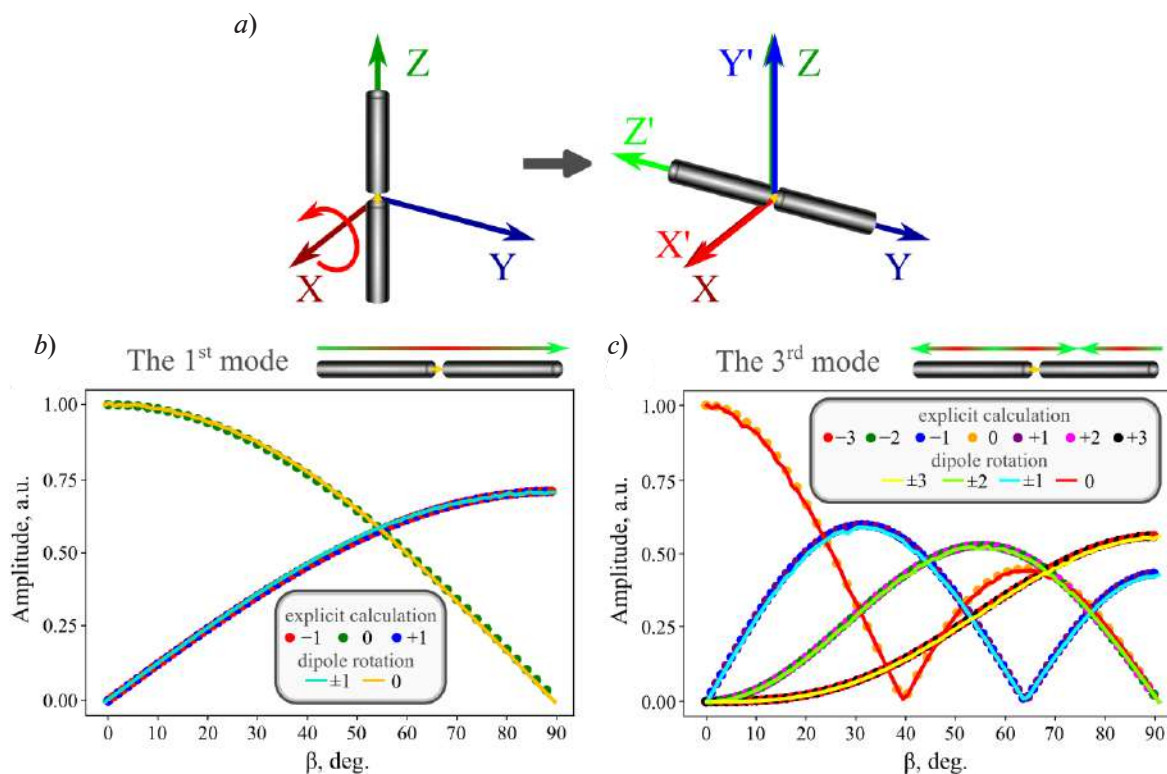


Fig. 1. Transformations of the basic antenna vector state during rotation: the axes rotation (a); comparison of the results of direct calculation using equation (2) with multipolar coefficients of the far field of a rotated dipole antenna at 1<sup>st</sup> (b) and 3<sup>rd</sup> (c) order mode

## Conclusion

Within the framework of this study, the generalized algorithm for constructing a multiplet antenna corresponding to a complex radiation pattern with features using spherical harmonic decomposition was described. A method for numerically obtaining the space of basis vectors to ensure the convergence of the algorithm is considered, as well as the inclusion of asymmetric diagrams by adding states corresponding to Eulerian rotations.

The use of such an algorithm in modern communication networks in the design of antenna terminals can help to develop selective radiation patterns applicable in a wide range of tasks from space and defense industries to household multi-user networks.

## REFERENCES

1. Kammoun A., Alouini M.S., Elevation beamforming with full dimension MIMO architectures in 5G systems: A tutorial. *IEEE Communications Surveys & Tutorials*. 21 (4) (2019) 3238–3273.
2. Ali E., Ismail M., Nordin R., Abdulah N.F., Beamforming techniques for massive MIMO systems in 5G: overview, classification, and trends for future research, *Frontiers of Information Technology & Electronic Engineering*. (18) (2017) 753–772.
3. Jackson J.D. *Classical electrodynamics*, John Wiley & Sons. (2021).





4. Sayanskiy A., Belov A., Yafasov R., et al., A 2D-programmable and scalable reconfigurable intelligent surface remotely controlled via digital infrared code, IEEE Transactions on Antennas and Propagation. 71 (1) (2022) 570–580.
5. Ma H., Kim J.S., Choe J.H., Park Q.H., Deep-learning-assisted reconfigurable metasurface antenna for real-time holographic beam steering, Nanophotonics. 12 (13) (2023) 2415–2423.
6. Zhao D., Gu P., Zhong J., et al., Millimeter-wave integrated phased arrays, IEEE Transactions on Circuits and Systems I: Regular Papers. 68 (10) (2021) 3977–3990.
7. He G., Gao X., Sun L., Zhang R., A review of multibeam phased array antennas as LEO satellite constellation ground station, IEEE Access. (9) (2021) 147142–147154.
8. Burtsev V.D., Vosheva T.S., Sedov A.P., et al., On the Far Electric Field Extraction. In 2024 IEEE International Conference on Microwaves, Communications, Antennas, Biomedical Engineering and Electronic Systems (COMCAS) IEEE, (2024) 1–5.
9. Burtsev V.D., Nikulin A.V., Seregin G.M., Filonov D.S. (in publication). Geometry designing for an antenna with the given radiation pattern, Nanoindustry, Issue 11s, (18) (135) (2025).
10. Schwinger J., Angular momentum, Springer Berlin Heidelberg, (2001).

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## Remote transport infrastructure monitoring system based on fiber-optic sensors

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**Abstract.** We present a low-power autonomous system for remote structural health monitoring of bridges and similar assets in rural/hard-to-reach areas. The method uses distributed macro-bending sections of standard fiber; load-induced loss is measured by optical time-domain reflectometry. The architecture minimizes components and transmits only incremental data via low-power radio or short satellite links, reducing cost and energy use. Laboratory tests detected 0.4 mm displacement; base spatial resolution was  $\approx 1.5$  m (0.5 m by interpolation) and dynamic range reached 67 dB. Field trials on a rural reinforced-concrete bridge confirmed autonomous logging of load-induced attenuation. Active-mode power  $\leq 2$  W enables long-term operation and cost-effective scaling to many sensing points.

**Keywords:** fiber-optic sensors, monitoring, transport infrastructure, LPWAN, autonomous system

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## Система мониторинга удалённой транспортной инфраструктуры на основе волоконно-оптических датчиков

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**Аннотация.** Представлена автономная система дистанционного мониторинга технического состояния мостов в сельских и труднодоступных районах. Метод основан на фиксировании потерь на макроизгибных участках волокна, измеряемых оптической рефлектометрией во временной области. Минимально обнаруживаемое перемещение в лабораторных условиях составляет 0,4 мм; базовое разрешение 1,5 м, динамический диапазон 67 дБ.

**Ключевые слова:** волоконно-оптические датчики, мониторинг, транспортная инфраструктура, LPWAN, автономная система



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### Introduction

In this work, increased attention is given to monitoring transportation infrastructure systems (bridges, tunnels, and others) using various technical means [1–3]. One of the key elements of any transportation infrastructure system (e.g., road or railway) is the bridge. Many sensors and instruments have been developed for real-time monitoring of its condition [4–6].

However, in rural and hard-to-reach areas continuous power and reliable communications are often unavailable, so inspections remain episodic; this motivates low-power, low-cost remote structural health monitoring. For such sites, traditional electrical sensors and high-end distributed optical systems (e.g., Brillouin/Raman) are constrained by reliability, cost, and maintenance complexity.

Optical measurements offer high accuracy [7–10], and optical fiber is immune to electromagnetic interference and resistant to corrosion [11–13]. Therefore, we consider macro-bending fiber sensors combined with OTDR as an economical, low-power solution applicable to rural bridges and similar assets.

### Materials and Methods

Fiber-optic deformation monitoring follows two main approaches: point FBG sensors that read spectral shifts [14] and distributed Raman/Brillouin systems for continuous stress profiling over tens of kilometers [15]. Both are accurate but costly and power-hungry, limiting use in low-budget, power-constrained projects.

As a low-cost alternative, we use macro-bending fiber sensors measured by optical time-domain reflectometry (OTDR), which provides distributed readings with adequate sensitivity and spatial resolution at minimal hardware cost. A macro-bending sensor is a standard single-mode fiber fixed at designated bends; loading increases bend-induced attenuation recorded by OTDR. Geometry is application-specific (e.g., U-loops), chosen by required sensitivity and robustness.

Although less sensitive than classical approaches ( $\approx 0.1$ – $0.2$  mm vs micron-level for FBG), this is adequate for bridges and overpasses where displacements of engineering interest are centimeter-scale. Differential measurement between idle and loaded states reduces temperature influence and avoids complex compensation, which is crucial for wide outdoor temperature ranges.

Bending the optical fiber causes light to leak from the core, resulting in additional attenuation. For single-mode fiber, this process is well described by an exponential dependence.

$$\alpha_b(R) = \alpha_0 \exp\left(-\frac{R}{R_C}\right), \quad (1)$$

where  $\alpha_b$  is the specific bend loss;  $R$  is the bend radius;  $\alpha_0$ ,  $R_C$  are the parameters determined using a calibration sample.

During OTDR operation, a short light pulse with a duration of  $\tau_p$  is injected into the fiber, after which the device records the backscattered power as a function of time.

$$z = \frac{v_g t}{2}, \quad (2)$$

where  $v_g$  is the group velocity of signal propagation.

One of the key metrological characteristics of an OTDR is its spatial resolution. It is limited, first, by the duration of the probing pulse  $\tau_p$  (determined similarly to formula 2, where  $\tau_p$  is substituted instead of  $t$ ). And second, by the spatial sampling step, which is determined by the clock frequency of the analog-to-digital converter  $f_s$ :

$$\Delta z_{adc} = \frac{v_g}{2f_s}, \quad (3)$$

The actual limit is determined by the greater of the two values.

In the implementation, the probing pulse is generated by a Fabry–Perot laser diode at a wavelength of 1550 nm, producing peaks of 8–10 mW; the 5 ns pulse duration is set by a driver based on an AD8009 and a BFR93A transistor (Fig. 1).

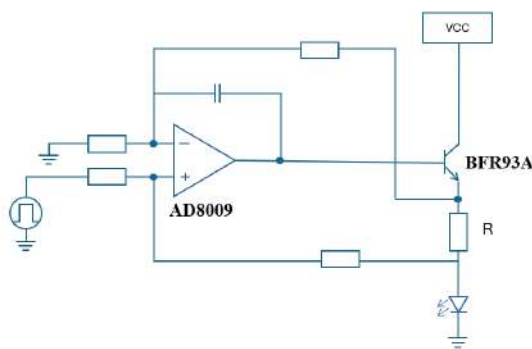


Fig. 1. Laser diode driver implementation for pulse generation

The reflected backscatter is received by an InGaAs PIN photodiode. The photodiode current is converted to voltage using an OPA857 transimpedance amplifier; an internal switch allows selecting a resistance of 5 k $\Omega$  (bandwidth 120 MHz) or 20 k $\Omega$  (bandwidth 60 MHz). The amplified signal is converted to a fully differential format by an ADA4937-1 driver and fed into a 12-bit AD9226 ADC operating at 65 MHz (Fig. 2).

For this implementation,  $\Delta z_{imp} \approx 0.5$  m and  $\Delta z_{adc} \approx 1.54$  m, which gives a spatial resolution of approximately 1.5 m. This value refers to the primary discretization: subsequent digital processing and interpolation between adjacent samples allow estimating the bend position with

up to 0.5 m accuracy. The dynamic range of the developed system is 67 dB when averaging 100 measurements. In practice, this range allows simultaneously tracking large deformations (attenuation increase by several decibels) and subtle deviations around 0.2 dB, corresponding to sub-millimeter deflections.

Instead of an FPGA, we use the STM32F4's DCMI to capture a 12-bit parallel stream; DMA writes frames to RAM without CPU. This replacement cut PCB cost by ~25% and reduced digital power to 0.7 W; total active power is  $\leq 2$  W with the 1.5 W analog front end switchable. A measurement takes ~0.5 s, after which the system enters deep sleep.

To address the issue of energy-efficient communication, two approaches are proposed. Synchronous LPWAN mesh networks provide ultra-low power consumption due to their synchrony and offer wide coverage through optimized message routing. In fully isolated areas, the “Gonets-M1” satellite modem or its counterpart “Marathon-IoT” can be used; a 40-second session once per hour transmits incremental reflectograms and consumes approximately 0.15 W·h.

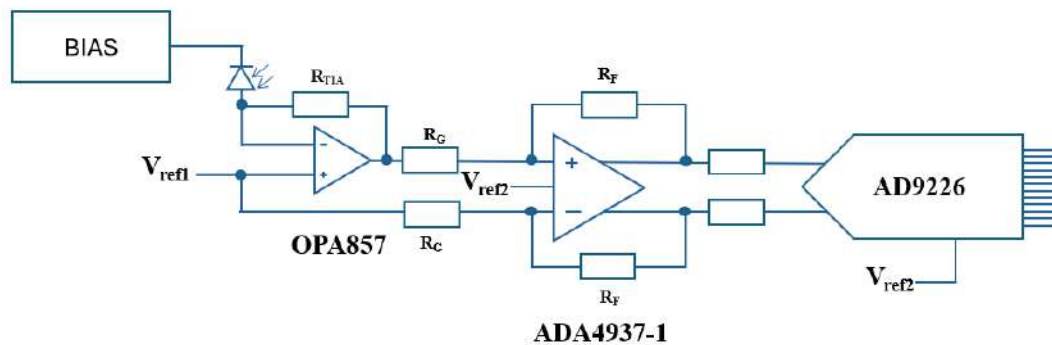


Fig. 2. Receiver circuit diagram of the reflectometer



### Results and discussion

To verify the prototype's functionality, a stationary setup was built with an adjustable fiber bend radius (from 50 to 20 mm). Dozens of stretch-and-release cycles were performed, measuring attenuation changes at each step. The experiments confirmed the exponential nature of losses and showed that a fiber displacement of just 0.4 mm led to a clearly detectable increase in attenuation, defining the system's sensitivity. With repeated tests, variation in results for the same radius did not exceed 0.05 dB, indicating good measurement reproducibility and no fiber degradation from repeated bending.

Field tests were conducted on a rural bridge made of reinforced concrete slabs (Fig. 3). U-shaped bends with a diameter of 25 mm were formed at the slab joints, and the measurement module was placed under the span, powered by an autonomous battery.



Fig. 3. Field testing on the bridge and bend formation

The load was applied by a passenger car weighing 1,500 kg, which crossed the center of the span three times with a stop. Each cycle caused an additional attenuation of about 1.5 dB, which completely disappeared after unloading. Fig. 4 presents the results of the bridge slab displacement studies.

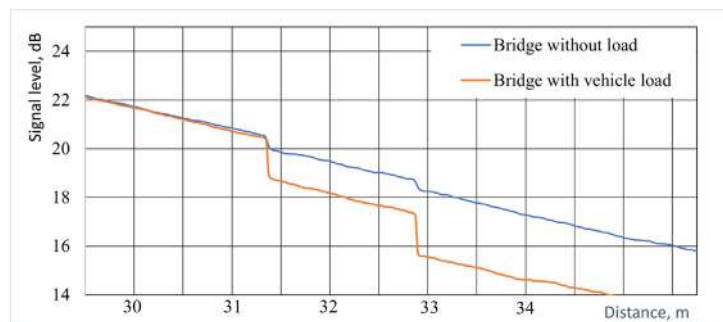


Fig. 4. Detected deformation on the reflectogram segment

Analysis of the obtained results (Fig. 4) confirmed the operability of the laboratory setup (prototype) and the adequacy of the technical solutions used in its implementation, both in terms of measurement and signal processing.

### Conclusion

Laboratory and field experiments in the Leningrad Region confirm the feasibility of the macro-bending OTDR system for remote monitoring of transportation structures. The prototype achieved a 67 dB dynamic range, 1.5 m base resolution (0.5 m by interpolation), 0.4 mm displacement sensitivity, and  $\leq 2$  W active power, supporting deployment with  $>100$  sensing points and enabling low-cost, long-term monitoring of bridges, overpasses, and tunnels.



## REFERENCES

1. Guo E., Hu H., Lai J., et al., Structural health monitoring of bridges using fiber-optic sensing, Structures. 78 (2025) 109193.
2. Lin Z., Gou X., Xu Z., Hai D., Monitoring technologies in tunnel construction, Tunnel Construction. 45 (4) (2025) 695–707.
3. Shi C., Zhang X., Zhu Z., et al., Distributed monitoring of underground transport facilities, Tunnelling and Underground Space Technology. 160 (2025) 106490.
4. Gotou H., Aoki Y., Oikawa D., et al., Recent advances in bridge monitoring, Structural Engineering International. 35(1) (2025) 118–124.
5. Komol M.M.R., Mizanur Rahman A.N.M., Podder A.K., et al., IoT-based structural monitoring of transport facilities, Transport and Telecommunication. 25 (1) (2024) 54–65.
6. Nishino T., Tanigawa H., Yagi T., et al., Optical methods for infrastructure diagnostics, Proceedings of SPIE. 13130 (2024) 131300E.
7. Davydov V.V., Vakorina D.V., Stepanenkov G.V., Optical methods for diagnostics of composite structures, Computer Optics. 48 (1) (2024) 93–101.
8. Davydov V.V., Provodin D.S., Goldberg A.A., Kochetkov I.D., Optical techniques in deformation analysis, Computer Optics. 48 (2) (2024) 217–224.
9. Grebenikova N.M., Davydov R.V., Rud V.Yu., Optical sensing methods for bridge monitoring, Journal of Physics: Conference Series. 1326 (1) (2019) 012012.
10. Davydov V.V., Reznikov B.K., Dudkin V.I., Fiber-optic methods in structural health monitoring, Energies. 16 (3) (2023) 1040.
11. Bylina M.S., Glagolev S.F., Diubov A.S., Advanced optical devices for diagnostics, Proceedings of SPIE. 12295 (2022) 122951A.
12. Ermolaev A.N., Krishpents G.P., Davydov V.V., Vysoczkiy M.G., Fiber-optic diagnostics of dynamic processes, Journal of Physics: Conference Series. 741 (1) (2016) 012171.
13. Davydov R.V., Saveleiv I.K., Lenets V.A., et al., Optical monitoring methods in computer science, Lecture Notes in Computer Science. 10531 (2017) 177–183.
14. Chubchev E.D., Dorofeenko A.V., Dolzhenko E.I., et al., Optical diagnostics of mechanical deformations, Measurement. 253 (2025) 117479.
15. Lei Y., Tang X., Li T., et al., Distributed optical monitoring systems, Optics Express. 33(7) (2025) 15827–15837.

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## Features of goniometric measurements in liquid media using triangular cuvettes

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**Abstract.** A new method for measuring the refractive index of liquid media using a triangular cuvette has been developed. The features of goniometric measurements of the refractive index of liquid media using a triangular cuvette with a right angle have been determined. A cuvette design has been developed for conducting long-term studies of refractive index changes over occupied volume, which is particularly relevant for hydrocarbon mixtures. The advantages of the developed method for measuring the refractive index over industrial refractometers are highlighted. The main ones are the ability to easily measure liquid media of varying transparency and to conduct long-term measurements of volatile media. The results of studies of various media are presented and compared with measurements on industrial refractometers.

**Keywords:** goniometric systems, triangular cuvette, features, laser radiation, measurement accuracy, liquid medium, refractive index

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Материалы конференции

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## Особенности гониометрических измерений жидких сред с использованием треугольных кювет

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**Аннотация.** Разработана новая методика измерения показателя преломления жидких сред с использованием треугольной кюветы. Определены особенности гониометрических измерений показателя преломления жидких сред с использованием треугольной кюветы с прямым углом. Разработана конструкция кюветы для проведения продолжительных исследований изменения показателя преломления по занимаемому объему, что особенно актуально для смесей углеводородов. Выделены преимущества разработанного метода измерения показателя преломления относительно промышленных рефрактометров. Основными из них являются возможность легко проводить измерения жидких сред различной прозрачности и проведение долговременных измерений летучих сред. Представлены результаты исследований различных сред и проведено их сравнение с измерениями на промышленных рефрактометрах.

**Ключевые слова:** гониометрическая система, треугольная кювета, особенности, лазерное излучение, показатель преломления, погрешность измерений, жидкие среды

**Ссылка при цитировании:** Клименко Р.П., Данилова В.И., Клименко В.П., Давыдов В.В., Особенности гониометрических измерений жидких сред с использованием треугольных кювет // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2025. Т. 18. № 3.2. С. 143–148. DOI: <https://doi.org/10.18721/JPM.183.228>

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## Introduction

Accurate measurements of various parameters are necessary for solving various problems in both research and practical applications [1, 2]. The methods used to perform these measurements must be universal (allowing for the investigation of a large number of media). Such methods include nuclear magnetic resonance, electron paramagnetic resonance, optical spectroscopy, and others [3–5]. These are expensive in terms of equipment and time-consuming research methods with limitations on the size of the images being studied. Not every laboratory can afford such equipment. Therefore, faster and simpler methods of studying the state of condensed media are used. One of them is related to refraction (the refractive index is measured) [6].

Currently, a large number of different methods have been developed for measuring the refractive index of a condensed medium. These include: the critical angle method, interference methods, Abbe refractometry, the differential method, and the goniometric method [7–9]. For use in laboratory conditions, goniometric measurements differ from others in their high functionality (it is possible to measure the refractive index of a medium in a liquid, solid, and, under pressure, gaseous state). Unlike interference methods, the goniometric system is less sensitive to mechanical vibrations and does not require complex adjustment.

These facts make the goniometric method of measuring the refractive index preferable when creating multifunctional experimental setups in small laboratories for studying condensed media, both liquid and solid. On the other hand, the use of goniometric measurements raises a number of difficulties related to the varying transparency of the media under study, their volatility, and the wide range of refractive index changes. This creates a number of peculiarities when performing goniometric measurements, which must be taken into account to ensure a high degree of reliability when monitoring the state of the media. To do this, it is necessary to ensure that the refractive index measurement error does not exceed 0.0001 in the measurement range from 1.32 to 1.77 [9–11]. This refractive index measurement range corresponds to 99% of all liquid media and their mixtures existing in the world. Therefore, the aim of this work is to establish these features and develop a method to ensure the measurement of the refractive index of a liquid medium with an error of 0.0001 or less in the specified range.

## Materials and Methods

An analysis of various designs and systems for measuring the refractive index  $n$  [7–11] showed the potential for developing a new system based on goniometric measurements. Based on data from various laboratory experimental goniometric installations [9, 11], we developed the following design (Fig. 1).

A fundamentally new feature of the experimental setup for measuring the refractive index  $n$  of liquid media is the use of various cuvettes (triangular in shape with a right angle and a lid), as well as a new method for determining  $n(\lambda_n, T_m)$  from the measured angle  $\varphi_1$ . This design also allows measurements of  $n(\lambda_n, T_m)$  to be made at any wavelength of laser radiation. The principle of measuring  $n$  remains unchanged; all that is needed is a laser with the appropriate wavelength (preferably in a standard housing) or a tunable laser.

To measure  $n$  of liquid media on the experimental setup, we designed triangular cuvettes with a right angle and a lid. Fig. 2 shows an example of one of the triangular cuvettes we designed and its layout.

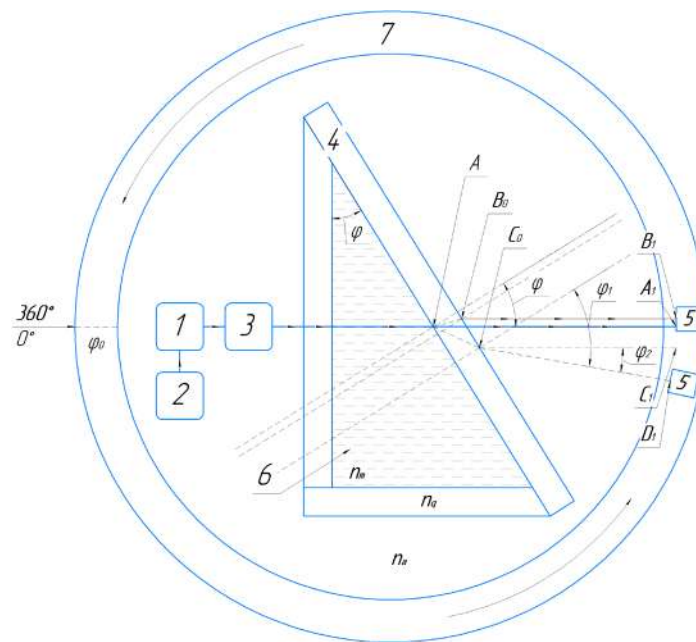


Fig. 1. Design of goniometric experimental setup for measuring the refractive index  $n$ : laser radiation source 1; laser radiation power control system 2, laser power supply unit; collimator 3; specially shaped rectangular cuvette 4; photodetector 5; test medium 6; rotary-movable device 7 for determining the angle

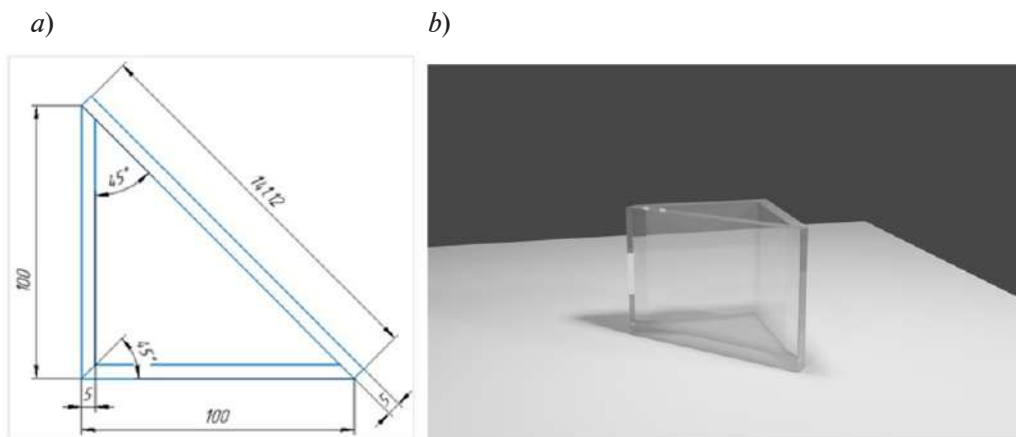


Fig. 2. Design of cuvette in the shape of an isosceles triangle (a), spatial model of cuvette (b)

The test medium 6 is placed in a triangular cuvette 4 (Fig. 1). A plane-parallel laser beam front is directed onto the wall of cuvette 4 after collimator 3. The laser radiation then passes through the medium layer and hits the edge of cuvette 4, which is positioned at an angle to the direction of propagation of the laser radiation front. The angle  $\varphi$  of the triangular cuvette 4 (Fig. 1) is the angle of incidence of the laser radiation on the cuvette wall, where refraction occurs at the boundary between two media (the medium under study and quartz (the material from which the cuvette is made)). Using a movable photodetector, the position of which is set according to the maximum recorded radiation, the angle  $\varphi_1$  is determined using the optical scale of the goniometer, and  $n$  is calculated. Unlike other goniometric measurement techniques, in this case only one angle  $\varphi_1$  is determined. At the same time, it is possible to calibrate the instrument scale, without changing the cuvette, by angles using reference liquids, which was previously not possible with other goniometric measurements. This gives rise to a number of peculiarities in the measurement data, which we have identified.

### Features of measurements using a triangular cuvette

The developed measurement method using a triangular cuvette has a number of features that significantly expand the research capabilities of goniometric measurements compared to standard optical cells [9, 11]. The main ones are as follows:

1. Laser radiation of different wavelengths from the visible range can be used for  $n$  measurements. The use of IR radiation is possible, but it will be difficult to determine the case of total internal reflection at the boundary between two media, and measurements may not be possible;
2. The use of a sealed cover, which does not create additional optical effects during measurements, allows for the study of volatile and hazardous liquid media and their mixtures;
3. The goniometer allows the cuvette to be moved horizontally and vertically. This makes it possible to study media with different degrees of transparency (by reducing the optical path of the laser beam in the medium, the attenuation of the laser radiation in terms of power is reduced). On the other hand, it is possible to study the distribution in mixtures that consist of media that do not react chemically with each other. For example, a mixture of gasoline. Study their distribution by fractions (various boundary effects between fractions) and determine the composition of the mixture and the concentrations of its components;
4. In mixtures formed by media dissolved in each other (for example, an aqueous solution of urine), it is possible to study the change in the refractive index gradient  $n$  along the height of the cuvette.

### Results and discussion

To verify the accuracy of determining  $n$  using the new method for goniometric measurements, hydrocarbon samples were studied. Fig. 3 shows the results of the study of changes in the refractive index  $n$  of AI-98 and AI-100 premium gasoline with changes in temperature  $T$ .

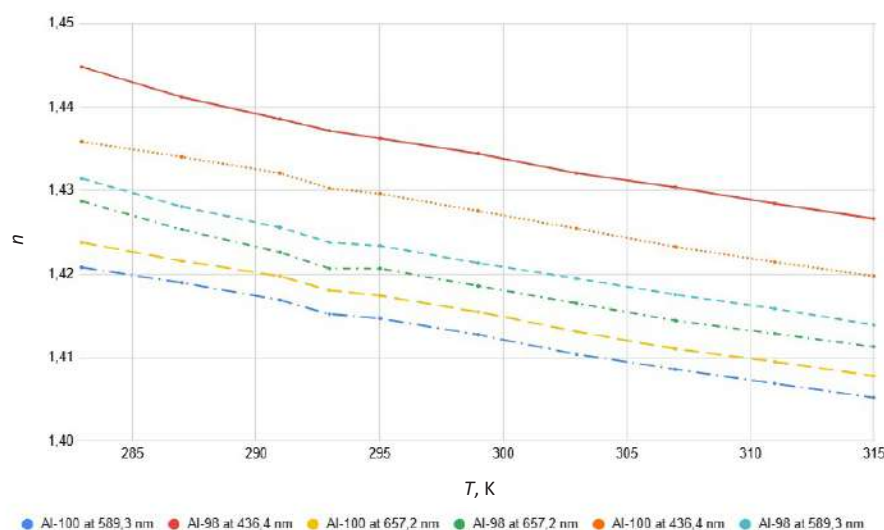


Fig. 3. Dependence of the change in refractive index  $n$  on the temperature  $T$  of AI-98 and AI-100 gasoline at three wavelengths of laser radiation

Using an Abbemat WR/MW industrial digital refractometer, the refractive indices of two gasoline samples were measured at three wavelengths at a temperature of  $T = 293$  K. The values of  $n$  obtained using the experimental setup and the industrial refractometer coincided within the measurement error limits.

Next, to verify the effectiveness of the new measurement method and the capabilities of the experimental setup, studies were conducted on Genesis Arm 5W-30 motor oil (Lukoil company) at temperature  $T$ , and the results were compared with the measurements obtained using the Abbemat WR/MW industrial refractometer (Table).

Analysis of the data obtained shows that they coincide within the measurement error. This once again confirms the possibility of using the developed experimental setup design, taking into account all the features of its operation, to measure  $n$  at different wavelengths and temperatures  $T$ .



Table

**Study of the refractive index  $n$  of Genesis arm 5W-30 motor oil  
(Lukoil company) from temperature change  $T$**

| $T, K$          | Laboratory goniometric system<br>with triangular cuvette | Abbemat WR/MW<br>Industrial Refractometer |
|-----------------|----------------------------------------------------------|-------------------------------------------|
| $283.2 \pm 0.2$ | $1.4704 \pm 0.0001$                                      | $1.47035 \pm 0.00005$                     |
| $285.0 \pm 0.2$ | $1.4701 \pm 0.0001$                                      | $1.46996 \pm 0.00005$                     |
| $287.1 \pm 0.2$ | $1.4695 \pm 0.0001$                                      | $1.46942 \pm 0.00005$                     |
| $291.1 \pm 0.2$ | $1.4680 \pm 0.0001$                                      | $1.46797 \pm 0.00005$                     |
| $295.0 \pm 0.2$ | $1.4663 \pm 0.0001$                                      | $1.46623 \pm 0.00005$                     |
| $299.1 \pm 0.2$ | $1.4648 \pm 0.0001$                                      | $1.46471 \pm 0.00005$                     |
| $303.0 \pm 0.2$ | $1.4634 \pm 0.0001$                                      | $1.46332 \pm 0.00005$                     |
| $306.1 \pm 0.2$ | $1.4619 \pm 0.0001$                                      | $1.46179 \pm 0.00005$                     |
| $310.2 \pm 0.2$ | $1.4604 \pm 0.0001$                                      | $1.46028 \pm 0.00005$                     |
| $313.0 \pm 0.2$ | $1.4589 \pm 0.0001$                                      | $1.45879 \pm 0.00005$                     |

### Conclusion

The research conducted and the results obtained showed that the use of the developed triangular cuvettes and the new method for measuring the refractive index  $n$ , taking into account all the peculiarities of their implementation, make it possible to obtain reliable results in laboratory conditions with an error of 0.0001 for almost all existing liquid media and their mixtures.

It should be noted that the developed measurement method is universal for radiation at different wavelengths, which was confirmed by the research results. With a specific set of cuvettes and lighting close to darkness using special glasses, it is possible to conduct research at IR wavelengths, which is currently implemented in industrial refractometers for researching liquid media only for wavelengths of 1550 nm (these devices are very expensive).

### REFERENCES

1. Fisher L.M., Bobyl A.V., Johansen T.H., et al., Anisotropic Origin of the Bending Instability of the Flux-Antiflux Interface in Type-II Superconductors, *Physical Review Letters*. 92 (3) (2004) 370021–370024.
2. Semenov A.A., Karmanenko S.F., Melkov A.A., et al., The propagation of magnetostatic surface waves in ferrite/superconductor structures, *Technical Physics*. 46 (10) (2001) 1218–1224.
3. Eremina R., Gippius A., Gafurov M., Trends in Magnetism, *Applied Magnetic Resonance*. 54 (4-5) (2023) 435–437.
4. Davydov V.V., Moroz A.V., Myazin N.S., et al., Peculiarities of Registration of the Nuclear Magnetic Resonance Spectrum of a Condensed Medium During Express Control of Its State, *Optics and Spectroscopy*. 128 (10) (2020) 1678–1685.
5. Manu V.S., Olivieri C., Veglia G., AI-designed NMR spectroscopy RF pulses for fast acquisition at high and ultra-high magnetic fields, *Nature Communications*. 14 (1) (2023) 4144–4156.
6. Karabegov M.A., Metrological and technical characteristics of total internal reflection refractometers, *Measurement Techniques*. 47 (11) (2004) 1106–1112.
7. Contreras-Tello H., García-Valenzuela A., Refractive index measurement of turbid media by transmission of backscattered light near the critical angle, *Applied Optics*. 53 (21) (2014) 4768–4778.
8. Chen J., Guo W., Xia M., et al., In situ measurement of seawater salinity with an optical refractometer based on total internal reflection method, *Optics Express*. 26 (20) (2018) 25510–25523.
9. Yurin A.I., Vishnyakov G.N., Minaev V.L., Krasivskaya M.I., Measurement of the refractive index using an autocollimation goniometer, *Scientific and Technical Journal of Information Technologies Mechanics and Optics*. 23 (5) (2023) 1073–1076.

10. **Davydov V.V., Smirnov K.J.**, An Optical Method of Monitoring the State of Flowing Media with Low Transparency That Contain Large Inclusions, *Measurement Techniques*. 62 (6) (2019) 519–526.

11. **Yurin A.I., Vishnyakov G.N., Minaev V.L.**, Estimate of Errors in Measurements of Refractive Index by Modified Prism Methods, *Measurement Techniques*. 66 (3) (2023) 168–172.

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## Radiation hardness of $n-p-n$ type bipolar transistor for voltage regulators

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**Abstract.** The characteristics (collector current, base current, common-emitter current gain) of  $n-p-n$  type bipolar transistor for voltage regulator depending on total ionizing dose radiation using projected X-ray research complex were established. The functional dependencies and model of common-emitter current gain depending on total ionizing dose have been obtained.

**Keywords:**  $n-p-n$  type bipolar transistor, ionizing dose effects, X-ray irradiation.

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Материалы конференции

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## Радиационная стойкость биполярного транзистора $n-p-n$ типа для стабилизаторов напряжения

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**Аннотация.** Для биполярного транзистора  $n-p-n$  типа для стабилизатора напряжения были установлены характеристики (ток коллектора, ток базы, коэффициент усиления по току) в зависимости от суммарной поглощенной дозы ионизирующего излучения с использованием спроектированного рентгеновского исследовательского комплекса. Получены функциональные зависимости и модель коэффициента усиления по току в зависимости от суммарной поглощенной дозы.

**Ключевые слова:** биполярный транзистор  $n-p-n$  типа, эффекты поглощенной дозы, рентгеновское излучение

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### Introduction

Study of the radiation hardness of voltage regulators to the total ionizing radiation dose effects is important goal for electronics [1]. It was earlier was established [2] that there is possibility to increase radiation hardness of voltage regulator IS-LS3-5V based on compensating method that using  $n-p-n$  type bipolar transistor included as additional element in its scheme. Therefore, study of  $n-p-n$  type bipolar transistor radiation-sensitive characteristics and establishment its radiation hardness to the total ionizing dose effects during ionizing radiation using X-ray research complex is important scientific task. Thus, solving this task will make it possible to increase the radiation hardness of voltage regulator integrated circuit with this transistor using above-mentioned compensating method and, as a result, the electronic devices of spacecraft equipment developed on this transistor could be stably operated under ionizing radiation conditions in space.

### Materials and methods

The  $n-p-n$  type bipolar transistor was designed by Bryansk State Technical University and then produced by JSC “GRUPPA KREMNY EL” by BiCMOS (Bipolar Complementary Metal Oxide Semiconductor) technology as element of some linear positive voltage regulator [2]. Investigation of  $n-p-n$  type bipolar transistor characteristics during ionizing radiation has been carried out using the earlier developed X-ray research complex (XRC) described in [3]. In particular, the characteristics study of  $n-p-n$  type bipolar transistor under radiation conditions was performed at following operating mode of XRC: anode voltage of 70 kV, anode current of 150  $\mu$ A, the rate of radiation dose accumulation was 150 un./s (units of the DRI-0401 comparator including in X-ray research complex), distance between the X-ray tube window and the sample of 25 mm.

### Results and discussion

The  $n-p-n$  type bipolar transistor was connected according to the typical scheme for measuring of the collector current, base current and common-emitter gain. Transistor was operated under radiation in next electrical mode: the collector-emitter voltage  $V_{CE}$  is 16 V (measured by Fluke 8845A multimeter) and two base currents  $I_B$  values of 100 nA and 1  $\mu$ A (measured by Keithley 6485 picoamperemeter).

Fig. 1 shows the collector current  $I_C$ , base current  $I_B$  and common-emitter current gain  $\beta$  depending on total ionizing dose  $D$  for investigated  $n-p-n$  type bipolar transistor. The value of collector current decrease with increasing of total ionizing dose for both base currents  $I_B$  (100 nA and 1  $\mu$ A). The current  $I_B$  (initial base current values: 100 nA and 1  $\mu$ A) lightly increases as total ionizing dose increase. The current gain  $\beta$  for transistor at  $I_B = 100$  nA (collector-emitter voltage is 16 V) at first increases from 71, then reach the maximal value of 101 at dose of  $24 \times 10^3$  un. and further decreases up to 9 at final total ionizing dose  $D = 800 \times 10^3$  un. In case when the base current is 1  $\mu$ A (common-emitter voltage is 16 V) the  $\beta$  decreases from 116 up to 14 at  $D = 800 \times 10^3$  un. It should be noted that established here current gain dependence  $\beta$  on total ionizing dose  $D$  depends on base currents  $I_B$  values for  $n-p-n$  analogous type bipolar transistor that was obtained during its irradiation by  $\gamma$ -ray radiation [4]. In addition, the same nonlinear dependence of current gain on total ionizing dose with extremum take places [4]. For engineers and developers of voltage regulators, that included same  $n-p-n$  type bipolar transistor, that operating under radiation conditions it is important to know the analytical dependence of common-emitter current gain  $\beta$  its transistor from radiation dose for calculation of addition resistance of compensation resistor in the feedback circuit for preventing of output voltage changing [2].

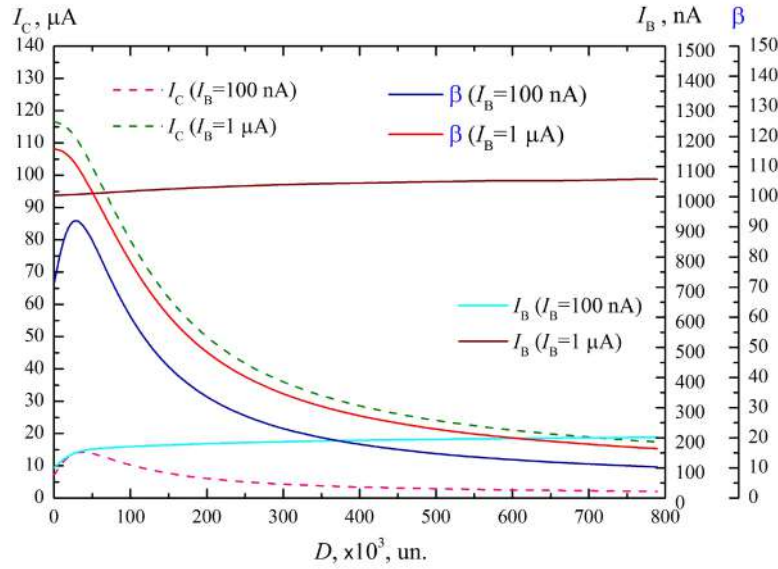


Fig. 1. Collector current  $I_C$ , base current  $I_B$  and common-emitter current gain  $\beta$  dependences on total ionizing dose  $D$  for  $n-p-n$  type bipolar transistor (collector-emitter voltage  $V_{CE}=16$  V)

Therefore, the analytical expressions have been obtained to assist design engineers based on regression analyses methods, especially, the analytical dependencies of the common-emitter gain  $\beta(D)$  on the total ionizing dose  $D$  for  $n-p-n$  bipolar transistor for two different base currents  $I_B$  ( $I_B = 100$  nA (Eq. 1) and  $I_B = 1$   $\mu$ A (Eq. 2),  $V_{CE}=16$  V) are following form:

$$\beta(D) = -1.982 \cdot 10^{-7} \cdot D^3 + 4.278 \times 10^{-4} \cdot D^2 - 30.5 \cdot 10^{-2} \cdot D + 83.463, \quad (1)$$

$$\beta(D) = -3.101 \cdot 10^{-7} \cdot D^3 + 6.427 \cdot 10^{-4} \cdot D^2 - 43.8 \cdot 10^{-2} \cdot D + 117.075, \quad (2)$$

where  $\beta$  is the common-emitter current gain,  $D$  is the total ionizing dose ( $10^3$  un.).

In modern engineering calculations of integrated circuits use special electronic circuit simulators widely known as SPICE (Simulation Program with Integrated Circuit Emphasis) programs (PSPICE, OrCAD, LTspice, Micro-Cap etc.) that are based on physico-mathematical models of electronic devices [5]. Further, for developing of a linear voltage regulator integrated circuit where included this  $n-p-n$  type bipolar transistors during ionizing radiation it is necessary have its SPICE-model [4]. As the basic for SPICE-model of  $n-p-n$  bipolar transistor was chosen the Ebers-Moll model [5]. In Fig. 2, *a* is shown the developed scheme of SPICE-model in LTspice program [5] for  $n-p-n$  type bipolar transistor operating under ionizing radiation which presented in SPICE subcircuit format text that included the following elements: base resistance (RB), collector resistance (RC), emitter resistance (RE), additional resistances (R3), arbitrary behavioral base current source (IBr), arbitrary behavioral collector current source (ICr), base node (B), collector node (C), emitter node (E). The function for base current source (IBr in Fig. 2, *a*) functionally dependent on irradiation time obtained on the basis of Ebers-Moll model is following form:

$$I = (1 - a_f) I_{es} e^{\frac{V(B,E)}{V_t} - 1} + (1 - a_r) I_{cs} e^{\frac{V(B,C)}{V_t} - 1} - 4.821 \cdot 10^{-15} t^2 + 2.661 \cdot 10^{-11} t, \quad (3)$$

where  $t$  is the irradiation time (s),  $V(B,E)$  is the voltage difference between node B and E in Fig. 2, *a* (V),  $V(B,C)$  is the voltage difference between node B and C in Fig. 2, *a* (V),  $a_f = 9.92 \cdot 10^{-1}$  is the the forward current gain of the common-base configuration,  $I_{es} = 7.26 \cdot 10^{-15}$  is base-emitter saturation current (A),  $a_r = 6.30 \cdot 10^{-1}$  is the reverse current gain of a common-base configuration,  $I_{cs} = 1.14 \cdot 10^{-15}$  is the base-collector saturation current (A),  $V_t = 25.9 \cdot 10^{-3}$  is the thermal voltage.



Similarly, the function for collector current source (ICr in Fig. 2, a) functionally dependent on irradiation time is next:

$$I = a_f I_{es} e^{\frac{V(B,E)}{V_t} - 1} - I_{cs} e^{\frac{V(B,C)}{V_t} - 1} - 1.09 \cdot 10^{-15} t^3 + 1.499 \cdot 10^{-11} t^2 - 6.744 \cdot 10^{-8} t, \quad (4)$$

where  $t$  is the irradiation time (s),  $V(B,E)$  is the voltage difference between node B and E in Fig. 2, a (V),  $V(B,C)$  is the voltage difference between node B and C in Fig. 2, a (V),  $a_f = 9.92 \cdot 10^{-1}$  is the forward current gain of the common-base configuration,  $I_{es} = 7.26 \cdot 10^{-15}$  is base-emitter saturation current (A),  $I_{cs} = 1.14 \cdot 10^{-14}$  is the base-collector saturation current (A),  $V_t = 25.9 \cdot 10^{-3}$  is the thermal voltage. Then the equations (3) and (4) described above were implemented in LTspice as SPICE subcircuit text (see Fig. 2, a) in accordance with LTspice command syntax using SPICE directive ".SUBCKT" [7]. In addition, the component's nominals, parameters and functions for functionally dependent base (IBr) and collector (ICr) current sources are indicated in the circuit text in Fig. 2, a (in particular, all parameters were included into subcircuit using the special [7] SPICE directive ".param" (see Fig. 2, a) for correct calculation in LTspice program using SPICE command syntax in the following form: forward current gain is 9.92e-1, base-emitter saturation current is 7.26e-15, reverse current gain is 6.30e-1, base-collector saturation current is 1.14e-14, thermal voltage is 25.9e-3). Then for developed SPICE-model in LTspice was create new symbol that define in Fig. 2, b as BJT. The developed SPICE-model for  $n-p-n$  type bipolar transistor then was connected as subcircuit in LTspice program (see Fig. 2, b) in accordance with common-emitter configuration (base current  $I_b = 1 \mu A$  and collector-emitter voltage  $V_{CE} = 16 V$ ) for its verification under ionizing radiation operating.

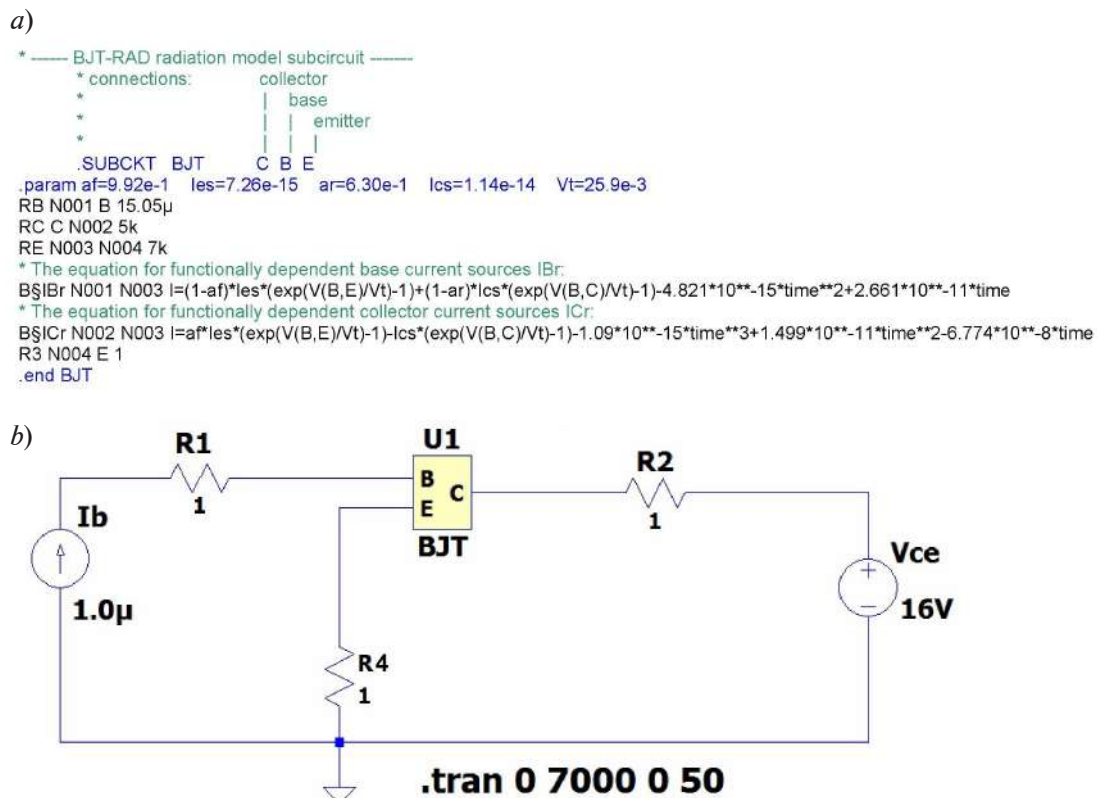


Fig. 2. Developed SPICE-model for  $n-p-n$  type bipolar transistor presented as SPICE subcircuit text (a); scheme in LTspice program for calculation of transistor's current gain dependence on ionizing radiation time for developed SPICE-model (BJT component, where B is base node, C is collector node, E is emitter node) at base current  $I_b = 1 \mu A$  and collector-emitter voltage  $V_{CE} = 16 V$

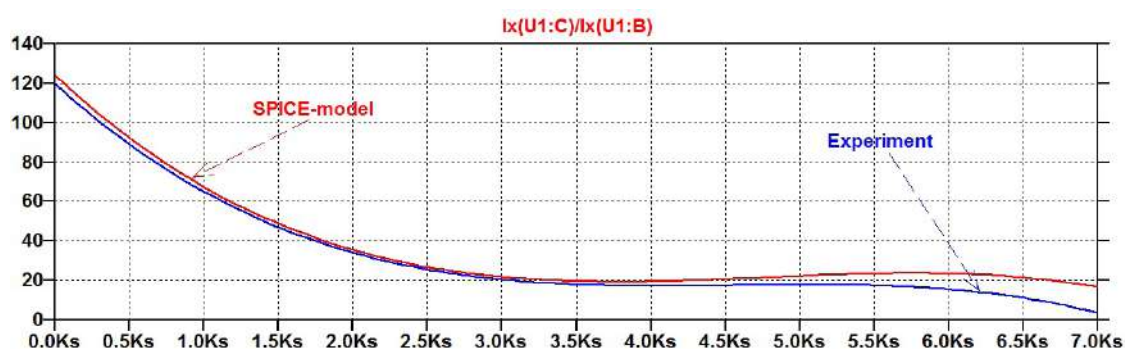


Fig. 3. Common-emitter current gain dependence on irradiation time (s) for  $n-p-n$  type bipolar transistor (base current is  $1\ \mu\text{A}$ , collector-emitter voltage is  $16\ \text{V}$ ) calculated by model in LTspice

Fig. 3 shows calculation in LTspice program [6] by above SPICE-model in transient analysis mode for common-emitter gain ( $I_x(U1:C)/I_x(U1:B) = \beta$ ) dependence on irradiation time ( $I_B = 1\ \mu\text{A}$ ,  $V_{CE} = 16\ \text{V}$ ) for  $n-p-n$  transistor. It can be seen that the calculated by SPICE-model and experimental dependencies are quite well comparable.

Thus, the proposed radiation dependent SPICE-model for the  $n-p-n$  bipolar transistor on the basis of the Ebers–Moll model give us possibility to perform in SPICE programs calculations of voltage regulator with this transistor included as additional element in its scheme for increasing its radiation hardness using compensating method described in [2].

### Conclusion

The radiation hardness for  $n-p-n$  type bipolar transistor was studied using X-ray research complex. The dependencies of collector current, base current and common-emitter current gain from total ionizing dose radiation have been obtained. Because of this, for common-emitter current gain transistor's were established analytical dependencies on total ionizing dose and proposed SPICE-model necessary for improvement voltage regulator's scheme functioning under radiation conditions.

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### REFERENCES

1. Gaul S.J., Vonno N., Voldman S.H., Morris W.H., Integrated Circuit Design for Radiation Environments, Wiley & Sons, Chichester. (2020).
2. Pilipenko K.S., Kulchenkov E.A., Rybalka S.B., Demidov A.A., Method for increasing of the voltage regulator radiation hardness, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 3.1 (17) (2024) 191–194.
3. Rybalka S.B., Demidov A.A., Kulchenkov E.A., Pilipenko K.S., Radiation behaviour study of linear voltage regulator, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 3.1 (17) (2024) 195–198.
4. Belous A.I., Solodukha V.A., Shvedov S.V., Space Electronics, Tekhnosfera, Moscow. (2015).
5. Sedra A.S., Smith K.C., Carusone T.C., Gaudet V., Microelectronic Circuits, Oxford University Press, Oxford/New York. (2020).
6. LTspice Simulator | Analog Devices. URL: <https://www.analog.com/en/design-center/design-tools-and-calculators/ltspice-simulator.html>. Accessed August. 30, 2025.
7. Farzin Asadi, Essential Circuit Analysis Using LTspice®, Springer International Publishing AG, Cham. (2023).

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## Long-term temperature resistance stability of gold-based multilayer electrodes for gas sensors

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**Abstract.** The long-term stability of resistive gas sensor microheaters was investigated. The microheaters were created as multilayered metallizations on a silicon oxide membrane. The behavior of Cr/Au/Cr and Cr/Ni/Au stacks was studied. The resistance of the Cr/Ni/Au stack stabilized after 15 hours of exposure due to gold burning into the chromium-nickel sublayer. Resistance drift is less than 7% after 48 hours of continuous operation at 350°C and 12% at 500°C. However, Cr/Au/Cr metallization cannot be used in high-temperature sensors because it degrades significantly at temperatures as low as 300°C. Stack capping with SiO<sub>2</sub> layer has low influence on initial forming stage and improves long-term stability.

**Keywords:** multilayer electrode, MEMS gas sensor, annealing, solid-state dewetting

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Материалы конференции

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## Долговременная температурная стабильность многослойных электродов на основе золота для работы в газовых датчиках

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**Аннотация.** Исследована долговременная стабильность микронагревателей резистивных газовых сенсоров. Микронагреватели создавались в виде многослойной металлизации на мембране оксида кремния. Изучено поведение стеков Cr/Au/Cr и Cr/Ni/Au как открытых, так и закрытых сверху слоем SiO<sub>2</sub>. Сопротивление стека Cr/Ni/Au стабилизируется через 15 часов выдержки вследствие вжигания золота в хромоникелевый подслой. Дальнейший дрейф сопротивления при длительной эксплуатации при 350°C

составляет менее 7%, при 500°C – 12% за 48 часов непрерывной работы. Металлизация Cr/Au/Cr не может быть использована в высокотемпературных сенсорах, поскольку существенно деградирует уже при 300°C. Покрытие нагревателя оксидом кремния не сказывается на его поведении на начальной стадии формирования и улучшает долговременную стабильность.

**Ключевые слова:** многослойный электрод, газовый датчик, разрушение контактов

**Финансирование:** Работа выполнена в рамках Государственного задания «Активные композитные материалы и методики анализа для (био)сенсорики» (код темы FSRM-2023 0009).

**Ссылка при цитировании:** Лаздин И.А., Кондратьева А.С., Комаревцев И.М., Эннс Я.Б., Казакин А.Н., Карасев П.А. Долговременная температурная стабильность многослойных электродов на основе золота для работы в газовых датчиках // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2025. Т. 18. № 3.2. С. 155–158. DOI: <https://doi.org/10.18721/JPM.183.230>

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## Introduction

Change of a semiconducting film resistivity after adsorption of molecules of an analyte is widely used to produce resistive gas sensors. Operating temperature of such semiconducting active layer varies in the range 40 to 900 °C [1–4]. Therefore, high requirements are imposed on long term stability of heating elements. In order to minimize power consumption, thin membranes are used as a substrate of the sensing layer, which in turn is heated by micro-electrodes deposited directly on membrane [5]. At present, Pt is typically utilized as the heating layer material for high temperature applications. In order to minimize cost of a microheating element production, nickel, nichrome, gold and other materials are considered to substitute platinum. Noble metals are preferable, since they do not oxidize in air during operation. The main problem with thin coated electrodes is change in their parameters during high temperature exposure. Long-term instability of heating elements is caused mainly by partial or complete destruction of metal layer caused by solid state dewetting and diffusion. In this contribution, the influence of long-term annealing of gold-based microheaters on the resistance of these electrodes is investigated.

## Materials and Methods

Microelectrodes were deposited onto the planar SiO<sub>2</sub>/SiN membrane of a gas sensing chip by e-beam evaporation and photolithography. Two material stacks, namely, Cr-Au-Cr and Cr-Ni-Au, schematically drawn in the Fig. 1, *a* were formed. 5 nm thick chromium layer was deposited first in all cases. Gold layer in both cases was 100 nm thick, the nickel layer between gold and chromium was 20 nm thick, and the capping chromium layer was 5 nm thick. Fig. 1, *b* presents topology of electrodes. Some of heating tracks were subsequently covered by SiO<sub>2</sub> layer deposited by DC magnetron sputtering. Electric resistance of the as-grown electrodes varied from 300 to 500 Ohm.

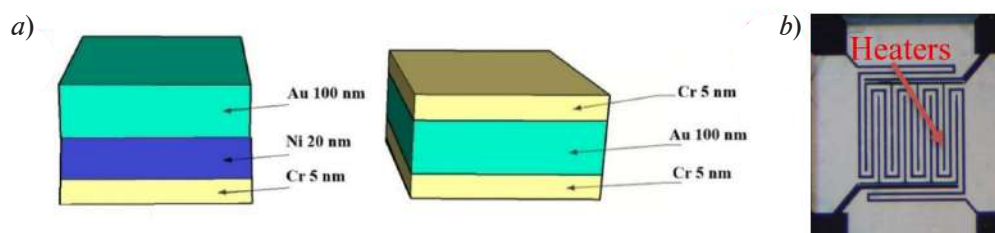


Fig 1. Stacks (*a*) and topology (*b*) of microheating electrodes





In order to investigate long term stability, artificial aging of the electrodes were used. Obtained structures were subjected to furnace thermal annealing in air ambient to assess the change in the heater resistance. The samples were loaded into furnaces preheated to required temperature and then abruptly removed from the hot furnace. Annealing temperatures were in the range from 300 to 500 °C. This is working temperature range of sensors detecting the most flammable and toxic compounds, so it is of interest to study the heater parameters at these temperatures.

### Results and Discussion

Fig. 2 presents change in micro-heater resistances after annealing. It is seen from Fig. 2 that resistance of the heating elements start to grow up. Even at low annealing temperature, resistance of stack made of Cr/Au/Cr increases by an order of magnitude, which is more than others demonstrate (see Fig. 2). An increase in resistance is initially observed in the case of Cr/Ni/Au stack annealed at 350 °C (see Fig. 2, *b*). This process stops after 15 hours and only slight decrease in resistance is observed during further investigation. Increase of a heater resistance goes faster at 500 °C. Contrary to previous case, at this high temperature initial forming is followed by significant decrease in resistance (see Fig. 2, *c*), this process can be used to adjust the heating electrode parameters before use at lower temperatures.

Coating with 150 nm silicon oxide capping has no effect on initial resistance increase and improves heater stability during further annealing (compare Fig. 2, *b*, *d*). This capping prevents accessing the microheater by gases from atmosphere preventing possible oxidation of thin layers of Cr or Ni in the stack.

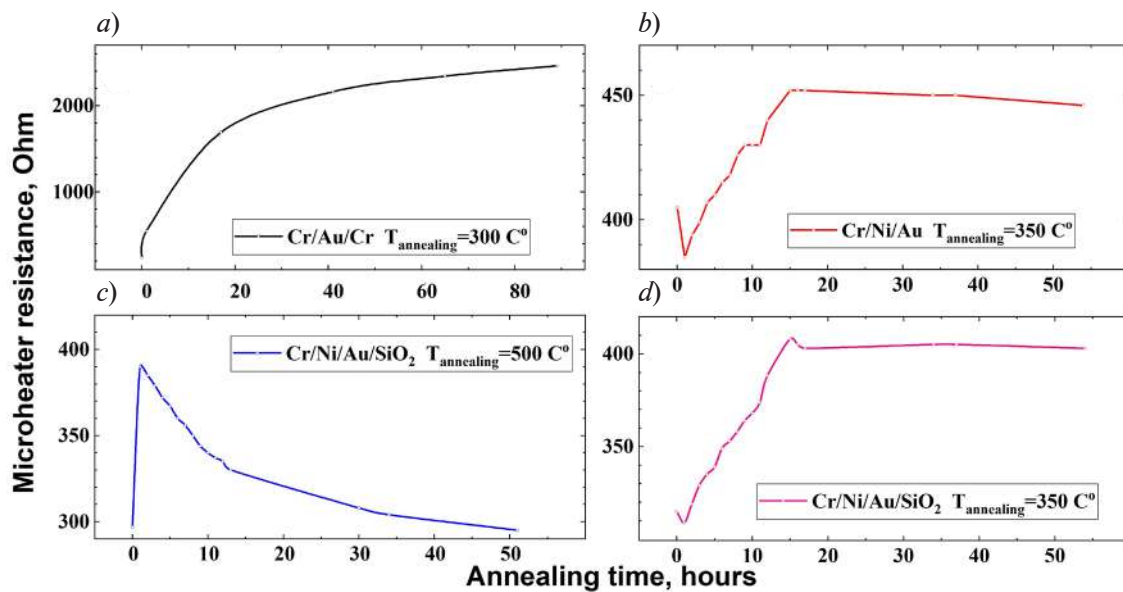


Fig. 2. Resistivity of electrodes annealed at different temperatures, as indicated

The experimental results demonstrate a significant effect of long-term annealing on the resistance of contact elements. According to previously published data, the main mechanism responsible for the change in resistance is dewetting – compression and partial destruction of a thin layer. It is widely observed for thin layers of materials with low adhesion to the surface at temperatures well below the melting point of the metal. Dewetting mechanisms for single-layer contacts made of various materials with high chemical stability (Au, Pt, Ag) are presented in detail in [6]. In our case of Cr/Au/Cr and Cr/Ni/Au stacks, same effect could appear leading to a decrease in the cross-section of the conductive layer and as a consequence to an increase in resistance. It is demonstrated that identical results of changing contact parameters.

When the annealing temperature of Cr/Ni/Au/SiO<sub>2</sub> stack is increased to 500 °C (see Fig. 2, *c*) an initial sharp increase in resistance is observed due to dewetting, and a subsequent long-term decrease due to the slow process of interdiffusion of the Ni sublayer into Au. For a stack without an insulating layer of silicon dioxide, the trend of resistance change over time at a

temperature of 500 °C is similar to the graph in Fig. 2, *c*. Conductive layer resistivity returns to its original value as a result of overgrowing along the interface of the two metals, with the formation of a Ni-Au solid solution similar to reported in [7].

Thus, the data obtained above show the need for a long-term temperature procedure for micro-heating elements based on the presented stacks for their stable operation at elevated temperatures.

### Conclusion

Performance of Cr/Au/Cr and Cr/Ni/Au structures used as heating microelectrodes for gas sensor and other microelectronic devices operating at temperatures ranging from 40 to 500 °C was evaluated. The least suitable stack option for micro-heating elements is configuration Cr/Au/Cr. Thin (~5 nm) chromium layer does not prevent the diffusion of gold into the substrate and the disintegration of gold conductive layer during prolonged heating above 300 °C. The Cr/Ni/Au layer is a good choice for applications operating at temperatures up to 350 °C. Aging at 500 °C could be used for the resistance tuning. The obtained time characteristics can also be used to recalculate the aging time of the sample at lower operating temperatures.

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### REFERENCES

1. Liu W., Gu D., Zhang J., Li X., et al., ZnSe/NiO heterostructure-based chemiresistive-type sensors for low-concentration NO<sub>2</sub> detection, *Rare Metals*. 40 (2021) 1632–1641.
2. Srivastava S., Gangwar A.K., Kumar A., et al., Room temperature RF magnetron sputtered nanocrystalline NiO thin films for highly responsive and selective H<sub>2</sub>S gas sensing at low ppm concentrations, *Materials Research Bulletin*. 165 (2023) 112330.
3. Vorobyeva N., Rumyantseva M., Platonov V., et al., Ga<sub>2</sub>O<sub>3</sub> (Sn) oxides for high-temperature gas sensors, *Nanomaterials*. 11 (11) (2021) 2938.
4. Leech P.W., Kibel M.H., Barlow A.J., et al., Ohmic contacts to *n*-type 3C-SiC using Cr/Ni/Au and Ni/Cr/Au metallizations, *Microelectronic Engineering*. 215 (2019) 111016.
5. Komarevtsev I., Kondrateva A., Lazdin I.A., et al., Microelectromechanical gas sensor of resistive type for detection of hydrogen sulfide down to low concentrations, *Materials Physics and Mechanics*. 52 (4) (2024) 9–22.
6. Greenbank W., Hirsch L., Chambon S., Electrode de-wetting as a failure mechanism in thermally-aged OPV devices, *Solar Energy Materials and Solar Cells*. 178 (2018) 8–14.
7. Bogatyrenko S., Formation of the solid solutions in the Au-Ni film system: In situ TEM study, *Technical Physics*. 59 (9) (2014) 1374–1377.

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## **Study of increasing the energy efficiency of monolithic integrated circuits of the radiometer receiving path using computer modeling methods**

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**Abstract.** The high current consumption of the amplifying cascades in the miniature case of the radiometric receiver with these microcircuits existing today leads to a significant increase in temperature inside the case and subsequent heating with distortion of the picture of the real field of internal temperatures and soil humidity. The existing problem can be solved by creating new active elements from specialized monolithic microwave chips - low-noise transistors, for which the requirements of high energy efficiency will be taken into account when designing heterostructures. The article presents the results of numerical simulation of a low-noise transistor with low power consumption for use in monolithic integrated circuits of an energy-efficient low-noise amplifier of a miniature radiometer.

**Keywords:** radiometric receiver, MMIC, HEMT, heterostructure, energy efficiency

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Материалы конференции

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## **Исследование повышения энергоэффективности монолитных интегральных схем приемного тракта радиометра методами компьютерного моделирования**

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**Аннотация.** Высокое потребление тока усилительными каскадами в миниатюрном корпусе радиометрического приемника с существующими на сегодняшний день этими микросхемами приводит к значительному повышению температуры внутри

корпуса и последующему нагреву с искажением картины реального поля внутренних температур и влажности почвы. Существующая проблема может быть решена путем создания новых активных элементов из специализированных монокристаллических СВЧ-чипов - маломощных транзисторов, для которых при проектировании гетероструктур будут учтены требования высокой энергоэффективности. В статье представлены результаты численного моделирования маломощного транзистора с низким энергопотреблением для использования в составе монокристаллических интегральных схем энергоэффективного маломощного усилителя миниатюрного радиометра.

**Ключевые слова:** радиометрический приемник, МИС СВЧ, энергопотребление, энергоэффективность

**Финансирование:** Работа выполнена при финансовой поддержке Российского научного фонда в рамках выполнения соглашения № 22-19-00063-П.

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## Introduction

The amplification path of the radiometric receiver must meet extremely high requirements for miniature size, accuracy in determining soil temperature and moisture, record low levels of intrinsic noise in the microwave range, etc.

The low level of received signals leads to the need to ensure the gain of the receiving path of the order of 80 dB with minimal levels of intrinsic noise. The construction of such a path requires several microcircuits with a total current consumption in the operating mode of the order of hundreds of milliamperes. Such current consumption of the amplifying stages in a miniature radiometer case, when using even the most modern microcircuits, leads to a significant increase in the temperature inside the case and subsequent heating of the radiometer with a distortion of the picture of the real field of temperatures and soil moisture. The existing problem can be solved by creating new active elements - specialized monolithic microwave microcircuits of low-noise transistors, for which the requirements of high energy efficiency will be taken into account already during the design of heterostructures, primarily low heat emission into the surrounding space, low noise level and sufficient gain [1].

## Materials and methods

For solving the above-mentioned problem, heterostructures of semiconductors of the A3-B5 group are promising. The experience accumulated by the authors of successful mathematical modeling and practical implementation of heterostructure microwave transistors with high electron mobility [2–5] allows us to speak about the reasonable probability of a successful solution to the above-mentioned problem of creating a special low-noise microwave transistor with reduced heat generation.

One of the most effective ways to significantly improve the energy efficiency of a heterostructured transistor is to perform numerical simulations using calibrated TCAD models. Provided that the behavior of the transistor is adequately displayed in numerical models, it is possible to estimate the degree of influence of changes in the design of a heterostructured transistor on its output parameters without significant financial, time, and other resources. At the first stage of the work, the degree of influence of several parameters on the output characteristics of the device was evaluated. Among these characteristics, the steepness of the transmission characteristic of the device occupies a special place as an indicator of its amplifying properties. At the same time,

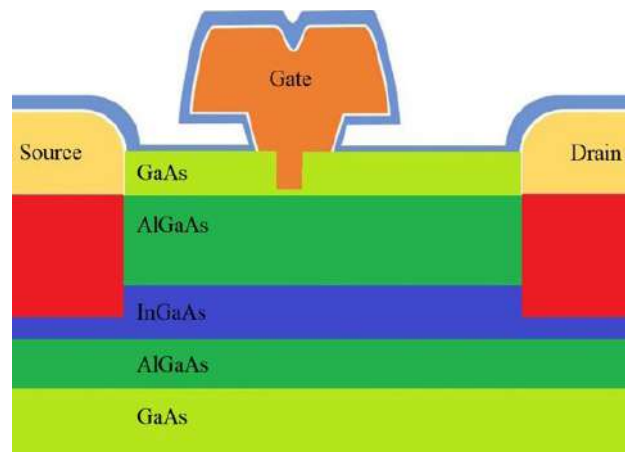


Fig. 1. Schematic view of the heterostructural transistor design

among the parameters of the transistor design, the most obvious for analysis are the depth of the gate in the gate groove, the length of the gate, and the distance between the transistor electrodes and the walls of the gate groove (Fig. 1).

The basic design of the transistor provides a high transconductance only when a sufficiently high drain current is reached. Thus, if it is possible to ensure a high transconductance with a low drain current, then we can expect a significant increase in the energy efficiency of a low-noise amplifier, given the small amplitude of the input signal and the absence of requirements for the output signal power level.

### Results and discussion

Thus, to solve this problem, the possibility of increasing the transconductance in the low current region by changing the topology of the transistor was evaluated. An analysis of the results of calculating the transfer characteristic and transconductance for various variants of the transistor topology showed that we can expect a decrease in the quiescent current of the transistor cascades by 20–25%, which is significant, but in some cases insufficient reason to change the design of monolithic integrated circuits in the amplification path of the radiometer.

As a result, minimal changes in the design of the heterostructure can be proposed, which can lead to a significant increase of transconductance in the low current range. Indeed, as can be seen in Fig. 2, the distribution of electrons in the channel of the basic version of the transistor near the locking point is highly heterogeneous in channel thickness.

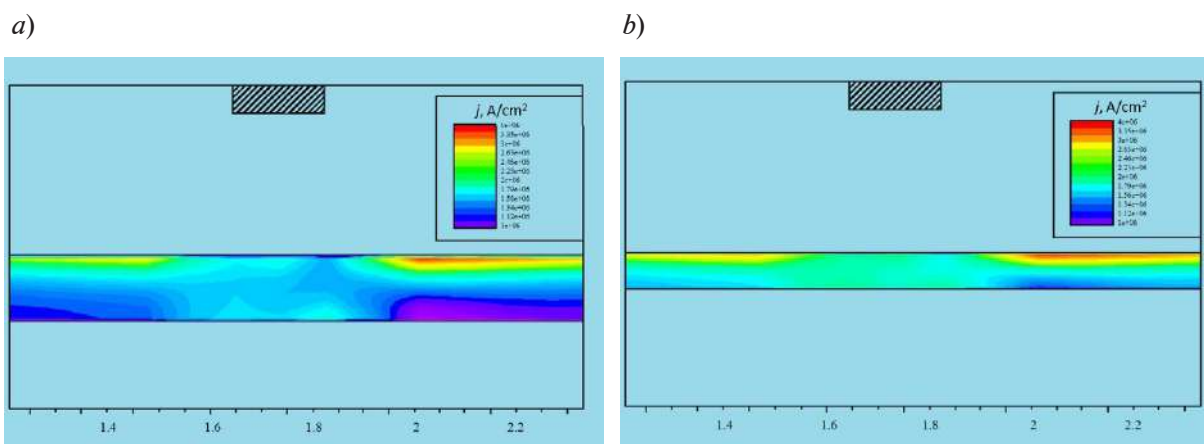


Fig. 2. Distribution of electrons in the gate region and channel of a low-noise transistor: the basic design of the heterostructure (a); a new design of the heterostructure with an optimized channel for operation in an energy-efficient mode (b)



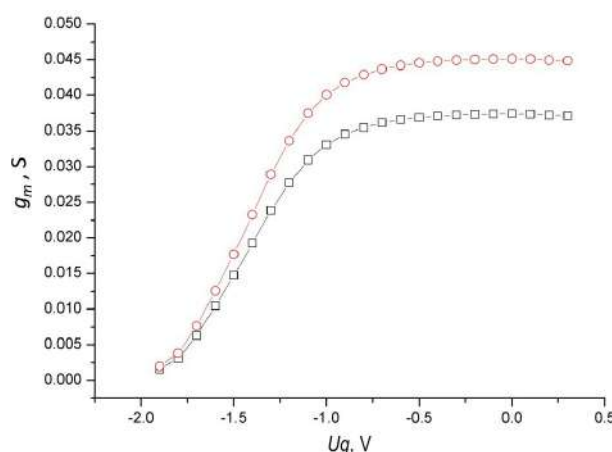


Fig. 3. Calculated transconductance characteristics of a transistor of conventional and new design. Circles (red lines) correspond to the new design thin channel, black lines to the conventional design

This may indicate a decrease in the efficiency of gate field control for current flow in the channel, which leads to a decrease of transconductance in this area of the characteristic. The fact is that for the selected indium content in the InGaAs solid solution, there is the maximum possible channel thickness that can be grown in a pseudomorphic mode. The misalignment of the lattice can be elastically accommodated, usually to a channel thickness of the order of 15–20 nm. It should be noted that the maximum channel thickness is needed to achieve high power of a transistor based on such a heterostructure. In our case, having found a strong heterogeneity in the distribution of charge carriers over the depth of the channel, we can suggest slightly reducing the thickness of the channel, which will increase the uniformity of current flow near the cutoff and, consequently, the controllability of the gate field while maintaining the overall localization of charge carriers in the quantum well. The results of calculations of the transistor heterostructure design are shown in Fig. 2.

As a result, the uniformity of the charge carrier distribution in the channel has significantly improved, which has led to an increase in the efficiency of gate field control and an increase in the transconductance, which is reflected in the calculation results shown in Fig. 3.

### Conclusion

The features of the proposed design of the heterostructured field effect transistor directly lead to a significant reduction in the current consumption of the entire microcircuit and to a simplification of its basic circuit. As a result, we were able to achieve a 30% reduction in quiescent current while maintaining a transconductance of more than 350 mS per mm. The practical significance of this work lies in the fact that the developed technique makes it possible to create more energy-efficient amplification stages for radiometric systems. This is especially important for miniature autonomous devices, where low power consumption is a fundamental requirement.



## REFERENCES

1. **Gawande R., Bradley R.**, Low-Noise Amplifier at 2.45 GHz, IEEE Microwave Magazine. 11 (1) (2010) 122–126.
2. **Kumar A.S., Dalcanele S., Uren M.J., et al.**, Gallium nitride multichannel devices with latch-induced sub-60-mV-per-decade subthreshold slopes for radiofrequency applications, Nat Electron. (2025).
3. **Tikhomirov V.G., Gudkov A.G., Agasieva S.V., et al.**, Increasing efficiency of GaN HEMT transistors in equipment for radiometry using numerical simulation, Journal of Physics Conference Series. 1410 (2019) 012191.
4. **Tikhomirov V.G., Chizhikov S.V., Gudkov A.G., et al.**, Numerical simulation of the parameters of an energy-efficient low-noise transistor for use in the amplification path of a miniature radiothermograph, St. Petersburg Polytechnic University Journal. Physics and Mathematics. 16 (3.1) (2023) 463–467.
5. **Tikhomirov V., Zemlyakov V., Volkov V., et al.**, Optimization of the parameters of HEMT GaN/AlN/AlGaIn heterostructures for microwave transistors using numerical simulation, Semiconductors. 50 (2) (2016) 244–248.

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### **Research and development of a deposition synthesis technology for piezoelectric BaTiO<sub>3</sub> thin films for use in sensors for dynamic and static pressures**

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**Abstract.** The prospects for creating heterostructures based on ferroelectric materials have been studied. The most suitable technological parameters for forming these structures have been identified. A detailed analysis of the crystalline structure of the obtained ferroelectric films has been carried out. It has been established that at the moment of deposition, when creating thin-film multilayer systems with a temperature of the sensitive element (SE) above 700 °C, the perovskite layer loses its ferroelectric characteristics.

**Keywords:** sensing element, piezoelectric thin films, magnetron sputtering, stoichiometric composition, pressure sensor

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Материалы конференции

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### **Исследование и разработка технологии синтеза напыления пьезоэлектрических тонких пленок BaTiO<sub>3</sub> для датчика быстропеременных и статических давлений**

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**Аннотация.** Изучены перспективы создания гетероструктур, на основе сегнетоэлектрических материалов. Выявлены наиболее подходящие технологические параметры для формирования данных структур. Проведен детальный анализ кристаллического строения полученных сегнетоэлектрических пленок. Установлено, что в момент напыления, при создании тонкопленочных многослойных систем с температурой чувствительного элемента (ЧЭ) выше 700 °C, перовскитный слой теряет свои сегнетоэлектрические характеристики.



**Ключевые слова:** чувствительный элемент, пьезоэлектрические тонкие пленки, магнетронное напыление, стехиометрический состав, датчик давления

**Ссылка при цитировании:** Агафонов Д.В., Гурин С.А., Новичков М.Д., Рыжов А.А., Волков В.С., Шепелева А.Э. Исследование и разработка технологии синтеза напыления пьезоэлектрических тонких пленок  $\text{BaTiO}_3$  для датчика быстропеременных и статических давлений // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2025. Т. 18. № 3.2. С. 164–167. DOI: <https://doi.org/10.18721/JPM.183.232>

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## Introduction

Currently, the application of methods for registering rapidly varying pressures is very broad, covering a wide range of tasks from fundamental research to practical engineering developments. In this regard, an active search for new functional materials and the development of synthesis technology for existing compounds are underway. Ferroelectrics in thin-film form are of particular interest, as piezoelectric pressure sensors are produced on their basis. The properties of piezoelectric films are determined by the technological deposition regimes, therefore it is important to determine the optimal conditions for forming layered heterogeneous structures for reliable and accurate operation of the pressure sensor.

## Materials and Methods

Perovskite ferroelectric films were fabricated using radio frequency (RF) reactive sputtering of a perovskite target with a composition of  $\text{Ba}_{0.8}\text{Sr}_{0.2}\text{TiO}_3$  (BST) in an oxygen atmosphere. A key advantage of this method is the ability to deposit structurally perfect metal oxide films while maintaining oxygen stoichiometry. The method offers a wide range of possibilities for varying growth parameters, including temperature, oxygen pressure, growth rate, and the substrate geometry relative to the RF electrode.

A schematic diagram of the sputtering system is shown in Fig. 1. The vacuum chamber for sputtering 1 is a stainless steel cylinder, on the base of which the external RF electrode is mounted. The vacuum system is connected to a pumping system 8. The working gas, argon ( $\text{Ar}$ ) or oxygen ( $\text{O}_2$ ), is fed from a gas cylinder through inlet 2 into the chamber 1. The ceramic target 3 is glued to the dielectric window 7 using K 400 adhesive. The K 400 adhesive contains boron nitride filler, which

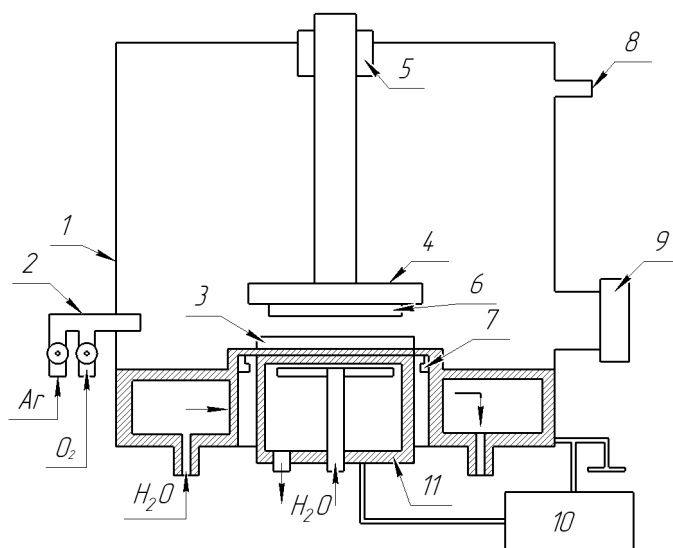


Fig. 1. Schematic of the experimental setup for ferroelectric thin film deposition

provides high thermal conductivity between the cathode and the target 3. This protects the target from overheating and cracking. The ceramic target 3 with a composition of BST has a diameter of 47 mm and a thickness of 3.5 mm. The dielectric window 7 consists of beryllium oxide and has a diameter of 60 mm. A quartz window 9 is used for optical monitoring of the RF discharge plasma in the reactive gas atmosphere inside the working chamber 1 and for visualizing the sputtering process.

The substrate 6 in the chamber 1 (Fig. 1) is mounted on a resistive heater 4 with a platinum coil. The heater with the substrate can be moved coaxially relative to the target by means of a manipulator equipped with a vacuum seal 5. A UV-1 high-frequency generator 10 is used as the RF discharge source. An alternating voltage with a frequency of 13.56 MHz is applied to the coaxial RF electrode 11. The master crystal oscillator with the first amplification stage is housed in a separate enclosure. The buffer amplifier is assembled with four GU-50 tubes and the output stage with two GU-80 tubes. A “Pi” matching network with adjustable inductance and capacitances was used as the matching unit. Control of the output power supplied to the RF electrode is achieved by changing the signal at the master crystal oscillator.

Initially, the deposition chamber is hermetically sealed and evacuated to a base pressure of approximately  $1 \cdot 10^{-3}$  Pa. Subsequently, high-purity oxygen is introduced into the chamber at a controlled flow rate of  $0.4 \pm 0.01$  L/min to achieve a residual oxygen partial pressure of approximately  $1.5 \cdot 10^{-2}$  Pa. Upon reaching the target pressure, the substrate is temperature-controlled and stabilized within the temperature range of 400–450 °C for approximately 5 minutes. Subsequently, an RF generator is activated, forming a high-frequency plasma discharge between the sputtering target and the heated substrate, with a target-to-substrate distance of approximately 60 mm, in the oxygen atmosphere. Throughout the perovskite film deposition process, the substrate thermocouple maintains the substrate temperature in the vicinity of approximately 600 °C. As a variation of this technology, a similar deposition process was also performed with a substrate temperature of approximately 700 °C.

### Results and Discussion

The study of the crystalline structure, phase composition, and structural quality of the obtained ferroelectric films was carried out using X-ray diffraction analysis. This allowed for the identification of structural components in the stoichiometric composition of the obtained perovskite films based on the set of interplanar spacings in their structure, according to the relative intensities of the corresponding lines on the X-ray diffractogram.

X-ray diffractograms obtained for films synthesized by magnetron sputtering are presented in Fig. 2. Analysis of the diffractogram of the ferroelectric film with stoichiometric composition (Fig. 2, *a*) confirms its crystalline structure. However, the diffractogram of the film deposited at a higher temperature (700 °C) (Fig. 2, *b*) indicates a disruption of the crystallographic orientation of the resulting structure, which negatively affects the stability of the ferroelectric properties of the material.

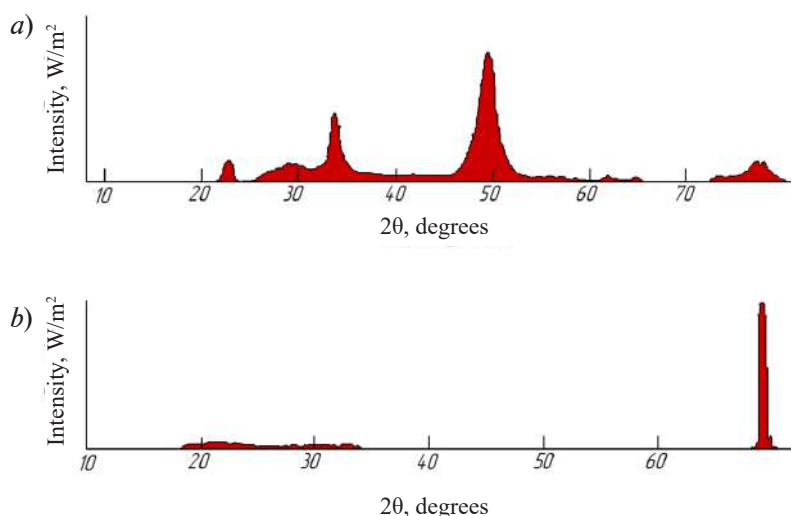


Fig. 2. X-ray diffractogram of a ferroelectric  $\text{BaTiO}_3$  film deposited at a temperature of 600 °C (*a*) and 700 °C (*b*)





Research aimed at creating BaTiO<sub>3</sub> films with a perovskite structure exhibiting ferroelectric properties using radio frequency (RF) plasma sputtering has revealed optimal deposition process parameters. It was established that to achieve the best characteristics, it is necessary to maintain a residual oxygen pressure in the reaction chamber at a level of  $\sim 1.5 \cdot 10^{-2}$  Pa, heat the substrate to a temperature of  $\sim 600$  °C, and set the cathode-anode voltage to 245 V. Ferroelectric films obtained in this manner are characterized by a dielectric constant of  $\sim 700$  and provide a capacitance tuning coefficient of  $\sim 1.5$ .

### Conclusion

A magnetron sputtering process has been developed, based on a comprehensive research program, to enable the deposition of barium titanate (BaTiO<sub>3</sub>) thin films exhibiting enhanced structural and functional stability. The optimized process parameters, derived from rigorous experimental investigation and theoretical modeling, facilitate the formation of crystalline BaTiO<sub>3</sub> films with reduced defect density and improved compositional homogeneity. These modifications contribute to a significant enhancement in the long-term operational stability of the resulting films, particularly under elevated temperatures and electrical field stresses. The specific parameters of the developed technological regime, including the target power, substrate temperature, working pressure, and gas composition, are crucial for achieving the desired film properties.

### REFERENCES

1. Mukhortov V.M., Golovko Y.I., Tolmachev G.N., Klevtsov A.N. The synthesis mechanism of complex oxide films formed in dense rf-plasma by reactive sputtering of stoichiometric targets, *Ferroelectrics*. 247 (1-3) (2000) 75–83.
2. Mukhortov V.M., Yuzyuk Yu.I., Heterostructures based on nanoscale ferroelectric films: preparation, properties and application. Rostov-on-Don: YUNTS RAS. (2008) 224.
3. Kochervinsky V.V., Structural aspects of piezoelectricity in crystallizing ferroelectric polymers using the example of homopolymer and copolymers of vinylidene fluoride. Series B. (11) (2003).
4. Afanasyev M.S., Mityagin A.Yu., Chucheva G.V., Tunable delay line of the signal MICROWAVE-band based on ferroelectric and diamond films, *Technology and construction in electronic equipment*. 3 (87) (2010) 3–6.

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## **A compact MEMS switch based on a cantilever with three elastic elements**

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**Abstract.** MEMS switches are of significant interest for advanced radioelectronic systems. High RF performance combined with small size and low power consumption make them promising for use in phased array antennas, wireless communication devices and navigation systems. This paper presents a resistive switch based on a cantilever with three elastic elements. The pull-in voltage and contact resistance are measured, and the results are compared with the calculated values. The switch provides lower resistance than previous devices.

**Keywords:** MEMS switch, cantilever, pull-in voltage, contact resistance, contact force

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Материалы конференции

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## **Компактный МЭМС-переключатель на основе кантилевера с тремя упругими элементами**

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**Аннотация.** МЭМС-переключатели представляют значительный интерес для перспективных радиоэлектронных систем. Высокие СВЧ характеристики в сочетании с малым размером и низким энергопотреблением делают их перспективными для использования в фазированных антенных решетках, устройствах беспроводной связи и навигационных системах. В работе представлен резистивный переключатель на основе кантилевера с тремя упругими элементами. Измерено его напряжение срабатывания и контактное сопротивление, результаты сопоставлены с расчетными значениями. Продemonстрировано снижение контактного сопротивления по сравнению с ранее созданными переключателями.

**Ключевые слова:** МЭМС-переключатель, кантилевер, напряжение срабатывания, контактное сопротивление, контактное усилие

**Финансирование:** Работа выполнена при финансовой поддержке РНФ, проект № 25-19-20107.

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## Introduction

Switches fabricated using microelectromechanical systems (MEMS) technology are actively considered as a new element base for microwave devices [1]. Small size, high isolation, low insertion loss and power consumption make them attractive for wireless communication and radar systems. MEMS switches use various operating principles, among which electrostatic one is the most common [2]. A conventional MEMS switch contains a cantilever suspended above driving and signal electrodes. Applying voltage to the driving electrode creates an electrostatic force that bends the cantilever and brings it in contact with the signal electrode. When the voltage is turned off, the cantilever returns to initial position under the elastic force. Electrostatic MEMS switches are fabricated using microelectronic technologies and can be integrated with CMOS circuits, enabling the development of advanced microwave devices [3].

The implementation of MEMS switches in microwave technology is hampered by their poor reliability. Micron-sized switches develop weak contact force, which does not allow achieving low and stable contact resistance. The force is usually increased by using large and complex-shaped electrodes. However, a compact and simple design is more preferable. In this paper, a miniature MEMS switch based on a cantilever with three elastic elements is presented. The shape and dimensions of the electrodes are specially selected to increase the contact and restoring forces, while the moving part remains small [4]. The pull-in voltage and contact resistance of the switch are measured. Experimental data are compared with calculation results. Reduced resistance in comparison to previously created devices is demonstrated.

## Materials and Methods

The switch is shown schematically in Fig. 1, *a*. The movable electrode is 50  $\mu\text{m}$  long and 60  $\mu\text{m}$  wide aluminum cantilever (Fig. 1, *b*). It has three elastic elements, each 10  $\mu\text{m}$  wide. The driving electrode surrounds the signal one in order to increase the area of electric field. The cantilever is 3.6  $\mu\text{m}$  thick and has two 0.3  $\mu\text{m}$  high contact bumps. The gap between the cantilever and the electrodes is of 1  $\mu\text{m}$ . The natural frequency of the cantilever is of 750 kHz. It provides

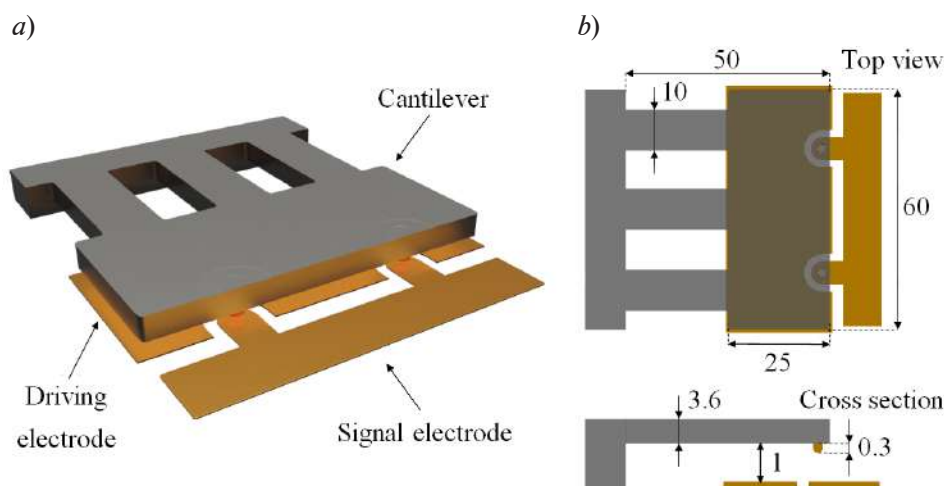


Fig. 1. MEMS switch based on a cantilever with three elastic elements: 3D image (*a*); top view and cross section (*b*), dimensions are given in micrometers

the actuation time of 0.7  $\mu\text{s}$  at a driving voltage of 90 V. The calculated pull-in voltage is of 85 V. The switch is fabricated on a thermally oxidized silicon wafer with a diameter of 100 mm using standard microelectronics techniques. The fabrication procedure is described in detail in the work [5]. The contact material is ruthenium.

The switches are tested under laboratory conditions without packaging. The testing is carried out in the cold switching mode, in which mechanical contact is first made and then the switching signal is applied. The switching signal is a constant voltage of 5 V, while the switching current is about 90 mA and is limited by a load resistance of 50  $\Omega$ . The actuation frequency is of 7 Hz. The contact resistance is calculated at each switching cycle using a resistive divider. The calculation is performed automatically by LabView software.

### Results and discussion

The average measured pull-in voltage is of 69 V, which is 18% lower than the calculated value. The reason for the discrepancy is the bending of the cantilever under internal mechanical stress. Due to the short cantilever length, this bending results only in a small change in the gap of 0.1  $\mu\text{m}$ , which does not lead to the switch failure.

The dependence of the contact resistance on the number of switching cycles for five samples is shown in Fig. 2, *a*. During the first 5,000 cycles, the switches demonstrate the resistance of 4–5  $\Omega$ . Then it varies from 4 to 8  $\Omega$ . Probably, the increase in resistance is explained by the formation of friction polymers on the surface of ruthenium contacts [6]. For the same reason, the resistance behaves unstable, increasing and decreasing several times during the test. Most of the samples withstood less than 100 thousand cycles and failed due to a short circuit between the driving electrode and the cantilever. A sharp increase in contact resistance above 10  $\Omega$  is observed before failure (samples 1, 3–5). The reason for this phenomenon is being investigated.

Fig. 2, *b* shows the test results for three types of switches: a device based on a cantilever with three elastic elements (green curve), a previously developed switch with two elastic elements (red curve) [7] and a switch with an active opening mechanism (blue curve) [8]. All three devices are fabricated using similar technology. A MEMS switch based on a cantilever with three elastic elements demonstrates the lowest contact resistance due to increased contact force.

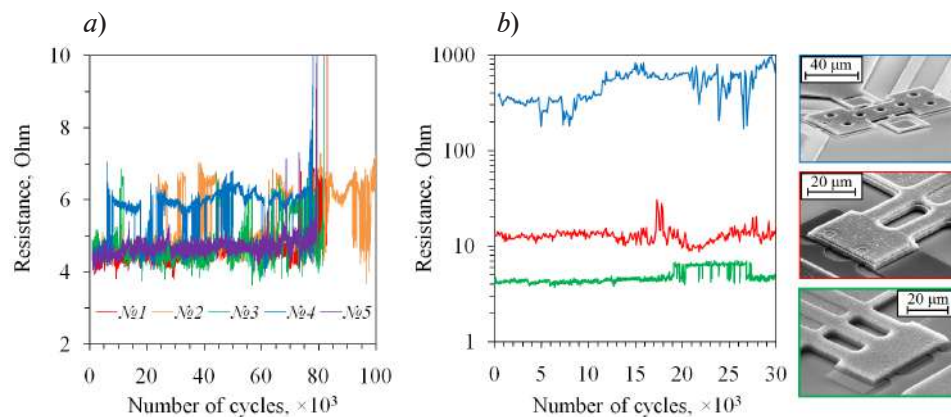


Fig. 2. Dependence of contact resistance on the number of switching cycles: for five switches with three elastic elements (*a*); for switches of three types (*b*)

### Conclusion

The paper presents an electrostatic MEMS switch based on a compact aluminum cantilever with a length of 50  $\mu\text{m}$ . The design of the switch provides maximum contact and restoring forces at small dimensions of the moving part. The pull-in voltage is of 69 V on average, which is 18% lower than the calculated value due to the bending of the cantilever under internal mechanical stress. The contact resistance is of 4–5  $\Omega$  for 5 thousand switching operations. Then it increases to 7–8  $\Omega$  and becomes unstable due to contamination of the contacts. However, the presented switch has significantly less resistance compared to previous developments of the authors.



## REFERENCES

1. **Rebeiz G.M., Patel C.D., Han S.K.**, The search for a reliable MEMS switch, *IEEE Microw. Mag.* 14 (2013) 57–67.
2. **Shao B., Lu C., Xiang Y., et al.**, Comprehensive Review of RF MEMS Switches in Satellite Communications, *Sensors*. 24 (10) (2024) 3135.
3. **Percy J.J., Kanthamani S.**, Revolutionizing wireless communication: A review perspective on design and optimization of RF MEMS switches, *Microelectronics Journal*. 139 (2023) 105891.
4. **Uvarov I.V., Belozеров I.A.**, Design Guideline for a Cantilever-Type MEMS Switch with High Contact Force, *Micro*. 4 (1) (2024) 1–13.
5. **Belozеров I.A., Uvarov I.V.**, MEMS Switch Based on a Cantilever with Increased Contact Force, *Russian Microelectronics*. 52(6) (2023) 475–482.
6. **Czaplewski D.A., Nordquist C.D., Dyck C.W., et al.**, Lifetime limitations of ohmic, contacting RF MEMS switches with Au, Pt and Ir contact materials due to accumulation of ‘friction polymer’ on the contacts, *J. Micromech. Microeng.* 22 (10) (2012) 105005.
7. **Belozеров I.A., Uvarov I.V.**, A compact MEMS switch for advanced radar systems, *St. Petersburg Polytechnic University Journal: Physics and Mathematics*. 75 (3.1) (2024) 178–181.
8. **Uvarov I.V., Marukhin N.V.**, A seesaw-type MEMS switch with enhanced contact force: the first results, *Journal of Physics: Conference Series*. IOP Publishing. 2086 (1) (2021) 012069.

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Conference materials

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## Structural and morphological characterization of InGaAs/InP 2.5 $\mu\text{m}$ photodetector heterostructures with different metamorphic buffer layer profiles

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**Abstract.** In<sub>0.83</sub>Ga<sub>0.17</sub>As/InP PIN-photodiode heterostructures with different metamorphic buffer layers' profiles have been grown by molecular beam epitaxy. Cross-section transmission electron microscopy images have been investigated to estimate the density of threading dislocations. Heterostructures' surface and its roughness have been researched by atomic force microscopy. The lowest dislocation density and surface roughness were observed in the heterostructure with a linear-graded metamorphic buffer layers (MBLs). MBLs were designed with a In mole fraction gradient of 0.18 rel. units/ $\mu\text{m}$ . Epitaxial growth was concluded with a final in situ high-temperature annealing step. Potential distribution of the heterostructures' cleaved surface has been researched by Kelvin probe force microscopy.

**Keywords:** metamorphic buffer layers, infrared photodetectors, molecular beam epitaxy

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Материалы конференции

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## Структурные и морфологические особенности гетероструктур InGaAs/InP фотодетекторов с длиной волны отсечки 2.5 мкм с различным профилем метаморфного буферного слоя

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**Аннотация.** In<sub>0.83</sub>Ga<sub>0.17</sub>As/InP PIN-фотодиодные гетероструктуры с различными профилями изменения состава метаморфных буферных слоев были выращены методом молекулярно-пучковой эпитаксии. Изображения просвечивающей электронной микроскопии в геометрии поперечного сечения были проанализированы для оценки плотности прорастающих дислокаций. Рельеф поверхности гетероструктур и шероховатость были исследованы с помощью атомно-силовой микроскопии. Среди исследованных образцов минимальными значениями плотности дислокаций и шероховатости поверхности характеризуется гетероструктура с метаморфным буферным слоем линейного профиля с градиентом состава 0,18 ат. ед./мкм, рост которого завершался in situ высокотемпературным отжигом. Распределение потенциала по поверхности скола гетероструктур было исследовано методом сканирующей Кельвин-зонд-микроскопии.

**Ключевые слова:** метаморфные буферные слои, инфракрасные фотодетекторы, молекулярно-пучковая эпитаксия

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## Introduction

InGaAs/InAlAs/InP photodetectors operating in the spectral range of 2.2–2.6 μm are valuable for applications like infrared spectroscopy, gas analysis, and night vision [1]. The goal of achieving high performance in this spectral range requires the use of In<sub>0.83</sub>Ga<sub>0.17</sub>As absorption layer. However, the lattice constant mismatch of 2.1% between the In<sub>0.83</sub>Ga<sub>0.17</sub>As absorption layer and the InP substrate makes it necessary to use metamorphic buffer layers (MBLs).

The mismatch of epitaxial layers' lattices leads to an increase in the threading dislocations density. In the present work, the influence of the MBLs' profile on the crystalline quality of the heterostructures has been investigated.

MBLs with continuous linear composition gradients, commonly used for the growth of InGaAs layers high in In content on InP and GaAs substrates, are reported to improve dislocation suppression, reduce dark currents [2], and decrease overall surface roughness [3]. Alternatively, in other work a step composition gradient achieved minimal surface roughness [4].

An interesting variation, not yet studied for InGaAs/InP metamorphic growth, is a square-root graded, or so called convex graded MBLs [5], where the composition changes non-linearly (steep grading near the substrate and moderate grading near the active region). This design was shown to enhance stress relaxation in highly mismatched InGaAs/GaAs heterostructures. We also investigated a step-linear MBLs. Furthermore, the thermocycling process during step-linear sample growth was performed after every step, which might be another mechanism for reducing dislocation density [6].

### Materials and methods

The semi-industrial molecular beam epitaxy Riber49 setup was used to manufacture PIN-photodiode heterostructures. Three structures were grown on  $N^+$ -type “epi-ready” InP (100) wafers. These samples differed in their MBLs’ profiles, and in this work they are labelled S-1, S-2 and S-3.

$N^+$ -In<sub>x</sub>Al<sub>1-x</sub>As metamorphic buffer layers with In mole fraction changing from 0.52 to 0.83 were used in all heterostructures. They were formed after a thin 100 nm lattice-matched In<sub>0.52</sub>Ga<sub>0.48</sub>As layer. MBLs’ width was 2 μm in all structures, and MBLs’ growth temperatures were maintained at 450–490 °C. Structure S-1 included convex-graded MBLs, where In mole fraction changed as  $x = 0.52 + 0.219\sqrt{z}$  where  $z$  is MBLs’ width in μm. Sample S-2 was made with linear-graded MBLs. In heterostructures S-1 and S-2 MBLs growth was followed by *in situ* thermal annealing with peak temperature rise up to 530 °C for 30 seconds and slow cooling to 50 °C over 25 minutes for an exposure period of 20 minutes. Structure S-3 was manufactured with step-graded MBLs consisting of five 200-nm-wide steps separated by 100-nm transition regions where In mole fraction changed linearly. The thermocycling process for sample S-3 involved a 100 °C temperature decrease over 2.5 minutes, then a return to the growth temperature over 2.5 minutes, which was repeated after every step. After MBLs, 1.5 μm In<sub>0.83</sub>Ga<sub>0.17</sub>As active layer was grown. The absorption layer was slightly n-doped using silicon (Si). At the end, 0.6 μm  $p^+$ -type contact layers doped with beryllium (Be) were formed on the top of the heterostructure.

In other studies, the application of inverse step is demonstrated [2]. We suppose that the inverse step similarly improves characteristics of heterostructures with different MBLs. Therefore, we find it necessary to first optimize the metamorphic buffer layers design and then apply the inverse step.

The cleavage of samples was done with a sharp scalpel from the substrate side of the samples. The cleaved surface was examined far enough from the edge of the samples so that the mechanical effect of the cleavage process had a minimal effect on the chipped surface.

Transmission electron microscopy (TEM) images were acquired with a JEM-2100F (Jeol) 200 kV Field Emission analytical electron microscope. Both the (001) heterostructure surface and the (110) cleavage surface morphologies of the samples were analysed by atomic force microscopy (AFM) under ambient conditions on a NTegra Aura setup (NT-MDT, Moscow, Russia), operating in semi-contact mode, using NSG11 probes with a stiffness coefficient of 5N/m and a radius of curvature of the probe needle tip of 10 nm. For the study of the cleaved surface potential distribution a Kelvin probe force microscopy (KPFM) using conductive probes was applied.

### Results and discussion

TEM images of analysed structures are presented in Fig. 1. All images demonstrate high dislocation density in the MBLs of approximately  $\sim 10^{11} \text{ cm}^{-2}$ . The dislocation densities in the active layer of heterostructures were calculated for samples S-2 and S-3. For S-2 its value is  $\sim 5 \cdot 10^8 \text{ cm}^{-2}$  and for S-3 it is  $\sim 5 \cdot 10^9 \text{ cm}^{-2}$ . Dislocation density for S-1 cannot be estimated due to the poor quality of the respective TEM image. Therefore, further research on the dislocation density in S-1 is required. In previous studies, a dislocation-free region was observed [7]. The current images, however, do not show it. The dislocation density values, presented in literature for similar metamorphic heterostructures, are typically  $\sim 10^7 \text{ cm}^{-2}$  [2]. In our work, this value is higher, which may be due to the absence of an inverse step in the MBLs, and can be further improved.

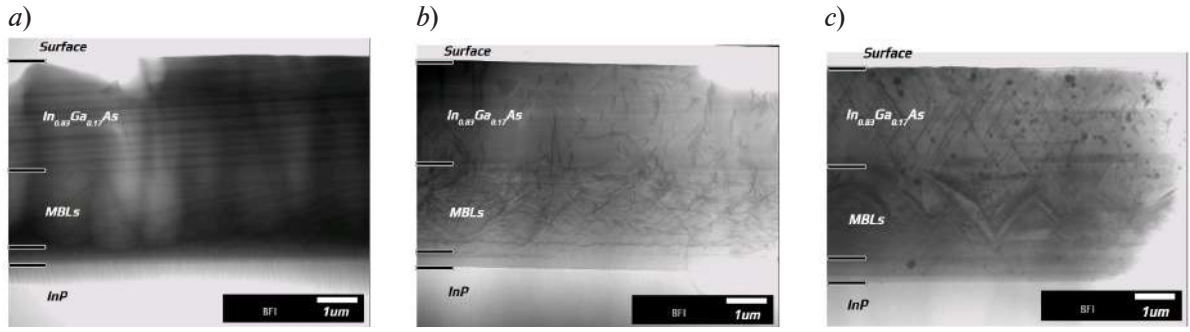


Fig. 1. TEM images of heterostructures S-1 (a), S-2 (b) and S-3 (c)

AFM images of heterostructures' surface, which are shown in Fig. 2, were analysed. Surface roughness was measured as root-mean-square (RMS). It is demonstrated that sample S-2 has the lowest RMS of 17.3 nm. In other studies, this value for MBE-grown linear MBLs is about 10–20 nm [2], which is in good agreement with our work. Non-linear MBLs on GaAs substrates demonstrate RMS of 1–2 nm for  $10 \times 10 \mu\text{m}^2$  surface area [5]. Therefore, it was expected that convex-graded MBLs on InP substrates would also show the best results. However, this structure revealed a much higher RMS value, suggesting that further research on the optimal growth conditions of InP-based convex-graded MBLs is required.

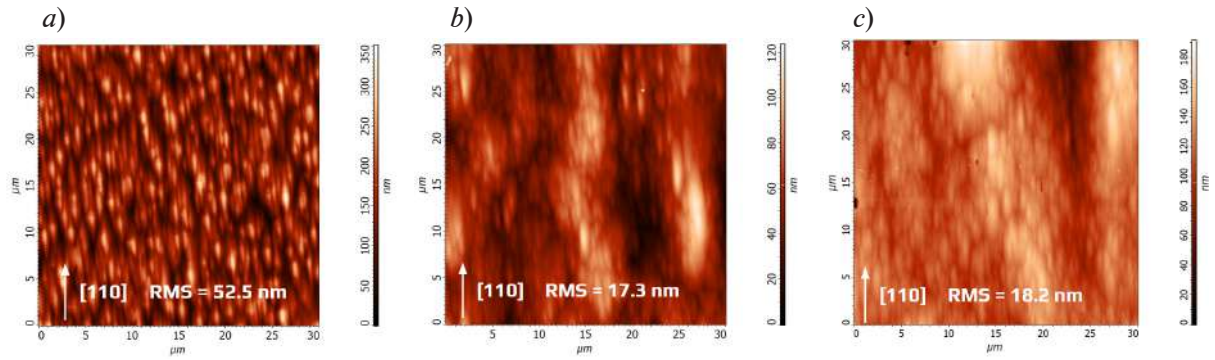


Fig. 2. AFM images of heterostructures' surface S-1 (a), S-2 (b) and S-3 (c)

All images reveal typical anisotropic features of the metamorphic structures' surface along the [110] direction [2]. We can conclude that usage of linear-graded MBLs not only decreases the dislocation density, but also leads to a better surface quality.

AFM and KPFM were used to better understand the cleavage morphology of three samples (Fig. 3).

Sample S-1 (Fig. 3, *a–d*) demonstrates a good correspondence between the heterostructure layer thicknesses observed in the AFM and KPFM images. The crystalline quality can be evaluated from images of the cleaved surface topography. The surface features, which appear as diagonal stripes, most likely, follow threading dislocations. A reduction of dislocation density is observed near the upper interface of MBLs. However, it is continued with a sharp increase in the absorption layer. A dislocation-free area can be seen only in *p*-layer.

Images of the heterostructure S-2 (Fig. 3, *e–h*) do not demonstrate diagonal surface irregularities, which can be associated with lower dislocation density. Nevertheless, this sample has a rougher cleavage surface. Profiles of surface topography and electric potential correlates, but there are some differences. For example, from 2 to 4  $\mu\text{m}$  potential remains almost constant, while surface height changes.

Analysis of sample S-3 (Fig. 3, *i–l*), similar to S-1, demonstrates surface features indicative of threading dislocations. In the active region, larger stripes are visible, but with a lower density, which may confirm the better compensation of elastic strain and the annihilation of threading dislocations. Irregularities are observed at the heterointerface between the metamorphic buffer layers and the active region on both AFM and KPFM images, which might show the formation of misfit dislocations [8].



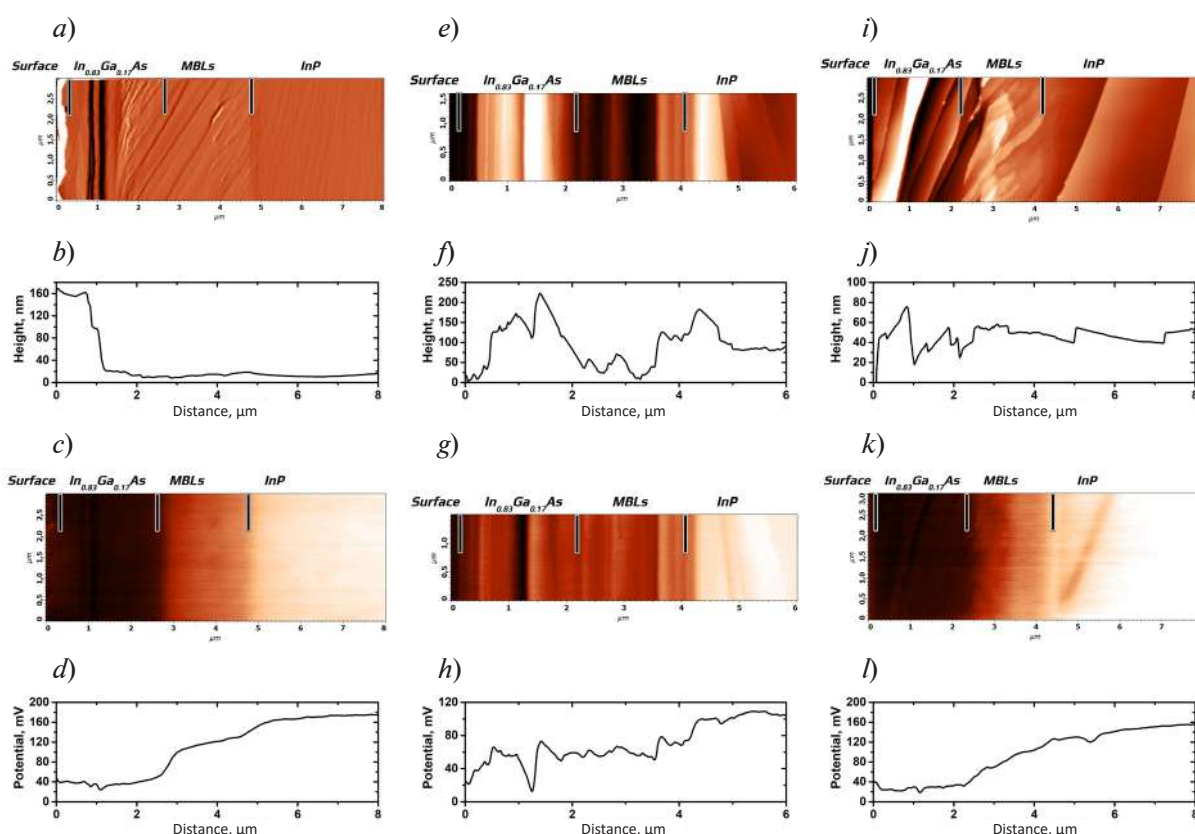


Fig. 3. AFM and KPFM measurements on the surface cross-section of samples S-1 (a–d), S-2 (e–h), S-3 (i–l)

In our work, we used the KPFM method to clearly illustrate the shape of the potential distribution on the law of change of the In mole fraction.

The electric potential profiles for all three samples show a decrease from the *n*-doped InP substrate to the *p*-layer. Local changes of a slope of the curve are noticeable, which might be connected with the band structure [9]. We believe that such a study of the cleavage potential can be used for the modelling of the band structure of the corresponding structures.

### Conclusion

In<sub>0.83</sub>Ga<sub>0.17</sub>As/InP PIN-photodiode heterostructures with different metamorphic buffer layers' profiles have been researched. It is demonstrated that the structure with a linear-graded buffer has the lowest dislocation density of  $\sim 5 \cdot 10^8 \text{ cm}^{-2}$  in the active layer and the least surface roughness (RMS = 17.3 nm). The cleavage topography and electric potential distribution of three samples were researched.

### REFERENCES

1. Burlakov I.D., Grinchenko L.Y., Dirochka A.I., Zaletaev N.B., Short wavelength infrared InGaAs detectors, *Advances in Applied Physics (Uspekhi Prikladnoi Fiziki)*. 2 (2) (2014).
2. Chen X., Gu Y., Zhang Y., Epitaxy and Device Properties of InGaAs Photodetectors with Relatively High Lattice Mismatch, *Epitaxy. InTech*. (2018).
3. Zakaria A., et al., Comparison of arsenide and phosphide based graded buffer layers used in inverted metamorphic solar cells, *Journal of Applied Physics*. 112 (2) (2012).
4. Pushkarev S.S., Galiev G.B., Klimov E.A., et al., Influence of metamorphic buffer design on electrophysical and structural properties of MHEMT nanoheterostructures In<sub>0.7</sub>Al<sub>0.3</sub>As/In<sub>0.7</sub>Ga<sub>0.3</sub>As/In<sub>0.7</sub>Al<sub>0.3</sub>As/GaAs, *Proc. SPIE 8700, International Conference Micro- and Nano-Electronics*. 870007 (2012).





5. Solov'ev V.A., Chernov M.Yu., Sitnikova A.A., et al., Optimization of the Structural Properties and Surface Morphology of a Convex-Graded  $\text{In}_x\text{Al}_{1-x}\text{As}$  ( $x = 0.05\text{--}0.83$ ) Metamorphic Buffer Layer Grown via MBE on GaAs (001), Semiconductors. 52 (1) (2018) 120–125.
6. Bolkhovityanov Y.B., Pchelyakov O.P., GaAs epitaxy on Si substrates: Modern status of research and engineering, Physics-Uspekhi. 51 (5) (2008) 437–456.
7. Vasilkova Ye.I., Pirogov Ye.V., Sobolev M.S., et al., Molecular beam epitaxy of metamorphic buffer for InGaAs/InP photodetectors with high photosensitivity in the range of 2.2–2.6  $\mu\text{m}$ , Condensed Matter and Interphases. 25 (1) (2023) 20–26.
8. Drozdov Yu.N., Danil'tsev V.M., Vostokov N.V., et al., Cross-sectional AFM of GaAs-based multilayer heterostructure with thin AlAs marks, Physics of Low-Dimensional Structures. 3 (4) (2003) 49–54.
9. Ladutenko K.S., Ankudinov A.V., Evtikhiev V.P., On the accuracy of quantitative measurements of the local surface potential, Technical Physics Letters. 36 (3) (2010) 228–231.

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## **InAsSb solid solution optocouple for carbon dioxide analysis**

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**Abstract.** This paper reports the results of work aimed at improving the performance of LEDs and photodiodes based on InAsSb solid solutions operating in the spectral range around 4.2  $\mu\text{m}$ , as well as improving the efficiency of optocouple based on them in the absorption band of carbon dioxide in a wide temperature range, including high temperatures. An increase in the characteristics of optoelectronic components was achieved: detectivity  $D^* = 3 \cdot 10^{10} \text{ (cm} \cdot \sqrt{\text{Hz}}) / \text{W}$  and LEDs' power  $\sim 100 \text{ } \mu\text{W}$  (200 mA) at room temperature. Based on the obtained optoelectronic components, a non-dispersive infrared carbon dioxide sensor with a limit of detection of 0.0025 vol.%, relative error of 0.1% of measurement in the 0–10 vol.% concentration was developed. The sensor featured a 2 cm optical path, a sampling interval of 128 ms, and a power consumption of less than 50 mW.

**Keywords:** InAsSb heterostructures, mid-wave IR LEDs, mid-wave IR photodiodes, nondispersive infrared gas sensor

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Материалы конференции

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## **Оптопары на основе твердых растворов InAsSb для детектирования углекислого газа**

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**Аннотация.** Сообщается о результатах работы, нацеленной на улучшение характеристик свето- и фотодиодов на основе полупроводников InAsSb, работающих в средневолновой ИК области спектра около 4.2 мкм, а также на повышении эффективности их работы как оптопары в полосе поглощения углекислого газа в широком интервале температур.

На основе представленных оптопар был разработан недисперсионный инфракрасный датчик углекислого газа.

**Ключевые слова:** гетероструктуры InAsSb, средневолновые ИК светодиоды, средневолновые ИК фотодиоды, недисперсионный инфракрасный газовый датчик



**Ссылка при цитировании:** Кунков Р.Э., Карандашев С.А., Климов А.А., Лухмырина Т.С., Ременный М.А., Оптопары на основе твердых растворов InAsSbP для детектирования углекислого газа // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2025. Т. 18. № 3.2. С. 178–182. DOI: <https://doi.org/10.18721/JPM.183.235>

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## Introduction

The first symptoms of the negative effect of CO<sub>2</sub> on the human body begin already at concentrations of about 0.1–0.15 % vol. Therefore, the permissible levels of carbon dioxide in industrial, office and residential buildings are strictly regulated. Non-dispersive infrared gas sensors based on LEDs and photodiodes are effective devices for gas analysis, characterized by high selectivity, long lifetime and sensitivity down to ppm units [1]. The requirements for such sensors are constantly increasing, resulting in the need to find solutions for: minimizing power consumption, size and weight of the sensor (SWaP minimization); increasing the efficiency of the optoelectronic components used; integration of optoelectronic and related electronic components.

To date, the most widely used sensors are those based on thermal sources and infrared (IR) radiation detectors [2], which typically exhibit high power consumption, low response speed, and relatively low sensitivity. Medium-wave IR photodiodes and optically excited light-emitting diodes (LEDs) based on lead salts [3] have also been employed in sensor development. However, their key drawback is the lack of long-term parameter stability.

A promising alternative to these devices is IR sensors utilizing light-emitting diodes (LEDs) and photodiodes (PDs) based on A<sup>3</sup>B<sup>5</sup> semiconductors, particularly InAsSb(P) solid-solution heterostructures, which offer high metallurgical stability and relatively low cost. For many years, IR optoelectronics laboratory of the Ioffe Institute has been developing and studying optoelectronic components based on diode heterostructures with an active layer of InAs<sub>1-x</sub>Sb<sub>x</sub> solid solution, including those operating in the ~ 4.2 μm wavelength range [4–6], as well as optical sensors derived from them [7]. The objectives of this study were: improving the performance of optoelectronic components (LEDs and PDs); enhancing their efficiency as optopairs over a wide temperature range; developing a compact, non-dispersive CO<sub>2</sub> sensor with a high level of integration of optical, optoelectronic, and electronic components.

## Results and Discussion

The studied LED and photodiode samples were fabricated from an *n*-InAsSbP/InAsSb<sub>*x*</sub>/*p*-InAsSbP heterostructure with an active/photosensitive InAsSb<sub>*x*</sub> (*x* = 0.08) region 4–3 μm thick, grown by LPE on *n*<sup>+</sup>-InAs (100) substrates. The key design features of the LEDs and photodiodes included: a flip-chip configuration with an active/photosensitive area diameter of ~140 μm and light input/output through a 20–40 μm substrate; immersion coupling of the chip with a 3.5 mm Si lens featuring an antireflection coating.

For the experimental LED and photodiode samples (LED42 and PD42), (Fig. 1, *a*, *b*) presents the electroluminescence spectra at a 200 mA pumping current in CW mode and the photosensitivity across a significantly extended temperature range of 200–500 K compared to previously published results. The photodiode's current responsivity and the LED's output power were also increased [7], achieved through optimization of the epitaxial structure design. Specifically, reducing the thickness of the active/photosensitive region minimized self-absorption of radiation and lowered the dark current.

In addition to the main optopair, the sensor incorporated a reference-channel photodiode (PD38) and two interference filters (IF42 and IF38), which split and filtered the LED42 emission to create the measurement (LED42-IF42-PD42) and reference (LED42-IF38-PD38) channels. Fig. 1, *c* shows the normalized spectral characteristics of these components at room temperature, along with the CO<sub>2</sub> transmission spectrum in the operational wavelength range.

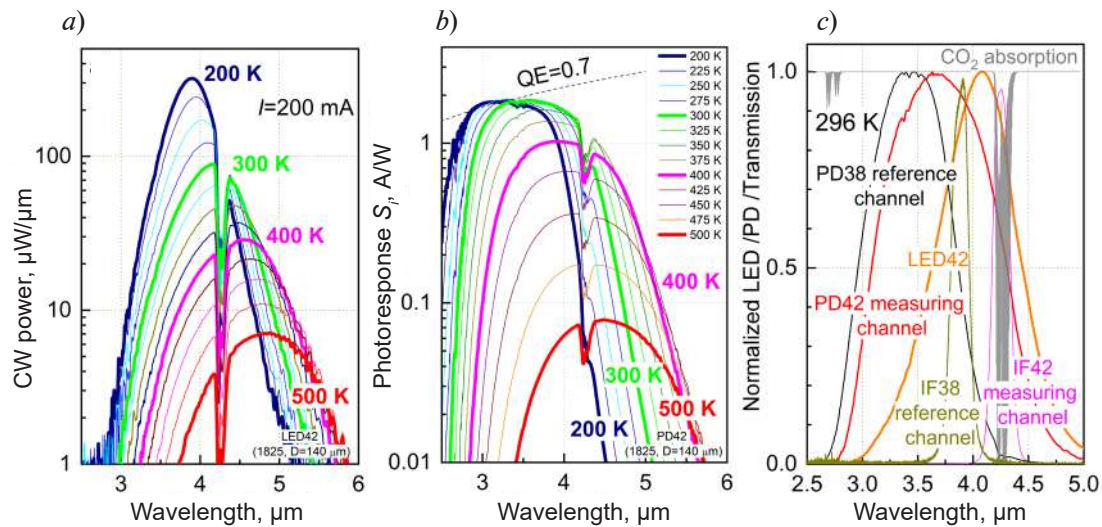


Fig. 1. Electroluminescence spectra (a) and current responsivity (b) in the temperature range of 200–500 K; normalized spectral characteristics of the optoelectronic components used and CO<sub>2</sub> transmission (c)

Based on the obtained temperature dependencies of zero bias resistance (Fig. 2, a), the noise characteristics of photodiodes PD42 and PD38 were calculated, as well as the total noise at the output of (photodiode) + (first-stage op-amp) system. The calculation was performed for a frequency bandwidth  $\Delta f = 1\text{ Hz}$ ,  $f > 10\text{ kHz}$  (i.e., outside the  $1/f$  noise region) using Eq. (1) [8]:

$$I_{n_{\Sigma}}(\Delta f) = \Delta f \cdot \sqrt{i_{n_{PD}}^2 + i_{n_{OP}}^2 + i_{fb}^2} = \Delta f \cdot \sqrt{\frac{4kT}{R_o} + i_{n_{OP}}^2 + \left(\frac{e_{n_{OP}}}{R_o}\right)^2 + \frac{4kT}{R_{fb}}} [A], \quad (1)$$

where the first term represents photodiode noise; the second and third terms correspond to the first-stage operational amplifier (op-amp) noise; and the last term represents the thermal noise of the feedback resistance in the first amplification stage. As seen in Fig. 2, a, the op-amp contributes significantly to the total noise, particularly at the extremes of the temperature range: at elevated temperatures, the dominant contribution comes from the op-amp's voltage noise ( $e_{n_{OP}}$ ), while at lower temperatures, the current noise ( $i_{n_{OP}}$ ) prevails.

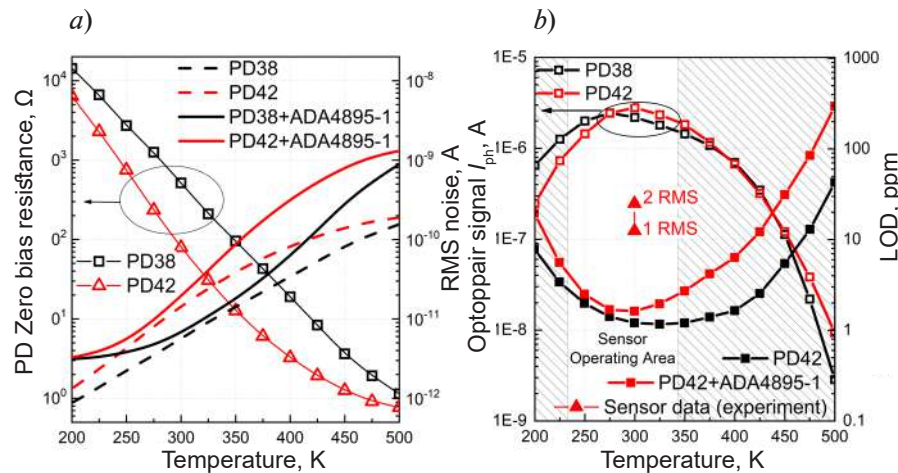


Fig. 2. Temperature dependencies for zero bias resistance and RMS noises of photodiodes both individually and in the op-amp circuit (a), and integrated optopair signals at 200 mA LED drive current and limit of detection, ppm (b)



Fig. 2, *b* shows the temperature dependencies of the optopair signals for the measurement and reference channels, calculated using Eq. 2:

$$I_{ph} = \int_{\lambda_1}^{\lambda_2} P_{LED}(\lambda) \cdot T_{IFx}(\lambda) \cdot S_{IPDx}(\lambda) d\lambda, \quad (2)$$

where  $P_{LED}(\lambda)$  is the spectral power distribution of LED42,  $T_{IFx}(\lambda)$  is the transmission spectrum of the interference filter, and  $S_{IPDx}(\lambda)$  is the current responsivity spectrum of the photodiode for the respective optopair.

To evaluate the limit of detection (LOD), the sensor's transfer function was calculated by introducing an additional multiplicative factor in Eq. 2 accounting for infrared absorption by CO<sub>2</sub> at a 2 cm optical path length:

$$I_{ph} = \int_{\lambda_1}^{\lambda_2} (1 - \exp(-k(\lambda) \cdot C \cdot d)) \cdot P_{LED42}(\lambda) \cdot T_{IF42}(\lambda) \cdot S_{IPD42}(\lambda) d\lambda, \quad (3)$$

where  $k(\lambda)$  is the spectral absorption coefficient of CO<sub>2</sub> (data from the HITRAN database),  $C$  is the gas concentration in vol.%, and  $d$  is the optical path length.

Fig. 2, *b* shows the calculated LOD for carbon dioxide in the temperature range of 200–500 K, derived from the obtained signal and noise dependencies along with the sensor's transfer function (assuming its minimal temperature variation). The calculation was performed for a frequency bandwidth of  $\Delta f = 1$  Hz. Experimental values obtained at room temperature during prototype testing (see Fig. 3) are also presented.

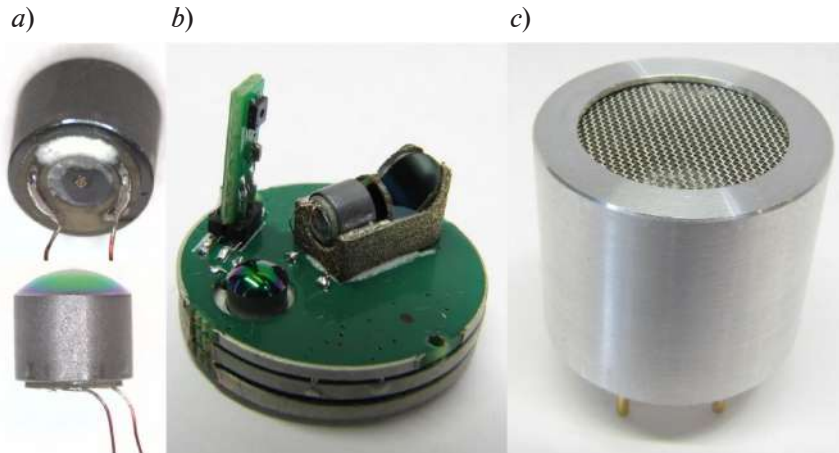


Fig. 3. Photographs of immersion light-emitting diodes and photodiodes (left), sensor during intermediate assembly (center), and fully packaged device in a  $\varnothing 20 \times 16$  mm housing (right)

The root-mean-square (RMS) noise was estimated at 15 ADC counts, with the useful signal ranging from 37127 to 85940 ADC counts. The LOD (defined as  $2 \times \text{RMS}$ , corresponding to 95% confidence level for normally distributed errors) reached  $\approx 0.0025$  vol.% (25 ppm). The relative measurement error did not exceed 0.1 % of the measured value across concentrations up to 10 vol.%.

A comparison of the prototype sensor's characteristics with commercially available counterparts [2, 3] demonstrated its superior performance in response speed (6–30 times faster), LOD (up to 2 times lower), and dynamic range (over 2 times wider).

### Conclusion

The paper presents the results of work on the development of LEDs and photodiodes based on InAsSb/InAsSbP heterostructures and NDIR carbon dioxide sensor operating in the mid-wave IR region of the spectrum. For the design of immersion LEDs and photodiodes with a wavelength



of about 4.2  $\mu\text{m}$ , the values of detectability  $D^* = 3 \cdot 10^{10} \text{ (cm} \cdot \sqrt{\text{Hz}})/\text{W}$  and LED power  $\sim 100 \mu\text{W}$  (CW current 200 mA) at room temperature are obtained. The NDIR carbon dioxide sensor with an optical path length of about 2 cm and average power consumption of 25 mW was characterized by a carbon dioxide limit of detection of 0.0025 vol.% and a relative measurement error of 0.1% in the concentration range up to 10 vol.%.

## REFERENCES

1. Kochelaev E.A., Petrov V.V., Design of a compact optical carbon monoxide sensor with a threshold sensitivity of 1 mg/m<sup>3</sup> (0.85 ppm). Evaluation of measurement selectivity, Optics and Spectroscopy. 131 (10) (2023) 1359.
2. “Dynamet” (UK) NDIR gas sensors. [Electronic resource]. URL: <http://www.dynamet.ru/pdf/tds0048.pdf>
3. “Optosense” (RU) NDIR gas sensors [Electronic resource]. URL: <https://optosense.ru/upload/iblock/212/ESAT.100700.00%20%D0%A0%D0%AD.pdf>
4. Zotova N.V., Ilyinskaya N.D., Karandashev S.A., et al., 4.2  $\mu\text{m}$  flip-chip LEDs with deep etch mesa, Semiconductors. 4 (6) (2006).
5. Zakheim A.L., Zotova N.V., Ilyinskaya N.D., et al., Uncooled wideband flip-chip photodiodes based on InAsSb ( $\lambda_{\text{cut off}} = 4.5 \mu\text{m}$ ), Semiconductors. 43 (3) (2009).
6. Ilyinskaya N.D., Karandashev S.A., Karpuhina N.G., et al., Photodiode  $1 \times 64$  linear array based on a double  $p\text{-InAsSbP}/n\text{-InAs}_{0.92}\text{Sb}_{0.08}/n^+\text{-InAs}$  heterostructure, Semiconductors. 50 (5) (2016) 657.
7. Sotnikova G.Yu., Gavrilov G.A., Aleksandrov S.E., et al., Low Voltage CO<sub>2</sub>-Gas Sensor Based on III–V Mid-IR Immersion Lens Diode Optopairs: Where we Are and How Far we Can Go, IEEE Sensors Journal. 10 (2) (2010) 225–234.
8. Gavrilov G.A., Matveev B.A., Sotnikova G.Yu., Maximum sensitivity of a photodetector based on A3B5 photodiodes of the mid-IR spectrum range, Semiconductors. 37 (18) (2011) 50 – 57.

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## Electron scattering in matter taking into account surface effects

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**Abstract.** This paper presents a model of inelastic electron scattering in a substance, taking into account surface effects. The surface effects were taken into account when calculating the differential cross sections of inelastic scattering based on the dielectric theory of Drude. In this paper, the transmission function was calculated when solving the transfer equation using two methods: the matrix method and the Monte Carlo method. Based on the transmission functions obtained, the energy spectra of X-ray photoelectron spectroscopy (XPS) were calculated. Computational and simulation models of inelastic electron scattering in matter have been proposed to implement methods for solving the transport equation.

**Keywords:** electron spectroscopy, inelastic scattering, surface effects, transmission function, Monte Carlo method

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## Рассеяние электронов с учетом поверхностных эффектов

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**Аннотация.** В данной работе представлена модель неупругого рассеяния электронов в веществе с учетом поверхностных эффектов. Поверхностные эффекты были учтены при расчете дифференциальных сечений неупругого рассеяния на основе диэлектрической теории Друде. В работе была посчитана функция пропускания при решении уравнения переноса двумя методами: матричным методом и методом Монте-Карло. На основе полученных функций пропускания были посчитаны энергетические спектры рентгеновской фотоэлектронной спектроскопии (РФЭС). Для реализации методов решения уравнения переноса были предложены расчетная и имитационная модели неупругого рассеяния электрона в веществе.

**Ключевые слова:** электронная спектроскопия, неупругое рассеяние, поверхностные эффекты, функция пропускания, метод Монте-Карло

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### Introduction

The problem of an adequate description of the energy losses of high-energy electrons passing through a layer of matter is of interest. This problem often concerns such fields as nano- and microelectronics, physics of nanostructures, metal science, etc.

The transmission function is the basic function of any electron spectroscopy, the physical meaning of which is the distribution function of electrons passing through a layer of matter according to the energy they lost as a result of inelastic scattering. This function was first obtained by L.D. Landau [1]. The results obtained in this work only qualitatively describe experimental data, the accuracy of Landau's solution is very low, this is primarily due to the fact that at that time the behavior of the differential cross section of inelastic scattering in the region of low energy losses was not known. Much later, in [2], Landau's solution was modified by using the threshold cross section of inelastic scattering, and in this work, the invariant immersion method derived a formula for the transmission function over scattering multiplicities, which describes the experiment better than Landau's solution.

The work [3] was one of the first in which surface effects were taken into account when calculating the transmission function. The idea was to represent the layer in the form of surface and bulk layers. The disadvantage of these methods is that some parameters are adjustable. However, there is another way. In [4–5], Differential Inverse Inelastic Mean Free Path (DIIMFP) are derived based on the dielectric theory of Drude, which depend on the scattering coordinate, the angle of entry (departure) of the electron, and the energy of the electron. Based on these DIIMFP, the surface effects on electron scattering in matter will be taken into account in this work.

### Materials and methods

We can find the transmission function if we solve the transfer equation:

$$\frac{dT_{in}(z, \Delta)}{dz} = \lambda_{in}^{-1}(z) \cdot \left[ -T_{in}(z, \Delta) + \int_0^{\Delta} T_{in}(z, \varepsilon) X_{in}(z, \Delta - \varepsilon) d\varepsilon \right], \quad (1)$$

$$T_{in}(0, \Delta) = \delta(\Delta),$$

where  $T_{in}(z, \Delta)$  is the transmission function,  $\lambda_{in}$  is the Inelastic Mean Free Path (IMFP),  $X_{in}(z, \Delta)$  is the unit-normalized differential cross section of inelastic scattering,  $z$  is the coordinate of the scattering point,  $\Delta$  is the energy loss.

Equation (1) can be solved using two methods: the matrix method and the Monte Carlo method. The matrix method is implemented if we represent the convolution in equation (1) as a product of matrices. When substituting matrices into the transfer equation, a matrix-vector equation is obtained, which is solved by methods of the theory of differential equations:

$$\mathbf{T}(z, \Delta) = \expm \left[ - \int_0^z \lambda_{in}^{-1}(z) (\mathbf{E} - \mathbf{A}(z)) dz \right] \mathbf{D}, \quad (2)$$

where  $\mathbf{E}$  is the identity matrix,  $\mathbf{A}(z)$  is the Toeplitz matrix, which is necessary for calculating the convolution,  $\mathbf{D}$  is the matrix equivalent of the Dirac function,  $\expm ( )$  is the matrix exponential function.



To implement the Monte Carlo method, it is necessary to create a simulation model of inelastic electron scattering in matter, and then use this model to calculate energy losses for at least 106 particles, and then plot the distribution as a histogram.

In this work, surface effects are taken into account when calculating the DIIMFP according to the dielectric theory of Drude [5]. When calculating the transmission function, it must be borne in mind that the ingress of an electron from a vacuum to a surface and the escape of an electron from a surface into a vacuum are two different processes that are described by two different formulas. In Fig. 1, *a* DIIMFP outside the layer of matter are shown, as can be seen when moving away from the surface of the layer, the DIIMFP of the process in which the electron falls to the surface decreases faster than the DIIMFP of the process in which the electron leaves the surface, this is explained by the presence of a surface charge. Fig. 2, *b* shows the dependence of the inverse IMFP, as can be seen from the graph, surface effects have a strong effect in the region of 10 Å on both sides of the boundary of the solid layer. It is important to note that the probability of an electron scattering and losing energy in a vacuum near the surface is not zero.

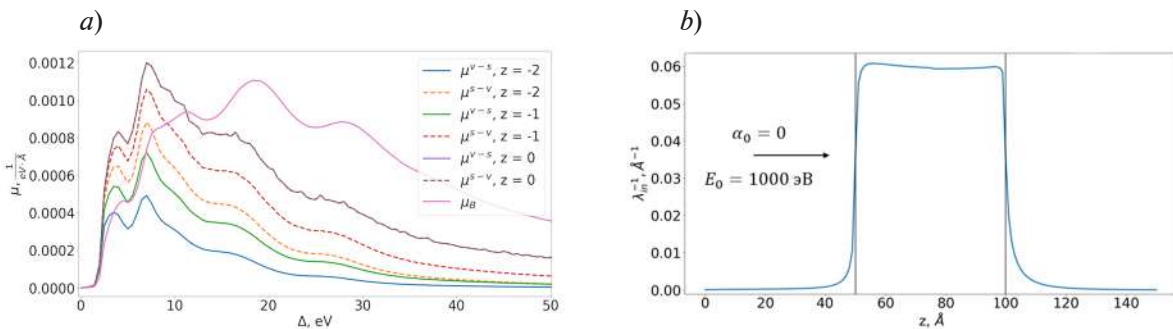


Fig. 1. Calculated DIIMFP for cases when an electron from a vacuum enters the surface of  $\mu_{\nu \rightarrow s}$  and when an electron leaves the surface of  $\mu_{s \rightarrow \nu}$ .  $\mu_B$  is the DIIMFP in the depth of the target ( $z \rightarrow \infty$ ). The  $z$  coordinates are given in angstroms (*a*), the dependence of the inverse IMFP for an electron with an energy of 1000 eV in copper on the scattering coordinate.

Vertical black lines show the boundaries of a solid (5 nm layer thickness) (*b*)

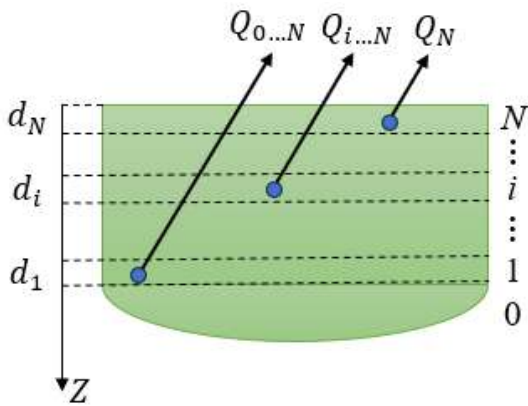


Fig. 2. Diagram of a multilayer target

When modeling the XPS spectrum, even from an unoxidized target, it is necessary to divide the layer into many homogeneous layers (Fig. 2.) in order to take into account, the surface effects. It should be noted that in this model there are layers that affect inelastic scattering, but in which no electrons are born, these are layers close to the surface of a solid body in a vacuum.

### Results and discussion

Fig. 3, *a* show the transmission functions calculated by the matrix method and the Monte Carlo method. As can be seen from the graphs, the results obtained by these methods are in good agreement (the mean square deviation is  $8.13 \cdot 10^{-4}$ ), which indicates the adequacy of the calculated and simulation models. For comparison,

the transmission function is calculated using the universal Tougaard formula [6], which does not take into account surface effects, as can be seen from the graphs, these transmission functions are very different.

Fig. 3, *b* shows the simulated XPS spectra for the Cu 2p line with and without consideration of surface effects. Here, the matrix method and the Monte Carlo method also agree well, which indicates the adequacy of the calculated and simulation models (the mean square deviation for the spectrum, taking into account surface effects and without taking into account surface effects, are

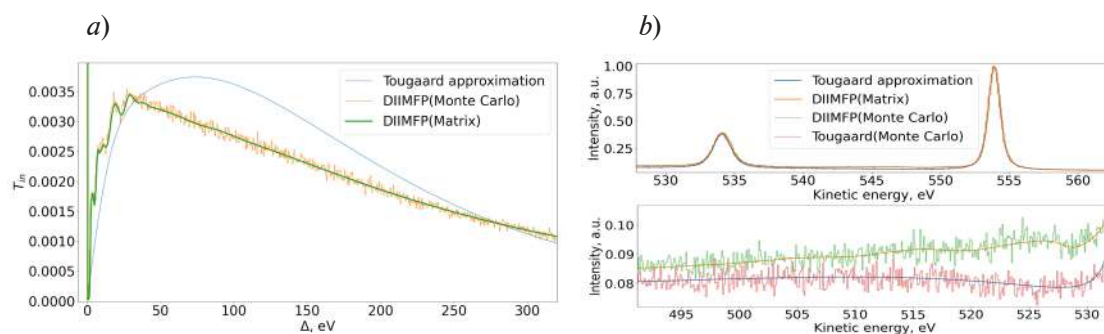


Fig. 3. Transmission functions calculated for a 5 nm thick copper layer. The electron energy is 1000 eV. Electrons fall to the surface normally (a), modeled XPS spectra of the Cu 2p line (b)

0.009 and 0.017, respectively). As can be seen from the graphs, the area of elastic peaks practically coincides, the qualitative difference is visible only for the background, because peaks appeared there due to the loss of energy by electrons to the excitation of surface plasmons.

### Conclusion

The paper proposes a model of inelastic electron scattering based on the dielectric theory of Drude, taking into account surface effects. The matrix method and the Monte Carlo method showed good agreement, confirming the adequacy of the models. Consideration of surface effects significantly affects the energy spectra of XPS in the inelastic background region (the appearance of surface plasmons).

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### REFERENCES

1. Landau L.D., On the loss of energy by fast particles due to ionization, J. Phys. USSR. (8) (1944) 201–209.
2. Afanas'ev V.P., Yagova N.V., Energy loss of kilovolt electrons in thin films, Zeitschrift für Physik B Condensed Matter. (92) (1993) 199–203.
3. Afanas'ev V., Lubenchenko A., Gubkin M., Quantitative interpretation of EELS and REELS spectra, The European Physical Journal B-Condensed Matter and Complex Systems. (37) (2004) 117–125.
4. Chen Y.F., Surface effects on angular distributions in X-ray photoelectron spectroscopy, Surface science. 124–115 (2002) (2-1) 519.
5. Li Y.C., et al., Influence of the direction of motion on the inelastic interaction between electrons and solid surfaces, Surface science. 76–67 (2005) (3-1) 589.
6. Tougaard S., Universality classes of inelastic electron scattering cross-sections, Surface and Interface Analysis: An International Journal devoted to the development and application of techniques for the analysis of surfaces, interfaces and thin films. 137 (1997) (3) 25–154.

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### **Photonic-electronic IC of a subterahertz GaAs-on-Si in-phase/quadrature mixer**

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**Abstract.** In this work, we propose a photonic-electronic integrated circuit of a 140 GHz in-phase/quadrature (I/Q) mixer based on the GaAs-on-Si platform which is in demand of next-generation wireless networks. The mixer conversion loss is ultimately limited by the on-chip power distribution network, exhibiting 7–8 dB insertion losses for the local oscillator and carrier signals with reflection losses as low as 28 dB. The circuit potentially ensures baud rates of up to 30 GHz which can be tuned. Although, the proposed integrated circuit is designed for operation at 140–150 GHz, it can be easily scaled-down for carrier frequencies of 280–300 GHz or even significantly higher. We believe that our findings should be of interest to developers of 6G wireless modules and systems.

**Keywords:** subterahertz, Si integrated photonics, GaAs diode, I/Q mixer, 6G communication

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Материалы конференции

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### **Фотонно-электронная ИС субтерагерцового I/Q смесителя на основе GaAs-на-Si**

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**Аннотация.** В данной работе предлагается фотонно-электронная интегральная схема I/Q смесителя для частоты 140 ГГц на основе GaAs-на-Si. Потери преобразования в смесителе ограничены встроенной сетью распределения мощности, которая обеспечивает

вносимые потери сигналов гетеродина и несущей на уровне 7–8 дБ при потерях на отражение до 28 дБ. Предлагаемая интегральная схема рассчитана на работу в диапазоне 140–150 ГГц, но ее можно масштабировать для несущих частот 280–300 ГГц и даже выше.

**Ключевые слова:** субтерагерц, Si интегральная фотоника, GaAs диод, I/Q смеситель, связь 6G

**Финансирование:** Исследование осуществлено в рамках Программы фундаментальных исследований НИУ ВШЭ (Разделы 1, 3) и Программы развития НИУ ВШЭ на 2025–2036 гг. в рамках Программы стратегического академического лидерства “Приоритет-2030” национального проекта “Молодежь и дети” (Разделы 2, 4).

**Ссылка при цитировании:** Беликов И.И., Рожкова П.В., Приходько А.Н., Гольцман Г.Н., Шураков А.С. Фотонно-электронная ИС субтерагерцового I/Q смесителя на основе GaAs-на-Si // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2025. Т. 18. № 3.2. С. 187–190. DOI: <https://doi.org/10.18721/JPM.183.237>

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## Introduction

Communication technologies have become an integral part of human daily life. Their capabilities continue to grow steadily in response to society’s needs for new services and applications. State-of-the-art fifth-generation networks and systems are to be replaced by even more capable sixth-generation (6G) technologies in the foreseeable future. The allocated frequency bands for 6G wireless channels are partly above 100 GHz which potentially enables the use of both conventional and radio photonic approaches for the carrier signal generation and processing [1, 2]. Given the heritage of conventional quadrature amplitude modulation schemes in microwave wireless channels, they should be incorporated naturally into future 6G wireless systems. Thus, subterahertz (sub-THz) coherent frequency conversion devices for efficient signal modulation and demodulation at far-beyond-gigahertz baud rates are in demand. In this work, we propose a photonic-electronic integrated circuit (IC) of a sub-THz in-phase/quadrature (I/Q) mixer based on the GaAs-on-Si platform.

## Materials and Methods

Fig. 1, *a* provides a three-dimensional (3D) schematic of the proposed I/Q mixer along with field patterns in its structural elements simulated at  $f = 140$  GHz. The simulations rely on a numerical S-parameter analysis similar to that reported by us earlier in [3]. The developed Si power distribution network (PDN) has a fixed waveguide cross-section of  $0.29\lambda_0 \times 0.23\lambda_0$  (width  $\times$  height) and radii of curvature of  $0.69\lambda_0$  in all circular segments with  $\lambda_0$  denoting free-space wavelength of a guided wave. The PDN comprises straight waveguide sections adjacent to the Y-junction of the local oscillator (LO) input. They have optical lengths of  $L_l$  and  $L_o$  that can be tuned to implement a precise  $90^\circ$  delay for quadrature up- and down-conversions at the desired frequency. The bottleneck in the proposed design is the conversion of the energy of the sub-THz waves propagating in the Si PDN into alternating currents in the GaAs planar Schottky diodes [4]. This is achieved at the PDN sections with diode-loaded metallic tapered slot lines (TSLs). The sections are terminated by distributed Bragg reflectors (DBRs) to enhance the conversion. The proposed GaAs-on-Si design is compatible with the quasi-vertical Schottky diode technology [5].

The performed preliminary numerical analysis at 140 GHz yields overall insertion losses for the LO and carrier signal input lines of 7–8 dB, with 6 dB power-splitting losses in Si PDN and 1.5 dB intrinsic to the transitions between single-mode waveguides of Si PDN and diode-loaded Ti/Au TSLs (see -S31, Fig. 1, *b*). The corresponding reflection losses are as low as 28 dB at the sub-THz LO port, and the isolation for the LO+carrier ports exceeds 13–16 dB. The developed PDN-to-diode transition provides an input frequency range of 135–145 GHz, which corresponds to a fractional bandwidth of 7%. In this range and at  $L_o - L_l = 0.16\lambda_0$ , the  $90^\circ$  optical delay line ensures phase accuracy of  $89 \pm 5^\circ$  for quadrature conversion with amplitude imbalance up to 1 dB.

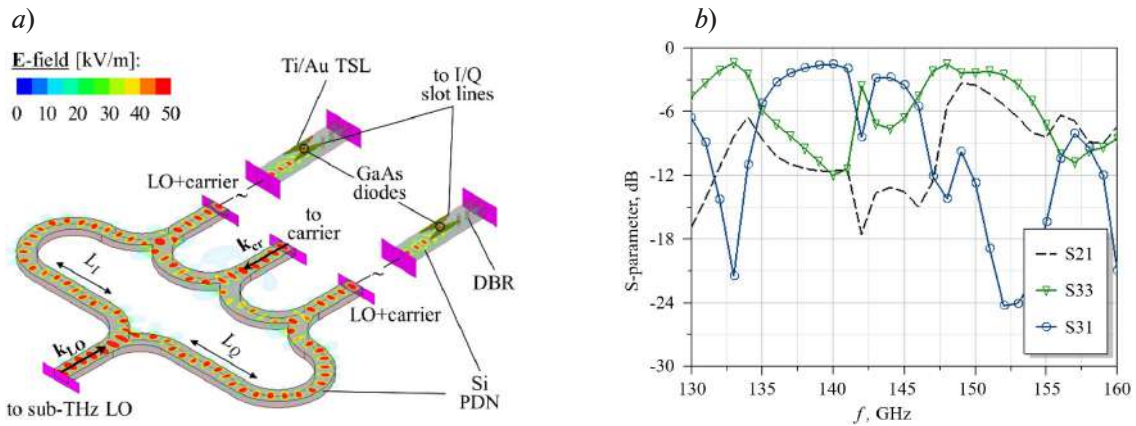


Fig. 1. 3D schematic of a 140 GHz I/Q mixer with a ribbon Si PDN (a),  $k_{LO}$  and  $k_{cr}$  are the wave vectors for LO and carrier signals and all abbreviations are denoted in the main text; scattering parameters of the PDN-to-diode transition (b), the PDN/TSL interface is represented by wave port 1, the DBR/free-space interface by wave port 2, the diode by lumped port 3

As a proof of concept, prototype of the device was manufactured in cleanroom process. The PDN with hexagonal lattice of openings with diameter of 100  $\mu\text{m}$  and lattice constant 135  $\mu\text{m}$  was performed in 450  $\mu\text{m}$ -thick Si wafer via BOSCH-process. To protect the elements of PDN during etching process the 20 nm-thick aluminum mask was preliminary performed using mask-less photolithography in lift-off process. As final step the residual aluminum mask was removed in wet KOH etchant. The deviation of linear dimensions of the device does not exceed 6%. Fig. 2, a provides photo of the prototype installed in measuring setup.

### Results and Discussion

We developed the measurement setup as follows. The microwave synthesizer equipped with the 12 $\times$ frequency multiplier is used as a source of signal providing 130–160 GHz frequency range. In order to measure the insertion losses of the carrier signal input lines of the developed PDN, the output of the source is connected through the main line of directional coupler to the PDN's port 3 as shown in Fig. 2, a. The power meter (PM) equipped with the data acquisition system (DAQ) is consequently connected to ports 1 and 2, while the remaining two ports of the PDN are loaded by matched loads. When measuring the return losses for ports 1 and 2, the DAQ-equipped PM is connected through the coupled line of directional coupler. The measured S-parameters are presented in Fig. 2, b. As one can clearly see, the optimum operation frequency is 147 GHz, where

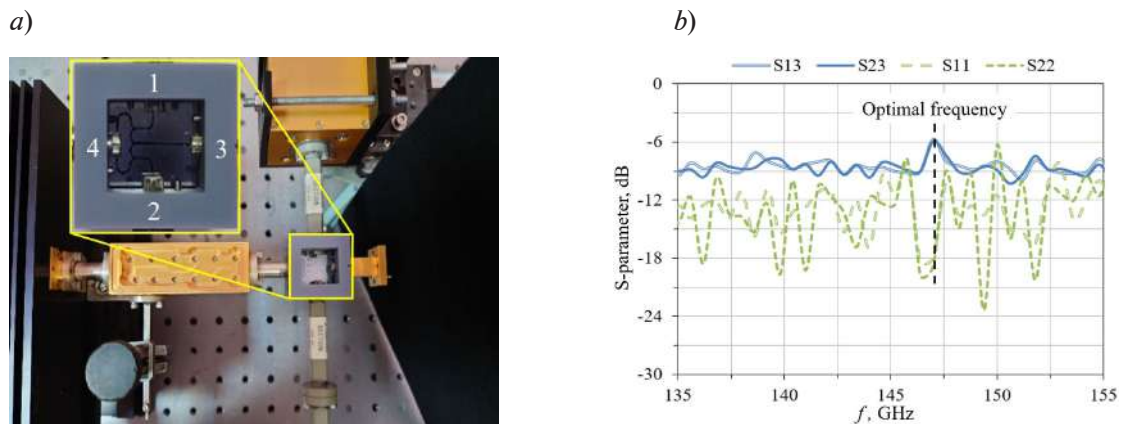


Fig. 2. Photo of the manufactured PDN with numerated ports in a measuring setup (a), ports 1 and 2 are outputs/inputs for the combined LO+carrier/the multiplied LO $\times$ I and LO $\times$ Q signals, ports 3 is the carrier signal input/output, and port 4 is the LO input; measured S-parameters of the PDN (b)

the measured insertion and return losses are equal to 6 dB and 18–20 dB, respectively. The LO input lines of the developed PDN exhibit bigger measured insertion losses, narrower operational bandwidth, but their accurate extraction requires further enhancement of the sampler holder.

The mixer design as it is ensures a baud rate of up to 25–30 GHz which is limited by the use of coaxial-to-planar interfaces in the I/Q signal input lines and low-inertial GaAs diodes [6]. We believe that our findings should be of interest to developers of 6G wireless modules and systems.

### Conclusion

We propose a photonic-electronic IC of a sub-THz I/Q mixer compatible with the GaAs-on-Si platform. Mixer conversion losses are ultimately limited by the embedded power distribution network, exhibiting 6 dB insertion losses for the local oscillator and carrier signals (excluding 1.5 dB intrinsic to the transitions between Si waveguide and nonlinear lumped elements) with reflection losses approaching 20 dB. The mixer design ensures a baud rate of up to 25–30 GHz which is currently limited by the use of coaxial-to-planar interfaces in the I/Q signal input lines. This, however, can be further improved if the terminators at the rear end of the distributed Bragg reflectors for enhanced coupling of the mixing elements are revised. Moreover, the proposed IC is designed for operation at 140–150 GHz, but can be easily scaled-down for carrier frequencies of 280–300 GHz or even significantly higher. We believe that our findings should be of interest to developers of 6G wireless modules and systems.

### REFERENCES

1. Dan I., Ducournau G., Hisatake S., et al., A terahertz wireless communication link using a super-heterodyne approach, *IEEE Transactions on Terahertz Science and Technology*. 10 (1) (2020) 32–43.
2. Harter T., Fullner C., Kemal J. N., et al., Generalized Kramers–Kronig receiver for coherent terahertz communications, *Nature Photonics*. 14 (10) (2020) 601–606.
3. Shurakov A., Belikov I., Prikhodko A., et al., Superconducting electronic-photonic platform for HEB-based terahertz spectrometers, *Applied Sciences*. 13 (10) (2023) 5892.
4. Shurakov A., Mikhalev P., Mikhailov D., et al., Ti/Au/n-GaAs planar Schottky diode with a moderately Si-doped matching sublayer, *Microelectronic Engineering*. 165 (2018) 26–31.
5. Nadri S., Moore C.M., Sauber N.D., et al., Thermal characterization of quasi-vertical GaAs Schottky diodes integrated on silicon. *IEEE Transactions on Electron Devices*. 66 (1) (2018) 349–356.
6. Vassos E., Churm J., Powell J., et al., Air-bridged Schottky diodes for dynamically tunable millimeter-wave metamaterial phase shifters. *Sci Rep* 11. 5988 (2021).

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### **Uplink satellite optical communication based on acousto-optic modulator**

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**Abstract.** High-speed data transfer is becoming increasingly necessary for modern satellite communication systems. To address growing bandwidth demands, optical technologies are proposed. Here we investigate an approach to designing an uplink optical communication system based on the acousto-optic modulation scheme. The preliminary findings suggest the applicability of this strategy to provide reliable communications with data rates up to 2.4 Mbps and a bit error rate of  $10^{-9}$ .

**Keywords:** satellite optical communications, acousto-optic modulator, Manchester encoding

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### **Восходящая спутниковая оптическая связь на основе акустооптического модулятора**

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**Аннотация.** Высокоскоростная передача данных становится все более необходимой для современных спутниковых систем связи. В связи с этим для удовлетворения



растущих потребностей предлагается использовать оптические технологии. Здесь мы исследуем подход к разработке системы оптической связи со спутником на основе схемы акустооптической модуляции. Предварительные результаты показывают применимость этого подхода для обеспечения надежной связи со скоростью передачи данных до 2,4 Мбит/с и частотой битовых ошибок  $10^{-9}$ .

**Ключевые слова:** спутниковая оптическая связь, акустооптический модулятор, манчестерское кодирование

**Финансирование:** Исследование выполнено за счет гранта Российского научного фонда № 25-22-00342.

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## Introduction

Modern satellite communication systems are experiencing growing demand for high-speed data transmission, driven by advancements in Earth remote sensing [1–3], inter-satellite communications [4–6], and satellite-based quantum key distribution [7–9]. The integration of laser communication into these fields—as opposed to traditional radio frequency technology—has emerged as a promising solution to meet this demand and offering higher bandwidth, lower latency, and greater resistance to electromagnetic interference. To address this challenge, our team deployed the Impulse-1 satellite (a 6U CubeSat) in 2023, with the goal of demonstrating bidirectional free-space optical communication [10].

To date, research has predominantly focused on downlink communication channels rather than uplinks, as the volume of downlink data significantly exceeds that of uplink transmissions. Moreover, uplink signals experience greater atmospheric attenuation due to turbulence and scattering, which demands a high-power laser source and external modulation. In this work, we present an optimized ground-to-satellite laser communication system based on a high-power laser module, a free-space acousto-optic modulator (AOM), and Manchester encoding.

## Methods and Results

External modulation of the laser beam is achieved through Bragg diffraction in an acousto-optic crystal. A piezoelectric transducer converts an applied radio frequency (RF) signal into an ultrasonic wave that propagates through the crystal. The resulting ultrasonic wave induces periodic variations in the crystal's refractive index, creating a volumetric phase grating within the material. The diffraction order depends on the incident light angle relative to the modulator. The maximum diffraction efficiency is achieved when the laser beam enters the crystal at the Bragg angle. This angle can be calculated using the Wulff–Bragg condition:

$$\theta_B = \arcsin\left(\frac{\lambda}{2n\Lambda_a}\right) = \arcsin\left(\frac{\lambda f_{RF}}{2nV_s}\right), \quad (1)$$

where  $\lambda$  is the wavelength of incident light,  $\Lambda_a$  is the acoustic wavelength,  $n$  is the refractive index of the acousto-optic crystal,  $f_{RF}$  is the frequency of the ultrasonic wave, and  $V_s$  is the speed of sound in the crystal.

The diffraction efficiency and amplitude modulation of light can be expressed as

$$\eta = \sin^2 \left( \frac{\pi}{\lambda \sqrt{2}} \sqrt{\frac{L}{W}} M_2 P_{RF} \right), \quad (2)$$

where  $L$  and  $W$  are the length and width of the piezoelectric transducer,  $M_2$  is the acousto-optic quality factor, and  $P_{RF}$  is the RF signal power.

The intensity of the diffracted light can be varied by adjusting the  $P_{RF}$ . In our case, the maximum efficiency value was 85%. The main system parameters are listed in Table 1.

Table 1

**Main system parameters**

| Optical parameters |           | Acoustic parameters |          |                 |                          |       |                            |
|--------------------|-----------|---------------------|----------|-----------------|--------------------------|-------|----------------------------|
| $\lambda$          | 808 nm    | $f_{RF}$            | 68 MHz   | $n$             | 1.46 (SiO <sub>2</sub> ) | $L$   | 30 mm                      |
| $P_{TX}$           | 35 W      | $P_{RF}$            | 20 W     | $V_s$           | 5960 m/s                 | $W$   | 5 mm                       |
| $P_{RX}$           | 5 $\mu$ W | $\theta_B$          | 3.2 mrad | $T_{rise/fall}$ | 40 ns/mm                 | $M_2$ | 1.56e-15 m <sup>2</sup> /W |

Notations:  $P_{TX}$  and  $P_{RX}$  are the optical powers of transmitter and receiver, respectively.

The AOM can be controlled using an RF driver, which is equipped with analog and digital inputs. The analog input adjusts the amplitude of the output RF signal. The digital input controls the signal waveform. By default, the driver's output RF signal is a sinusoidal waveform with a frequency of 68 MHz. Fig. 1 shows the experimental setup for testing optical communication technology.

The proposed communication system employs a multimode fiber laser module with a power output of 35 W. For experimental validation, we used a commercial single-mode 808 nm laser diode as the light source, integrated into a custom-designed driver and coupled via multimode fiber to a collimator. The emitted light was focused by a lens into the center of the AOM crystal and then recollimated using the same lens to minimize divergence. The incidence angle was

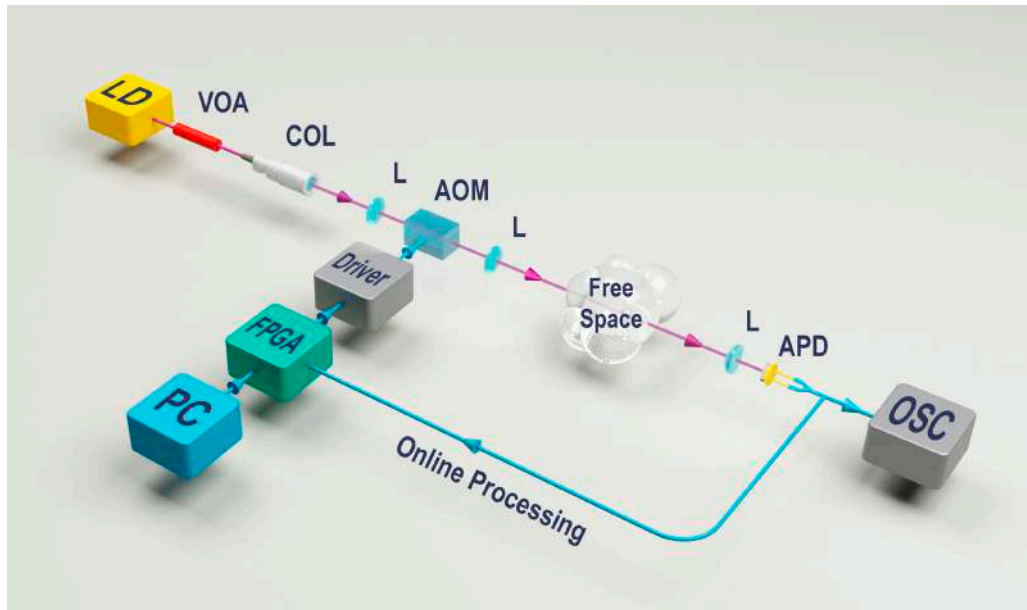


Fig. 1. Experimental setup for demonstrating of the communication system: LD is the laser diode, VOA is the variable optical attenuator, COL is the collimator, L is the lens, AOM is the acousto-optic modulator, APD is the avalanche photodiode, OSC is the digital oscilloscope, FPGA is the field-programmable gate array, PC is the personal computer

precisely adjusted to maximize diffraction efficiency. The field programmable gate array (FPGA) generates the data signal and transmits it to the AOM driver. At the physical layer, we used Manchester encoding. The modulated laser beam was then focused onto an avalanche photodiode for optical-to-electrical signal conversion. The electrical signal was recorded using a digital oscilloscope and further processed by the FPGA.

We evaluated the modulation depth (MD), quality factor ( $Q$ ), and bit error rate (BER) across different data rates at an optical power of  $5 \mu\text{W}$ . At data rates up to 2 Mbps, the MD equaled 100%, while at 4 Mbps, it decreased to 50% (see Fig. 2, *a*). For error rate assessment, we adhered to the stringent industry standard of  $\text{BER} \leq 10^{-9}$  [11, 12], which requires an  $Q \geq 6$  [13]. The system meets these specifications at data rates up to 2.4 Mbps (see Fig. 2, *b*).

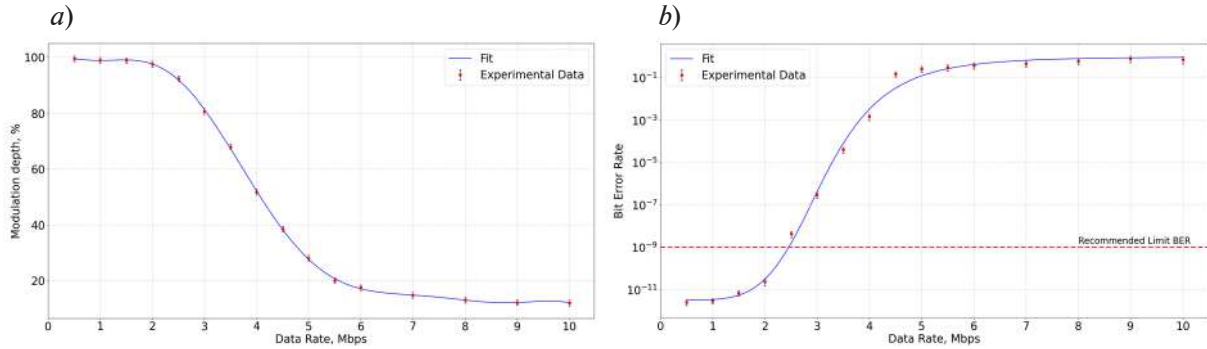


Fig. 2. Characteristics of the communication system measured in laboratory: modulation depth (*a*) and bit error probability (*b*)

System performance parameters are calculated by following equations:

$$\text{MD} = \frac{P_{\max} - P_{\min}}{P_{\max} + P_{\min}}, \quad (3)$$

where  $P_{\max}$  and  $P_{\min}$  are the optical powers that define the modulation depth;

$$Q = \frac{P_s^1 - P_s^0}{P_n^1 - P_n^0}, \quad (4)$$

where  $P_s^1$ ,  $P_s^0$ ,  $P_n^1$  and  $P_n^0$  are the optical power levels associated with the signal and noise while encoding bits “1” and “0”;

$$\text{BER} = \frac{1}{Q\sqrt{2\pi}} \exp\left(-\frac{Q^2}{2}\right). \quad (5)$$

### Conclusion

The maximum data rate at a specified BER was determined experimentally. We have demonstrated that laser communication with a satellite as part of the Impulse-1 mission is feasible using a technical solution such as acousto-optic modulation based on Manchester encoding at 2.4 Mbps with BER of  $10^{-9}$ .

### REFERENCES

1. Hui M., Zhai S., Wang D., et al., A review of leo satellite communication payloads for integrated communication, navigation, and remote sensing: Opportunities, challenges, future directions, IEEE Internet of Things Journal. (2025).
2. Fevgas G., Lagkas T., Sarigiannidis P., Argyriou V., Advances in remote sensing and propulsion systems for earth observation nanosatellites, Future Internet. 17 (1) (2025) 16.

3. Sheng M., Guo C., Huang L., Integrated Communication, Navigation, and Remote Sensing in LEO Networks with Vehicular Applications, IEEE Wireless Communications. (2024).
4. Carrasco-Casado A., Biswas A., Fields R., et al., Optical communication on CubeSats—Enabling the next era in space science, In 2017 IEEE International Conference on Space Optical Systems and Applications (ICSOS). IEEE. (2017) 46–52.
5. Carrizo C., Knappek M., Horwath J., et al., Optical inter-satellite link terminals for next generation satellite constellations, In Free-Space Laser Communications XXXII. SPIE. 11272 (2020) 8–18.
6. Spicer J., Lau S., Aucoin R., Results of SDA-standard-compatible optical inter-satellite link testing between Kepler Communications LEO satellites, In Free-Space Laser Communications XXXVII. SPIE. 13355 (2025) 1335502.
7. Liao S.K., Cai W.Q., Liu W.Y., et al., Satellite-to-ground quantum key distribution, Nature. 549 (7670) (2017) 43–47.
8. Khmelev A., Duplinsky A., Bakhshaliev R., et al., Eurasian-scale experimental satellite-based quantum key distribution with detector efficiency mismatch analysis, Optics Express. 32 (7) (2024) 11964–11978.
9. Li Y., Cai W.Q., Ren J.G., et al., Microsatellite-based real-time quantum key distribution, Nature. (2025) 1–8.
10. Miller A.V., Pismeniuk L.V., Duplinsky A.V., et al., Vector—towards quantum key distribution with small satellites, EPJ Quantum Technology. 10 (1) (2023) 52.
11. Walsh D., Moodie D., Mauchline I., et al., Practical bit error rate measurements on fibre optic communications links in student teaching laboratories. In 9th International Conference on Education and Training in Optics and Photonics (ETOP), Marseille, France, Paper ETOP021. (2005).
12. Al-Gailani S.A., Salleh M.F.M., Salem A.A., et al., A survey of free space optics (FSO) communication systems, links, and networks, IEEE Access. 9 (2020) 7353–7373.
13. Elganimi T.Y., Performance comparison between OOK, PPM and PAM modulation schemes for free space optical (FSO) communication systems: Analytical study, International Journal of Computer Applications. 79 (11) (2013).

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## High-sensitivity and low-noise GaN-based ultraviolet photodetectors

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**Abstract.** This study presents the fabrication of ultraviolet metal-semiconductor-metal photodetectors based on ultrathin epitaxial layers GaN grown on sapphire substrates. The devices were characterized through current-voltage measurements and sensitivity and noise characteristics calculations. At a bias voltage of 1 V, the PDs demonstrated a responsivity of  $156 \text{ mA}\cdot\text{W}^{-1}$  and a noise-equivalent power of  $0.4\cdot 10^{-22} \text{ W}\cdot\text{Hz}^{-0.5}$ , which highlight their high-sensitivity and low-noise performance.

**Keywords:** ultraviolet photodetector, GaN, metal-semiconductor-metal

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Материалы конференции

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## Высокочувствительные и малошумящие ультрафиолетовые фотодетекторы на основе GaN

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**Аннотация.** В настоящей работе представлены ультрафиолетовые фотодетекторы типа металл-полупроводник-металл на основе ультратонких эпитаксиальных слоев GaN, выращенных на подложках  $c\text{-Al}_2\text{O}_3$ . Вольт-амперные характеристики устройств были исследованы в темноте и при ультрафиолетовом освещении, в результате чего были определены их чувствительность и эквивалентная мощность шума —  $156 \text{ mA}\cdot\text{Вт}^{-1}$  и  $0.4\cdot 10^{-22} \text{ Вт}\cdot\text{Гц}^{-0.5}$  соответственно при напряжении 1 В.

**Ключевые слова:** ультрафиолетовый фотодетектор, GaN, металл-полупроводник-металл

**Финансирование:** Работа выполнена при поддержке Министерства образования и науки (Государственное задание № FSRM-2023-0006).





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### Introduction

Ultraviolet photodetectors (UV PDs) are critical components in a wide array of applications, including environmental monitoring, flame detection, medicine and optical communication systems [1]. In addition, there is a growing demand for high-performance UV sensors that can combine high sensitivity and low noise.

Among many materials, GaN has emerged as a leading candidate for fabricating these devices due to wide bandgap ( $\sim 3.4$  eV), which provides UV selectivity without expensive optical filters, as well as its exceptional thermal stability, radiation resistance, and high electron mobility [2]. These properties of GaN make this semiconductor an excellent alternative to silicon, the detectors based on which have low UV sensitivity and degrade under prolonged exposure to UV radiation.

There are various types of PDs designs, but the most attractive ones are metal-semiconductor-metal (MSM) PDs, which offer high speed and sensitivity as well as ease of fabrication [3]. In this article, high-sensitivity and low-noise UV MSM PDs fabricated on ultrathin GaN epitaxial layers are presented.

### Materials and Methods

GaN epitaxial layers were synthesized by plasma-assisted molecular beam epitaxy (PA MBE) using Veeco GEN 200 industrial type MBE setup on sapphire ( $c\text{-Al}_2\text{O}_3$ ) substrates. The surface morphology of the synthesized samples was characterized using a scanning electron microscope (SEM) Supra 25 Zeiss. The electrical properties of the GaN epitaxial layers, including conductivity type and concentration of charge carriers in the GaN epitaxial layers were assessed using Hall effect measurements based on the Van der Pauw four-point probe method using the Ecopia HMS-3000 system.

MSM PDs with Ni/Au semitransparent interdigitated electrodes were fabricated on the grown layers using standard laser lithography technique, e-beam and thermal vacuum evaporation. Lithography was carried out on a Heidelberg DWL 66FS setup, metal sputtering was performed on an BOC Edwards Auto 500 system. The thickness of the metallization was determined using an Ambios XP-1 profilometer.

The current-voltage ( $I$ – $V$ ) characteristics of the formed PDs were measured in the dark and under UV illumination with a wavelength of 365 nm using Agilent B1500A semiconductor device parameter analyzer.

### Results and discussion

The 200 nm GaN layer grown on the sapphire substrate exhibits a labyrinth-like surface morphology (Fig. 1, *a*, *b*). This structure is probably a result of the Volmer–Weber growth mode [4], driven by elastic stress arising from the significant lattice mismatch between GaN and  $c\text{-Al}_2\text{O}_3$  ( $\sim 16\%$ ). It is important to note that the rough surface morphology can potentially provide more efficient absorption of incident photons and lead to an increase in PDs responsivity compared to devices based on smooth layers.

Hall effect measurements confirmed n-type conductivity of undoped GaN epitaxial layers with a carrier concentration of  $6.4 \cdot 10^{18} \text{ cm}^{-3}$ . Such a high value can be associated with the three-dimensional MBE growth of GaN layers and with a large number of defects in them.

Fig. 1, *c* shows PDs with semitransparent Ni/Au (5/10 nm) interdigitated electrodes fabricated on synthesized ultrathin GaN epitaxial layers.

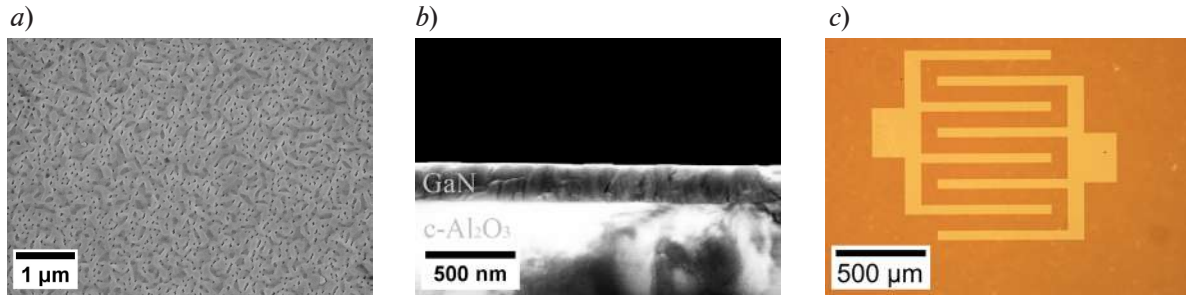


Fig. 1. SEM images of the GaN/c-Al<sub>2</sub>O<sub>3</sub> epitaxial structure: cross-section (a) and plan view (b), optical image of the PDs (c)

During  $I$ – $V$  measurements, it was observed that exposure to UV radiation leads to an increase in device current (Fig. 2, a). In addition, the PDs exhibit a relatively low dark current (0.02 mA at 1 V bias). The highest value of the photocurrent to dark current ratio (which determines the noise characteristics of the devices) was observed at low voltages (at 0.05 V) and was 39, at higher voltages this ratio was greater than 1.

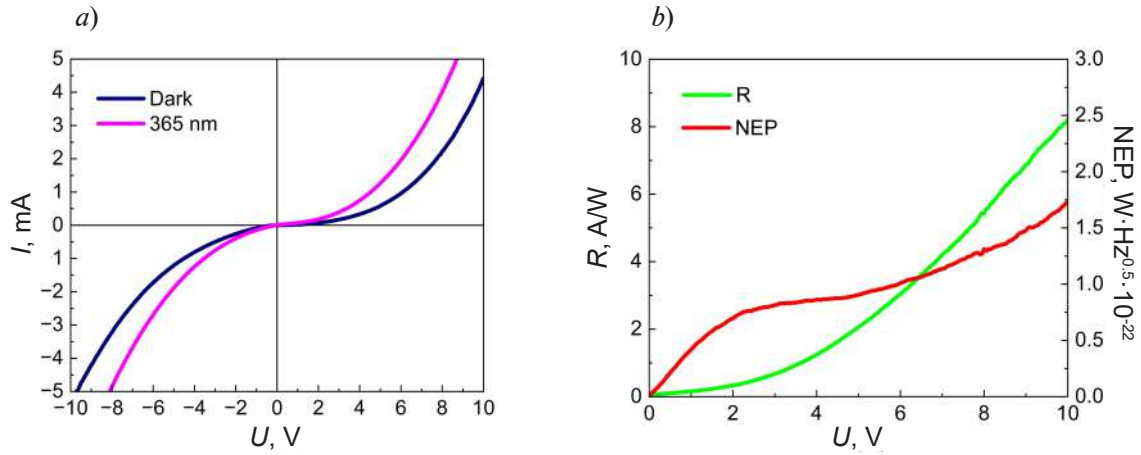


Fig. 2.  $I$ – $V$  characteristics (a) and voltage dependence of photoresponse and NEP (b) of the formed PDs

In addition, the device performance was evaluated by determining responsivity ( $R$ ) [5]:

$$R = \frac{I_{365nm} - I_d}{P_{opt}} = \frac{I_{ph}}{P_d \cdot A}, \quad (1)$$

where  $I_{365nm}$  the current measured upon UV illumination,  $I_d$  is the dark current,  $I_{ph}$  is the photocurrent,  $P_{opt}$  is the optical power,  $P_d$  is the power density and  $A$  is the active area of the device. Also, noise equivalent power (NEP) of the fabricated devices was calculated using the following equation [5]:

$$NEP = \frac{\sqrt{2eI_d}}{R}, \quad (2)$$

where  $e$  is electron charge. The responsivity and NEP values at 1 V for the PDs were 156 mA·W<sup>−1</sup> and 0.4·10<sup>−22</sup> W·Hz<sup>−0.5</sup>. These results are comparable to PDs based on thin nanostructured GaN epitaxial layers reported in literature [6]. As noted above, the high responsivity value can be associated with the rough surface morphology, providing a large area of interaction of photons with the semiconductor. This could also provide a low value of the NEP. Thus, in this work, high-sensitivity and low-noise UV MSM PDs based on ultrathin GaN were demonstrated.

### Conclusion

In this work, UV high-sensitivity and low-noise PDs based on the GaN/c-Al<sub>2</sub>O<sub>3</sub> were demonstrated. It was found that the fabricated devices have a responsivity and noise equivalent power equal to 156 mA·W<sup>-1</sup> and 0.4·10<sup>-22</sup> W·Hz<sup>-0.5</sup> at 1 V respectively. These results contribute to the development of high-performance GaN-based UV PDs.

### REFERENCES

1. **Cheng K.Y.**, III–V Compound Semiconductors and Devices, CRC Press. (2020).
2. **Bi W.W., Kuo H.-Ch.H., et al.**, Handbook of GaN semiconductor materials and devices, CRC Press. (2017).
3. **Wilson G.A., DeFreez R.K.**, Improving diode-laser-induced fluorescence detection of airborne biological particles by exciting multiple biofluorophores, Chemical and Biological Sensing V. – SPIE. 5416 (2004) 157–167.
4. **Daruka I., Barabasi A.-L.**, Dislocation-Free Island Formation in Heteroepitaxial Growth: A Study at Equilibrium, Physical Review Letters. 79 (19) (1997) 3708–3711.
5. **Aggarwal V., Ramesh C., Varshney U., et al.**, Correlation of Crystalline and Optical Properties with UV Photodetector Characteristics of GaN Grown by Laser Molecular Beam Epitaxy on A-Sapphire, Applied Physics A. 128 (11) (2022) 989.
6. **Nasiri N., Jin D., Tricoli A.**, Nanoarchitectonics of visible-blind ultraviolet photodetector materials: critical features and nano-microfabrication, Advanced Optical Materials. 7 (2) (2019) 1800580.

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## Spectral composition of radiation from microlaser coupled to waveguide

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**Abstract.** We investigate the mode composition of a microdisk laser coupled with an optical waveguide. The output spectra of emission and light-current characteristic of the microlaser obtained from the output edge of the waveguide are studied. The microlaser demonstrates single-mode emission in consecutive ranges of injection currents, that are alternated with pronounced mode hopping. The intensity of the modes changes non-monotonically with the growth of the pump current. Such a behavior, which we attribute to the laser self-heating, results in numerous kinks in the light-current curve. The kink-free current range in which single-mode lasing is maintained reaches 25 mA.

**Keywords:** whispering gallery mode, microdisk laser, mode switching, single mode lasing

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## Спектральный состав излучения микролазера, сопряженного с волноводом

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**Аннотация.** Исследован спектральный состав и ватт-амперные характеристики излучения микродискового лазера, связанного с оптическим волноводом. Наблюдалось переключение лазерных мод с ростом тока накачки. При этом в диапазонах тока накачки между переключением мод лазерная генерация имела одномодовый характер. Такое поведение обусловлено саморазогревом лазера и приводит к множественным изломам на ватт-амперной характеристике. Диапазон токов, в котором не наблюдается скачков интенсивности и сохраняется одномодовая генерация, достигает 25 мА.

**Ключевые слова:** моды шепчущей галереи, микродисковый лазер, переключение мод, одномодовая лазерная генерация



**Финансирование:** Исследование осуществлено в рамках Программы фундаментальных исследований НИУ ВШЭ.

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## Introduction

The realization of photonic integrated circuits (PICs) using III-V semiconductors has recently attracted great interest due to the possibility of combining both classical PIC components (waveguides, splitters, interferometers, etc.) and active elements (radiation sources, receivers) on one platform [1]. Microdisk (MD) lasers with an active region based on quantum dots (QDs), characterized by high Q-factor ( $\sim 10^5$ ) and small size, are promising candidates for signal sources in PICs [2]. The directional light output from such microlasers can be achieved by coupling them with lateral optical waveguides (OW) [3]. The light-current ( $L-I$ ) characteristics of MD lasers obtained from the edge of the coupled OW play a critical role in information processing applications, particularly in the context of promising direct modulation [4]. Here we study the correlation between the current injected to a MD laser, output power and peculiarities of emission spectra transmitted through an OW made of the same heterostructure.

## Materials and Methods

The heterostructure under study was fabricated by Metal-Organic Chemical Vapor Deposition on an  $n^+$ -GaAs substrate  $6^\circ$ -misoriented off (100) plane. It consists of bottom  $n$ -doped (Si) and top  $p$ -doped (Zn)  $\text{Al}_{0.39}\text{Ga}_{0.61}\text{As}$  cladding layers of  $1.55\text{ }\mu\text{m}$  thickness each, with 620-nm-thick  $i$ -GaAs waveguiding layer in between and 0.35- $\mu\text{m}$ -thick  $p^{++}$ -GaAs contact layer. An active region was located within the waveguiding layer and included five layers of  $\text{In}_{0.4}\text{Ga}_{0.6}\text{As}/\text{GaAs}$  QDs [5] with 40 nm GaAs spacers. MD lasers with diameter of 40  $\mu\text{m}$ , coupled to OW with a length of about 440  $\mu\text{m}$  were formed by electron lithography and plasma reactive ion etching. On top of the microlasers, individual ohmic AgMn/Ni/Au contacts were formed to the  $p^{++}$ -GaAs layer. Substrate was thinned and AuGe/Ni/Au metallization was deposited on its bottom side to serve as a common  $n$ -contact. All MD lasers were studied at room temperature under continuous-wave pumping. To collect electroluminescence (EL) of microlaser coupled to the OW, Mitutoyo  $\times 20$  microobjective was focused on the OW end. The EL spectra were registered using an optical spectrum analyzer (Yokogawa AQ 6370C) and light-current ( $L-I$ ) curves were measured using Thorlabs S155C power meter.

## Results and Discussion

Fabricated devices demonstrated lasing at room temperature under continuous-wave pumping. The threshold current for microlasers were about 17 mA. Here, we focused on the MD laser that demonstrated single-mode emission at consecutive pump current intervals with mode switching in between. The studied range of pumping currents 0–75 mA was mainly limited by thermal rollover.

A typical  $L-I$  curve of 40  $\mu\text{m}$  MD laser obtained from the edge of the OW is presented in Fig. 1, *a* as a solid line. Lasing threshold of the studied MD laser was determined to be equal to 17 mA by analysis of the EL spectra. The knee on the  $L-I$  curve, which typically corresponds to the lasing threshold, is not visible in Fig. 1, *a* due to the high contribution of spontaneous emission. An increase in the pumping current leads to a nonmonotonic growth of the MD laser optical power, i.e. local minima and maxima are observed. To understand the cause of this behavior, we studied the spectral characteristics of the microlaser. Lasing spectra of the MD laser corresponding to different pump currents are shown in Fig. 1, *b*. Lasing starts via the



mode I, which has a wavelength of about 1051 nm at the threshold current. Further increase of the current leads to a slow redshift of the lasing wavelength up to a pumping current of 27 mA, where an abrupt change in wavelength occurs caused by mode hopping.

The intensities of certain lasing modes, from I to V, are shown in Fig. 1, *a* by symbols. Each data point was obtained by fitting a mode line in the EL spectrum with a Gaussian curve. The behavior of the  $L-I$  curves correlates well with the changes in the optical power of the lasing modes. For example, each time the intensity of a certain mode decays, a local minimum is observed on the  $L-I$  curve. Some of the observed raises on the  $L-I$  curve are correlated with mode switching process, happening at pumping currents, easily identified in Fig. 2, *a*. In between these current values the studied device demonstrates single-mode lasing emission. The other of the observed  $L-I$  curve peculiarities coincide with change in lasing mode intensity, as observed at currents 53, 60, 63, 74 and, less pronounced, at 40 mA.

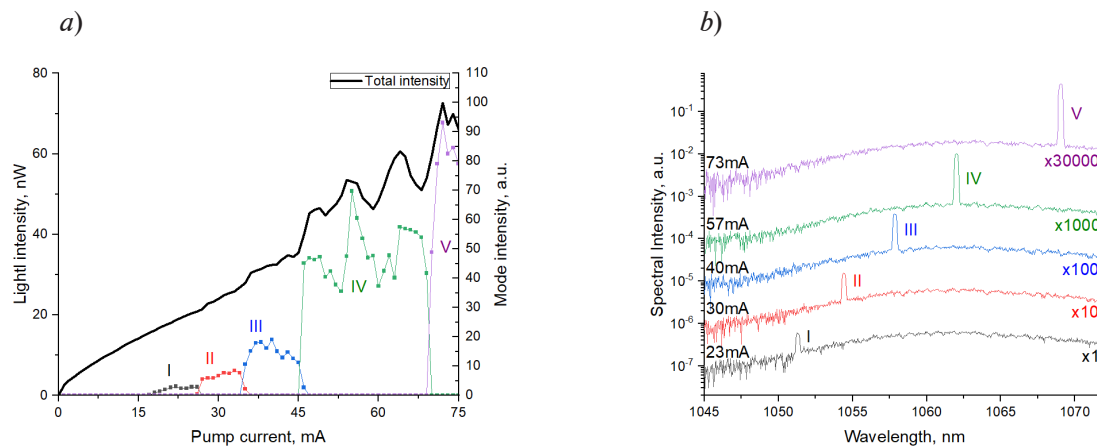


Fig. 1. Intensities of modes (symbols) and light intensity (solid line) of the investigated microdisk laser as a function of pump current (*a*). Spectra at different pump currents (*b*) color codes of modes are the same on both graphs

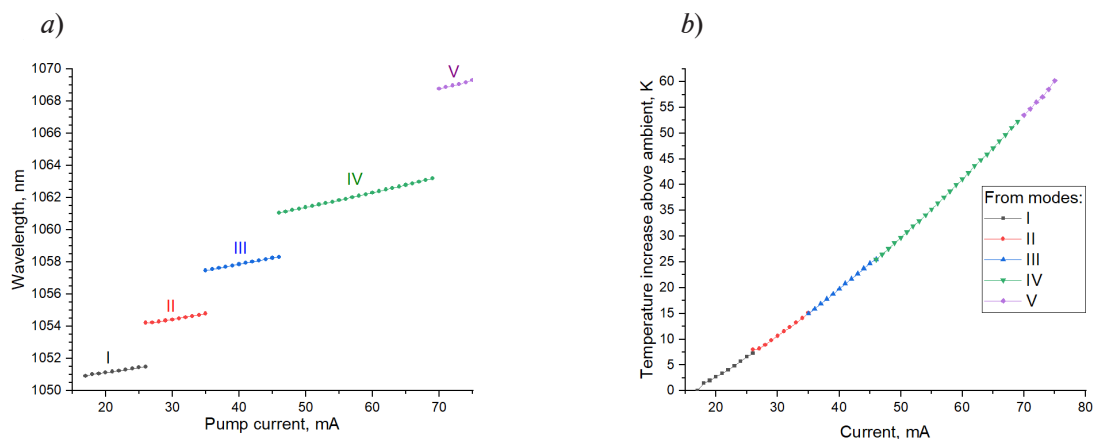


Fig. 2. Dependences of mode wavelengths (*a*) and temperature of laser self-heat (*b*) on pump current

The same slope of the current-induced redshift is observed for all lasing modes, as illustrated in Fig. 2, *a*. To evaluate an increment of the device temperature above the ambient temperature, a temperature coefficient of 80 pm/K obtained in work [6] was used (Fig. 2, *b*). The dependence of excess temperature on current changes from a linear to a quadratic function for higher currents in agreement with the model of Ref. [7]. The temperature increment of 60 K was estimated for the current at which thermal rollover starts.



We associate both redshift and mode hopping with self-heating of the device. On the one hand, the raise of the microlaser temperature causes a drift in the structure refractive index that leads to a redshift of the wavelength of a particular optical mode. On the other hand, self-heating of the device results in a narrowing of the bandgap and, as a result, in a redshift of the active region gain profile. A combination of these effects leads to mode hopping [8]. Increased intensity of modes IV and V compared to modes I–III can be explained by their spectral position lying outside of the OW absorption region. The interval of currents in which the IVth mode persists is 25 mA and is about two times greater than that for other modes. The spectral distance between modes IV and V is also twice the average for the other consecutive pairs of modes.

### Conclusion

In this work spectral composition of MD laser radiation collected from the coupled OW was studied. We noticed peculiarities on the  $L$ – $I$  curve. Some of them correspond to the laser mode switching and the appearance of the next whispering gallery mode in the EL spectrum. We attribute the mode switching behavior to the self-heating of the device under study, which leads to a redshift in the active region gain spectrum. It was shown that a stable output of single-mode emission of MD laser through a coupled OW can be achieved over a large range of pumping currents (25 mA).

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### REFERENCES

1. Dietrich C.P., et al., GaAs integrated quantum photonics: towards compact and multi-functional quantum photonic integrated circuits, *Laser & Photonics Reviews*, 10 (6) (2016) 870–894.
2. Kryzhanovskaya N., et al., III–V microdisk/microring resonators and injection microlasers, *J. Phys. D: Appl. Phys.*, 54 (45) (2021) 453001.
3. Lv X.-M., et al., Analysis of vertical radiation loss and far-field pattern for microcylinder lasers with an output waveguide, *Opt. Express, OE.*, 21 (13) (2013) 16069–16074.
4. Kryzhanovskaya N.V., et al., Direct modulation characteristics of microdisk lasers with InGaAs/GaAs quantum well-dots, *Photon. Res., PRJ*, 7 (6) (2019) 664–668.
5. Maximov M.V., et al., Light emitting devices based on quantum well-dots, *Applied Sciences*, 10 (3) (2020) 1038.
6. Kryzhanovskaya N., et al., Continuous-wave lasing at 100° C in 1.3  $\mu\text{m}$  quantum dot microdisk diode laser, *Electronics Letters*, 51 (17) (2015) 1354–1355.
7. Zhukov A.E., et al., Impact of self-heating and elevated temperature on performance of quantum dot microdisk lasers, *IEEE Journal of Quantum Electronics*, 56 (5) (2020) 1–8.
8. Zhukov A.E., et al., Quantum-dot microlasers based on whispering gallery mode resonators, *Light Sci Appl.*, 10 (1) (2021) 80.

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## Modeling weather-resilient laser communication: PPM performance with SNSPD in satellite links

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**Abstract.** Laser communication using satellites represents a promising avenue for data transmission in geographically distant areas without advanced infrastructure. This approach is characterized by its high transmission rate and low power requirements, providing substantial benefits over optical fiber and radio communication. However, the optical channel should exhibit greater transparency for light transmission, resulting in a severely restricted application of this technique for information transmission during adverse weather conditions or over long distances. To mitigate the limitations, the employment of a superconducting single-photon detector as a receiver has been proposed. Here, we provide a numerical analysis of a laser communication system to determine the atmospheric attenuation thresholds required to establish a reliable laser link using the pulse position modulation (PPM) scheme and superconducting nanowire single-photon detectors (SNSPD).

**Keywords:** laser communication, satellite, SNSPD, PPM

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Материалы конференции

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## **Моделирование устойчивой к атмосферным воздействиям лазерной связи: характеристики PPM с SNSPD в спутниковых линиях связи**

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**Аннотация.** Лазерная связь со спутником является перспективным методом передачи данных в географически удаленных регионах с недостаточно развитой инфраструктурой. Данная технология обладает высокой скоростью передачи информации и низким энергопотреблением, что обеспечивает ее существенные преимущества перед традиционными способами связи. Однако критически важным требованием к оптическому каналу является высокая прозрачность для эффективного распространения светового сигнала, что накладывает значительные ограничения на применение данного метода в условиях неблагоприятных метеорологических явлений или на значительных расстояниях. Для снижения указанных ограничений предложено использование сверхпроводникового однофотонного детектора (СПОД) в качестве приемного устройства. В ходе численного моделирования лазерной системы связи были определены пороговые значения атмосферного ослабления, при которых обеспечивается надежная установка соединения при применении схемы фазово-импульсной модуляции (PPM) в сочетании со СПОД.

**Ключевые слова:** лазерная связь, спутник, сверхпроводниковый однофотонный детектор, PPM

**Финансирование:** Данная работа была проведена при поддержке Министерства образования и науки Российской Федерации в рамках Программы стратегического академического лидерства «Приоритет 2030» (Стратегический проект «Квантовый интернет»).

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## **Introduction**

Laser communication between low Earth orbit satellites and ground stations represents a promising advancement in data transmission technologies [1]. While offering notable advantages in data rate and energy efficiency, this method faces inherent limitations that prevent its widespread adoption for long-distance communication. However, the use of superconducting





detectors, characterized by minimal dead time, high quantum efficiency, and low dark count rates, enables the detection of signals significantly attenuated by atmospheric absorption, scattering, and adverse weather conditions [2–5].

Given that these detectors exhibit low timing jitter and sharp signal rise times, PPM proves to be the most efficient encoding scheme. According to the PPM scheme, information is encoded by the temporal position of a pulse within a predefined time slot, allowing the transmission of multiple bits per symbol [6]. We conduct a theoretical study of laser beam attenuation under clear atmospheric circumstances and signal-to-noise dependence, and we calculate the threshold for extra losses that might compensate for adverse weather impacts in order to achieve reliable laser communication in this system.

### Methods and Results

One of the key parameters in modeling optical laser communication is signal attenuation ( $C_{att}$ ), which for a satellite-to-ground link depends on the spacecraft's orbital parameters:

$$C_{att} = C_{dif}(h, w_0, \lambda, \theta_{El}) \cdot C_{pointing}(\theta_{err}) \cdot C_{weather}(\kappa) \cdot C_{turb}(\theta_{El}, \lambda) \cdot C_{ref}(\theta_{El}), \quad (1)$$

where  $C_{dif}$  is the the attenuation due to optical beam diffraction,  $C_{pointing}$  is the losses from spacecraft pointing errors toward the ground station,  $C_{turb}$  is the atmospheric turbulence-induced attenuation,  $C_{weather}$  is the the atmospheric attenuation coefficient,  $h$  is the the spacecraft's orbital altitude,  $\lambda$  is the the laser wavelength,  $\theta_{El}$  is the the spacecraft's elevation angle above the ground station,  $w_0$  is the the output aperture radius (beam waist) of the spacecraft's optical system,  $\theta_{err}$  is the pointing error of the spacecraft relative to the ground station,  $\kappa$  is the the atmospheric extinction coefficient.

The optical link budget between laser terminal Vector and a ground station employing a 600 mm aperture receiver was computationally analyzed (see Fig. 1).

The aforementioned dependencies of signal attenuation in the satellite-to-ground communication channel and the background noise level enable determination of the signal-to-noise ratio during optical signal detection at the ground station using SNSPD. It also allows us to estimate the bit error rate (BER) for the PPM scheme [6] with the number of time slots ( $L = 4$ ) as

$$\text{BER}_{\text{PPM}} = \frac{1}{2} \text{erfc} \left( \frac{1}{2\sqrt{2}} \sqrt{\text{SNR} \frac{L}{2} \log_2 L} \right). \quad (2)$$

Numerical simulations were performed to evaluate the potential enhancement of the link budget through implementation of a superconducting nanowire single-photon detector as the receiver

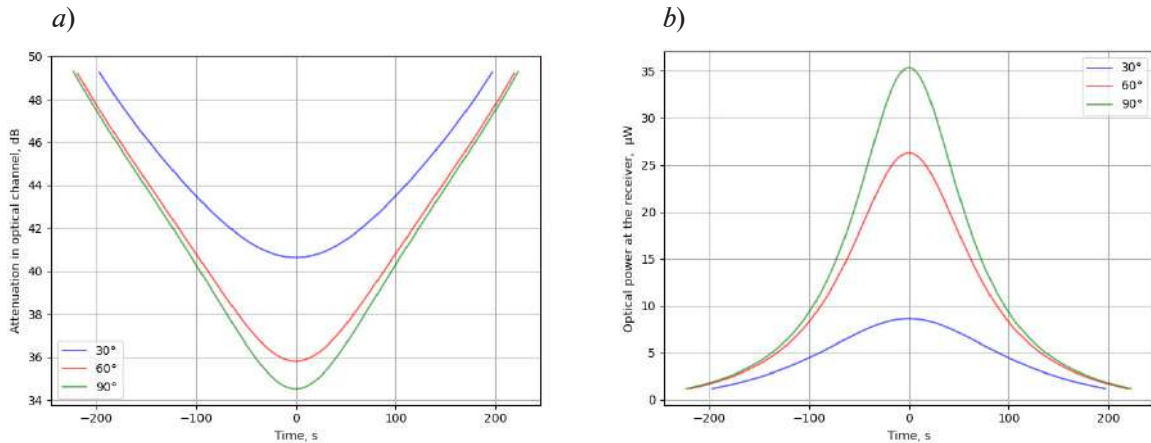


Fig. 1. Optical attenuation of a laser link (a). Optical power at the receiver according to the characteristics of laser terminal Vector [7, 8] and Eq. 1 (b)

(see Fig. 2). The minimum optical power was calculated based on two target bit error rate values:  $\text{BER} = 10^{-3}$ , selected as the threshold at which error-correcting codes (such as LDPC) enable error-free communication, and  $\text{BER} = 10^{-12}$ , chosen to ensure a 0.01% probability of a single error occurring per satellite communication session. The noise signal was normalized such that one data transmission period (3.125 MHz) corresponded to 1 and 0.5 noise photons, respectively, for the two BER cases under consideration.

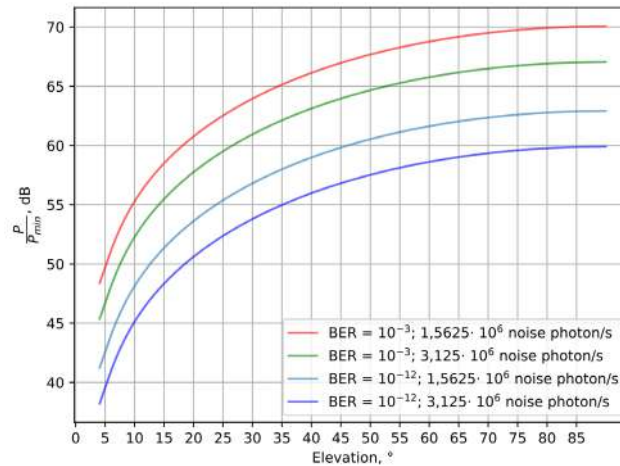


Fig. 2. Atmospheric attenuation thresholds with different BER and noise rate for laser terminal Vector

### Conclusion

We have demonstrated that an SNSPD-based laser communication system employing PPM can tolerate additional losses up to 70 dB while maintaining a BER of  $10^{-3}$  at 0,5 noise photons per period, and 60 dB at an ultra-low BER of  $10^{-12}$  with 1 noise photons per period ( $\theta_{El} = 90^\circ$ ). These loss budgets have confirmed that the system is capable to maintain stable satellite links through moderate atmospheric obscuration.

### REFERENCES

1. Kaushal H., Kaddoum G., Optical communication in space: Challenges and mitigation techniques, IEEE communications surveys & tutorials. 19 (1) (2016) 57–96.
2. Hao H., Zhao Q.Y., Huang Y.H., et al., A compact multi-pixel superconducting nanowire single-photon detector array supporting gigabit space-to-ground communications, Light: Science & Applications. 13 (1) (2024) 25.
3. Willis M.M., Kerman A.J., Grein M.E., et al., Performance of a multimode photon-counting optical receiver for the NASA lunar laser communications demonstration, In International Conference on Space Optical Systems and Applications (ICSOS). (2012).
4. Grein M.E., Kerman A.J., Dauler E.A., Willis M.M., et al., An optical receiver for the lunar laser communication demonstration based on photon-counting superconducting nanowires, In Advanced Photon Counting Techniques IX, SPIE. 9492 (2015) 11–16.
5. Dauler E.A., Robinson B.S., Kerman A.J., et al., 1.25-Gbit/s photon-counting optical communications using a two-element superconducting nanowire single photon detector, In Advanced photon counting techniques SPIE. 6372 (2006) 286–293.
6. Elganimi T.Y., Performance comparison between OOK, PPM and PAM modulation schemes for free space optical (FSO) communication systems: Analytical study, International Journal of Computer Applications. 79 (11) (2013).
7. Miller A.V., Pismeniuk L.V., Duplinsky A.V., et al., Vector – towards quantum key distribution with small satellites, EPJ Quantum Technology. 10 (1) (2023) 52.
8. Khmelev A.V., Ivchenko E.I., Miller A.V., Duplinsky A.V., Kurochkin V.L., Kurochkin Y.V., Semi-empirical satellite-to-ground quantum key distribution Model for realistic receivers, Entropy. 25 (4) (2023) 670.

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## **Influence of the nonlinear effects on the high bit rate fiber-optics communication system**

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**Abstract.** Fiber-optic telecommunication systems provide high information capacity, defined as the product of bit rate and transmission distance. To achieve high information capacity, it is necessary to take into account all the effects that affect symbol pulses in optical fiber. Experimental investigation has shown that control of the symbol pulse spectrum allows us to identify the effects of their self-action and achieve maximum information capacity of the telecommunication system.

**Keywords:** fiber-optic communication system, optical fiber, dispersion-shifted fiber, nonlinear effects, Phase Self Modulation

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Материалы конференции

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## **Влияние нелинейных эффектов на высокоскоростную-волоконно-оптическую систему связи**

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**Аннотация.** Волоконно-оптические телекоммуникационные системы обеспечивают высокую информационную емкость, определяемую как произведение скорости передачи данных на дальность передачи. Для достижения высокой информационной емкости необходимо учитывать все эффекты, которые влияют на символьные импульсы в оптоволокне. Экспериментальное исследование показало, что управление спектром символьных импульсов позволяет выявить эффекты их самовоздействия и достичь максимальной информационной емкости телекоммуникационной системы.

**Ключевые слова:** волоконно-оптическая система связи, оптическое волокно, волокно со смещенной дисперсией, нелинейные эффекты, фазовая самомодуляция

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## Introduction

Long-haul fiber-optic distance data transmission involves the use of high-power symbol optical pulses. Given the small size of the mode spot in single-mode optical fiber, nonlinear effects have an impact. Nonlinearity results in a change in the spectrum of the optical signal, and this can be easily controlled using optical spectral analysis.

The change in the shape of the envelope occurs later and these changes are difficult to register. It is necessary to know the effect of nonlinearity for each case. In general, this depends not only on the optical fiber parameters and the input power, but also on the specific laser and its chirp. In dense wavelength division multiplexing (DWDM) systems, the quality of data transmission is affected by linear (loss, dispersion) effects and nonlinear effects (Carrier-Induced Phase modulation, CIP, Four-Wave Mixing, FWM, Stimulated Raman Scattering, SRS, Stimulated Brillouin Scattering, SBR, and others) [1–5].

Some nonlinear effects appear when the pulse power exceeds the threshold level or when there are the large number of spectral channels. The CIP-effect is present not only in DWDM systems, but in single channel system also. So we investigated CIP effect in the high bitrate fiber-optic communication system.

## Experimental Results and Discussion

Nonlinear properties of optical fibers are most clearly manifested in the region of anomalous (negative) dispersion. In the region of negative values of group velocities, compensation of dispersion broadening of the pulse by nonlinear effects and formation of a soliton is possible. The joint effect of group velocity dispersion (GVD) and self-phase modulation (SPM) on the process of propagation of an optical pulse is of key importance.

In the presence of nonlinear phase self-modulation, the phenomenon of modulation instability occurs. In many nonlinear systems, the stationary wave state turns out to be unstable. The combined action of nonlinear and dispersion effects can be studied by solving the basic propagation equation.

The propagation equation in the case where losses can be neglected is

$$i \frac{\partial A}{\partial z} = \frac{1}{2} \beta_2 \frac{\partial^2 A}{\partial t^2} - \gamma |A|^2 A$$

is the nonlinear Schrödinger equation, where  $A(z, t)$  is the amplitude of the wave packet envelope,  $\beta_2$  is the value of the group velocity dispersion,  $\gamma$  is the nonlinearity parameter for phase self-modulation. In the case of continuous radiation, the amplitude  $A$  at the beginning of the optical fiber ( $z = 0$ ) does not depend on  $t$ .

In the region of negative dispersion ( $\beta_2 < 0$ ), the solution of the nonlinear Schrödinger equation becomes unstable, since spontaneous modulation of the steady state occurs. Nonlinear effects lead to the broadening of the signal spectrum in the optical fiber. The maximum gain of the nonlinear signal occurs at the frequencies that are separated from the signal frequency by the value  $\Delta f$  [1, 2]:

$$\Delta f = \pm \frac{1}{2\pi} \sqrt{\frac{2\gamma P_o}{|\beta_2|}},$$

where  $P_o$  is the input optical pulse power. This results in the appearance of two side spectral maxima. In the used Non-Zero Dispersion-Shifted fiber (NZDSF) these parameters are: the group velocity dispersion  $\beta_2 = -2.5 \text{ ps}^2/\text{km}$ , nonlinear coefficient  $\gamma = 2.5 \text{ W}^{-1} \text{ km}^{-1}$  at the wavelength  $\lambda = 1.55 \text{ }\mu\text{m}$ .

Even when only one pump radiation propagates in the fiber, CIP can lead to spontaneous decay of the stationary harmonic wave into the periodic train of pulses. Spontaneously emitted or thermal photons act as the optical signal, amplified by modulation instability. Therefore, direct evidence of CIP can be the presence of two additional spectral components located symmetrically relative to the central frequency  $f_o$  with a spectral detuning  $f = f_o \pm \Delta f$ .



The experimental study was carried out with the measuring stand included the telecommunication DWDM equipment (Fig. 1). The experimental setup included: the laser source ( $\lambda = 1550$  nm), optical Er-doped amplifier; optical fiber; attenuator; optical spectrum analyzer. Initial pulse power changes from a 1 dBm to 24 dBm in the optical fiber.

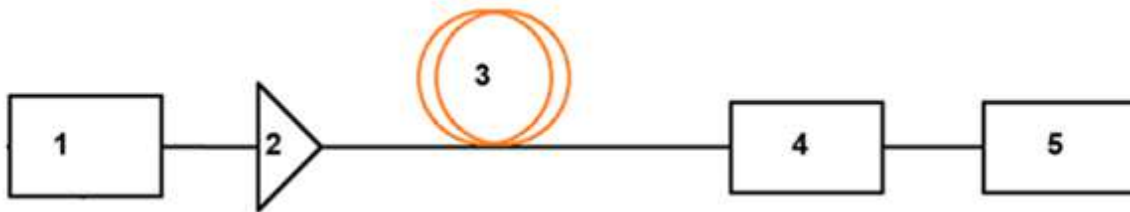


Fig. 1. Structural block diagram of the measuring stand:  
laser source ( $\lambda = 1550$  nm) 1, optical Er-doped amplifier 2, optical fiber 3,  
attenuator 4, optical spectrum analyzer Yokogawa AQ6370C 5

The results of the experimental investigation are presented in the Fig. 2. Change of the optical signal spectrum at  $\lambda = 1550$  nm is the result of CIP-effect.

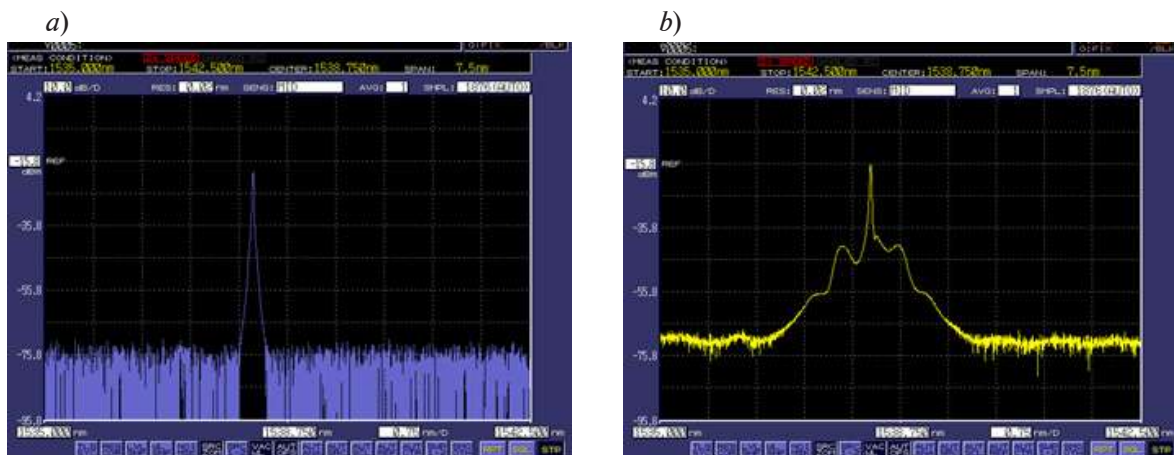


Fig. 2. Optical signal spectrum at the input (a) and output (b) of the optical fiber

Nonlinearity leads to the change in the spectrum optical signal and this is easy to control by optical spectrum analyzer (Fig. 3)

Experimental investigation has shown that nonlinear effect imposes limitations on the initial optical pulse power in high bit rate DWDM telecommunication system.

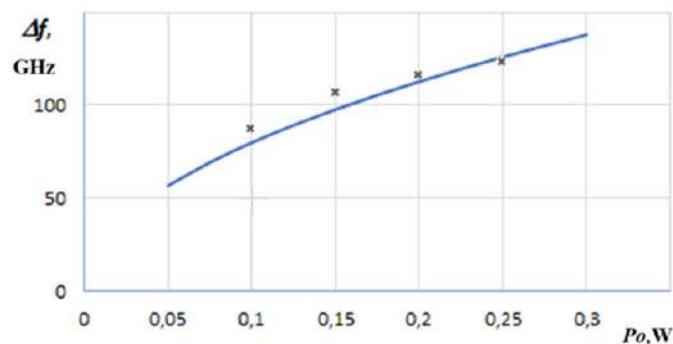


Fig. 3. Dependence of  $\Delta f$  on the input optical signal power  $P_0$   
The points x mark the measurement results

### Conclusion

Thus, nonlinear effects have the significant impact on the parameters of symbol pulses when transmitting an optical signal over a single-mode fiber optic cable. With increasing bit rate, the initial pulse power and the communication transmission length, the influence of nonlinear effects increases.

### REFERENCES

1. **Agrawal G.**, Fiber-Optics Communication Systems, G. Agrawal, 5th Edition - New York. 2021.
2. **Agrawal G.**, Nonlinear Fiber Optics, 6th Edition, Elsevier. 2019.
3. **Pozdnyakov A.A., Andreeva E.I.**, Experimental study of data transmission in a long-haul passive span fiber-optic line with high information capacity, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 16 (3.1) (2023) 379–383.
4. **Ferreira M.**, Nonlinear Effects in Optical Fibers. John Wiley & Sons, Inc., Hoboken, New Jersey, USA. 2011.
5. **Andreeva E.I.**, Properties of Temporary Optical Solitons in Optical Fibers and the Possibility of their Use in Telecommunications. Proceedings of Telecommunication Universities. 4 (1) (2018) 5–12.

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## **Experimental study of the FWM-effect in the fiber-optic system with wavelength division multiplexing**

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**Abstract.** Four-wave mixing (FWM) is the intermodulation phenomenon in the optical signal, as a result of which several linearly polarized optical waves interact. An experimental study of the Four-Wave Mixing effect in standard single-mode fiber (SSMF) and nonzero dispersion-shifted fiber (NZDSF) was carried out, with two and three wavelengths. An experimental investigation was carried out with the typical DWDM equipment. It was shown that FWM-effect has the significant influence on the propagation of the symbol pulses in dispersion - shifted optical fiber.

**Keywords:** fiber-optic communication system, Wavelength Division Multiplexing, optical fiber, dispersion-shifted fiber, nonlinear effects, Four-Photon Mixing

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Материалы конференции

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## **Экспериментальное исследование FWM-эффекта в волоконно-оптической системе с мультиплексированием с разделением длин волн**

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**Аннотация.** Четырехволновое смешение (FWM) – это явление интермодуляции в оптическом сигнале, в результате которого взаимодействуют несколько линейно поляризованных оптических волн. Было проведено экспериментальное исследование эффекта четырехволнового смешивания в стандартном одномодовом волокне (SSMF) и волокне с ненулевым сдвигом дисперсии (NZDSF), с двумя и тремя рабочими длинами волн. Экспериментальное исследование проводилось на обычном оборудовании DWDM. Было показано, что FWM - эффект оказывает существенное влияние на распространение символьных импульсов в оптическом волокне со смешением дисперсии.

**Ключевые слова:** волоконно-оптическая система связи, мультиплексирование с разделением длин волн, оптическое волокно, волокно со смещенной дисперсией, нелинейные эффекты, четырехфотонное смешение



**Ссылка при цитировании:** Андреева Е.И., Кассихин В.Р. Экспериментальное исследование FWM-эффекта в волоконно-оптической системе с мультиплексированием с разделением длин волн // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2025. Т. 18. № 3.2. С. 214–217. DOI: <https://doi.org/10.18721/JPM.183.243>

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## Introduction

Fiber-optic communication lines serve as the backbone of contemporary data networks, enabling high-bandwidth and robust long-distance data transfer. In wavelength division multiplexing (DWDM) systems, the quality of data transmission is affected by linear (loss, dispersion) effects and nonlinear effects, such as Four-Wave Mixing (FWM), Stimulated Raman Scattering (SRS), Stimulated Brillouin Scattering (SBR), Carrier-Induced Phase modulation (CIP), and others [1–5]. In the processes of SRS and SBR, the optical fiber is a nonlinear medium and plays an active role, since vibrations of its molecules are involved. In parametric processes, one of which is four-wave mixing, the optical fiber acts as the passive medium in which optical waves interact through the nonlinear response of the electrons of the outer shells excited by them.

FWM is characterized by the low threshold of manifestation, therefore it requires an assessment of the impact on the Bit Error Rate (BER).

The essence of the effect is that when four linearly polarized optical waves with frequencies  $\omega_1$ ,  $\omega_2$ ,  $\omega_3$  and  $\omega_4$  interact, photons of one frequency can be destroyed and rotons of other frequencies can be created while maintaining the pulse energy. There are two types of four-wave mixing [1–2]:

the energy of two photons is transferred to two new ones, generated at the frequencies:

$$\omega_3 + \omega_4 = \omega_1 + \omega_2;$$

the energy of three photons is transferred to the fourth, generated at the frequency:

$$\omega_4 = \omega_1 + \omega_2 + \omega_3.$$

The first case was investigated with two DWDM-channels.

## Experimental Results and Discussion

The experimental study was conducted with the typical telecommunication DWDM equipment (Fig. 1.).

The experimental setup included: the laser sources: 1 is the laser source ( $\lambda_1=1536,6\text{nm}$ ), 2 is the laser source ( $\lambda_2=1537.4\text{nm}$ ), 3 is the laser source ( $\lambda_3=1538.2\text{nm}$ ); 4 is the multiplexor; 5 is the optical Er-doped amplifier; 6 is the optical fiber; 7 is the attenuator; 8 is the optical spectrum analyzer. A multiplexer receives the 1 dBm signal from laser sources and transmits multiplexed signal to the amplifier. The erbium amplifier provided up to 24 dBm of optical power in the optical fiber.

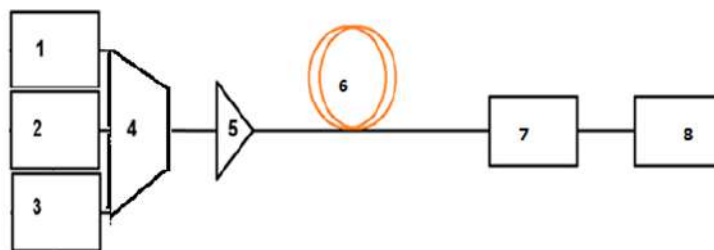


Fig. 1. Optical block diagram of the experimental setup: laser sources 1–3 (laser source with wavelength  $\lambda_1 = 1536.6 \text{ nm}$ , laser source with wavelength  $\lambda_2 = 1537.4 \text{ nm}$ , and laser source with wavelength  $\lambda_3 = 1538.2 \text{ nm}$ ), multiplexor 4, optical Er-doped amplifier 5, optical fiber 6, attenuator 7, optical spectrum analyzer 8

The dispersion-shifted optical fiber (NZDSF) parameters: Kerr nonlinearity coefficient  $\gamma = 2.5 \text{ W}^{-1}\text{km}^{-1}$ , dispersion  $2 \text{ ps/nm/km}$  ( $\beta_2 = -2.5 \text{ ps}^2/\text{km}$ ), loss  $0.2 \text{ dB/km}$ .

The standard single-mode optical fiber (SSMF) parameters: Kerr nonlinearity coefficient  $\gamma = 1.2 \text{ W}^{-1}\text{km}^{-1}$ , dispersion  $D = 16.67 \text{ ps/nm/km}$  ( $\beta_2 = -20 \text{ ps}^2/\text{km}$ ), loss  $0.2 \text{ dB/km}$ .

The experimental investigation was carried out with telecommunication DWDM equipment. Optical signals at  $\lambda_3$  and  $\lambda_4$  are the result of FWM- effect (Fig. 2). There is the optical signal spectrum at the end of optical cable of  $22.5 \text{ km}$  length as the example of the experimental study.

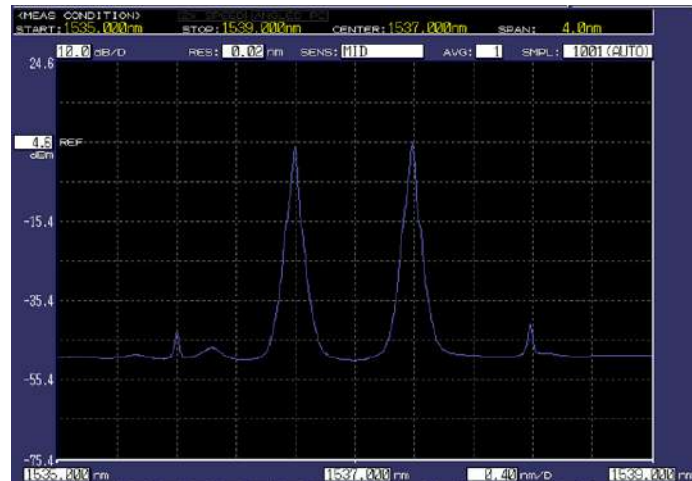


Fig. 2. Optical pulse spectrum with 2 laser sources at the end of optical cable of  $22.5 \text{ km}$  length

The experimental investigation was telecommunication DWDM equipment. Optical signals at  $\lambda_4$ ,  $\lambda_5$ ,  $\lambda_6$  and  $\lambda_7$  are the result of FWM-effect (Fig. 3).

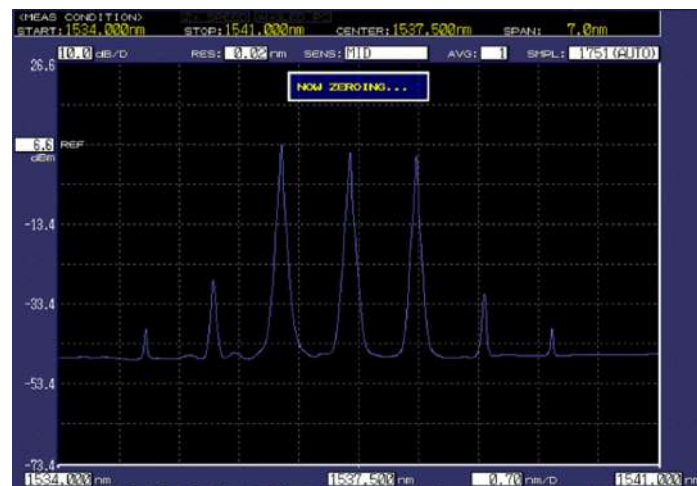


Fig. 3. Optical pulse spectrum with 3 laser sources at the end of optical cable of  $22.5 \text{ km}$  length

Experimental investigation has shown that FWM effect imposes limitations on the initial optical pulse power in DWDM telecommunication system. As the number of working channels increases, the number and power of interference located at the wavelengths of the working channels of the DWDM-system increase too.

### Conclusion

Thus, the experimental study of FWM effect in SSMF and NZDSF was carried out. It was shown that FWM - effect has significant influence on the propagation of the symbol pulses in dispersion - shifted optical fiber in DWDM communication systems.



## REFERENCES

1. **Agrawal G. G.**, Fiber-Optics Communication Systems. 5th Edition. New York. 2021.
2. **Agrawal G.**, Nonlinear Fiber Optics. 6th Edition. Elsevier. 2019.
3. **Yakovlev N.V., Bykov A.V., Andreeva E.I.**, Effect of the FWM and SRS on the fiber optics wavelength multiplexing system parameters. “Saint Petersburg OPEN 2021” 8th International School and Conference on Optoelectronics, Photonics, Engineering and Nanostructures St. Petersburg, Russia, May 25 – 28. 2021.
4. **Ferreira M.**, Nonlinear Effects in Optical Fibers. John Wiley & Sons, Inc., Hoboken, New Jersey, USA. 2011.
5. **Andreeva E.I.**, Feature of optical soliton sequence propagation in single-mode fiber. Journal of Physics: Conference Series. (2020) 012125.

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### **Relationship between the luminous flux drop of LED matrices during tests with thermal resistance and parameters of the emission spectrum**

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**Abstract.** Accelerated tests of LED matrices under the action of electric current under conditions of thermal cycling and vibration were carried out. It was determined that the value of the luminous flux decay correlates with the junction-to-case thermal resistance of the matrices and the value of the  $K_s$  coefficient, which determines the ratio of the luminous flux of optical emission in the near infrared region of the spectrum from 760 nm to 900 nm to the luminous flux in the spectrum range from 470 nm to 760 nm. The correlation coefficient between the luminous flux decay and the junction-to-case thermal resistance is 0.7, and the correlation coefficient between the luminous flux decay and the  $K_s$  coefficient is 0.48.

**Keywords:** LED matrices, accelerated testing, luminous flux decay, thermal resistance, emission spectrum, correlation

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Материалы конференции

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### **Исследование связи темпа спада светового потока светодиодных матриц с тепловым сопротивлением и параметрами спектра излучения**

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**Аннотация.** Проведены ускоренные испытания светодиодных матриц под действием электрического тока в условиях термоциклирования и вибрации. Определено, что



величина спада светового потока излучения коррелирует с тепловым сопротивлением переход-корпус матриц и значением коэффициента  $K_s$ , определяющего отношение светового потока оптического излучения в ближней инфракрасной области спектра от 760 нм до 900 нм к световому потоку в диапазоне спектра от 470 нм до 760 нм. Коэффициент корреляции между спадом светового потока излучения и тепловым сопротивлением переход-корпус составляет 0,7, а коэффициент корреляции между спадом светового потока излучения и коэффициентом  $K_s$  составляет 0,48.

**Ключевые слова:** светодиодные матрицы, ускоренные испытания, спад светового потока, тепловое сопротивление, спектр излучения, корреляция

**Финансирование:** Работа выполнена при поддержке Минобрнауки РФ в рамках Государственного задания ИРЭ им. В.А. Котельникова РАН (FFWZ-2025-0001).

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## Introduction

One of the promising areas of application of LED matrices is their use in the lighting equipment of aircraft. Currently, LED matrices are beginning to be used both in internal and external lighting equipment, including taxi lights, takeoff and landing lights, and navigation beacons. The service life and reliability of such devices largely depend on the operating conditions, primarily on the ambient temperature and current load mode [1–3]. LED devices used in on-board lighting and signaling equipment of aircraft are subject to sharp changes in ambient temperature in a wide range over a short period of time. However, to date, the relationship between the reliability of LED matrices when operating under thermal and electrical cycling conditions and thermal characteristics has not been sufficiently investigated. In this regard, the task of investigation the degradation processes of LED matrices when operating in the electrical cycling mode and under temperature change conditions and determining the parameters by which it is possible to identify LED matrices prone to accelerated degradation is relevant.

## Materials and Methodes

The LED matrices of the GWP9LR31.EM - DURISS 8 type, consisting of eight series-connected crystals, are investigated. The matrix supply voltage is 24 V, the maximum current is 200 mA. The matrices were tested for 16 hours under electrical and thermal cycling and vibration conditions. The duration of one temperature cycle was 4 hours: the temperature in the test chamber was maintained at  $T = +115\text{ }^{\circ}\text{C}$  for 1.5 hours, at  $T = -60\text{ }^{\circ}\text{C}$  for 1.5 hours, the temperature changed over 30 minutes. The duration of one electrical cycle was 30 minutes: a current of 190 mA was passed through the matrices for 15 minutes, and the matrices were switched off for 15 minutes. Electrical and thermal cycling of the matrices was accompanied by broadband vibration of 6.8 g. The accelerated test mode is equivalent to 1300 hours of LED matrices operation under natural operating conditions of an aircraft.

During the tests, the changes in the luminous flux and emission spectra, junction-to-case thermal resistance, current-voltage characteristics of the LED matrices were monitored. The luminous flux and emission spectra were measured in the photometric sphere using an OL770 spectroradiometer at a current of 30 mA. The  $I$ – $V$  characteristics were measured using an automated setup using the LabView graphical programming environment, consisting of a Keithley 6500 precision multimeter used to measure the current and a Tektronix DMM4040 digital multimeter used to measure the voltage on the LED matrix. The junction-to-case thermal resistance  $R_{\text{TJ-C}}$  of the LED matrices was measured according to the method presented in [4, 5]. The  $R_{\text{TJ-C}}$  thermal resistance determines the overheating temperature of the active region of the matrix crystals relative to the case temperature.

## Results and discussion

The emission spectrum of the LED matrix of the investigated type is shown in Fig. 1.

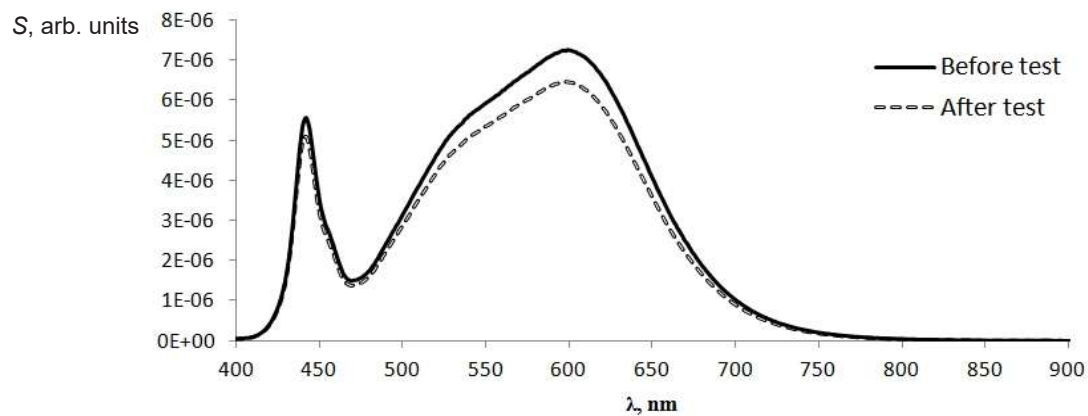


Fig. 1. LED matrix emission spectrum

The spectral section in the wavelength range from 400 nm to 470 nm is formed by the emission of the matrix crystals. The spectral section in the wavelength range from 470 nm to 900 nm is formed by the luminescence of the phosphor covering the matrix crystals. The blue light of the matrix crystals is absorbed by the phosphor. The excited phosphor ions return to the ground state, emitting photons in the yellow-green region of the visible spectrum. Partial reabsorption is possible: some of the photons emitted by the phosphor ions (especially photons in the short-wavelength part of the luminescence spectrum) are absorbed by the phosphor. These reabsorbed photons can re-excite the ions in the phosphor. Since the luminescence spectrum of phosphor ions is broad and shifted to the long-wave region, the secondary emitted photon will have a longer wavelength than the initially reabsorbed photon. This phenomenon is associated with the Stokes shift. In addition, this process can occur repeatedly within a phosphor particle or between particles. Thus, the long-wave section of the phosphor emission spectrum in the near infrared range, approximately from 760 nm to 900 nm, is mainly formed due to secondary emission [6–8].

A coefficient has been introduced that determines the ratio of the luminous flux of optical emission in the near infrared region of the spectrum from 760 nm to 900 nm to the luminous flux in the spectrum range from 470 nm to 760 nm:

$$K_s = \frac{\int_{470}^{900} S(\lambda) d\lambda}{\int_{470}^{760} S(\lambda) d\lambda} \cdot 100\%. \quad (1)$$

It was found that the  $K_s$  coefficient is a temperature-sensitive parameter. For this purpose, the emission spectra of the matrices were measured in a Combitherm CH 3-150 thermostat in the temperature range from 30 °C to 70 °C. The emission spectra of the LED matrices were measured by an Ocean Optics USB2000+VIS-NIR spectrometer. To eliminate self-heating of the matrix crystals during spectrum measurement, a small current of 300 μA was passed through the matrices. It is evident from Fig. 2 that  $K_s$  increases with increasing temperature, and the  $K_s(T)$  dependence is nonlinear.

As the temperature increases, the emission spectrum of the LED matrix crystals shifts to the long-wave region. The absorption spectrum of the phosphor also shifts to the long-wave region. In this case, the phosphor becomes capable of absorbing photons with lower energy, which leads to an increase in the probability of reabsorption with increasing temperature. Thus, as the temperature increases, the proportion of emission in the near infrared region of the spectrum increases relative to the radiation formed by the phosphor.

A positive correlation between the value of the  $K_s$  coefficient and the junction-to-case thermal resistance was found in a sample of 60 matrices: the correlation coefficient is 0.65.

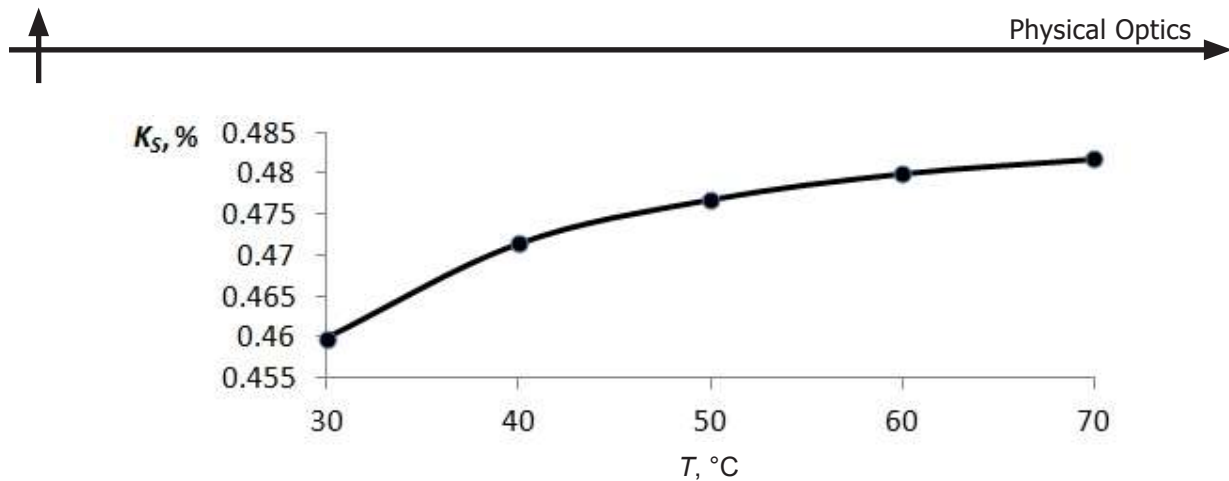


Fig. 2. Dependence of the coefficient  $K_s$  on temperature

Based on the results of thermal resistance measurements, six matrices were selected from 60 matrices whose thermal resistances cover the range from the minimum to the maximum value within the investigated sample. The minimum is 2.0 K/W, the maximum is 3.3 K/W. These six matrices were tested in the mode presented above. After the tests, all six matrices experienced a decrease in luminous flux. The smallest decrease was observed in matrices No. 7 and 30, by 4.90%, and the largest in matrices No. 11, 37 and 51 (Table 1).

Table 1

Results of measurements of LED matrix parameters

| LED array | $R_{\text{TJ-C}}, \text{K/W}$ | $K_s, \%$ | Luminous flux drop $\Delta\Phi, \%$ |
|-----------|-------------------------------|-----------|-------------------------------------|
| 7         | 2.1                           | 0.410     | 4.90                                |
| 11        | 3.3                           | 0.415     | 5.39                                |
| 13        | 2.0                           | 0.405     | 4.93                                |
| 30        | 2.1                           | 0.413     | 4.90                                |
| 37        | 2.7                           | 0.408     | 5.71                                |
| 51        | 2.6                           | 0.417     | 5.65                                |

The decrease in luminous flux correlates with the value of the junction-to-case thermal resistance (correlation coefficient 0.7) and with the value of the  $K_s$  coefficient (correlation coefficient 0.48): those matrices in which the active region overheating temperature is higher have a higher degradation rate.

During the testing of LED matrices, the emission intensity decreases in the entire range of the emission spectrum (Fig. 1). The decrease in the range of 400–470 nm is due to the degradation of crystals, and the decrease in the range of 470–900 nm is due to the decrease in the emission intensity of crystals and the degradation of the phosphor [9].

### Conclusion

It is shown that the value of the luminous flux drop of LED matrices correlates with the values of the junction-to-case thermal resistance and the value of the coefficient determining the share of the luminous flux of optical emission in the near infrared region of the spectrum to the luminous flux of emission formed by the phosphor. These parameters can be used to identify potentially unreliable LED matrices prone to accelerated degradation.

It is also shown that it is more appropriate to consider the degradation of white LED emission as the combined degradation of the crystal-phosphor system, although the crystal is the dominant component of this system due to the fact that it is the initiating factor of the phosphor emission.



## REFERENCES

1. Gu C., Li L., Ye N., Chang H., Reliability evaluation method of LED lighting matrix considering degradation and catastrophic failure, IOP Conference Series: Materials Science and Engineering. 1043 (2021) 042006.
2. Trefilov P.M., Romanova M.A., Mamchenko M.V., Study of Degradation of LED Lighting Devices and Reliability of Their Power Supplies under Long-Term Operation in Real Conditions, 2024 8th International Conference on Information, Control, and Communication Technologies (ICCT). (2024) 1–5.
3. Frolov I.V., Sergeev V.A., Khodakov A.M., Zaitsev S.A., Study of changes in the characteristics of LED matrices of an onboard lamp during current tests. Journal of Radio Electronics [electronic journal]. 8 (2021) (In Russian).
4. Patent 2772930 RU, IPC G01R 31/26. Method for measuring the thermal resistance of the junction-case of an LED / Sergeev V.A., Frolov I.V., Radaev O.A., Zaitsev S.A., Kozlikova I.S.; applicant and patent holder Federal State Budgetary Scientific Institution V.A. Kotelnikov Institute of Radio Engineering and Electronics of the Russian Academy of Sciences. – No. 2021123790; declared 06.08.2021; published 27.05.2022. Bulletin No. 15. (In Russian).
5. Sergeev V., Frolov I., Radaev O., et al., Remote control of thermal parameters of LEDs and LED matrices by radiation characteristics, Semiconductor lighting technology. 2 (2023) 20–26.
6. Ueda J., & Tanabe S., Temperature dependence of photoluminescence spectra and dynamics in Ce<sup>3+</sup>-doped Y<sub>3</sub>Al<sub>5</sub>O<sub>12</sub> (YAG:Ce) phosphor, Journal of Luminescence. 157 (2015) 263–268.
7. Setlur A.A., Heward W.J., Gao Y., et al., Crystal chemistry and luminescence of Ce<sup>3+</sup>-doped Lu<sub>2</sub>CaMg<sub>2</sub>(Si,Ge)<sub>3</sub>O<sub>12</sub> and its use in LED based lighting, Chemistry of Materials. 18 (14) (2006) 3314–3322.
8. Bachmann V., Ronda C., Meijerink A., Temperature quenching of yellow Ce<sup>3+</sup> luminescence in YAG:Ce, Chemistry of Materials 21 (10) (2009) 2077–2084.
9. Fan J., Mohamed M.G., Qian C., et al., Color shift failure prediction for phosphor-converted white LEDs by modeling features of spectral power distribution with a nonlinear filter approach. Materials. 10 (7) (2017) 819.

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## Laser cleaning of plaster

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**Abstract.** The paper is devoted to experimental study of laser cleaning of plaster. Nowadays laser technologies are widely used in the preservation of Cultural Heritage, and laser cleaning is most frequently used technique in artworks conservation. However, laser cleaning of plaster sculptures and architectural decorations is not yet established. Experimental results of divestment of model samples and 20th century plaster sculpture by means of pulsed Nd:YAG laser (generating at wavelengths of 1064 nm, 532 nm and 355 nm) and fiber laser with wavelength of 1064 nm are presented.

**Keywords:** Laser cleaning, Cultural Heritage, artworks, restoration, plaster

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Материалы конференции

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## Лазерная очистка гипса

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**Аннотация.** Статья посвящена экспериментальному исследованию лазерной очистки гипса. В настоящее время лазерные технологии широко применяются в области сохранения культурного наследия, и лазерная очистка используется наиболее часто в реставрации произведений искусства. Однако лазерная очистка гипсовых скульптур и архитектурных элементов пока еще не получила практического применения. Представлены экспериментальные результаты очистки модельных образцов и гипсовой скульптуры XX века с помощью импульсного Nd:YAG-лазера, генерирующего на длинах волн 1064 нм, 532 нм и 355 нм, а также волоконного лазера с длиной волны 1064 нм.

**Ключевые слова:** лазерная очистка, культурное наследие, произведения искусства, реставрация, гипс

**Ссылка при цитировании:** Парфёнов В.А., Елефтериادي Э.А. Лазерная очистка гипса // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2025. Т. 18. № 3.2. С. 223–228. DOI: <https://doi.org/10.18721/JPM.183.245>

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## Introduction

In the last two decades, laser technologies have been increasingly used in the preservation of cultural heritage. The most widely used technology is laser cleaning, which is used in restoration and conservation to remove natural deposits and anthropogenic pollutants from the surface of monuments [1]. Currently, the most refined cleaning of stone, in particular, marble and limestone. As for other materials, including gypsum, each of them requires the development of an individual laser application methodology, which requires targeted research.

Due to the simplicity of plaster processing, it is widely used in the creation of sculptures and small architectural forms, including stucco decorations and bas-reliefs. However, this material is very fragile, porous and gyroscopic, which makes the restoration of plaster objects a very difficult task. Traditional methods of gypsum restoration cleaning based on the use of chemical and mechanical methods are ineffective, and sometimes lead to significant surface damage that causes irreversible changes in the state of preservation of monuments. With this in mind, laser cleaning is potentially a promising alternative method for the preservation of plaster artifacts, due to the possibility of a delicate and controlled effect on the surface to be cleaned.

Currently, very few publications are devoted to laser cleaning of plaster in the scientific literature [1–3]. This indicates the scientific novelty of research in this area. In this paper, experimental studies were conducted on the possibility of using laser cleaning of gypsum using Nd:YAG and fiber lasers operating at different wavelengths and having different pulse durations in order to determine the optimal laser treatment modes.

## Materials and methods

Model samples were prepared for experiments on laser cleaning of gypsum. They were small (about  $3 \times 3$  cm<sup>2</sup> in size) plates, on the surface of which dust pollution, typical of gypsum objects in the collections of many museums, was artificially simulated. To do this, graphite dust was applied to the surface of plaster plates and rubbed into it (Fig. 1).

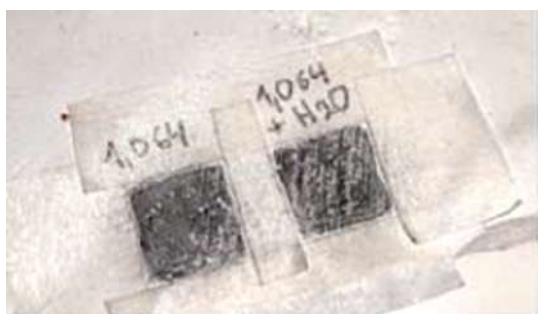


Fig.1. Plaster samples with artificial contaminations

Three different lasers were used to clean the model samples:

1. Pulsed solid-state Nd:YAG laser with a tube pump and a compact emitter connected to the power supply unit by a flexible cable, inside of which there is a water cooling tube and electrical wires. The successful ergonomic design of the emitter allows one to hold it in hands and easily move it relative to the surface to be treated (Fig. 5) This laser operates in a Q-switched mode at two wavelengths, at the main wavelength of 1064 nm and at the wavelength of the second harmonic of 532 nm and has a pulse duration of 20 ns and a beam diameter of 6 mm. In the experiments, the pulse energy was 100 mJ, and the pulse repetition rate was 2 Hz.
2. Pulsed fiber ytterbium laser with a wavelength of 1064 nm, a pulse duration of 100 ns and a pulse repetition rate of up to 100 kHz. This laser is also equipped with a small-sized “gun” that can be held in hands during the cleaning process. The maximum average laser power is 100 watts, but in experiments the power level did not exceed 10 W. The laser radiation spot is a rectangle about  $1 \times 20$  mm in size, which is formed by separate consecutive pulses deployed in a line.
3. Pulsed solid-state Nd:YAG lamp-pumped laser operating at a wavelength of the 3rd harmonic of 355 nm in Q-switched modulation mode. It has a maximum average power of 5 W, a pulse duration of 10 ns and a pulse repetition rate of up to 50 kHz. This is a commercial laser designed for marking products of the electronic industry, as a result of which it is equipped with a system of two galvanometric mirrors that provide high-speed scanning of the laser beam along a given trajectory, as well as a focusing system that forms a spot in the focal plane with a diameter of about 10 microns. In our experiments, gypsum was treated with a defocused beam in order to eliminate its mechanical damage.

The condition of the samples before and after laser cleaning was monitored using an optical microscope. In addition, the reflection coefficient and the color characteristics of the surface were measured. These measurements were carried out using a portable spectrophotometer Spectro Guide (BYK Gardner GmbH, Germany). The color characteristics were monitored using an international color scale The CIE (Commission International de l'Eclairage) 1976 ( $L^*a^*b^*$ ), or briefly CIE LAB system, which is widely used for recording the chromatic coordinates. This system, referred to as colorimetry, is an effective tool for visualizing the color. The symbols  $L^*$ ,  $a^*$ , and  $b^*$  represent the following:  $a^*$  is a red-green component of color (it can be varied in the range from or  $-127$  (green) up to  $+127$  (red)),  $b^*$  is a yellow-blue component of color (it can be varied in the range from or  $-127$  (blue) up to  $+127$  (yellow)), and  $L^*$  is a brightness, which characterizes black-white color shades ( $L^* = 0$  for black, and  $L^* = 100$  for white). The change of characteristics of the analyzed surface may be found by means of measurements of differences in reflectance spectrum. Various factors, such as deterioration processes in the image area, materials content, surface hardness and granules size (in case of porous materials), can influence changes of colors.

### Results and discussion

The choice of lasers for cleaning in monument restoration is usually based on consideration of their optical properties. The general rule is that in order to reduce the risk of damage to monuments as a result of heating their surface during laser treatment, it is necessary to choose the laser wavelength in such a way that a high reflection coefficient is provided for this wavelength. But at the same time, the pollution layer, on the contrary, must effectively absorb laser radiation. With this in mind, at the initial stage of the experiments, measurements of the reflection coefficient of pure plaster (before artificial contamination) were carried out, which showed that it has a high reflection in a wide spectral range with a maximum in the range of 950–1050 nm (Fig. 2). Taking this into account, lasers with a wavelength of about 1 micron are well suited for cleaning plaster, including an Nd:YAG laser (with a primary wavelength of 1064 nm) and a fiber laser (with the same wavelength). As for the second and third harmonics of the Nd:YAG laser radiation, they were supposed to be used to select optimal laser processing modes, including, among other things, as a result of varying the wavelength when working with both prototypes and real artifacts.

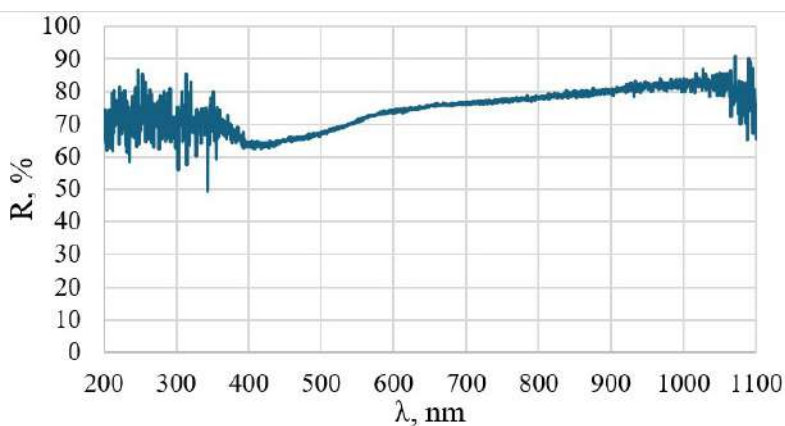


Fig. 2. Reflectance spectrum of pure plaster

When working with all lasers, even with comparable values of radiation energy density, different results were obtained in terms of the effectiveness of laser cleaning and related effects. In all cases, surface contamination was removed, but sometimes a number of negative effects were noted. In particular, mechanical damage and discoloration of the plaster could occur.

Mechanical damage during operation with all lasers was eliminated due to careful selection of the energy density of the laser radiation. At the same time, the delicate cleaning technique consists in starting work by setting the lowest values of this parameter, gradually (step by step) increasing it until the effect of removing impurities is achieved, and individually when working with each sample. As for the color change (plaster acquired a yellowish tinge instead of the original white color (Fig. 3)), then this problem was most effectively solved only when working with Nd:YAG with a wavelength of 355 nm.

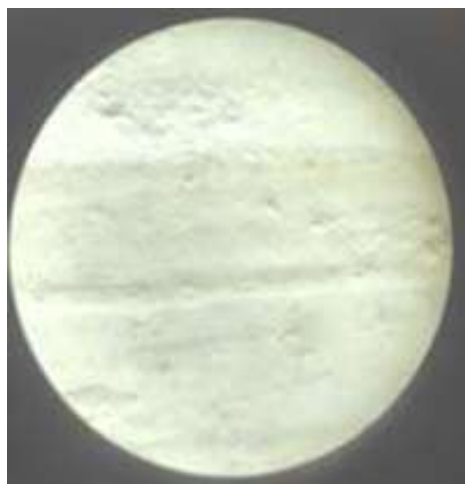


Fig. 3. Plaster model sample: the upper part is pure plaster, the lower part is the area from which graphite was removed using a laser

Fig. 4 shows the color characteristics of plaster after cleaning with various types of lasers. From this diagram, it can be seen that for the Nd:YAG laser with a wavelength of 1064 nm, the value of parameter  $b^*$  increased by 8 units (offset to the yellow side) compared with the sample of pure gypsum, and the value of parameter  $a^*$  increased by 1.7 units (offset to the red side). The  $L$  parameter has also noticeably deteriorated. At the same time, despite the same wavelength of the fiber laser, the yellowing effect is much less pronounced for it, and is almost completely absent when working with the third harmonic of the Nd:YAG laser. Another interesting experimental fact should be noted – radiation with a wavelength of 355 nm makes it possible to lighten a surface that has turned yellow when working with an Nd:YAG laser with a wavelength of 1064 nm.

It should be noted that all the experimental results listed above are purely empirical and await explanation. Mechanical damage to the plaster surface by an Nd:YAG laser with a wavelength of 1064 nm and their less pronounced character when treated with a fiber laser with the same wavelength can be explained by the difference in pulse duration (20 ns and 100 ns, respectively), which leads to a higher peak radiation power in the first case.

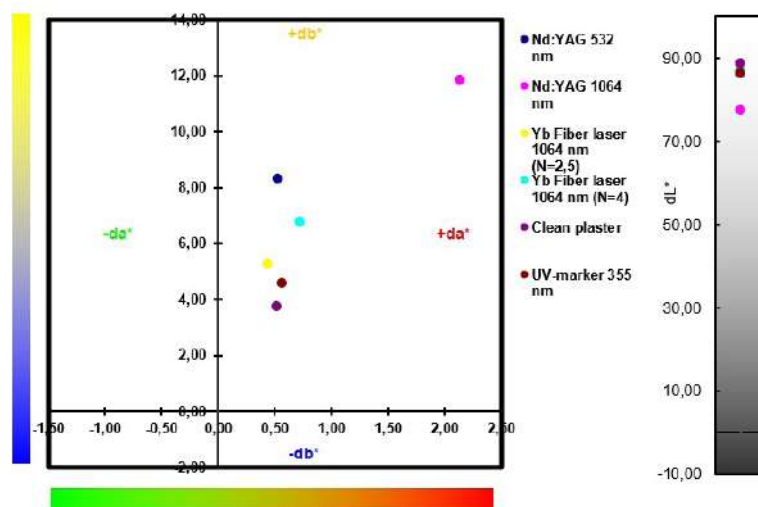


Fig. 4. Color characteristics of plaster after cleaning with various types of lasers

As for the answer to the question of the causes of plaster yellowing when working with a laser with a wavelength of 1064 nm and the absence of the same effect at a wavelength of 355 nm, this requires additional research. However, this has long been a well-known problem in laser restoration, which was first noted when cleaning marble and limestone monuments [4]. There are several hypotheses explaining this phenomenon, but experts still have not come to a consensus [5]. Apparently, the same is the case in the case of plaster.

In addition to working with model samples, in this work, trial clearings of the monument of the 20th century were carried out – the plaster bust of General A.N. Maksimenkov, the first head of the Military Medical Museum (St. Petersburg). On the surface of this monument there are multiple (total number of layers – 6) oil paints, which the museum experts would like to remove. In the experiments, we used a 2-wavelength (1064 nm and 532 nm) Nd:YAG laser described



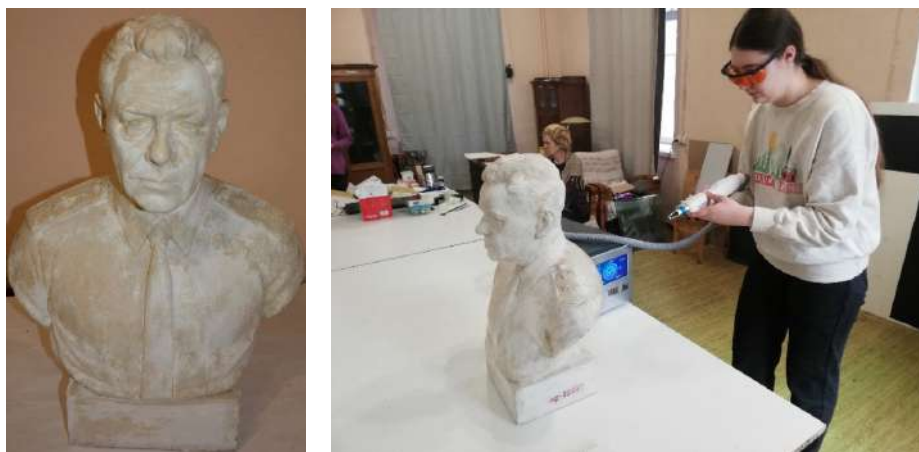


Fig. 5. Plaster sculptural portrait of general A.N. Maksimenkov: general view (left), process of laser cleaning (right)

in the section ‘Materials and Methods’. Unfortunately, cleaning at both wavelengths proved ineffective, since the laser allowed only the topmost layer of paint to be removed. Nevertheless, an interesting practical result of the experiments is the fact that wet laser cleaning proved to be more effective than dry. The same can be said about the advantage of the wavelength of 532 nm compared to 1064 nm. Apparently, for the restoration of this monument, it is necessary to use a cleaning technique combining the use of a laser and chemical treatment, as described in [6]. But this will be the next stage of our work, the results of which we will report after its completion.

### Conclusion

In this paper, a comparative assessment of the effectiveness of laser cleaning of gypsum surfaces using three types of lasers is carried out. Based on the experimental studies carried out, it can be concluded that the best results in removing artificially created impurities from graphite dust are provided by a pulsed Nd:YAG laser with a wavelength of 355 nm and a pulse duration of 10 ns.

Since the work did not investigate the removal of other types of contamination of monuments, and the restoration of the sculptural portrait of general A. Maksimenkov is still ongoing, the results obtained should be considered preliminary. The authors of the article plan to continue their research and publish their results in a separate article.

### REFERENCES

1. **Cooper M.**, Laser Cleaning in Conservation: An Introduction. Butterworth-Heinemann, Oxford. 1998.
2. **Pelosi C., Fodaro D., Sforzini L., et al.**, Study of the laser cleaning on plaster sculptures, The effect of laser irradiation on the surfaces, *Optics and Spectroscopy*. 6 (114) (2013) 917–928.
3. **Pelosi C., Fodaro D., Sforzini L., et al.**, Laser cleaning experiences on sculptures’ materials: Terracotta, plaster, wood, and wax, In: *SPIE Proceedings*. (9065) (2013) 253–273.
4. **Vergès-Belmin V., Dignard C.**, Laser yellowing: myth or reality, *Journal of Cultural Heritage*. (4) (2003) 238–244.
5. **Siano S., Giamello M., Bartoli L., et al.**, Laser cleaning of stone by different laser pulse duration and wavelength, *Laser Physics*. 1 (18) (2008) 1–10.
6. **Vasilieva A., Kareva A., Parfenov V.**, Complex study of a painted gypsum XVIII century bas-relief by optoelectronic methods to develop a combined cleaning technique, *Heritage*. 6 (2) (2023) 1891–1902.

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## Background illumination in the guidance system for laser communication on the Impulse-1 satellite

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**Abstract.** Satellite laser communication requires high-precision mutual pointing between the satellite and the ground station, which is achieved by detecting a beacon laser on a tracking camera and adjusting the optical axis. Here we research the detection procedure of the laser beacon by onboard satellite camera, focusing on the relationship between laser power, beam divergence, and background illumination influenced by seasonal and geographical factors. Considering a test image from the “Impulse-1” spacecraft, we demonstrate that a 3W laser with a 3 mrad beam divergence illumination can exceed background levels by up to 20 times, improving detection as the satellite rises above the horizon, especially when positioned directly overhead.

**Keywords:** cubesat, spacecraft guidance, satellite optical communications, laser beacon

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## Определение интенсивности фоновой засветки в системе наведения лазерной связи на космическом аппарате «Импульс-1»

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**Аннотация.** Лазерная спутниковая связь требует высокоточной взаимной ориентации между спутником и наземной станцией. Это достигается путем обнаружения лазерного маяка с помощью камеры слежения и корректировки направления оптической оси. Настоящее исследование рассматривает обнаружение наземных лазерных маяков бортовой камерой спутника, учитывая взаимосвязь между мощностью лазера на земле, расходимостью луча и фоновой освещенностью, зависящей от сезонных и географических факторов. Анализируя тестовое изображение со спутника «Импульс-1», показано, что лазер мощностью 3 Вт с расходимостью луча 3 мрад для показанного места и времени суток может превышать уровень фоновой освещенности до 20 раз, при пролете через надир.

**Ключевые слова:** кубсат, спутниковая оптическая связь, лазер, маяк

**Финансирование:** Работа выполнена при поддержке Министерства образования и науки Российской Федерации в рамках Программы стратегического академического лидерства «Приоритет 2030» (Стратегический проект «Квантовый интернет»).

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## Introduction

The orientation procedure of the satellite to the ground station is a complex and multi-stage problem, involving numerous calculations [1]. However, the final high-precision pointing is performed by using a laser beacon that illuminates the satellite from the ground station with a directed laser beam. To detect the laser beacon by the onboard camera reliably, the power of the incoming laser radiation must exceed the background illumination originating from the Earth's surface. This background noise may vary greatly depending on the time of year and the latitude of the ground station, since the station may be positioned in complete darkness or in direct sunshine. Therefore, proper selection of the laser beacon's power and beam divergence must account for the background illumination conditions, which can be assessed using images acquired by the satellite's onboard camera.

Here we provide experimental data of the background illumination detected on the camera of the Impulse-1 satellite and compare them to the irradiance expected from the beacon laser of the ground station [2, 3].

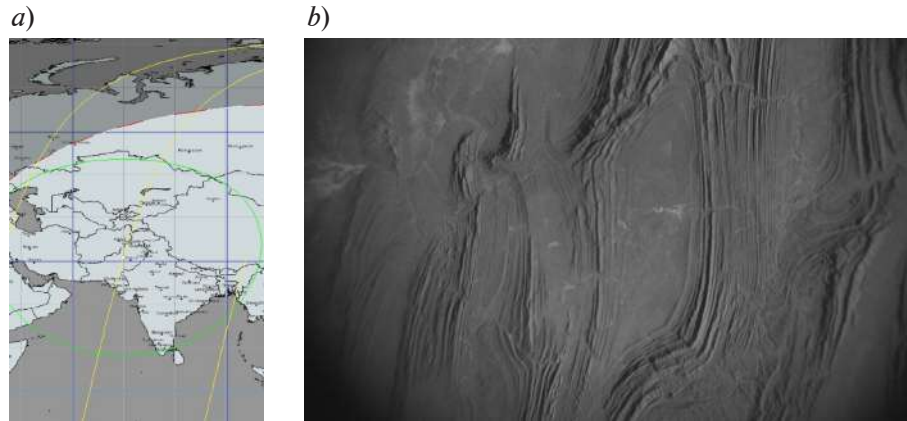


Fig. 1. Satellite's orbit passing over Pakistan and the terminator line for this time of day (a); image of the Balochistan region as observed by the satellite's camera (b)

### Materials and methods

To enhance the contrast between the background radiation and the beacon, we use a narrowband 10 nm filter with the center wavelength of 670 nm which corresponds to a quantum efficiency of 53% for the Sony IMX 392 sensor used in the guidance camera of the “Impulse-1” spacecraft. Test image was taken with an exposure time of 3 milliseconds during clear weather while flying over the territory of Balochistan (Pakistan) on December 11, 2024, at 4:40 UTC.

Based on the known sensitivity parameters of the matrix, measured in accordance with the EMVA 1288 standard [3] as well as the parameters of the optical system of the spacecraft [4], we calculate the amount of light on each individual pixel of the sensor for a given image, considering exposure time and gain. The image is divided into 25 separate sections. For each section, the average energy value for each pixel is calculated, expressed in W/mI, along with the average number of photons that have reached the pixel. To assess the image quality, the number of overexposed and dark pixels was calculated for each section of the image.

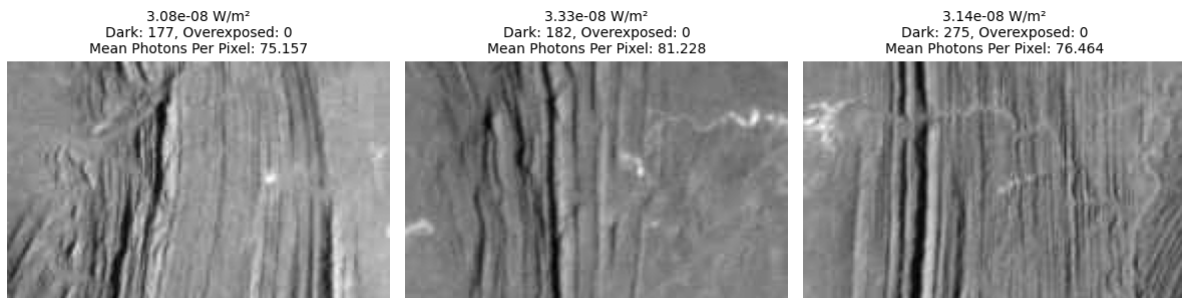


Fig. 2. Image sections with measured values of mean illumination intensity per pixel

### Results and discussion

If a laser with a beam divergence ( $\theta$ ) of 3 mrad and 3W power ( $P$ ) is stationed at the ground station, the spot size at a distance ( $L$ ) of 500 km – 1200 km will vary from 1.5 km to 12 km, and the intensity ( $I$ ) of the radiation will approximate values from  $10^{-6}$  to  $3 \cdot 10^{-8}$ :

$$I = \frac{P}{\pi \left( \frac{\theta L}{2} \right)^2}. \quad (1)$$



Upon hitting approximately one pixel on the sensor matrix, the illumination from the laser will be 1 to 20 times brighter than the average background illumination for the given scenario. This indicates that under lighting conditions corresponding to the captured image, the satellite, as it rises above the horizon, begins to detect the laser beacon with increasing brightness, registering maximum intensity at the moment of passing directly over the ground station. To exclude additional factors complicating the calculations, only the central parts of the image are taken into account.

### Conclusion

This study provides an analysis of the optical camera system aboard the “Impulse-1” satellite, specifically focusing on its capability to detect a ground-based laser beacon for precise guidance. The results highlight the critical role of laser power and beam divergence in ensuring reliable detection against varying background illumination conditions, which can fluctuate significantly based on geographical and temporal factors. Using this method, it is possible to calculate the appropriate power and beam divergence for various conditions and geographical locations. Such data may prove useful in the design of a space-based laser communication network that will possess high bandwidth and reduced energy consumption [5, 6].

### REFERENCES

1. Kozlov S.I., Kolovsky I.K., Khokhlov A.I., Types of orbits and their impact on the design of orientation and stabilization systems for Earth’s artificial satellites, World Science. 4 (13) (2018) 324–334.
2. Khmelev A.V., Duplinsky A.V., Mayboroda V.F., et al., Recording of a single-photon signal from low-flying satellites for satellite quantum key distribution, Tech. Phys. Lett. 47 (12) (2021) 858–861.
3. Duplinsky A.V., Khmelev A.V., Merzlinkin V.E., et al., Scalable satellite network for quantum key distribution based on CubeSat, Bulletin of Tomsk State University. Management, Computing and Informatics. 63 (2023) 103–110.
4. Jähne B., Emva 1288 standard for machine vision: Objective specification of vital camera data, Optik & Photonik. 5 (1) (2010) 53–54.
5. Miller A.V., et al., Vector – towards quantum key distribution with small satellites, EPJ Quantum Technology. 10 (1) (2023) 52.
6. Kartsan I.N., Concept of development of intersatellite laser communication. Siberian Aerospace Journal. 24 (2) (2023) 247–259.
7. Kazantsev S.G., Laser technologies for the telecommunication platform of a small spacecraft, Issues of Electromechanics. Proceedings of VNIEM. 163 (2) (2018) 29–47.

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## Hong–Ou–Mandel interference on free charged particles

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**Abstract.** The Hong–Ou–Mandel effect (HOM) is used in many fields of quantum optics and quantum technologies. It is well known that this effect occurs when two identical photons in different modes hit a beam splitter (BS) with a reflection coefficient of  $R = 1/2$ . The classical effect consists in the interaction of two photons and was first experimentally demonstrated by Hong and co-authors in 1987. In this paper, it was shown that this effect can be realized using free charged particles. It was determined when this effect would manifest itself. The results obtained for HOM have an analytical form, which simplifies its analysis. The Hong–Ou–Mandel effect is of fundamental importance in quantum physics and quantum computer science, as it demonstrates quantum entanglement and interference. The results of the research can be used in problems of quantum physics and quantum computer science.

**Keywords:** HOM effect, free electrons, photons, quantum optics

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Материалы конференции

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## Интерференция Хонга – Оу – Манделя на свободных заряженных частицах

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**Аннотация.** Эффект Хонга – Оу – Манделя (ХОМ) используется во многих областях квантовой оптики и квантовых технологий. Хорошо известно, что этот эффект возникает, когда два одинаковых фотона в разных режимах попадают на светоделитель (BS) с коэффициентом отражения  $R = 1/2$ . Классический эффект заключается во взаимодействии двух фотонов и был впервые экспериментально продемонстрирован Хонгом и соавторами в 1987 году. В этой статье было показано, что этот эффект может быть реализован с использованием свободных заряженных частиц. Было определено, когда этот эффект проявит себя. Результаты, полученные для ХОМ-эффекта, имеют аналитическую форму, что упрощает их анализ. Эффект Хонга – Оу – Манделя имеет фундаментальное значение в квантовой физике и квантовой информатике, поскольку он демонстрирует квантовую запутанность и интерференцию. Результаты исследования могут быть использованы в задачах квантовой физики и квантовой информатики.

**Ключевые слова:** ХОМ-эффект, свободные электроны, фотоны, квантовая оптика

**Финансирование:** Работа выполнена при финансовой поддержке Российского научного фонда № 00093-72-24.

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## Introduction

The HOM effect was first demonstrated experimentally by Hong et al. in 1987 [1]. HOM interference appears in many contexts, both in fundamental research in quantum mechanics and in practical implementations of quantum technologies [2]. A HOM interferometer scheme was presented in [1], one of the main elements of which was a beam splitter (BS). To observe quantum interference, a BS close to 1:1 (having reflectivity  $R = 1/2$  and transmittance  $T = 1/2$ ) is chosen. The theoretical explanation of the HOM effect based on constant  $R$  and  $T$  and bosonic photon statistics is quite simple [2].

HOM is a quantum phenomenon observed when two identical photons pass together through a beam splitter. If the photons are absolutely identical in all quantum parameters, such as polarization, frequency, and phase, and arrive at the beam divider at the same time, then they will interact in such a way that both photons will exit the divider in the same direction, instead of being randomly distributed between two possible directions. This effect is a quantum analogue of binary encoding in programming, used in experiments on quantum teleportation, quantum cryptography and in the development of quantum computers.

It has recently been shown that the statistical properties of photons in the interaction of a two-mode electromagnetic field with free charged particles can be identical to a beam splitter [3]. Thus, the interaction of photons with free electrons is a new and interesting direction for research [4–7]. At present, studies related to the HOM effect in the interaction of photons with free charged particles have not been encountered in the literature and may be interesting not only as a theoretical direction, but also as an experimental one.

## Materials and methods

There are many methods of entangling photons, but one way or another, all methods are reduced to the interaction of incoming electromagnetic waves with matter, in the process of such interaction, photons are entangled, and then quantum-entangled photons appear. The efficiency of generating such quantum entangled photons can vary and depends on many factors. Studies on plasmonic platforms based on the interaction of electrons with photons are considered promising. For example, plasmons can be controlled using electrons and photons, electrons can be used to change the quantum statistics of photons, and quantum statistics of photons can be transmitted to electrons. That is why free electrons are interesting from a practical point of view, since as a result of such an interaction, quantum entangled photons appear.

Thus, the study of the interaction of photons with electrons is an important part of modern physics and quantum technologies. To calculate the HOM effect, it is necessary to find the correlation function. When using free electrons, the correlation function can be obtained in the form:

$$P_{1,2} = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} |\xi_1(t_1, t_2, \tau) - \xi_2(t_1, t_2, \tau)|^2 dt_1 dt_2,$$

$$\xi_1(t_1, t_2, \tau) = \frac{1}{2\pi} \int \phi(\omega_1, \omega_2) T(\omega_1, \omega_2) e^{-i\omega_1(t_1 - \tau)} e^{-i\omega_2 t_2} d\omega_1 d\omega_2, \quad (1)$$

$$\xi_2(t_1, t_2, \tau) = \frac{1}{2\pi} \int \phi(\omega_1, \omega_2) R(\omega_1, \omega_2) e^{-i\omega_2(t_1)} e^{-i\omega_1(t_2 - \tau)} d\omega_1 d\omega_2,$$



where  $\tau$  is the delay time of photons between themselves in modes 1 and 2,  $\phi(\omega_1, \omega_2)$  is the spectral function,  $R(\omega_1, \omega_2)$  and  $T(\omega_1, \omega_2)$  is the coefficient of reflection and transmission of photons on free electrons, which looks like:

$$R = \frac{\sin^2\left(\Omega t_{BS} / 2\sqrt{1+\varepsilon^2}\right)}{(1+\varepsilon^2)}; \varepsilon = \frac{\omega_2 - \omega_1}{\Omega}, \quad (2)$$

$$T = 1 - R, \quad \Omega = \frac{8\pi u_1 u_2}{(\omega_1 + \omega_2)V},$$

where  $V$  is the quantization volume,  $u_1$  and  $u_2$  are the polarizations of the first and second photons with frequencies  $\omega_1$  and  $\omega_2$  respectively,  $t_{BS}$  is the interaction time of photons with free electrons.

### Results and Discussion

Next, the spectral function was chosen in the form:

$$\phi(\omega_1, \omega_2) = C e^{-\frac{(\omega_1 + \omega_2 - \Omega p)^2}{2\sigma_p^2}} e^{-\frac{(\omega_1 - \omega_{01})^2}{2\sigma_1^2}} e^{-\frac{(\omega_2 - \omega_{02})^2}{2\sigma_2^2}}. \quad (3)$$

Function (3) allows to analyze the value of  $P_{1,2}$  for two cases of practical interest. The first case is spontaneous parametric scattering (SPR), for example, for  $\Omega p = 2\omega_0$ ;  $\omega_0 = \omega_{01} = \omega_{02}$ ;  $\sigma_1 = \sigma_2 = \sigma$  – SPR type I, where  $\sigma_p$  – beam pumping bandwidth,  $\omega_0$  and  $\sigma$  – The center frequency and bandwidth are respectively for both the signal and the idle beams. The second case is if  $\sigma_p \rightarrow \infty$ , then it will be a case of Fock states. As a result, a correlation function was obtained. The calculation of this correlation function showed that the HOM effect can be realized on free electrons. The calculation results are presented in Fig. 1.

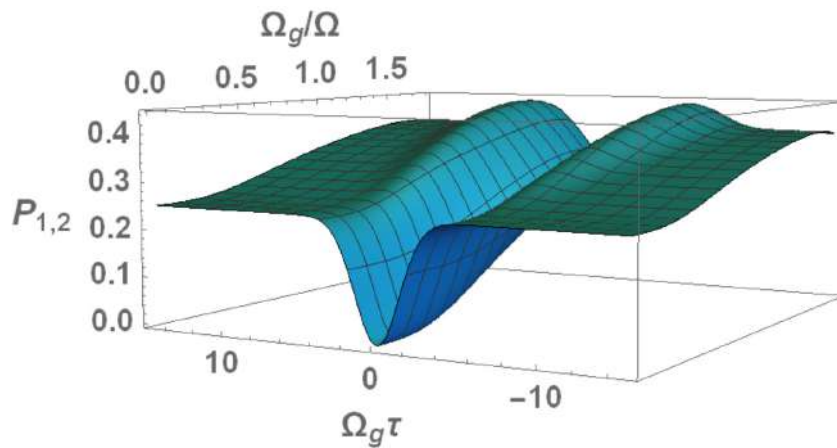


Fig. 1. Calculation of the correlation function in the case of identical photons falling on free electrons is presented. The calculation is presented in the form of two parameters: the time delay between the 1st and 2nd photons and the value determining the spectral width of the photons

In Fig. 1, the value  $\Omega_g$  is defined as:  $\Omega_g = \sqrt{\frac{4\sigma_1^2\sigma_2^2 + (\sigma_1^2 + \sigma_2^2)\sigma_p^2}{\sigma_1^2 + \sigma_2^2 + \sigma_p^2}}$ .

Here  $\Omega_g$  is some frequency related to the characteristics of the source itself. For example, in the case of photons in Fock states  $\Omega p$  it is necessary to aim at infinity and it will turn out  $\Omega_g$  the order of dispersion of incident photons. There is a minimum on the resulting graph, which drops to zero. This minimum is called the “HOM dip” and it is this minimum that identifies that the original photons are identical.

### Conclusion

Thus, in this paper it is shown that the HOM effect for two photons is observed on free charged particles. In order for the HOM effect on free charged particles to be fulfilled, i.e. for  $P_{1,2}(\tau = 0) = 0$ , one additional condition  $\Omega_g/\Omega \ll 1$  must be fulfilled compared to the theory of the HOM effect on a beam splitter. In other words, it is necessary that the spectral width of the incident photons be many times smaller than the frequency  $\Omega$ . The time delay during scattering by free electrons is performed in the same way as it is done in the case of a beam splitter. The first and second photons are sent to the beam splitter with some delay. Another option is to change the distance from the electrons to the first and second detectors, which also leads to a time delay. This is an interesting conclusion, which suggests that free electrons can act as a beam splitter when interacting with photons.

This article shows that this effect is also realized on free electrons, which has not been shown before.

### Acknowledgments

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### REFERENCES

1. Hong, C.K., Ou Z.Y., Mandel L., Measurement of subpicosecond time intervals between two photons by interference, Phys. Rev. Lett. 59 (1987) 2044–2046.
2. Bouchard F., Sit A., Zhang Y. et al., Two-photon interference: the Hong-Ou-Mandel effect, Rep. Prog. Phys. 84 (2021) 012402.
3. Makarov D.N., Makarova K.A., Quantum beam splitter based on free charged particles, Opt. Lett. 49 (2024) 3042–3045.
4. Makarov D.N., Quantum entanglement of photons on free electrons, Results in Physics. 49 (2023).
5. Baranes G., Ruimy R., Gorlach A., Kaminer I., Free electrons can induce entanglement between photons, Quantum Information. 8 (2022).
6. You C., Hong M., Bhusal N., et al., Observation of the modification of quantum statistics of plasmonic systems, Nature Communications. 12 (2021).
7. Dahan R., Gorlach A., Haeusler U., et al., Imprinting the quantum statistics of photons on free electrons, Science. 73 (2021).

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## Thermal management of solar cells through down-conversion nanoparticles

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**Abstract.** Silicon-based solar cells are currently the most widely used, accounting for 90.9% of the global photovoltaic module production. Solar radiation in the wavelength range of 400 to 1200 nm is effectively absorbed by crystalline silicon solar cells and converted into electrical energy, and the remaining energy is converted into thermal energy. The efficiency of silicon-based solar cells is very sensitive to temperature. For every 1 °C increase in the temperature of the photovoltaic panel, the efficiency will decrease by 0.5–0.65%. Down-conversion nanoparticles can convert ultraviolet rays into visible light that is easy for photovoltaic panels to absorb. This paper first established a thermodynamic model for coating titanium dioxide nanoparticles with a grain size of 20 nm on the surface of crystalline silicon solar panels and experimentally confirmed that this method can effectively reduce the operating temperature of silicon-based photovoltaic panels while ensuring electrical performance.

**Keywords:** crystalline silicon solar cells, down-conversion, nanoparticles, reduction of solar cell temperature

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Материалы конференции

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## Терморегулирование солнечных элементов с помощью наночастиц даун-конверсии

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**Аннотация.** Кремниевые солнечные элементы в настоящее время наиболее широко распространены, составляя 90,9% мирового производства фотоэлектрических модулей. Солнечное излучение в диапазоне длин волн 1200–400 нм эффективно поглощается кристаллическими кремниевыми солнечными элементами и преобразуется в электрическую энергию, тогда как оставшаяся энергия превращается в тепловую. Эффективность кремниевых солнечных элементов крайне чувствительна к температуре. При повышении температуры фотоэлектрической панели на каждый 1 °C эффективность снижается на 0,5–0,65%. Наночастицы даун-конверсии способны преобразовывать ультрафиолетовые лучи в видимый свет, легко поглощаемый фотоэлектрическими панелями. В данной работе впервые разработана термодинамическая модель нанесения наночастиц диоксида титана размером 20 нм на поверхность кристаллических кремниевых солнечных панелей, а также экспериментально подтверждено, что данный метод эффективно снижает рабочую температуру кремниевых фотоэлектрических панелей при сохранении их электротехнических характеристик.

**Ключевые слова:** кристаллические кремниевые солнечные элементы, даун-конверсия, наночастицы, снижение температуры солнечных элементов

**Финансирование:** Работа выполнена при частичной поддержке стипендиальной программы CSC (China Scholarship Council) (проект № 202409010253).

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## Introduction

The thermal energy in photovoltaic panels originates primarily from solar radiation. When photons in the solar spectrum possess energy exceeding the bandgap energy ( $E_g$ ), only the portion equivalent to  $E_g$  is utilized to drive the photoelectric effect and generate charge carriers, whereas the surplus energy ( $h\nu - E_g$ ) is dissipated as heat within the cell. As illustrated in Fig. 1, silicon-based solar cells ( $E_g = 1.12$  eV) exhibit high external quantum efficiency in the 450–1000 nm wavelength range. However, ultraviolet radiation below 400 nm constitutes the dominant source of thermal loss in these devices [2].

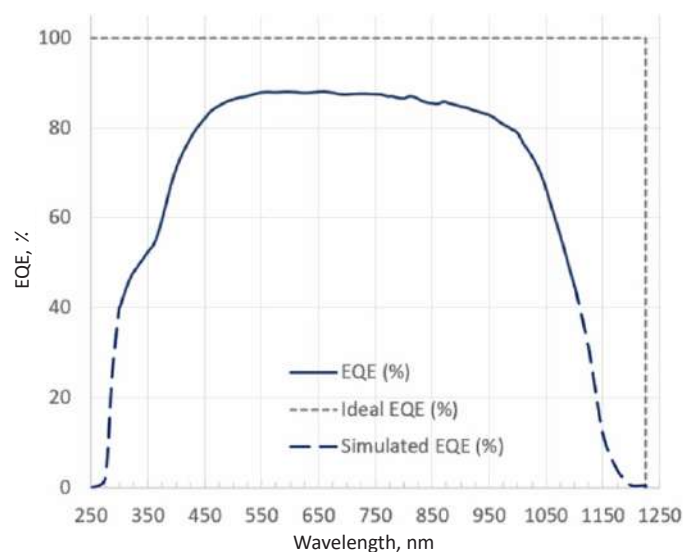


Fig. 1. External quantum efficiency of monocrystalline silicon solar cells

Titanium dioxide ( $\text{TiO}_2$ ) is a familiar n-type semiconductor with a wide bandgap of 3.2 eV in the anatase phase, strong absorption of ultraviolet light, high chemical stability, non-toxicity, and high photocatalytic activity [3, 4]. However, the main limiting factor of pure  $\text{TiO}_2$  nanoparticles is its ultrafast recombination rate of charge carriers (measured in nanoseconds). This is because there are a large number of dangling bonds and defects on its surface, which dominates non-radiative recombination, resulting in extremely low photoluminescence quantum efficiency. By selectively doping rare earth ions into the  $\text{TiO}_2$  matrix, it can slow down the recombination rate of electron-hole pairs, resulting in unique persistent photoluminescence [5]. Coating rare earth-doped titanium dioxide nanoparticles on the surface of solar cells can effectively convert ultraviolet light into visible light, and its extremely small grains are transparent to visible light, thereby reducing the operating temperature of solar cells and increasing the converted electrical energy [4–5].

### Materials and Methods

We first established a thermodynamic model for solar panels coated with  $\text{Eu}^{3+}$  doped  $\text{TiO}_2$  nanoparticles, providing a theoretical basis for the experiments. Fig. 2 shows the transfer of heat and energy from a photovoltaic panel.

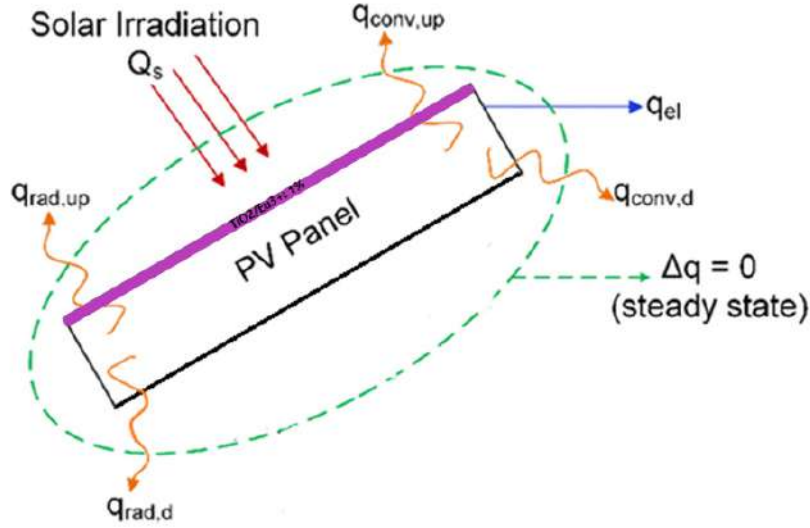


Fig. 2. Schematic diagram of the thermodynamic system of photovoltaic panels

Obviously, the heat balance formula is:

$$P_{heat} = P_{loss}. \quad (1)$$

Total absorbed power of photovoltaic panels (AM1.5):

$$P_{abs} = A Q_S \varepsilon_0, \quad (2)$$

where  $A$  is photovoltaic panel area,  $Q_S$  is the normal solar radiation, and  $\varepsilon_0$  is absorption capacity of the surface of a photovoltaic panel.

Since the band gap of titanium dioxide nanoparticles is 3.0–3.2 eV, they have strong absorption capacity for UVA. The 20 nm grain size is much smaller than the wavelength of visible light (400–700 nm), and the scattering effect is weak, so it is almost transparent to visible light and infrared light. Energy absorbed by 20nm  $\text{TiO}_2$  nanoparticles:

$$P_{abs, \text{TiO}_2} = A Q_S \cdot [\varepsilon_{\text{TiO}_2, UV} \cdot f_{UV} + \varepsilon_{\text{TiO}_2, Vis} \cdot (1 - f_{UV})], \quad (3)$$

where  $f_{UV} = 0.05$  (the energy proportion of ultraviolet light in AM1.5),  $\varepsilon_{\text{TiO}_2, UV}$  is absorption rate of ultraviolet light by  $\text{TiO}_2$  nanoparticles, roughly equal to 0.9,  $\varepsilon_{\text{TiO}_2, Vis}$  is absorption rate of  $\text{TiO}_2$  nanoparticles to visible light is roughly equal to 0.05.

The power absorbed by polysilicon is:

$$P_{abs, Si} = P_{abs} - P_{abs, \text{TiO}_2}. \quad (4)$$

Photoluminescent power:

$$P_{PL} = P_{abs, \text{TiO}_2, UV} \cdot \eta_{PL} = A Q_S \cdot \varepsilon_{\text{TiO}_2, UV} \cdot f_{UV} \cdot \eta_{PL}. \quad (5)$$

Reabsorption and escape power:

$$P_{re-abs} = P_{PL} \cdot EQE(\lambda), \quad (6)$$

$$P_{escape} = P_{PL} \cdot [1 - EQE(\lambda)], \quad (7)$$

where  $EQE(\lambda)$  is external quantum efficiency.

Heat accumulation:

$$P_{heat} = P_{abs, Si} \cdot (1 - \eta_{Si}) + P_{abs, TiO_2} \cdot (1 - \eta_{PL}) + P_{re-abs} \cdot (1 - \eta_{Si}). \quad (8)$$

Heat loss:

$$P_{loss} = 2hA(T_s - T_a) + 2\varepsilon\sigma A(T_s^4 - T_a^4), \quad (9)$$

where  $h$  is convective heat transfer coefficient, assume  $h = 10 \text{ W}/(\text{m}^2 \cdot \text{K})$ .  $T_s$  is photovoltaic panel temperature,  $T_a$  is ambient temperature,  $T_a = 23 \text{ }^\circ\text{C}$ ,  $\varepsilon$  is surface emissivity,  $\sigma$  is Stefan-Boltzmann constant.

Based on the above formulas, we can derive the theoretical operating temperature of the solar panel coated with Eu-doped  $\text{TiO}_2$  nanoparticles at room temperature as  $T_s = 319.0\text{K}$ .

To better understand the effects of down-conversion photoluminescent nanoparticles on solar panel operating temperatures, we initially developed a thermodynamic model for theoretical analysis. Subsequent experimental validation confirmed the temperature-reduction capability of this approach. For comparative testing, we exposed two  $100 \text{ mm} \times 100 \text{ mm}$  polycrystalline silicon solar panels (supplied by Telecom-STV Company) to AM1.5 midday sunlight for one hour: Sample 1 coated with  $20 \text{ nm}$   $\text{Eu}^{3+}:1\%$  doped  $\text{TiO}_2$  nanoparticles, and Sample 2 as an uncoated reference standard. Temperature measurements were recorded throughout the exposure period, followed by electrical performance characterization using a CT-1000 solar module  $I-V$  tester.

### Results and discussion

The actual measurement results show that the temperature of the solar panel covered with  $\text{Eu}^{3+}$  doped  $\text{TiO}_2$  nanoparticles is  $1.8 \text{ K}$  lower than the standard one. As shown in Fig. 3, the open circuit voltage  $V_{OC}$  and short circuit current  $I_{SC}$  have increased slightly, and the photoelectric conversion efficiency has increased by  $0.6\%$  (Table 1). The result obtained by theoretical calculation based on the thermodynamic model is  $2.5 \text{ K}$ . The error of  $0.7 \text{ K}$  may be because the

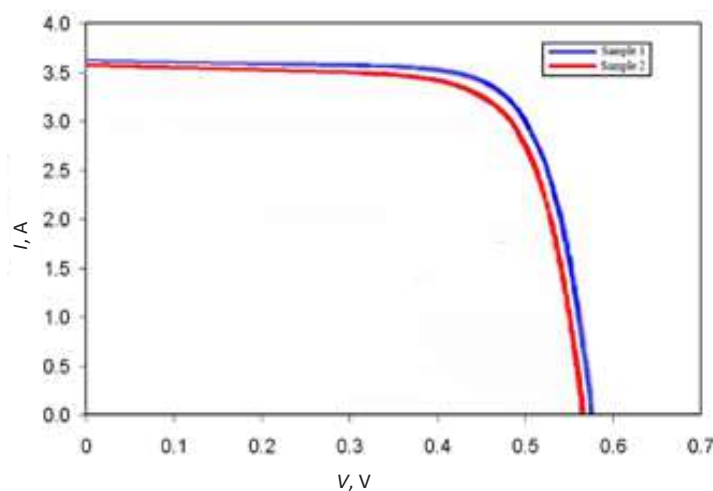


Fig. 3. Current-voltage ( $I-V$ ) curves of two samples

Table 1

Parameters of the studied samples

| sample | $T$ , K | $V_{oc}$ , V | $I_{sc}$ , A | $\eta$ |
|--------|---------|--------------|--------------|--------|
| 1      | 319.7   | 0.574        | 3.561        | 19.5%  |
| 2      | 321.5   | 0.562        | 3.553        | 18.9%  |

model assumes that the nanoparticles are closely connected and 100% covered on the surface of the solar cell. And all the photons emitted by the titanium dioxide nanoparticles are injected into the silicon matrix. This shows that if the covering technology of the nanoparticles is improved and the anti-reflection layer is added, the temperature of the solar panel can be lower and the efficiency  $\eta$  can be higher.

### Conclusion

The effects of down-conversion nanoparticles on both thermal regulation and electrical output of solar cells were systematically investigated. Thermodynamic modeling and controlled experiments demonstrated that this photoluminescent coating strategy reduced the module operating temperature by 1.8 K while simultaneously increasing energy conversion efficiency by 0.6%. However, the theoretical operating temperature remains 0.7 K lower than experimental measurements, indicating that subsequent research requires improvements in the coating process for photoluminescent layers and selection of materials with higher photoluminescence quantum yields.

### REFERENCES

1. **Rahmanian S., Rahmanian-Koushkaki H., Omidvar P., Shahsavar A.**, Nanofluid PCM heat sink for building integrated concentrated photovoltaic with thermal energy storage and recovery capability, *Sustainable Energy Technologies and Assessments*. 46 (2021) 101223.
2. sciencetech-inc. <https://www.sciencetech-inc.com/page/quantum-efficiency>. Accessed Mar. 19, 2025.
3. **Mohamed Zikriya, Nadaf Y.F., Vijai Bharathy P., Renuka C.G.**, Luminescent characterization of rare earth  $Dy^{3+}$  ion doped  $TiO_2$  prepared by simple chemical co-precipitation method, *Journal of Rare Earths*. 37 (2019) 24–31.
4. **Au V.T., Tran H., Lien N., et al.**, Synthesis of titanium dioxide nanotubes via one-step dynamic hydrothermal process. *Journal of Materials Science*. 49 (2014) 5617–5625.
5. **Henderson M.A.**, A surface science perspective on  $TiO_2$  photocatalysis, *Surface Science Reports*. 66 (2011) 185–297.

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## Effect of inclusion of titanium dioxide microparticles on the properties of PVDF/TiO<sub>2</sub>

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**Abstract.** In the course of the study, a method for obtaining a composite PVDF film with titanium dioxide microparticles was proposed. The work studied the effect of adding different amounts of titanium dioxide microparticles on the surface morphology and roughness of the resulting material. The spectral characteristics of PVDF/TiO<sub>2</sub> films were studied. The electrophysical characteristics of the films were analyzed depending on the concentration of added titanium dioxide microparticles.

**Keywords:** microparticles, TiO<sub>2</sub>, PVDF, composite materials, atomic force microscopy

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Материалы конференции

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## Влияние включения микрочастиц диоксида титана на свойства композитных пленок ПВДФ/TiO<sub>2</sub>

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**Аннотация.** В ходе исследования предложен способ получения композитной пленки ПВДФ с микрочастицами диоксида титана. В работе изучено влияние добавления различного количества микрочастиц диоксида титана на морфологию поверхности и шероховатость полученного материала. Изучены спектральные характеристики пленок ПВДФ/TiO<sub>2</sub>. Проведен анализ электрофизических характеристик пленок в зависимости от концентрации добавленных микрочастиц диоксида титана.

**Ключевые слова:** микрочастицы, TiO<sub>2</sub>, ПВДФ, композиционные материалы, атомно-силовая микроскопия

**Финансирование:** Исследование выполнено в рамках государственного задания Министерства науки и высшего образования Российской Федерации (тема № FSFN-2024-0014).



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## Introduction

Polyvinylidene fluoride and its copolymers have excellent piezoelectric properties, which allows to significantly expand the areas of application of PVDF products [1]. The polymer consists of 5 crystalline phases, which differ significantly in properties, primarily mechanical, optical and electrophysical. [2] It is important to note that without polarization or additional post-production processing, products can have extremely low mechanical properties, including an overly developed surface, which can limit the areas of their application [3]. Adding various materials to the polymer matrix can help in structuring PVDF, form intermolecular bonds, and also cause spontaneous polarization of the material [4]. Titanium dioxide is a biocompatible and crystalline material and can be used for structuring and as additional crystal formation points when obtaining films [5]. The main objective of this work is to evaluate the effect of the inclusion of  $\text{TiO}_2$  microparticles on the morphology, transparency and phase composition of the polymer, which is important for the creation of various devices based on PVDF and its copolymers. [6, 7].

## Materials and Methods

**Particle preparation.** To obtain composites, titanium dioxide nanoparticles were used, obtained by a standard method [6], in which 21 ml of the mixture (13 ml – isopropyl alcohol and 8 ml of titanium butoxide) was slowly added to 180 g of water heated to 135 °C, after which the mixture was heated for 2 hours at 145 °C, after which the heating was turned off and the mixture was stirred for another 5 days. Then the suspension was concentrated and dried in a drying cabinet at 57 °C.

**Obtaining composite films.** Weighed portions of titanium dioxide nanoparticles were weighed in falcons (5–20% relative to the amount of PVDF), after which 14 ml of a 5% PVDF solution in DMF were added to them, then the mixture was homogenized by stirring on a multirotator for 2 hours and 10 minutes using ultrasound treatment. After that, the suspensions were cast into Petri dishes and kept at 80 degrees for 28 hours.

**Atomic Force Microscopy.** The morphology and ferroelectric properties of the PVDF film with  $\text{TiO}_2$  nanoparticles were studied using scanning probe microscopy with NTEGRA Prima (NT-MTD, Zelenograd, Russia) using FMG01/Pt cantilevers with platinum coating.

**FTIR spectroscopy.** FTIR spectra of the films were recorded using an FT-803 FTIR spectrometer with an attenuated total internal reflection attachment manufactured by Simex LLC (Russia, Novosibirsk). Single FTIR attachment, diamond crystal. The range of IR spectra recording was 550–4000  $\text{cm}^{-1}$ , resolution 2  $\text{cm}^{-1}$ . The IR spectrum of pure  $\text{TiO}_2$  particles was recorded in transmission in a NaCl tablet using a PerkinElmer 1760X FTIR spectrometer, range 400–4000  $\text{cm}^{-1}$ , resolution 4  $\text{cm}^{-1}$ .

## Results and Discussion

The morphological and optical (transparency in the visible range) characteristics of films obtained with different contents of titanium microparticles were studied. Scanning probe microscopy data when introducing microparticles reduces the value of the mean square roughness of the film from 220 nm (the value for the outer rougher side of the control film) to 12 nm (Table 1). Spherical particles of micron sizes are observed on the surface of the control film (Fig. 1). From the AFM data it is evident that the inclusion of any amount of titanium dioxide in the polymer matrix significantly reduces the roughness, which may be due to the intermolecular interaction of the polymer and microparticles.

Table 1

Data from piezoresponse force microscopy

| TiO <sub>2</sub> concentration, % | Side       | $d$ , $\mu\text{m}$ | Rms, nm | VPFM, pA | LPFM, pA |
|-----------------------------------|------------|---------------------|---------|----------|----------|
| Control                           | Outer side | 7                   | 220     | 21       | 52       |
|                                   | Inner side | 5                   | 19      | 28       | 66       |
| 5                                 | Outer side | —                   | 15      | −1       | 51       |
|                                   | Inner side | —                   | 2       | 6        | 56       |
| 10                                | Outer side | —                   | 12      | −5       | −13      |
|                                   | Inner side | —                   | 3       | −3       | 56       |
| 20                                | Outer side | —                   | 6       | −5       | −59      |
|                                   | Inner side | —                   | 3       | 27       | 169      |

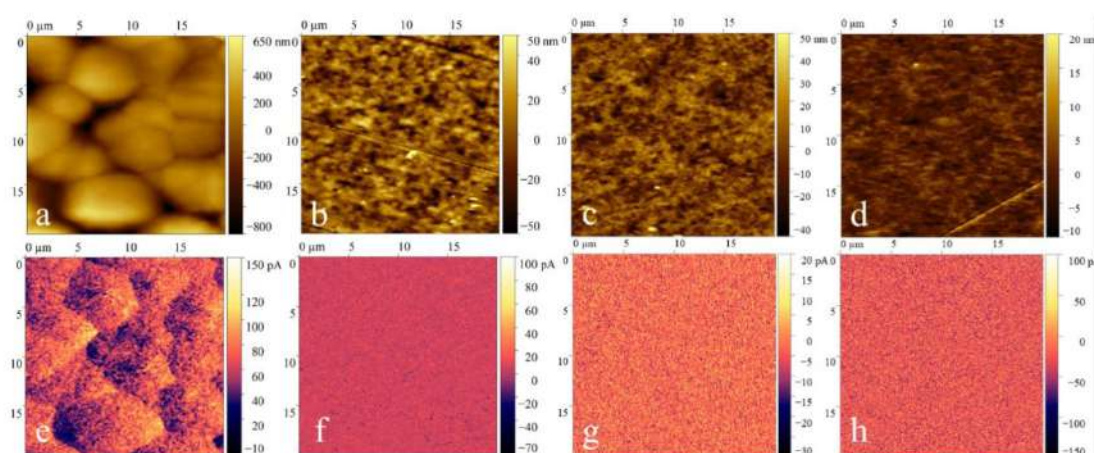


Fig. 1. AFM/PFM images of PVDF/TiO<sub>2</sub> composite films

The optical spectroscopy results demonstrate a significant change in turbidity after the inclusion of titanium dioxide microparticles (see Fig. 1). Turbidity in the visible part of the spectrum decreased from 79% to 9% for the film with 5% titanium dioxide nanoparticles. This effect may be associated with the formation of more compact supramolecular structures, as well as with the predominant content of the transparent  $\gamma$ -phase in PVDF.

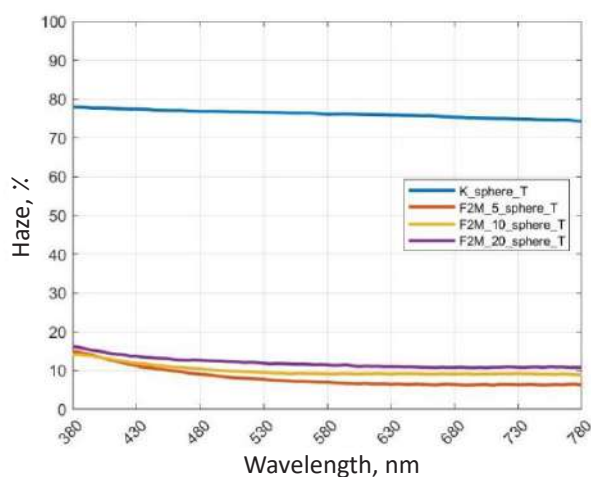


Fig. 2. Wavelength dependence of turbidity of PVDF films with incorporated titanium dioxide

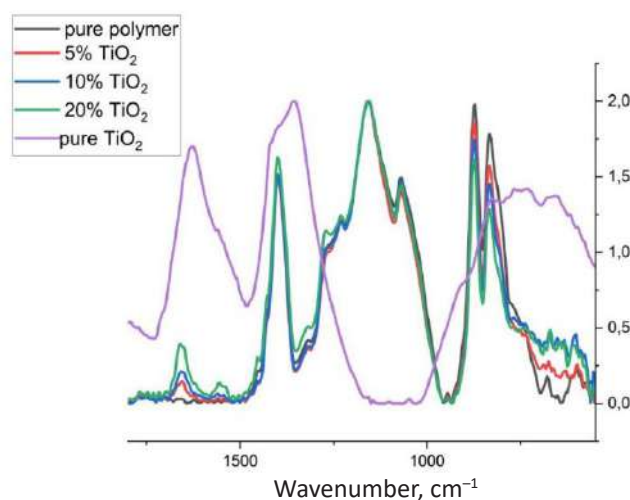


Fig. 3. FTIR spectra of PVDF/TiO<sub>2</sub> composite films, pure PVDF and microparticles TiO<sub>2</sub>

The FTIR spectroscopy data (Fig. 3) confirm the formation of a composite material, which is noticeable by the shift of the band at 1650 cm<sup>-1</sup>, which is characteristic of TiO<sub>2</sub>. The shift of the band is associated with the formation of intermolecular bonds of nanoparticles with the CH- and CF- groups. In addition, by changing the intensities of the characteristic CF- vibration bands in the region of 700–840 cm<sup>-1</sup>, a change in the phase composition and conversion from the  $\alpha$ -phase to  $\beta$  and  $\gamma$ -phase are noticeable, which leads to a change in the optical properties.

### Conclusion

In this paper, we propose a new method for producing a composite of titanium dioxide and PVDF microparticles. The effect of particle number on the optical characteristics, surface morphology, and electrical properties is determined. The proposed method can be used as a basis for producing composite films of PVDF and its copolymers with specified roughness and phase composition of the composite material.

### REFERENCES

1. Mitchell M.J., et al., Engineering precision nanoparticles for drug delivery, *Nature reviews drug discovery*. 20 (2) (2021) 101–124.
2. Zhou A., et al., Abatement of sulfadiazine in water under a modified ultrafiltration membrane (PVDF-PVP-TiO<sub>2</sub>-dopamine) filtration-photocatalysis system, *Separation and Purification Technology*. 234 (2020) 116099.
3. Saxena P., Shukla P.A., Comprehensive review on fundamental properties and applications of poly (vinylidene fluoride) (PVDF), *Advanced Composites and Hybrid Materials*. 4 (2021) 8–26.
4. Kochervinskii V.V., et al., The Effect of Electric Aging on Vinylidene Fluoride Copolymers for Ferroelectric Memory, *Nanomaterials*. 14 (12) (2024) 1002.
5. Vodyashkin A.A., et al., Green synthesis of titanium dioxide nanoparticles suitable for creating PVDF-TiO, *St. Petersburg Polytechnic University Journal. Physics and Mathematics*. 17 (3.2) (2024) 288–291.
6. Mohammadpourfazel S., et al., Future prospects and recent developments of polyvinylidene fluoride (PVDF) piezoelectric polymer; fabrication methods, structure, and electro-mechanical properties, *RSC advances*. 13 (1) (2023) 370–387.
7. Bhadwal N., Ridha B.M., Kamran B., Review of piezoelectric properties and power output of PVDF and copolymer-based piezoelectric nanogenerators, *Nanomaterials*. 13 (24) (2023) 3170.

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## **Investigation of metal-enhanced photoluminescence of zinc oxide films induced by platinum nanoparticles of different sizes**

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**Abstract.** This study examines the influence of platinum nanoparticles on plasmon-enhanced photoluminescence in films prepared from semiconductor zinc oxide nanocrystals. Metal nanoparticles with different average sizes from 48 to 82 nm were synthesized by a gas discharge method with additional in-flow heat treatment at 985 °C and deposited by dry aerosol printing on quartz glass followed by ZnO film fabrication. The relationship between the size of nanoparticles processed in the tube furnace and the working gas flow rate as well as the correlation between the enhancement factor of ZnO ultraviolet photoluminescence and the size of the Pt nanoparticles were established. A relationship between the photoluminescence enhancement factor and layers' configuration in nanostructures was also found. Theoretical calculations were also performed to determine the effects of plasmonic enhancement of ZnO photoluminescence.

**Keywords:** platinum nanoparticles, spark discharge, tube furnace, plasmonic nanostructures, ultraviolet metal-enhanced photoluminescence

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## **Исследование усиленной металлом фотолюминесценции пленок оксида цинка в присутствии наночастиц платины разного размера**

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**Аннотация.** Данное исследование посвящено изучению влияния наночастиц платины на плазмон-усиленную фотолюминесценцию в пленках, приготовленных из полупроводниковых нанокристаллов оксида цинка. Металлические наночастицы со средними размерами от 48 до 82 нм были синтезированы методом газового разряда с дополнительной термической обработкой в потоке газа при 985 °C и нанесены методом сухой аэрозольной печати на кварцевое стекло с последующим формированием

пленки ZnO. Были установлены зависимость между размером наночастиц, обработанных в трубчатой печи, и скоростью потока рабочего газа, а также корреляция между коэффициентом усиления ультрафиолетовой фотолюминесценции ZnO и размером наночастиц Pt. Также была обнаружена зависимость между коэффициентом усиления фотолюминесценции и конфигурацией слоев в наноструктурах. Кроме того, были проведены теоретические расчеты для определения эффектов плазмонного усиления фотолюминесценции ZnO.

**Ключевые слова:** наночастицы платины, газовый разряд, трубчатая печь, плазмонные наноструктуры, ультрафиолетовая металло-усиленная фотолюминесценция

**Финансирование:** Российский научный фонд (проект № 22-19-00311-П, <https://rscf.ru/en/project/22-19-00311/>).

**Ссылка при цитировании:** Санатулина А.Ф., Новосёлов А.К., Вершинина О.В., Лизунова А.А. Исследование усиленной металлом фотолюминесценции пленок оксида цинка в присутствии наночастиц платины разного размера // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2025. Т. 3.2 № .18. С. 247–252. DOI: <https://doi.org/10.18721/JPM.183.250>

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## Introduction

Modern nanotechnology offers diverse fabrication methods for plasmonic nanostructures, with applications in photonics, electronics, biomedicine, and microscopy [1–3]. Pt nanoparticles exhibit plasmonic resonance in the ultraviolet region and attract scientists for the development of various biological, optoelectronic and catalytic devices [4, 5]. Designing of plasmonic structures capable of amplifying electromagnetic fields within targeted spectral regions is employed in a variety of custom devices such as solar cells [6, 7], bio and chemical sensors. Therefore, it is important to study their dimensional and optical properties. To study the enhancement of photoluminescence (PL) near plasmonic structures based on noble metal nanoparticles, zinc oxide nanoparticles are commonly used as an ultraviolet phosphor, owing to their widespread applications in pharmaceutical, cosmetic and electrical industries [8]. Therefore, it is of considerable interest to study the interaction of Pt nanoparticles (NPs) with zinc oxide NPs in order to evaluate the possibility of using plasmon enhancement of photoluminescence in the ultraviolet range. The purpose of this work is to study the dependence of photoluminescence enhancement of ZnO films in the presence of Pt nanostructures with varying sizes and configurations formed by dry aerosol printing from nanoparticles, synthesized by a gas discharge method with additional heat treatment at 985 °C. The role of layer sequence in nanostructure design to optimize the amplification properties is also investigated. The novelty of this work is the use of a gas discharge setup combined with a tubular furnace to change the size of Pt NPs by precisely regulating the gas flow and to show application of obtained Pt NPs for plasmon-enhanced luminescence.

## Methods and materials

Pt nanoparticles were synthesized in a pulsed-periodic gas discharge using electric erosion of Pt electrodes in the form of cylinders with outer and inner diameters of 8 mm and 7 mm, respectively, containing pure material (99.9999%) in an argon atmosphere with a chemical purity of 6.0 at an excess pressure of 0.6 atm. To achieve this, a voltage of 1.5 kV was applied between the electrodes, with a current of 30 mA, a generation frequency of 500 Hz, and a capacitor capacity of 40 nF. The obtained primary nanoparticles were transported along the gas path and then subjected to modification in a tube furnace heated to 985 °C. The synthesis was carried out at various gas flow rates (50, 100 and 300 ml/min) using Pt electrodes. The sintered nanoparticles were subsequently focused through a nozzle and deposited on quartz glass substrates by means of dry aerosol printing. The formation of Pt films took place at a constant distance from the nozzle



to the substrate of 2.5 mm and a constant step between the lines of 150 micrometers. The velocity of the substrate relative to the nozzle varied from 1000 to 6000 micrometers/s.

Three different film configurations were created for Pt nanoparticles prepared at 100 ml/min flow rate: Pt+ZnO+Pt, ZnO+Pt and Pt+ZnO. To create a Pt+ZnO+Pt design, Pt nanoparticles were first deposited to quartz glass via dry aerosol printing. Subsequently, a layer of ZnO nanocrystals from liquid suspension was applied over the surface of the obtained Pt films by micro-plotter printing using a commercial SonoPlot GIX Microplotter II in a semi-contact printing mode. Finally, an additional Pt nanoparticle layer was applied to complete the structure. The ZnO+Pt configuration was fabricated by initial deposition of ZnO nanocrystals on quartz substrate, followed by dry aerosol printing of Pt nanoparticles. To create a Pt+ZnO design, Pt nanoparticles were applied to quartz glass by dry aerosol printing. Subsequently, a ZnO nanocrystal layer was fabricated atop the Pt film via microplotter printing. Ultraviolet-emitting reference films were prepared by microplotter deposition of pure 27 nm in size ZnO nanoparticles dispersed in isopropanol, demonstrating photoluminescence peak at 377 nm. Their emission intensity provided a baseline for quantitative comparison with designed Pt+ZnO nanostructures of different design (Pt+ZnO, ZnO+Pt, Pt+ZnO+Pt). To do this, the corresponding Pt+Pt PL spectrum was subtracted from the Pt+ZnO+Pt spectrum, and the corresponding Pt spectrum was subtracted from the ZnO+Pt and Pt+ZnO spectra. Pt+ZnO design were used to evaluate the influence of metal nanoparticles size on the amplification of ZnO photoluminescence. The morphology of the nanoparticles was examined using a transmission electron microscope (TEM) Jeol JEM 2100 (200 kV). The absorption spectra of film plasmon nanostructures were analyzed using a JASCO V-770 spectrophotometer. The photoluminescence spectra of the obtained films were measured on a Jasco 8300 fluorimeter with an excitation wavelength (Ex) of 325 nm (the power of the exciting radiation is 3.8 eV).

To study the luminescence enhancement of semiconductor zinc oxide nanocrystals in the presence of platinum nanoparticles, luminescence spectra were compared for films of various configurations with platinum nanoparticles and films with suspensions of semiconductor zinc oxide nanocrystals.

## Results and Discussion

It follows from the TEM images (Fig. 1, *a–c*) that the Pt powder was composed of nearly spherical particles. The selected area electron diffraction (SAED) pattern presented in the inset of Figure 1d consists of rings corresponding to interplanar spacings of 2.26, 1.96, 1.39 and 1.17 Å. These values are in good agreement with those characteristics of (111), (200), (220), and (311) planes of face-centered cubic crystal system of Fm3m platinum. According to the data from the TEM image analysis, the nanoparticles synthesized at a flow rate of 50 ml/min have an average size of  $82 \pm 24$  nm (Fig. 1, *a*), at a flow of 100 ml/min –  $75 \pm 25$  nm (Fig. 1, *b*), NP produced at a flow of 300 ml/min characterized by the average size  $48 \pm 21$  nm (Fig. 1, *c*). The size-distribution of nanoparticles follows a log-normal function. (Fig. 1, *e*). It was found that the nanoparticles size decreases linearly with increasing flow rate (Fig. 1, *f*).

The obtained Pt metal nanoparticles exhibited the resonance absorbance in the ultraviolet range from 270 to 300 nm [9], which were deposited on the quartz substrate and covered by the homogeneous layer of ZnO nanocrystals.

Fig. 2, *a* demonstrates the significant impact of nanostructural design, specifically the layer order and arrangement of Pt metal nanoparticles with an average size of  $75 \pm 25$  nm relative to the phosphor ZnO crystals, on the observed photoluminescence enhancement. All fabricated structures maintained a consistent average thickness for the pure Pt metal layers at a wavelength of 325 nm. The optimal photoluminescence enhancement was achieved in the Pt+ZnO configuration, where the zinc oxide phosphor layer was deposited atop the platinum nanoparticle array, yielding a maximum gain factor of 40% relative to the pure ZnO reference.

The second goal of the work was to obtain the influence of Pt nanoparticle size on the enhancement of ZnO films in multilayer Pt+ZnO nanostructures. Fig. 2, *b* presents a comprehensive analysis of plasmon-enhanced luminescence in Pt+ZnO multilayer nanostructures, namely, the dependence of the enhancement factor and intensity of ZnO PL (insert) in the presence of Pt nanostructures with an optical density from 0.15 (measured at a wavelength of 325 nm) with various metal NPs sizes. A non-linear dependence was obtained, which showed growth of PL with

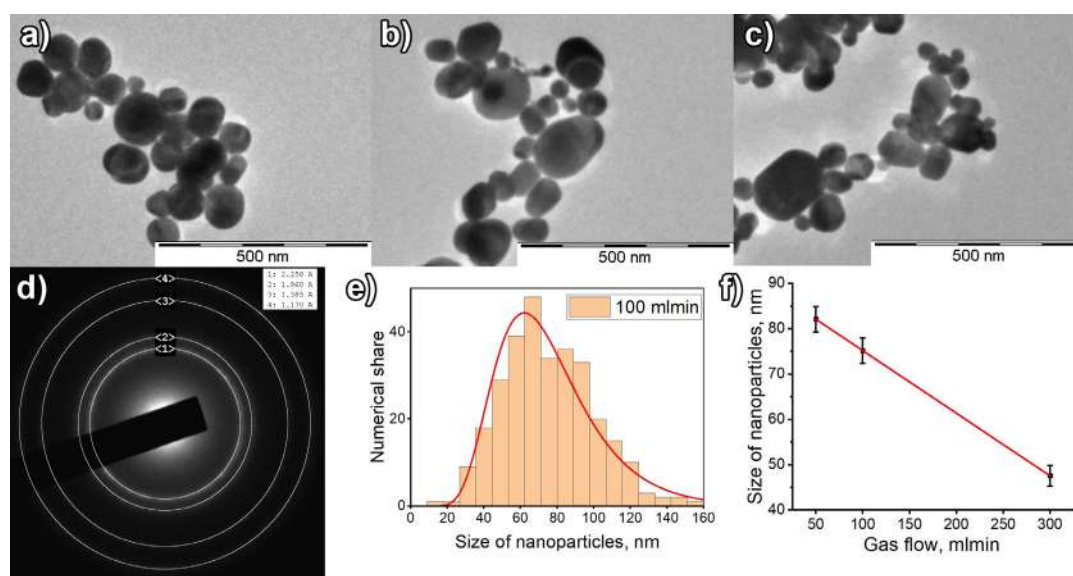


Fig. 1. Dimensional properties of produced Pt nanoparticles by spark discharge with additional in-flow thermal treatment at 985 °C: TEM image of Pt nanoparticles, synthesized in a gas flow rate of: 50 ml/min (a); 100 ml/min (b); 300 ml/min (c), the typical SAED pattern of the Pt nanoparticles (d), histogram of the size distribution of nanoparticles obtained at a flow of 100 ml/min with log-normal approximation (e), the dependence of the average size of Pt NPs via the gas flow rate (f)

increasing size of metal NPs. The maximum luminescence enhancement was achieved for the largest Pt nanoparticles, with an average diameter of 82 nm, and compiled a maximum enhancement factor of 43% relative to the pure ZnO reference. In contrast, systems with smaller NPs average size (48–75 nm) exhibited quenching up to ~73–80 % compared to pure ZnO film PL.

To probe plasmonic luminescence enhancement in Pt nanoparticles, we calculated the enhancement factor using Mie theory, incorporating influence of quantum yield of emitter (non-radiative energy transfer) [10]. Simulations were performed for the sample with polydisperse lognormal size distribution of Pt NPs and an average size of  $75 \pm 25$  nm. Fluorescence intensity map was calculated in the ultraviolet region from 200 to 600 nm for phosphor with intrinsic quantum yield  $Q_0 = 0.13$  and emission wavelength at 380 nm similar to the case of the employed ZnO nanoparticles via the distance between the surface of a metal nanoparticles and an emitter and presented

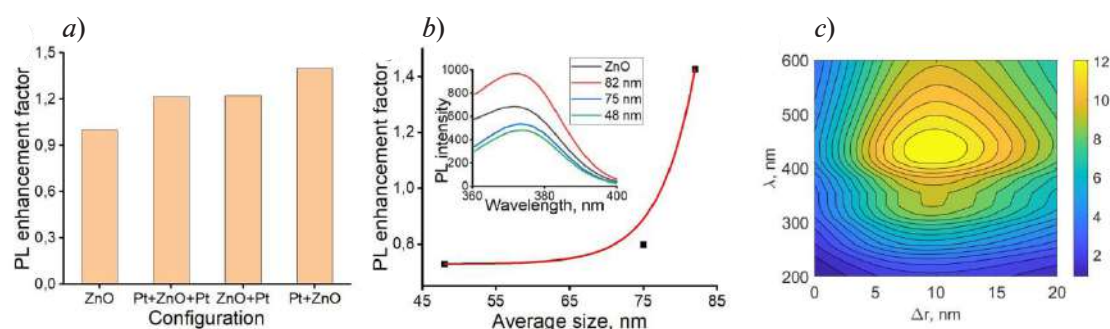


Fig. 2. PL properties of obtained nanostructures: the luminescence enhancement factor of ZnO film via the order of layers' configuration with Pt NPs (a), relationship between the PL enhancement factor and the average size of Pt nanoparticles in Pt+ZnO design (b) and PL spectra of the obtained multilayer Pt+ZnO nanostructures (b: insert), calculated photoluminescence intensity enhancement factor map versus Ex wavelength and metal-emitter spacing for polydisperse Pt nanoparticles with mean diameter of 75 nm (c)





in a Fig 2, *c*. Fig. 2, *c* results in the growth of the enhancement factor from 2 to 8 times at the Ex wavelength of 325 nm depending on distance between the metal NP and emitter.

A study was conducted [11], which showed a 7-fold increase in photoluminescence for platinum nanoparticles of 80 nm in size at an excitation wavelength of 325 nm, which is consistent with our theoretical studies. Also, in comparison with the articles [12], our method allows us to control the size of platinum nanoparticles and considers the interaction of platinum nanoparticles with ZnO crystals, rather than with a continuous film. According to the study [10] of zinc oxide films in the presence of Al nanoparticles, the worst enhancement is for the Al+ZnO+Al structure, and the best gain is for the Al+ZnO structure, which is consistent with the data obtained for Pt+ZnO films. For aluminum nanoparticles, it was also found that photoluminescence increases by 50 percent with an increase in particle size from 10 to 55 nm [13]. The same correlation is true for platinum particles, on which photoluminescence increases by 67 percent with an increase in particle size from 48 to 82 nm.

The discrepancy between theoretical and experimental data can be caused by several factors. Our method does not allow us to adjust the distance between platinum particles and ZnO crystals, which may affect the maximum possible enhancement (Fig. 2, *c*). The model also considers the amplification in the presence of a single ZnO particle, whereas the experiment involves the interaction of several ZnO particles with a platinum particle and plasmon coupling between metal NPs.

### Conclusion

Thus, we reported size- and configuration-dependent plasmonic enhancement of ZnO luminescence in the presence of Pt nanoparticles. We have demonstrated the possibility of production of platinum particles of different sizes in a gas discharge using additional in-flow sintering in a tubular furnace and get Pt NPs with average sizes of  $82 \pm 24$ ,  $75 \pm 25$  and  $48 \pm 21$  nm were at flow rates of 50, 100 and 300 ml/min, respectively. It was found that the best configuration for creating multilayer nanostructures is Pt+ZnO, where ZnO nanocrystal layer was fabricated atop the Pt film deposited on quartz by dry aerosol printing. It was found that Pt nanoparticles revealed the average size 82 nm are optimal ones to achieve the maximum plasmon-enhancement factor of ZnO the photoluminescence up to 1.43 times in ultraviolet region. Theoretical calculations established the growth of the enhancement factor from 2 to 8 times via the increase of particle-emitter spacing from 1 to 10 nm.

### REFERENCES

1. Kruis F.E., Fissan H., Peled A., Synthesis of nanoparticles in the gas phase for electronic, optical and magnetic applications—a review, *Journal of Aerosol Science*. 29 (5–6) (1998) 511–535.
2. Sokovnin S.Yu., Il'Ves V.G., Production of Nanopowders Using Pulsed Electron Beam. *Ferroelectrics*, 436 (1) (2012) 101–107.
3. Dhand C., Dwivedi N., Loh X.J., et al., Methods and strategies for the synthesis of diverse nanoparticles and their applications: a comprehensive overview, *RSC Advances*. 5(127) (2015) 105003–105037.
4. Bauch M., Toma K., Toma M., et al., Plasmon-Enhanced Fluorescence Biosensors: a Review, *Plasmonics*. 9 (4) (2014) 781–799.
5. Thrithamarassery Gangadharan D., Xu Z., Liu Y., et al., Recent advancements in plasmon-enhanced promising third-generation solar cells, *Nanophotonics*. 6 (1) (2017) 153–175.
6. Wang Y., Zhang J., Liang W., Rational Design of Plasmonic Metal Nanostructures for Solar Energy Conversion, *CCS Chemistry*. 4 (4) (2022) 1153–1168.
7. Yu P., Yao Y., Wu J., Effects of Plasmonic Metal Core -Dielectric Shell Nanoparticles on the Broadband Light Absorption Enhancement in Thin Film Solar Cells, *Scientific Reports*. 7 (1) (2017) 7696.
8. Kołodziejczak-Radzimska A., Jesionowski T., Zinc Oxide—From Synthesis to Application: A Review. *Materials*. 7(4) (2014) 2833–2881.
9. Lizunova A.A., Novosyolov A.K., Khramov E.S., et al., Absorbance Variation of Plasmon Al and Pt Nanostructures Formed by Dry Aerosol Printing for Label-Free Detection of BSA Luminescence, *Bulletin of the Russian Academy of Sciences: Physics*. 88 (S2) (2024) S211–S216.



10. **Lizunova A.A., Malo D., Guzatov D.V., et al.**, Plasmon-Enhanced Ultraviolet Luminescence in Colloid Solutions and Nanostructures Based on Aluminum and ZnO Nanoparticles, *Nanomaterials*. 12 (22) (2022) 4051.

11. **Ma K., Zhou X., Kan C., et al.**, Pt nanoparticles utilized as efficient ultraviolet plasmons for enhancing whispering gallery mode lasing of a ZnO microwire via Ga-incorporation, *Physical Chemistry Chemical Physics*. 23 (11) (2021) 6438–6447.

12. **Chen S., Pan X., He H., et al.**, 60-fold photoluminescence enhancement in Pt nanoparticle-coated ZnO films: role of surface plasmon coupling and conversion of non-radiative recombination, *Optics Letters*. 40 (12) (2015) 2782.

13. **Malo D.**, Investigation of plasmon-enhanced ultraviolet luminescence of zinc oxide semiconductor nanocrystals in the presence of aluminum nanoparticles synthesized by gas-phase methods: dis. (2024).

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## Memristive effect in hydrothermal ZnO structures

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**Abstract.** In this paper, we investigate the memristor properties of ZnO microstructures synthesized by hydrothermal method. ZnO is a promising material for obtaining energy-efficient memory elements due to its compatibility with CMOS technologies, low cost, and good scalability. In this study, hexagonal ZnO micropriams with a diameter of  $\sim 10\text{ }\mu\text{m}$  and a thickness of  $\sim 2\text{ }\mu\text{m}$  were obtained. The study of the current-voltage characteristics revealed a unipolar memristor effect with switching between the high (HRS) and low (LRS) resistance states when applying both positive and negative voltage. The switching ratio  $I_{\text{ON}}/I_{\text{OFF}}$  was  $10^2$  for forward bias and  $10^4$  for reverse bias. The obtained results demonstrate the potential of ZnO structures for application in non-volatile memory with low power consumption.

**Keywords:** zinc oxide, hydrothermal, memristor

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Материалы конференции

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## Мемристорный эффект в гидротермальных структурах ZnO

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**Аннотация.** В данной работе исследуются мемристорные свойства микропризм ZnO, синтезированных гидротермальным методом. ZnO является перспективным материалом для создания энергоэффективных элементов памяти благодаря своей совместимости с КМОП-технологиями, низкой стоимости и хорошей масштабируемости. В ходе исследования получены гексагональные микропризмы ZnO диаметром ~10 мкм и толщиной ~2 мкм. Исследование вольт-амперных характеристик выявило униполярный мемристорный эффект с переключением между состояниями с высоким (HRS) и низким (LRS) сопротивлением при подаче как положительного, так и отрицательного напряжения. Коэффициент переключения  $I_{ON}/I_{OFF}$  составил  $10^2$  для прямого смещения и  $10^4$  для обратного смещения. Полученные результаты демонстрируют потенциал микроструктур ZnO для применения в энергонезависимой памяти с низким энергопотреблением.

**Ключевые слова:** оксид цинка, гидротермальный, мемристор

**Финансирование:** Работа выполнена при поддержке Министерства науки и высшего образования Российской Федерации (грант № FSRM-2023-0009; проект FSMG-2025-0005), Российского научного фонда (Грант 24-12-00225) и СПбГУ (проект 122040800254-4).

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## Introduction

Memristors have become one of the most promising candidates in the field of fabricating miniature non-volatile memory elements [1]. A memristor is a nonlinear resistor, which conductivity depends on the electric charge flowing through it. Among their advantages are low power consumption, fast resistive switching between a high-resistance state (HRS) and a low-resistance state (LRS), good scalability.

Zinc oxide (ZnO) is a proven wide-bandgap semiconductor material [2] known for its piezoelectric properties [3], which allows it to be used as a material for resistive switching. Its advantages include its high content in nature, which determines its low cost, compatibility with CMOS technologies in terms of process integration, as well as the scalability of the resulting devices, down to nanometer sizes.



Despite the fact that the memristor effect was previously demonstrated in ZnO nanostructures of various geometries [4, 5], the prospects for their application in memory device fabrication technologies were determined, additional system studies are required to determine the optimal geometry of ZnO-based nanostructures to observe a stable memristor effect with low switching power consumption and fast response.

### Methodology

Hydrothermal synthesis is a method of growing various materials and compounds, based on the use of physical and chemical processes that take place in aqueous solutions at slightly elevated temperatures often used to obtain ZnO nanostructures [6].

In our study, we use a silicon substrate Si (100) coated with a 100 nm thick Ag layer for the hydrothermal synthesis of ZnO nanostructures. An aqueous solution of zinc acetate was used as a seed layer. The seed layers were deposited by the spin coating method. A solution of zinc acetate was dropwise applied to the substrate using a Pasteur pipette. Then, the substrate with the solution was spun in a centrifuge at 4000 rpm for 30 s. After the centrifuge, the sample was placed on a furnace and annealed at 350 °C for 3 minutes. A total of 3 such layers were deposited.

To study the memristor properties of zinc oxide, hexagonal microprisms were synthesized on the prepared substrate. The growth solution consists of equimolar aqueous solutions of  $\text{Zn}(\text{NO}_3)_2$  and hexamethylenetetramine (HMTA) with a concentration of  $100 \text{ mmol} \cdot \text{L}^{-1}$ . Additionally, sodium citrate at a concentration of  $5 \text{ mmol} \cdot \text{L}^{-1}$  was added to the growth solution to suppress vertical growth and stimulate lateral growth. Citrate ions are negatively charged, so they selectively bind to  $\text{Zn}^{2+}$  ions on the (0001) surface, block growth along the c axis and stimulate it in the [01 $\bar{1}$ 0] and [21 $\bar{1}$ 0] directions. This process leads to pronounced lateral growth and a decrease in the aspect ratio of the structures, which leads to the formation of hexagonal microprisms. The following reactions occur during the synthesis:



During the synthesis, a constant temperature of 85°C was maintained. The synthesis duration was 3 hours. After synthesis, the samples were washed with deionized water and annealed in a furnace at a temperature of 350 °C for 5 minutes. The fabrication scheme of the experimental sample is shown in Fig. 1.

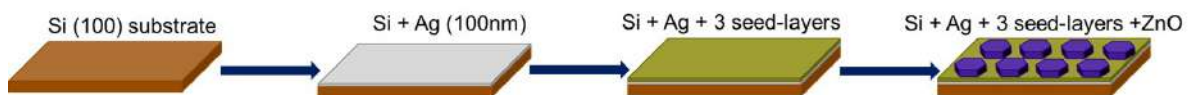


Fig. 1. Fabrication scheme

The study of the current-voltage characteristics in order to detect the memristive effect in the synthesized ZnO structures was carried out using the NTegra Aura, NT-MDT SI setup. The TipsNano HA<sub>FM</sub>/W<sub>2</sub>C probe was used. To measure the current-voltage characteristics, two probes were applied to the Ag/ZnO structure. One of the probes served as the upper (positive) contact to ZnO, the second as the lower (negative) contact to Ag.

### Results

ZnO structures in the geometry of hexagonal prisms with a  $\sim 10 \mu\text{m}$  diameter and a  $\sim 2 \mu\text{m}$  thickness were synthesized (Fig. 2).

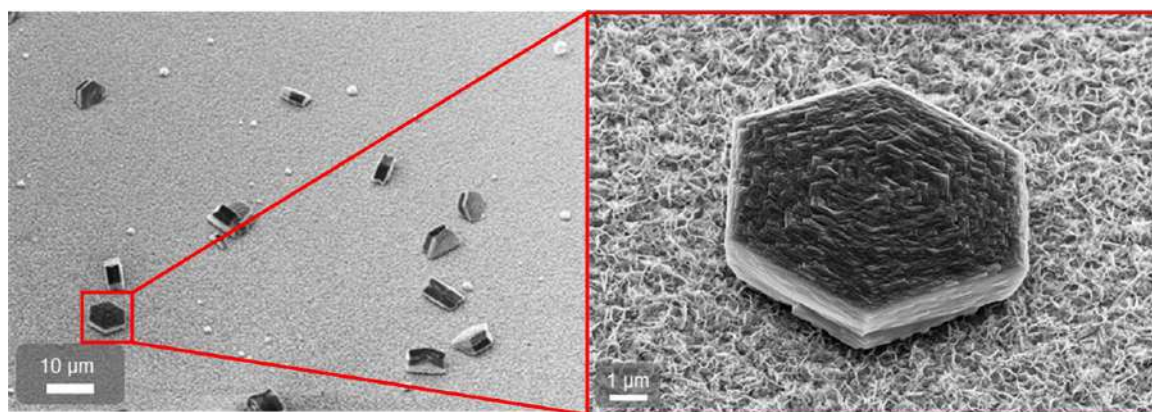


Fig. 2. SEM images of the synthesized sample

The  $I$ – $V$  characteristic is divided into 4 stages (Fig. 3). At stage I, a positive voltage is applied to the sample (forward bias) transition from the high-resistance state to the low-resistance state. During the initial application of voltage (blue curve in Fig. 3, *a*), positively charged oxygen vacancies  $V_{\text{O}}^{+}$  drift toward the negatively charged electrode, forming a conducting channel in the ZnO semiconductor, significantly reducing the resistance of the Ag/ZnO/probe structure. This process is referred to as SET (turn-on). Thus, for a given polarity of the applied voltage, the Ag/ZnO/probe structure is in the low-resistance state (LRS). The “turn-on” voltage,  $V_{\text{SET}}$ , was 5.6 V. Stage II corresponds to LRS (red curve in Fig. 4, *a*). At stage III, a negative voltage is applied to the sample (reverse bias). A transition from the high-resistance state (HRS) to LRS is observed (blue curve in Fig. 3, *b*), as with the application of positive voltage.  $V_{\text{SET}}$  was 7.2 V. Stage IV corresponds to LRS (red curve in Fig. 3, *b*).

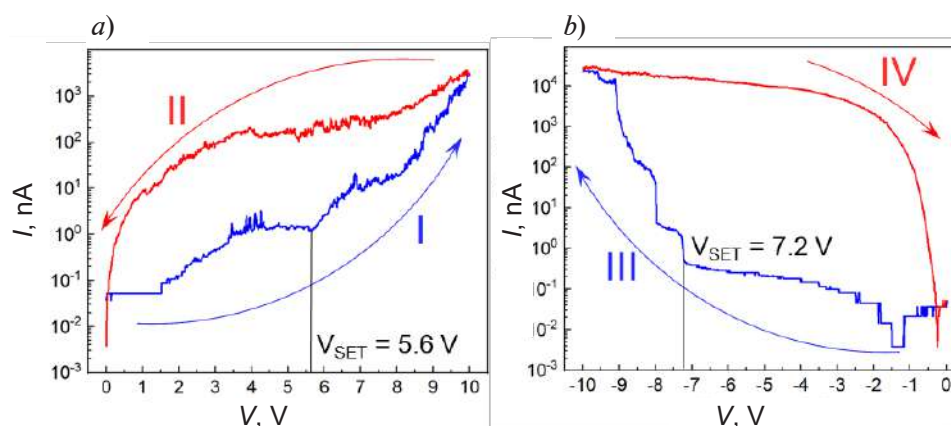


Fig. 3. Current–voltage characteristics of the synthesized sample: forward bias (*a*); reverse bias (*b*)

The transition from HRS to LRS with the application of both positive and negative voltage indicates the unipolar nature of the obtained memristor. When applying forward voltage, the ratio of the “on” current to the “off” current  $I_{\text{ON}}/I_{\text{OFF}} = 10^2$ . In the case of applying reverse voltage  $I_{\text{ON}}/I_{\text{OFF}} = 10^4$ .

### Conclusion

The results confirmed occurrence of the memristor effect in hexagonal ZnO microprisms synthesized by the hydrothermal method. The unipolar nature of resistance switching, as well as high values  $I_{\text{ON}}/I_{\text{OFF}}$  indicate the prospects of using ZnO as an active material for next-generation memory elements. Further research should be aimed at obtaining methods for the ordered synthesis of zinc oxide in order to fabricate contacts to its surface.





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### REFERENCES

1. Li Y., Wang Z., Midya R., et al., Review of memristor devices in neuromorphic computing: materials sciences and device challenges, *Journal of Physics D: Applied Physics*. 51 (50) (2018) 503002.
2. Kadinskaya S.A., Kondratev V.M., Kindyushov I.K., et al., Deep-Level Emission Tailoring in ZnO Nanostructures Grown via Hydrothermal Synthesis, *Nanomaterials*. 13 (1) (2022) 58.
3. Nikolaeva A.V., Kondratev V.M., Kadinskaya S.A., et al., ZnO nanowire-based flexible sensors for pressure and temperature monitoring, *Materials Science in Semiconductor Processing*. 189 (2025) 109253.
4. Paul S., Harris P.G., Pal C., et al., Low cost zinc oxide for memristors with high on–off ratios, *Materials Letters*. 130 (2014) 40–42.
5. Chew Z.J., Li L., A discrete memristor made of ZnO nanowires synthesized on printed circuit board, *Materials Letters*. 91 (2013) 298–300.
6. Xu H.Y., Wang H., Zhang Y.C., et al., Hydrothermal synthesis of zinc oxide powders with controllable morphology, *Ceramics International*. 30 (1) (2004) 93–97.

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### Features of determining relationships in aqueous biological solutions between biophysical constants and environmental parameters using optical methods

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**Abstract.** The relevance of early diagnostics of chronic kidney disease (CKD) is due to it high prevalence and asymptomatic course of the disease in the early stage. There is a need to develop new approaches to the diagnosis of early-stage kidney damage that are accessible, non-invasive and reliable, with an emphasis on the use of optical methods. A new method of rapid diagnosis based on refractometric measurement of the refractive index of urine has been proposed. New relationships between the refractive index, osmolality  $O_s$ , and density  $\rho$  have been established. Based on the values of  $O_s$  and  $\rho$ , doctors determine the presence of kidney disease or damage at an early stage (the patient is then referred for clinical examination). The proposed method provides high accuracy (the refractive index measurement error of  $\pm 0.00005$  in a wide temperature range of 288–303 K made it possible to determine  $O_s$  and  $\rho$  based on these measurements with an error of 2 mOsm/l and 0.00015 g/cm<sup>3</sup>, which is sufficient to determine kidney damage at an early stage. This makes it competitive when compared to traditional methods of rapid kidney function testing (urinalysis, test strips, and mobile density meters). The results obtained for the diagnosis of kidney function were clinically confirmed during the examination of patients. This confirms the possibility of using refractometry for rapid diagnosis of kidney condition to detect damage at an early stage.

**Keywords:** kidney, early-stage damage, refractometry, osmolality, density, urine, rapid diagnostics

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## **Особенности определения связей в водных биологических растворах между биофизическими константами и параметрами среды с использованием оптических методов**

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**Аннотация.** Актуальность ранней диагностики хронической болезни почек (ХБП) обусловлена их высокой распространенностью и бессимптомным течением заболевания на начальной стадии. Обоснована необходимость разработки новых подходов к диагностике определения поражения почек на ранней стадии, ориентированных на доступность, неинвазивность и достоверность, с акцентом на использование оптических методов. Предложен новый метод экспресс-диагностики, основанный на рефрактометрическом измерении показателя преломления мочи. Установлены новые зависимости между показателем преломления, осмолярностью  $O_s$  и плотностью  $\rho$ . По значениям  $O_s$  и  $\rho$  врачи определяют наличие заболеваний почек или их поражение на ранней стадии (далее пациент направляется на клиническое обследование). Предложенный метод обеспечивает высокую точность (погрешность измерения показателя преломления  $\pm 0.00005$  в широком диапазоне изменения температур 288–303 К позволила обеспечить определение на основе этих измерений  $O_s$  и  $\rho$  с погрешностью 2 мОсм/л и 0,00015 г/см<sup>3</sup>, что достаточно для определения поражения почек на ранней стадии. Это делает его конкурентоспособным при сравнении с традиционными способами экспресс-контроля состояния почек (урометрия, тест-полоски и мобильный измеритель плотности). Полученные результаты по диагностике состояния почек получили клиническое подтверждение при обследовании пациентов. Это подтверждает возможность применения рефрактометрии для экспресс-диагностики состояния почек для выявления их поражения на ранней стадии.

**Ключевые слова:** почки, оптическое излучение, рефрактометрия, осмолярность, плотность, моча, экспресс-диагностика, ранняя стадия

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### **Introduction**

Chronic kidney disease (CKD) is a serious medical and social problem of mankind [1, 2]. According to the World Health Organization, the prevalence of CKD in the adult population reaches 16 percent or more [3–5]. Kidney disease is characterized by a long asymptomatic course and late diagnosis [3–5]. In most cases, pathology is detected only at stages 3–4, when therapeutic treatment options are significantly limited and treatment requires significant material costs [5–7]. This situation is due to the lack of reliable, accessible and easy-to-use methods of express diagnostics, unlike other areas of personalized medicine [8, 9].

Modern methods of express diagnostics of kidney condition used in clinical practice have a number of significant limitations. Urometry, despite its prevalence, is characterized by a significant measurement error ( $\pm 0.005$  g/ml) and a pronounced dependence of the results on ambient temperature [10, 11]. In addition, visual assessment of the position of the liquid meniscus in the urometer introduces a significant subjective component into the measurement process. Test strips, although convenient to use, have limited accuracy due to color interpretation of results and high sensitivity to the presence of protein, glucose, and drugs in urine [12]. Another important disadvantage is their limited shelf life and demanding environmental conditions. The use of mobile density meters is unsatisfactory in terms of measurement accuracy  $\rho$  (should be  $\pm 0.0001$  g/ml or less) or in terms of operating costs and the price of the device itself for a large number of users (small medical institutions, polyclinics and personal use).

All this makes the development of new approaches to screening renal pathology at an early stage an extremely urgent task. Therefore, the aim of the work is to develop a method for express control of kidney condition on the basis of optical measurements and techniques for detection of kidney lesions at an early stage based on the results of measurements.

### Materials and methods

In modern clinical medicine, data on the state of urine density are mainly used for rapid diagnosis of renal status [10–12]. There are no big problems to measure urine density in a stationary laboratory using an ultrasonic density meter with an error of 0.2%. There are also various models of spectrophotometers for the study of urine samples. It should be noted that the determination of urine osmolarity  $O_s$  is of particular importance in clinical diagnosis of renal diseases [3–6]. This parameter serves as an important indicator of the functional state of the kidneys and water-electrolyte balance of the organism [3–6]. However, the existing methods of determining this parameter, in particular osmometry, require the use of complex laboratory equipment, considerable time expenditure and special conditions of analysis, which limits their use even in routine clinical practice [2–6, 12].

The new control method we propose makes it possible to reduce the problem of determining  $O_s$  in clinical conditions and to determine  $O_s$  in express mode (currently unachievable). In addition, it is proposed to determine the density  $\rho_u$  of urine based on the measured refractive index  $n_u$ . We propose using the results of a single measurement of  $n_u$  in a urine sample to determine the values of  $O_s$  and  $\rho_u$ , taking into account the temperature  $T$ , with an error margin that will allow for the early detection of kidney disease. This approach has made it possible not only to obtain representative quantitative characteristics of the studied indicators, but also to conduct an interparametric comparison with a high degree of reliability.

Urine samples were used as research objects. Samples were collected from patients in various physiological states, including normohydration, dehydration, and conditions accompanied by water-salt imbalance. This variety of conditions allowed us to cover a wide range of osmolality, density, and refractive index values, which, in turn, ensured high data variability and the ability to identify consistent patterns. More than 150 people were examined. Measurements were taken using certified equipment, which minimized the influence of external factors and increased the reliability of the results. Taken together, this made it possible to establish relationships between the parameters studied and draw reasonable conclusions about the nature of their connection in the context of changes in the physiological state of the body.

In order to establish these dependencies, simultaneous studies on certified equipment of the change in  $n_u$ ,  $O_s$  and  $\rho_u$  from the change in temperature  $T$  were carried out as follows. A urine sample was collected from the patient. Then from this sample, three urine samples were placed in a density meter, osmometer and refractometer. Synchronized measurements were made of the change in these quantities from changes in temperature  $T$ , which will be the base parameter in the construction of  $O_s(n_u)$  and  $\rho_u(n_u)$  relationships in the future. The temperature was varied in the range from 288 to 303 K, which corresponds to the standards of urine sample diagnostics [1–6].

The refractive index was measured using a mobile refractometer SNEL-105, which operates on autonomous power (measurement error  $\pm 0.00005$ ). This device can be used for rapid testing without any problems. This was a distinctive feature of the experimental study (the equipment used for rapid testing at the sampling site would not change). The density of the



urine samples was determined using a DSA 5000 M ultrasonic densitometer (a laboratory device with an error of 0.00001 g/ml). Osmolarity was measured using an OSKR-1M osmometer with a cryostat (measurement error of 1 mOsm/l in the measurement range from 500 to 2000 mOsm/l). This range includes  $O_s$  values that correspond to the onset of early-stage kidney disease (581–732 mOsm/l).

## Results and discussion

The paper cites one example of experimental testing of our proposed method for rapid diagnosis of kidney condition. From a sample of studies involving 150 patients, 10 urine samples were selected from patients of different ages and genders who did not complain of kidney problems. The selection criterion was slight excess weight (no more than 15% deviation from the normal height-weight ratio). This was a recommendation from doctors at the First Saint Petersburg State Medical University (Saint Petersburg). Figs. 1 and 2 show examples of the dependence of  $n_u$  and  $\rho_u$  on temperature  $T$  for sample 1 (patient 1).

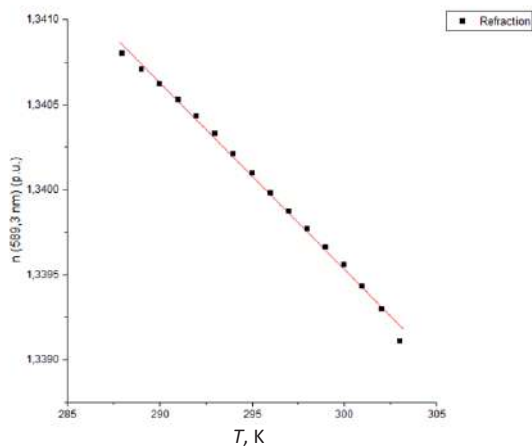


Fig. 1. Dependence of  $n_u$  on  $T$

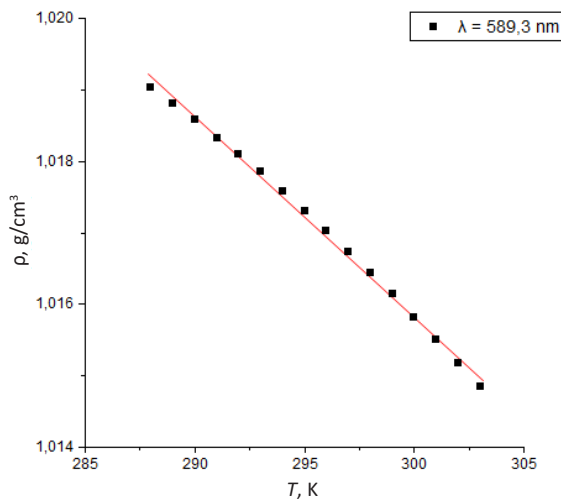


Fig. 2. Dependence of  $\rho_u$  on  $T$

Using the least squares method, linear approximation models describing the established dependences were obtained from the experimental data:

$$\rho = 2.4322n - 2.2444,$$

$$O_s = 33.128\rho - 33.107.$$

These dependences are represented in Figs. 3 and 4. The validity of the obtained approximations was confirmed by statistical processing of the results: correlation coefficients were calculated and the significance of regression dependencies was evaluated. To increase the reliability and reproducibility of the experimental data, each measurement was repeated three times, after which the obtained values were averaged. This approach ensured the stability of the results to random deviations and allowed us to form reasonable conclusions about the nature of relationships between osmolarity, density and refractive index of aqueous biological urine solutions. Similarly, using the experimental data (Fig. 3, 4), a linear relationship between osmolarity and density of the solution under study was established:  $O_s = 33.128\rho - 33.107$ . The results obtained confirm that osmolarity can be indirectly estimated by measuring the density as well as the refractive index, which significantly simplifies the analysis procedure and makes it more accessible in conditions of limited laboratory resources.

For the remaining 10 urine samples, the same studies were performed. Analytical relationship between  $\rho_u(n_u)$  obtained through the results shows that average value for the coefficient  $a$  equals 2.4343 and the average value for the coefficient  $b$  equals 2.2479. The general formula for

describing the relationship is:  $\rho_u = an_u + b$ . The deviation of coefficient  $a$  from the average value for a group of 10 samples is  $\pm 0.0215$ , which is about 1% of the average value. The deviation of coefficient  $b$  from the average value for a group of 10 samples is  $\pm 0.0127$ , which is less than 1% of the average value.



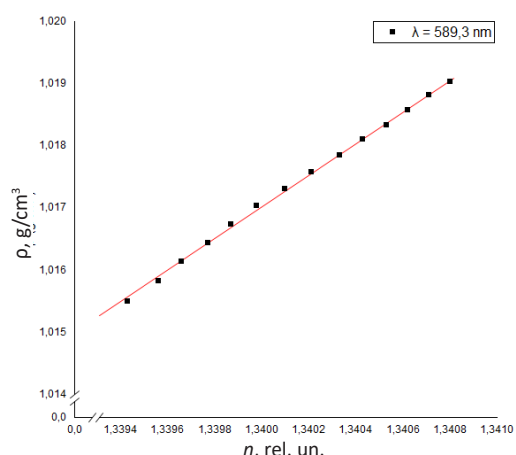


Fig. 3. Density dependence on refractive index

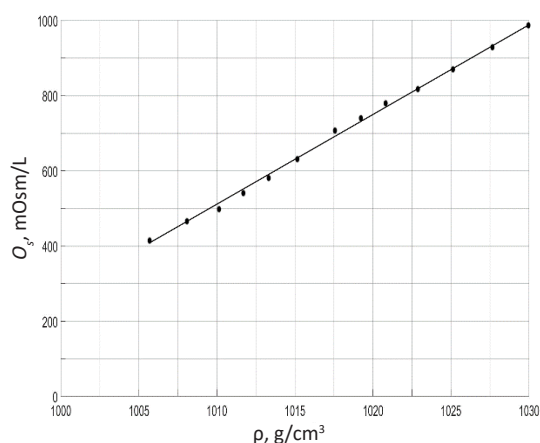


Fig. 4. Osmolarity dependence on density

Similar tests were conducted on a sample of 13 patients who did not show signs of early kidney disease during rapid diagnosis.

To ensure the implementation of the rapid diagnosis method for early kidney disease based on the measurement of the refractive index using a mobile refractometer SNEL-105 or two devices (a refractometer and a mobile densitometer), or a mobile densitometer (density meter), average dependencies for patient groups are required (with suspected early-stage kidney disease or no such suspicion).

Fig. 5 shows examples of the final dependences of density change on refractive index and osmolality on density, averaged over samples from the two groups of patients considered. Analysis of the results obtained shows that measurements of the refractive index  $\pm 0.00005$  in a wide range of temperatures  $T$  to 288–303 K allow for an error of 2 mOsm/L and 0.00015 g/cm<sup>3</sup> when determining  $O_s$  and  $\rho$  based on these measurements, which is sufficient for detecting kidney damage at an early stage. The dependences (Fig. 5) show areas of both early-stage kidney disease and the absence of disease.

This level of accuracy is entirely satisfactory for doctors. The early stage of kidney disease in terms of osmolality is in the range of 581–732 mOsm/L, and in terms of density, 1.0141–1.0152 g/cm<sup>3</sup>. The relative errors are less than 1%, which fully meets the requirements for rapid diagnosis.

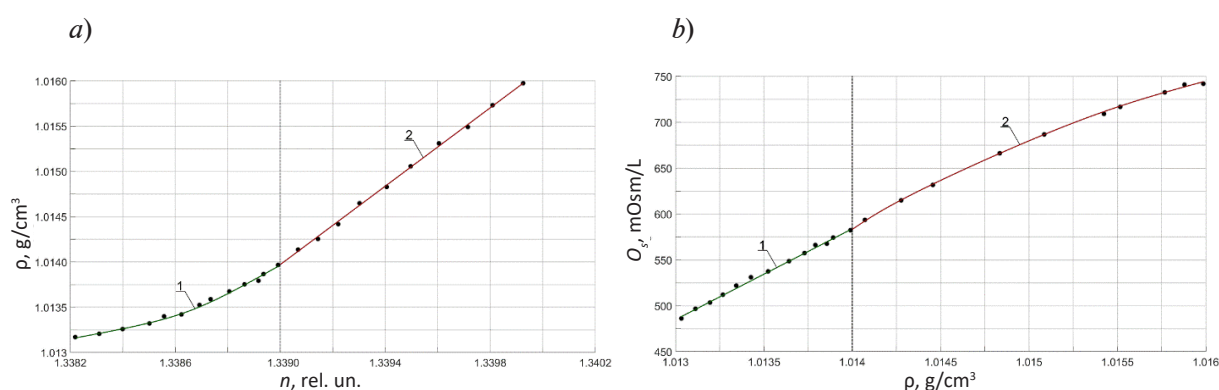


Fig. 5. Density dependence on refractive index (for two groups of patients).

Graph 1 corresponds to patients without kidney damage, graph 2 corresponds to patients with early stage kidney disease (a). Osmolarity dependence on density (for two groups of patients). Graph 1 corresponds to patients without kidney damage, graph 2 corresponds to patients with early stage kidney disease (b)

## Conclusion

Studies conducted on samples from more than 150 patients and the results obtained confirmed the validity of constructing dependencies  $\rho_u(n_u)$  and  $O_s(n_u)$  based on the established correlation between three physicochemical parameters of aqueous urine solutions. These dependences can be used for rapid diagnosis of kidney disease at an early stage and to monitor the effect of drugs during treatment, as the measurement process is simple to implement and painless (it can be performed as many times per day as necessary), unlike invasive methods such as blood sampling.

Based on the results of studies using the newly developed methodology, the following should be noted. More than 150 people who felt well and did not complain of kidney problems were examined. Twelve people were found to have suspected early-stage kidney disease. All twelve people underwent a full clinical examination at the First Pavlov State Medical University of St. Petersburg using certified equipment. Nine people who were not suspected of having early-stage kidney disease and the authors of the article also underwent the examination. The examination consisted of laboratory blood and urine tests, as well as diagnosis of kidney condition using certified equipment.

In 11 out of 12 patients with suspected early-stage kidney disease, doctors confirmed the diagnosis based on the results of the examinations; in one patient, the diagnosis was not confirmed. In 13 patients from the group where no early-stage kidney disease was suspected, doctors confirmed the absence of kidney disease based on the results of the examination.

According to express diagnostics, the refractive index measurements we offer can be compared with density measurements using the VIP-2MR mobile densitometer (measurement error 0.0001 g/cm<sup>3</sup>). The measured value of  $\rho$  is also used to diagnose kidney disease at an early stage (confirmed by a clinical examination – diagnosis). Unlike a mobile refractometer, this device is almost twice as expensive and its maintenance during measurements is at least five times more expensive than when using a refractometer. Therefore, it is more expedient to use two refractometers with broader functional capabilities than one mobile densitometer. This is especially true in conditions that require high-speed and repeated analysis, which is desirable in order to understand the effectiveness of drugs during treatment.

## REFERENCES

1. Verlov N.A., Burdakov V.S., Ivanova L.A., et al., Role of urinary tract microbiota and urine proteome in urolithiasis pathogenesis, *Nephrology*. 28 (2) (2024) 85–93.
2. Vakorina V.D., Stepanenkov G.V., Express kidney monitoring method for early detection of kidney damage, *St. Petersburg State Polytechnical University Journal. Physics and Mathematics*. 17 (3.2) (2024) 321–325.
3. Verlov N.A., Burdakov V.S., Kulakov I.A., et al., A new approach to assessing the level of uromodulin in urine, *Clinical laboratory diagnostics*. 68 (12) (2023) 728–734.
4. Biggeri A., Stoppa G., Facciolo L., et al., All-cause, cardiovascular disease and cancer mortality in the population of a large Italian area contaminated by perfluoroalkyl and polyfluoroalkyl substances (1980–2018), *Environmental Health: A Global Access Science Source*. 23 (1) (2024) 42.
5. Iakovleva A.V., Verlov N.A., Zaleskiy M.G., et al., Pathogenic Role of Posttranslational Isoforms of Uromodulin, *Biophysics*. 68 (3) (2023) 489–494.
6. Gogoi P., Valan J.A., Privacy-preserving predictive modeling for early detection of chronic kidney disease, *Network Modeling Analysis in Health Informatics and Bioinformatics*. 13 (1) (2024) 16.
7. Jairoun A.A., Al-Hemyari S.S., Shahwan M., et al., Community pharmacist-led point-of-care eGFR screening: early detection of chronic kidney disease in high-risk patients, *Scientific Reports*. 14 (1) (2024) 7284.
8. Guzenko M.M., Mazing M.S., Zaitseva A.Y., Application of Optical Analysis Methods for Noninvasive Monitoring of the Blood Oxygen Saturation Level, *Biophysics*. 68 (2) (2023) 306–311.
9. Davydov R., Zaitseva A., Davydov V., et al., New Methodology of Human Health Express Diagnostics Based on Pulse Wave Measurements and Occlusion Test, *Journal of Personalized Medicine*. 13 (3) (2023) 443.
10. Vestergaard A.H.S., Jensen S.K., Heide-Jorgensen U., Risk factor analysis for a rapid progression of chronic kidney disease, *Nephrology Dialysis Transplantation*. 39 (7) (2024) 1150–1158.
11. Russa A.L., Serra R., Faga T., et al., Kidney Fibrosis and Matrix Metalloproteinases (MMPs), *Frontiers in Bioscience Landmark*. 29 (5) (2024) 192.
12. Musolino M., D'Agostino M., Zicarelli M., et al., Spice Up Your Kidney: A Review on the Effects of Capsaicin in Renal Physiology and Disease, *International Journal of Molecular Sciences*. 25 (2) (2024) 791.

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Conference materials

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## Utilizing long short-term memory neural network for effective prediction of electrocardiosignals and pathology identification

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**Abstract.** Currently, neural networks (NN) are becoming an increasingly common tool in the field of diagnosis of diseases of the cardiovascular system. These architectures demonstrate high accuracy in analyzing complex data such as electrocardiosignals (ECS). Among various NN types, long-term memory (LSTM) stands out as a powerful method for analyzing time series. This technology has the ability to remember long-term dependencies in data, which makes it particularly useful for processing sequential data, including ECS. However, using the standard electrocardiography (ECG) method, it is impossible to obtain complete information about the stages of development of cardiovascular pathologies. The current trend towards increasing the informative value of the ECS has led to the development of a new method of ultra-high resolution electrocardiography (UHR ECG). This method significantly improves the detection of pathologies in the cardiovascular system in various areas of ECG treatment and also allows the detection of early markers of acute myocardial ischemia. UHR ECG provides an opportunity for a more detailed analysis of cardiac signals, which can be crucial in the early diagnosis and treatment of cardiovascular diseases. In this work, a six-layer LSTM was used to predict the shape of ECS obtained using the UHR ECG method in experimental rats. The experiments were aimed at modeling acute myocardial ischemia in order to identify trends in the development of markers of this pathology. The results of the study may contribute to the creation of more effective methods for diagnosing and monitoring cardiovascular diseases.

**Keywords:** ultra-high resolution electrocardiography, electrocardiosignal, neural network, prediction, long short-term memory networks, coronary heart disease, ischemia

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Материалы конференции

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## **Использование нейронной сети с долгой краткосрочной памятью для эффективного прогнозирования электрокардиосигналов и идентификации патологии**

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**Аннотация.** Среди различных типов нейронных сетей (НС) сети с долгой краткосрочной памятью (LSTM) обладают способностью запоминать долгосрочные зависимости в данных, что делает их особенно полезной для обработки длинных последовательных данных, включая электрокардиосигналы (ЭКС). Однако, используя стандартный метод электрокардиографии (ЭКГ), невозможно получить полную информацию о стадиях развития сердечно-сосудистых патологий, включая ишемическую болезнь сердца. Современная тенденция к повышению информативности ЭКГ привела к разработке нового метода электрокардиографии сверхвысокого разрешения (ЭКГ СВР). В этой работе была использована шестислойная сеть с долгой краткосрочной памятью для прогнозирования формы ЭКС, полученных с помощью метода ЭКГ СВР у подопытных крыс в ходе экспериментов по моделированию острой ишемии миокарда.

**Ключевые слова:** электрокардиография сверхвысокого разрешения, электрокардиосигнал, нейронная сеть, прогнозирование, долгая краткосрочная память, ишемическая болезнь сердца, ишемия

**Финансирование:** Финансовая поддержка работы была обеспечена Минобрнауки РФ, номер государственной регистрации темы № 1023032800366-6, тема № FZZM-2025-0011.

**Ссылка при цитировании:** Денисова Е.А., Кордюкова А.А., Шевяков Д.О. Использование нейронной сети с долгой краткосрочной памятью для эффективного прогнозирования электрокардиосигналов и идентификации патологии // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2025. Т. 18. № 3.2. С. 265–268. DOI: <https://doi.org/10.18721/JPM.183.253>

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### **Introduction**

The analysis of signals obtained using electrocardiography (ECG) using neural networks (NN) is one of the most promising areas in the field of cardiology and medical diagnostics. It is expected that in the future, combining these technologies will become the norm in medical practice [1–3]. ECG is a key tool for diagnosing various diseases of the cardiovascular system (CVS), including coronary heart disease and myocardial infarction. However, using the standard ECG method, it is impossible to obtain complete information about the stages of development of cardiac muscle pathologies [4].

The current trend towards increasing the informative value of the ECG has led to the creation of a new proprietary technique of ultra-high resolution electrocardiography (UHR ECG), the purpose of which is to identify pathological changes in the CVS in classical areas of electrocardiosignal (ECS) processing and in areas that are usually considered artifacts [5]. The method is being developed by the team of one of the leading scientific schools of the Russian Federation, Radioelectronic and Information Tools for assessing the physiological parameters of living Systems.





When using the UHR ECG method, the signal is recorded using two channels: a low-frequency (LF), similar to a standard ECG, and a high-frequency (HF) containing micropotentials. According to the hypothesis described in the study [5], the main marker of the development of myocardial ischemia in experimental animals is a decrease in the average spectral power density of the HF part of the spectrum of the received signal. And one of the key tasks in these studies is to predict the shape of the UHR ECS based on existing recordings in order to identify and capture changes associated with the pathology at an early stage. In this work, six-level long short-term memory (LSTM) was used to predict the shape of UHR ECS. To train and test the NN, a set of data was used, obtained from Vistar experimental rats during experiments on modeling acute myocardial ischemia at the Institute of Experimental Medicine of the Almazov National Research Medical University [6].

### Materials and Methods

A recurrent neural network with LSTM has been applied to predict the shape of the UHR ECS based on the current context. LSTMs are specifically designed to work with consistent data and effectively identify long-term dependencies. The LSTM architecture includes special “memory cells” that can hold information for a long time and control the process of forgetting it. Each such cell consists of three main components: an inlet valve, a forgetting valve, and an outlet valve. These elements help determine which information will be saved, which will be forgotten, and which will be transmitted to the network outputs [7].

To train and test the model, a dataset was collected, including 80 records of UHR ECS. The training sample consisted of 98% of the data, and the test sample consisted of the remaining 2%, which were used to adjust the hyperparameters. During preprocessing, the UHR ECS recordings were filtered according to the algorithm described in [8]. In addition, each signal was split into fragments lasting 1 second (6250 samples). These studies are conducted on the basis of Laboratory 235 “Radio- and optoelectronic devices for the diagnosis of human diseases” of the Institute of Analytical Instrumentation of the Russian Academy of Sciences.

### Results and Discussion

The a six-layer LSTM has been trained for 50 epochs. The mean absolute error (MAE), which shows how much, on average, the model’s predictions deviate from the actual values, was 0.0300. For the validation dataset, the MAE is 0.0304, which indicates a good accuracy of the trained model.

As an example, Fig. 1 shows the result of using LSTM to predict the shape of UHR ECS during the experiment. The gray line in the figure marks a fragment of the UHR ECS, the shape of which the trained model was supposed to predict, and the black line shows the predicted signal obtained as a result of using the model.

The graph shows that the predicted signal largely coincides with the original signal. This indicates the high accuracy of the LSTM model in predicting ECS patterns, which is a positive result.

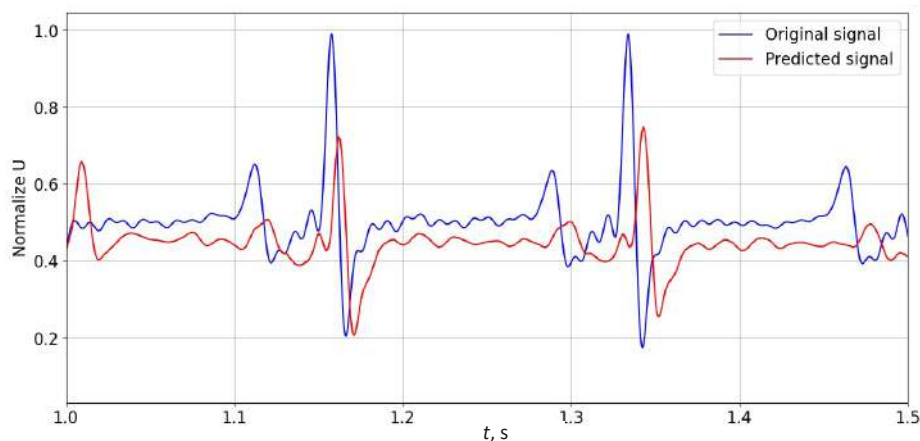


Fig. 1. Original and predicted UHR ECS

It should also be noted that in the area of the isoline, the received signal has fewer parasitic oscillations that are not characteristic peaks of the ECS wave, which indicates that the model is able to extract diagnostically significant information against the background of noise and interference during training.

### Conclusion

In the course of the study, it was shown that neural networks, in particular LSTM, demonstrate high accuracy in analyzing complex data, such as ECS obtained using the UHR ECG method, due to the ability to remember long-term data dependencies. The results obtained show that the model is able to accurately predict changes in the shape of the EC during experiments on modeling acute myocardial ischemia in experimental rats, which is crucial for the early detection of markers of the development of the pathology under study. Using LSTM for ECS analysis offers a promising strategy that can significantly improve the diagnosis and monitoring of heart disease, especially with regard to early detection of coronary artery disease.

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### REFERENCES

1. Liu X., Deep Learning in Electrocardiography: Review of Methods and Applications. Journal of the American College of Cardiology. 81 (18) (2023) 1655–1667.
2. Hannun A.Y., Rajpurkar P., Haghpanahi M., et al., Cardiologist-Level Arrhythmia Detection and Classification in Ambulatory Electrocardiograms Using a Deep Neural Network. Nature Medicine. 25(1) (2019) 65–69.
3. Rajpurkar P., Cardiologist-Level Arrhythmia Detection with Deep Learning. Nature Biomedical Engineering. 2 (2017) 1–4.
4. Gulyaev Y.V., Zaichenko K.V., Ultra-high resolution electrocardiography, Tasks. Problems. The prospects, Biomedical radioelectronics. 9 (2013) 5–15.
5. Zaichenko K.V., Kordyukova A.A., Logachev E.P., Luchkova M.N., Application of Radar Techniques of Signal Processing for Ultra-High Resolution Electrocardiography, Biomedical Engineering. 55 (1) (2019) 31–35.
6. Zaichenko K.V., Zhmyleva A.A., Khrapov S.O., et al., Application of modern technologies in new ultra-high resolution electrocardiography method, IEEE Xplore library. (2020) 0004–0007.
7. Hwang H.J., A Novel Deep Learning Model for ECG Classification Using Convolutional Neural Network and Long Short-Term Memory, IEEE Access. 7 (2019) 34723–34733.
8. Zaichenko K.V., Afanasenko A.S., Kordyukova A.A., et al., Development of an algorithm for preprocessing ultra-high resolution electrocardiosignals, St. Petersburg Polytechnic University Journal. Physics and Mathematics. 16 (3.2) (2023) 307–311.

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Conference materials

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## Marker ink based dye as a tool for intravital high-resolution visualization of cells on a silicon

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**Abstract.** When creating new bioelectronic devices, including bioimpedance cytosensors, there is a need for optical monitoring of cell interactions with bioelectrodes. Typically, fluorescent dyes are used for this purpose, which are usually expensive and require strict storage conditions. In this paper, we propose a technology for visualizing living cells on opaque surfaces such as silicon using do-it-yourself low-cost dye called ABDS (A Beauty Dye for Staining), which is based on permanent marker red ink. We have shown that the use of ABDS allows one to obtain more detailed images of cells in respect to cost-free reflected light modes without using any dye at all. Moreover, the ABDS utilization makes it possible to study cells at the edge of the opaque bioelectronic device cell culturing chamber, which is difficult when using simple reflected light modes due to strong optical distortions caused by the formation of a cells medium meniscus.

**Keywords:** Cell visualization, HeLa, ABDS, silicon, PETG

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Материалы конференции

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## **Краситель на основе чернил перманентного маркера как инструмент для высокоразрешающей визуализации живых клеток на кремнии**

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**Аннотация.** При создании новых биоэлектронных устройств, в том числе биоимпедансных цитосенсоров, возникает необходимость в оптическом контроле взаимодействия клеток с биоэлектродами. Обычно для этих целей используются флуоресцентные красители, которые, как правило, обладают высокой стоимостью и требуют специальных условий хранения. В данной работе мы предлагаем технологию визуализации живых клеток на непрозрачных поверхностях, таких как кремний, которая основана на применении красителя под названием ABDS (A Beauty Dye for Staining) – самодельного дешевого реактива на основе чернил красного перманентного маркера. В ходе ее выполнения мы показали, что изображения клеток, окрашенных с помощью ABDS, обладают значительно лучшей детализацией по сравнению с фотографиями полученными с помощью не требующих расходных материалов режимов отраженного света. Кроме того, использование ABDS также позволяет изучать клетки на краю непрозрачной культивационной камеры биоэлектронного устройства, в то время как из-за оптических искажений, вызванных образованием мениска у клеточной среды, применение методов на основе регистрации отраженного света в таких условиях становится неэффективным.

**Ключевые слова:** визуализация клеток, HeLa, ABDS, кремний, PETG

**Финансирование:** Работа поддержана Министерством образования и науки Российской Федерации (FSRM-2024-0001).

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### **Introduction**

Nowadays, ones of the rapidly developing areas of bioelectronics are impedance cytosensors engineering and living neurons based devices development [1–4]. These devices are typically presented as modified Petri dishes with an array of microelectrodes on the bottom, which are also called multielectrode arrays (MEAs). Although commercial MEAs are widely used in biology and medicine today to monitor cell proliferation, drug testing, cancer research, etc., these devices are still under active development, one of the challenges for which is the search and improvement of MEA materials. For example, one of the most promising materials for MEA fabrication – the silicon, semiconductor electronics fundamental brick – has been intensively used over the past decades to create high-resolution MEA combined with CMOS technology [5–7]. Such a scientific trend is motivated by the silicon biocompatibility, existence of the developed silicon industry,



and the ability to use integrated circuitry approaches for improving the MEA spatial resolution. However, silicon, like many other semiconductors, is an opaque material in the visible range of light, which complicates the diagnostics of living cells lying on it. In particular, opaque silicon is not compatible with classical transfer light and phase-contrast modes for intravital cell monitoring, and only reflected light and fluorescence non-inverted microscopy are available as relatively simple silicon MEA optical bio-diagnostic. At the same time, the reflected light mode usually produces a low-contrast picture of cells, since its video signal includes background image data [7, 8], whereas cell images obtained using fluorescence microscopy are clearer [8, 9], but require the use of expensive dyes [10]. To overcome the last problem, it is possible to use self-fluorescence cells, which e.g. enable the expression of green fluorescence protein (GFP) [6]. However, most cells do not produce fluorescence proteins, and their gene modification may be more expensive than the use of dyes. Moreover, GFP staining provides images of low detailed cells.

Recently, we have introduced an intravital cell dye called ABDS, which can be prepared from permanent red marker inks [10]. ABDS allows high-resolution imaging of cells, allowing for much more detailed examination of cell morphology than is possible with reflected light and GFP, which provides the solution of the mentioned above cells visualization problem for silicon based MEAs. Thus, in this study, we aim to show the advantages of the ABDS usage for cell visualization on the silicon substrates.

### Materials and Methods

To test the proposed method for the visualization of cells in opaque silicon, we have used HeLa cells and a MEA-like device fabricated from a silicon wafer [Si (111), surface coated with natural silicon dioxide], PDMS Sylgard 184 (DowCorning, Germany, 10/1 PDMS/hardening agent ratio), and a 3D-printed rings of polyethylene terephthalate glycol (PETG, models available at <https://cults3d.com/ru/3d-model/instrument/small-mea-ring-with-guide-frame>). The rings were fabricated on a Flying Bear S1 3D printer (Zhejiang FlyingBear 3D Technology Co., Ltd, China) using PETG plastic from Guangzhou Zhiwen Technology (China). The devices were fabricated by gluing 3D printed rings to silicon wafers using PDMS according to the protocol [11]. The resulting MEA prototypes were then washed with soap and water, rinsed with deionized water, and sterilized with ethanol. The HeLa cells were obtained from the cell culture bank of the Institute of Cytology of the Russian Academy of Sciences. The day before the experiment, the cells were seeded on MEA prototypes and cultured at 37 °C and 5% CO<sub>2</sub> in DMEM medium (Biolot, Russia) with 5% FBS (Sigma Aldrich, USA) and 0.15% gentamicin (Biolot, Russia). Before the experiment, cells were stained with ABDS to visualize the membrane according to the protocol described in [10]. Finally, the cells' medium was then replaced by PBS with DAPI dye (ThermoFisher Scientific, USA) for cell viability check. The microphotographs of HeLa cells were taken using a Leica DM 4000 B non-inverted microscope equipped with a light emitted diode (LED) and mercury metal halide EL6000 fluorescent lamp (Leica, Germany) incident light-sources. Accordingly, the cell images were acquired in three modes: BF-BF mode, when the cells were illuminated with white incident light from the EL6000 without color filters (BF-BF is the name of the microscope software settings that provide such image registration); LED mode, when the cells were illuminated with incident white light from an LED source without color filters; and fluorescence mode labeled as N2.1 in the photographs by the name of the used cube filter [12], when the cells were illuminated with green light (516–560 nm) from the EL6000, with the fluorescence signal detected at 580 nm.

### Results and Discussion

The obtained results are shown in Fig. 1 and Fig. 2. As can be seen in Fig. 1, at 10X magnification, clear images can be obtained by using reflected light modes without usage of any dyes as well as using cells visualizing with ABDS. But at higher magnification 20X both BF-BF and LED modes do not allow to visualize cells with sufficient clarity. At the same time, the visualization method which uses ABDS is free from such drawbacks and allows one to obtain a sufficiently clear image of cells even at 20X magnification. This effect can be connected with the wide-band spectrum of the EL6000 and LED light sources, which leads to chromatic aberrations smoothing the image [13]. Moreover, the usage of the white-band spectrum lighting can influence the semiconductor device functioning much stronger than narrow band fluorescence radiation. In addition, in the reflected



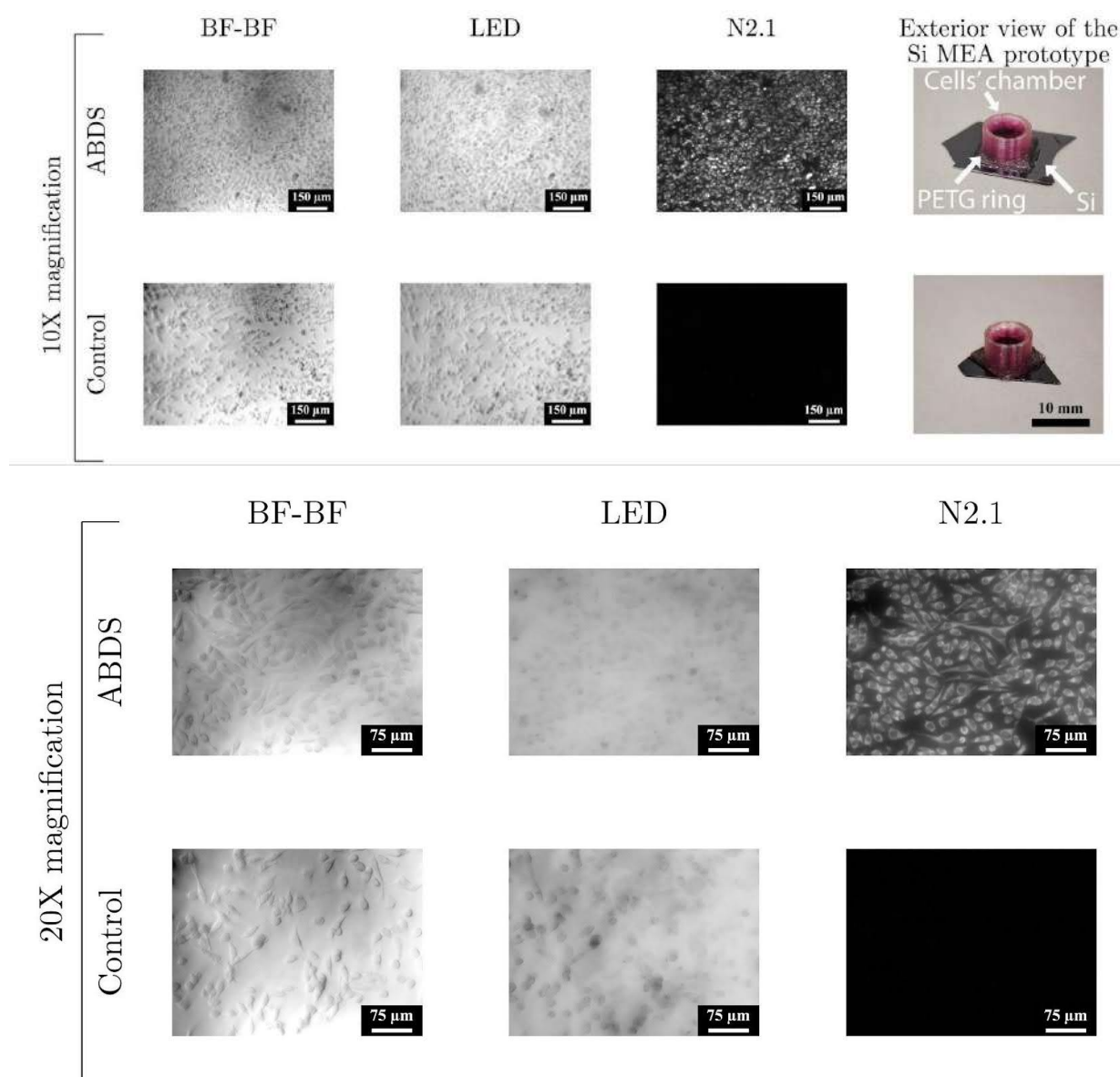


Fig. 1. Visualization of cells on the surface of a silicon MEA prototype. It is seen that at 10X magnification, cells are clearly visible both in reflected light (BF-BF and LED) and ABDS staining (N2.1 cube) modes. However, at 20X magnification, visualization of cells using ABDS achieves significantly higher image clarity compared to reflected light. ABDS staining allows to see in detail the membrane of the cells, nuclei shadow, and focal contacts. Control images, where cells were not treated with ABDS, show no background silicon fluorescence for the ABDS (N2.1) channel

light mode, no output optical filters are used, which leads to blinding the CCD-camera (Leica DFC 345 FX, Leica, Germany) and dropping the image quality. In contrast, the ABDS signal is pumped and detected in relatively narrow bands, which eliminate the blinding and aberration effects.

It is also worth noting that ABDS staining allows one to examine cells located near the edge of the silicon MEA prototype Petri dish (compare with [11]). In Fig. 2, it is clearly seen that in the BF-BF and LED modes images the cells cannot be distinguished at the edge due to the optical distortions caused by meniscus formation, while the ABDS fluorescence in the cells allows a clear image to be obtained since for the fluorescence signal there are less optical artifacts. During experiments we do not detect significant DAPI fluorescence, which confirms the biocompatibility of the proposed staining technique.

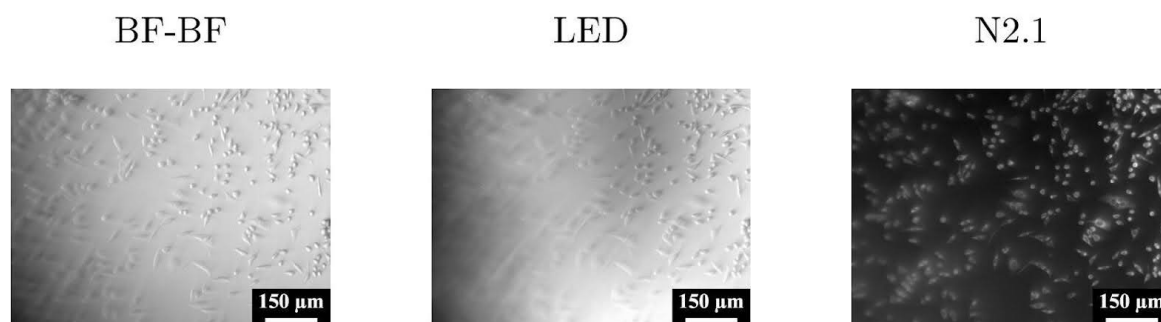


Fig. 2. Visualization of HeLa cells near the edge of a Petri dish on the surface of a silicon MEA prototype (20X magnification)

### Conclusion

In this work, we proposed a method for visualizing cells on the opaque surface of silicon wafers using ABDS dye, created on the basis of a red permanent marker ink. The advantages of the resulting technology are its low cost, versatility, and significantly better clarity of the resulting images compared to simple reflected light regimes. We hope that our proposed method for visualizing cells on opaque substrates will significantly simplify the development of new cytosensors and the selection of optimal materials for their manufacture.

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### REFERENCES

1. Stupin D.D., Kuzina E.A., Abelit A.A., et al., Bioimpedance spectroscopy: basics and applications, *ACS Biomaterials Science & Engineering*. 6 (7) (2021) 1962–1986.
2. Neroev V.V., Astakhov Yu.S., Lobanova M.M., et al., Artificial vision: advances, topical issues, and prospects, *Russian Ophthalmological Journal*. 3 (11) (2018) 3–27.
3. Wen G J., ed., *Electric cell-substrate impedance sensing and cancer metastasis*. Springer Science & Business Media. (17) 2012.
4. Bisio M., Pimashkin A., Buccelli S., et al., Closed-loop systems and in vitro neuronal cultures: Overview and applications, *In Vitro Neuronal Networks: From Culturing Methods to Neuro-Technological Applications*. (2019) 351–387.
5. Taiyun C., Park J.S., Butts J.C., et al., A multi-modality CMOS sensor array for cell-based assay and drug screening, *IEEE transactions on biomedical circuits and systems*. 6 (9) (2015) 801–814.
6. Jeffrey A., Mukherjee A., Wu W., et al., Multi-parametric functional imaging of cell cultures and tissues with a CMOS microelectrode array, *Lab on a Chip*. 7 (22) (2022) 1286–1296.
7. Sian P.T., Chen Y., Wong C.C., et al., High density CMOS electrode array for high-throughput and automated cell counting, *Sensors and Actuators B: Chemical*. 181 (2013) 842–849.
8. Rost F., *Fluorescence Microscopy, Applications*, Editor(s): John C. Lindon, *Encyclopedia of Spectroscopy and Spectrometry (Second Edition)*, Academic Press. (2010) 619–624
9. Dobrucki J.W., Kubitscheck U., *Fluorescence microscopy, Fluorescence microscopy: From principles to biological applications*. (2017) 85–132.
10. Abelit A.A., Boitsova N.A., Yakovleva L.E., et al., A Beauty Dye Staining (ABDS)—inexpensive marker-ink based open-source alternative for commercial membrane vital dyes. *bioRxiv*. (2025).
11. Stupin D.D., Boitsova N. A., Dubina Ph.M., et al., Autostainer feature for multielectrode arrays: proof-of-concept, *St. Petersburg Polytechnic University Journal: Physics and Mathematics*, 75 (3.1) (2024) 320–324.
12. Range of Filter Cubes, <https://sheffield.ac.uk/media/6371/download>, access date 07.09.25
13. Clarke T., Chromatic Aberration in Digital Photomicrographs from Microscopes Requiring Compensating Eyepieces, *Microscopy Today*. 4 (12) (2004) 34–37.

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## Scattering of ultrashort laser pulses on some polymers and plasmids

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**Abstract.** The paper shows a method for the theoretical calculation of the spectrum of interaction between an ultrashort laser pulse and complex polyatomic objects. The calculation is shown on some plasmids DNA. The special feature of the calculation is the speed of processing the results. The method allows you to consider the scattering on all the atoms included in the molecules, while the calculation is performed quickly enough, due to the use of symmetries in the structure of the object in question. The method is suitable only for molecules with repeating regions in their structure, such as some plasmids and polymers, including DNA molecules with repeating nitrogenous bases. The calculation is based on the Hartree–Fock–Slater method. Before mathematical modeling, the molecule is built in the Avogadro program. The coordinates of the constructed model are used for the calculation. To date, the processing of experimental data obtained during operation of ultrashort pulses is difficult. The proposed method can help in deciphering the experimental data and reduce the processing time of the results.

**Keywords:** ultrashort laser pulses, plasmids DNA, scattering spectra

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Материалы конференции

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## Рассеяние ультракоротких лазерных импульсов на некоторых полимерах и плазмидах

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**Аннотация.** В статье представлен метод теоретического расчета спектра взаимодействия ультракороткого лазерного импульса со сложными многоатомными объектами. Расчет показан на примере некоторых плазмидных ДНК. Особенностью расчета является время обработки результатов. Метод позволяет учитывать рассеяние на всех атомах, входящих в состав молекул, при этом расчет выполняется достаточно быстро, благодаря использованию симметрий в структуре рассматриваемого объекта. Этот метод подходит только для молекул с повторяющимися участками в их структуре, таких как некоторые плазмиды и полимеры, включая молекулы ДНК с повторяющимися азотистыми основаниями. Расчет основан на методе Хартри–Фока–Слейтера. Перед математическим моделированием молекула строится в программе Avogadro. Для расчета используются координаты построенной модели. На сегодняшний день обработка

экспериментальных данных, полученных при работе с ультракороткими импульсами, затруднена. Предлагаемый метод может помочь в расшифровке экспериментальных данных и сократить время обработки результатов.

**Ключевые слова:** ультракороткие лазерные импульсы, плазмидная ДНК, спектры рассеяния

**Финансирование:** Исследование проводилось при поддержке государственного задания Российской Федерации № FSRU-2024-0005.

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## Introduction

Currently spectroscopy is one of the most promising methods for studying complex molecular structures. There are different types of radiation used in spectroscopy, but in present, one of the most popular types is ultrashort laser pulse spectroscopy. With their help, many models of proteins and molecules have already been deciphered, as indicated by the marks in the world database of proteins and molecular compounds [1–3]. Using ultrashort pulses allows you to work on the same time scale as a molecule. Thus, it becomes possible to study the structure of a molecular compound before it changes, for example, under the influence of the environment. This is relevant specifically for protein compounds, since they are the ones that are difficult to crystallize, which complicates the experiment by other methods. To date, experiments using ultrashort pulses are actively underway in Hamburg, at a free electron laser installation. Decoding the received data is a complex process, especially if the object under study is a polyatomic structure. There are different ways to decipher the spectra obtained during scattering, but all of these are quite laborious and time-consuming. This article will show a method that reduces the calculation time for the model of the scattering spectrum of ultrashort laser pulses using examples of some plasmids and polymers.

## Materials and methods

The calculation is based on the method described in [4, 5]. The method is derived from a theoretical description of the interaction of an ultrashort pulse with a test substance using numerical modeling and the Dirac–Hartree–Fock–Slater model. To simplify the decoding of molecular structures, it is proposed to conduct theoretical modeling of the interaction in order to obtain a reference diffraction pattern. But if there are repeating sections or links in the studied molecule, then the method can be simplified. The main calculation of the spectrum is carried out according to the formula:

$$\frac{d^2\varepsilon}{d\Omega_k d\omega} = \frac{[\mathbf{E}_0 \mathbf{n}]^2}{(2\pi)^2} \frac{|\tilde{h}(\omega)|^2}{c^3} \left\langle \sum_{i=1}^s N_{e,i} N_{A,i} (1 - |F_i|^2) + \sum_{i,j=1}^s \delta_{i,j} N_{e,i} N_{e,j} F_i F_j^* \right\rangle, \quad (1)$$

where  $N_{e,i}$  is the number of electrons in the atom of the  $i$ th variety;  $N_{A,i}$  is the number of atoms of the  $i$ th variety.  $F_i = \frac{1}{N_{e,i}} \int \rho_{e,i}(\mathbf{r}) e^{-i\mathbf{p}\mathbf{r}} d^3\mathbf{r} = 1$  is a form factor of the atom of the  $i$ th variety with an electron density  $\rho_{e,i}(\mathbf{r})$ .

Coefficient  $\delta_{i,j} = \sum_{A_i, A_j} e^{-i\mathbf{p}(\mathbf{R}_{A_i} - \mathbf{R}_{A_j})}$  depends only on the coordinates of atoms of the  $i$ th variety





(with  $A_i$  number), which position is determined by the radius vector  $\mathbf{R}_{A_i}$ . Eq. (1) is analytical, which contributes to a fairly simple calculation of spectra. The calculation of the electron density is difficult here. But if there are repeating sections in the molecule, the interference factor can be calculated in another way:

$$\delta_{i,j} = \sum_{\alpha=1}^S \sum_{n_{\alpha}=0}^{N_{\alpha}} e^{ip\mathbf{R}_{n_{\alpha}}} \sum_{A_i \in R_{\alpha,1}} e^{ip\mathbf{R}_{A_i}} \sum_{\beta=1}^S \sum_{n_{\beta}=0}^{N_{\beta}} e^{-ip\mathbf{R}_{n_{\beta}}} \sum_{A_j \in R_{\beta,1}} e^{-ip\mathbf{R}_{A_j}}. \quad (2)$$

Here, the interference factor is calculated by the sum of the repeated sections. For example, a DNA molecule has three repeating nitrogenous bases. Calculations within a single nitrogenous base are taken into account, and then the result is summed up by the number of repetitions. In this paper, the varieties of plasmids' ring forms are considered: one ring and two rings. Interestingly, gel electrophoresis is mainly used to study such structures. In the gel, plasmids begin to move under the influence of electricity, and the magnitude of their movement in the gel helps to distinguish large ring shapes from smaller ones. The ring plasmid of DNA is a closed DNA helix. Let us replace one spiral period with one element, as illustrated in Fig. 1.

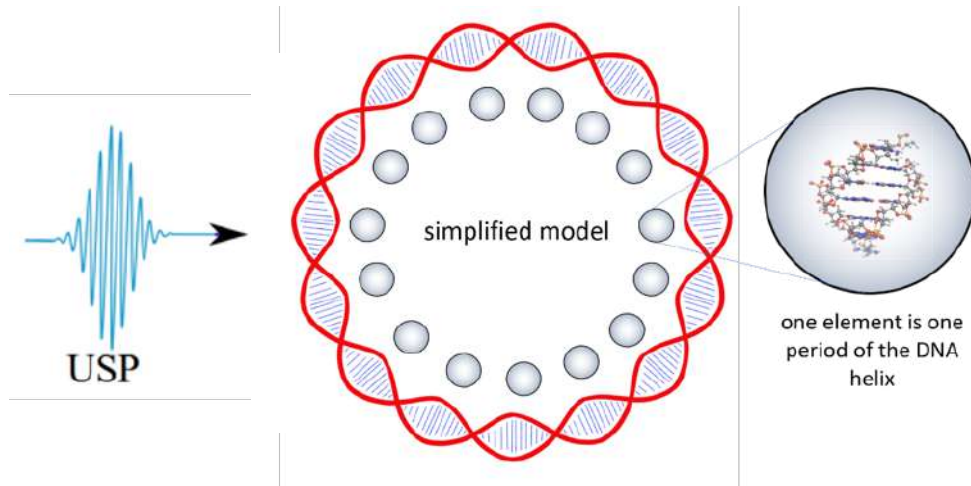


Fig. 1. Simplified model of the DNA ring plasmid

The position of plasmid DNA after gel electrophoresis in agarose gel provides an understanding of its structure. The method is simple and relatively inexpensive, and it has proven itself well. But this method couldn't help to evaluate changes in plasmids, such as ruptures. In addition, the method has a high error rate, since the difference between some forms of plasmids is small, for example, one ring and two rings of the DNA helix. In this paper, the use of ultrashort pulses for the analysis of such structures is proposed. Let us perform the calculation on the simplified structure of two ring plasmids. A supercoiled DNA plasmid will be used as the second sample for the study in Fig. 2.

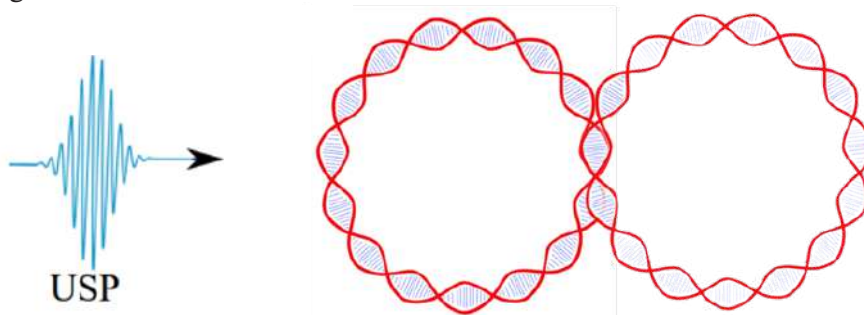


Fig. 2. Simplified model of a doubled circular DNA plasmid

## Results and discussion

In this study the main objective is to identify the difference in the shapes of the spectra from two circular DNA plasmids. These shapes are interesting because despite a complex geometric arrangement of atoms in the structure, their number may practically not change. It is necessary to check whether the proposed method can capture changes only in the geometric position of the atoms. A simplified form of DNA plasmids, idealized rings, is used for this task. Theoretical modeling of the interaction of an ultrashort laser pulse with plasmids obtains results that shown on the following contour plots of scattering spectra (Fig. 3).

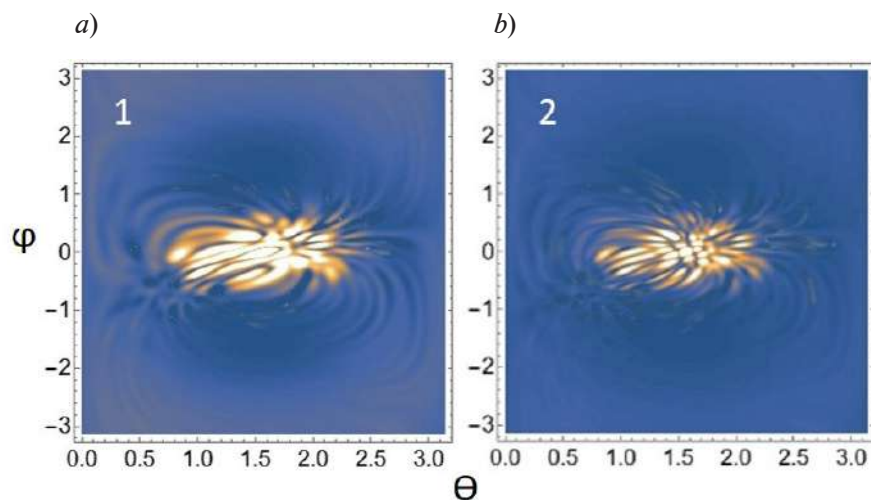


Fig. 3. Contour graph of the scattering spectrum during the interaction of an ultrashort laser pulse with a plasmid: ring plasmid of DNA (a); supercoiled plasmid of DNA (b)

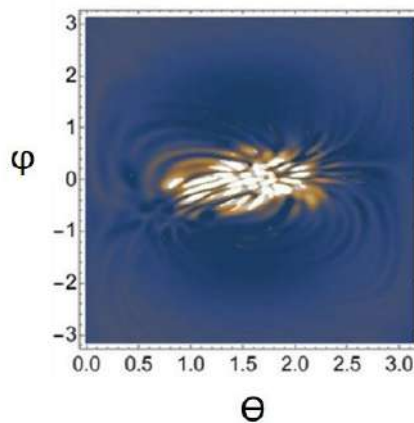


Fig. 4. Difference between the spectra. To visualize the difference between the obtained spectra, the contour graph images were superimposed on each other. The image of the DNA superplasmid spectrum is cut out in white

Here  $\theta$  is the angle between the spiral axis and the scattering direction  $n$ ,  $\varphi$  is the angle between the x-axis and the projection  $n$  on a plane perpendicular to the axis of the spiral. As can be seen from the graphs obtained, the spectrum of the DNA plasmid has a large number of spots. This is due to the large number of atoms, as well as the re-emission in repetitive areas. The laser pulse irradiated DNA as shown in Figs. 1, 2. The spectra differ significantly, although they are based on the same shape and the position of the main spots near the central maximum has the same direction.



### Conclusion

As a result, a method is shown that makes it possible to calculate the structure of DNA plasmids using a simplified model. According to the results, the method enables to detect changes in the plasmid structure. Using the proposed method, it is possible to more accurately assess the structure of complex DNA.

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### REFERENCES

1. Neil M.C., Free electron X-ray lasers, Science. (4) (2010) 814–821.
2. Tet I., Compact X-ray free-electron laser emitting in the sub-angstrom region, Nat. Photon. 6 (2012) 540–544.
3. Chapman H.N., Femtosecond X-ray protein nanocrystallography, Nature. (470) (2011) 73–77.
4. Makarov D.N., Kharlamova A.A., Scattering of Attosecond Laser Pulses on a DNA Molecule during Its Nicking and Bending, Int. J. Mol. Sci. (24) 2023.
5. Kharlamova A.A., Calculation of the Interference Coefficient of the Polyatomic Molecular Structure of DNA, J of Biomedical Photonics and Eng. 9 (4) 2023.

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## Development of an optical spectroscopy-based non-invasive vasodilation assessment method

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**Abstract.** This study investigates feasibility of a novel spectrophotometric method for the assessment of endothelial dysfunction (ED) in substitution for standard ultrasound flow-mediated dilation test (FMD). Using an 18-channel optical analyzer (410–940 nm), tissue optical spectra during reactive hyperemia were assessed in 21 patients with ED-related condition (atherosclerosis, coronary heart disease, post-COVID syndrome) and 11 control subjects. Vascular occlusion test (VOT) was performed on the subjects with 3-minute ischemia of the brachial artery at 180 mmHg. Statistical analysis revealed significant differences ( $p < 0.05$ ) in absorption of light at specified wavelengths (410, 560, 585, 610, 680, 705, 760, 860 nm) between groups with most pronounced differences in atherosclerosis patients. Results show promise for ED detection without operator-dependent ultrasound measurements, but further validation against FMD is required.

**Keywords:** endothelial dysfunction, spectrophotometry, non-invasive diagnostics, reactive hyperemia

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Материалы конференции

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## Разработка неинвазивной спектрофотометрической методики диагностики эндотелиальной дисфункции

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**Аннотация.** В ходе работы проведен сбор данных изменения оптических спектров тканей в ходе окклюзионной пробы. Использован 18-канальный оптический анализатор, работающий в диапазоне 940–410 нм. На нескольких длинах волн были обнаружены статистически значимые ( $p < 0,05$ ) различия между двумя группами испытуемых.



**Ключевые слова:** эндотелиальная дисфункция, спектрофотометрия, неинвазивная диагностика

**Финансирование:** Исследование проводилось при поддержке гранта Российского научного фонда № 24-21-00404.

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## Introduction

Endothelial dysfunction (ED) serves as a significant predictor of vascular wall morphological changes in various cardiovascular diseases including hypertension, atherosclerosis, and coronary artery disease [1]. This pathological condition exhibits systemic manifestation, affecting both large vessels and microcirculatory networks [2–3]. While flow-mediated dilation (FMD) remains the gold standard diagnostic approach, its clinical application faces limitations due to substantial costs and significant operator dependence, creating a demand for alternative diagnostic solutions. Current research focuses on developing non-invasive, accessible, wearable, and precise methods for ED detection, with spectrophotometric techniques emerging as particularly promising.

The primary objective of this study was to explore feasibility of a spectrophotometric approach for non-invasive ED diagnosis. To achieve this, several key tasks were accomplished. A series of tissue optical spectra were recorded using a vascular occlusion test (VOT). Statistical analysis was then performed to access differences between ED patients and healthy controls. Finally, method's potential utility in monitoring therapeutic efficacy was evaluated.

## Materials and Methods

The study included 18 patients with endothelial dysfunction and 18 healthy controls (< 45 years). Participants underwent comprehensive screening for risk factors including atherosclerosis, ischemic heart disease, severe COVID-19 (past year) [4–5], cancer, diabetes, advanced age, and obesity BMI > 40 (body mass index).

All the measurements were performed using an 18-channel optical analyzer (410–940 nm), [6–7] developed in the Institute of Analytical Instrumentation RAS (Russian Academy of Sciences) St. Petersburg, featuring three multi-spectral LEDs [38] and an array of wave-specific photodetectors. To assess tissue light interactions device utilizes reflectance-mode absorption spectroscopy principles with both the light source and detector positioned on the same side of the examined tissue, recording back-scattered radiation with a maximum penetration depth of 2.5 mm. two configurations (refers to the physical setup of the probe, specifically the distance between the light source and the detector) were developed (5 mm and 10 mm) for measurements at different tissue depths (2.5 mm and 5 mm respectively), with this study employing the 5 mm sensor configuration. The key measured parameter was surface energy flux density ( $E_e$ ), representing the radiant flux per unit area incident on the photodetector surface, which quantifies the intensity of back-scattered tissue radiation.

To achieve the study objectives, we used VOT to record induced changes in microcirculatory response. Experimental protocol comprised three sequential phases: rest (30 seconds seated rest), loading (3-minute cuff inflation to 180 mmHg on the mid-upper arm), and recovery (10-second decompression followed by 3-minute 50-second rest), totaling 7 minutes 30 seconds. For the seated occlusion test, the sensor unit was fixed securely on the inner right forearm with LEDs facing the skin, maintaining full contact with minimal pressure. Continuous measurements were recorded every 5 seconds throughout the procedure. All acquired data was transmitted in real-time to a laptop for storage and further analysis.



Statistical analysis consisted of several steps. First, each measurement was normalized to a range of 1 and shifted so that the starting point was set to zero. Linear interpolation was then used to bring each measurement to a length of 100 points. Inspired by the classical approach, area under the curve (AUC) was calculated to form an experimental and study groups for every wavelength, measured using the formula:

$$y_{ij} = \sum_{k=1}^{100} x_{ijk},$$

where  $i$  stands for a wavelength and  $j$  for a measurement. Finally, a non-parametric Mann–Whitney U-test was used to compute statistical significance in differences between groups, followed by a false discovery control using Benjamini-Hochberg method, with 0.05 being chosen as a threshold.

### Results and discussion

Several wavelengths were found to have statistical difference between groups (Fig. 1). Notably, patients with endothelial dysfunction-associated conditions (hypertension, atherosclerosis, coronary artery disease, post-COVID sequelae) exhibited significant spectral deviations at 410, 560, 585, 610, 680, 705, 760 and 860 nm, compared to control group, demonstrating the method's sensitivity to pathological microcirculatory changes.

This hints that a classification algorithm can be used for automatic ED detection with potential success. Further work would include validation studies comparing this approach with the conventional FMD method and a development of method to detect ED. These advancements could significantly improve early detection and management of endothelial dysfunction in clinical practice.

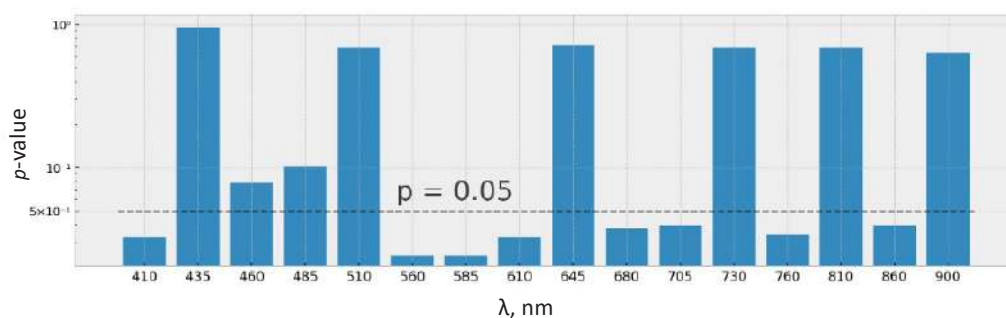


Fig. 1. Calculated  $p$ -values at various wavelengths (410–900 nm) after multiple-hypothesis correction procedure. Dashed line represents a threshold of statistical significance (0.05)

### Conclusion

The spectrophotometric method is widely acclaimed [9–10] and in this work it is shown that is promising for non-invasive endothelial dysfunction diagnosis by detecting optical spectral changes during reactive hyperemia. It identifies significant differences between high-risk patients and healthy individuals, with advantages over FMD such as reduced variability, portability, and multi-parameter assessment. Further validation, protocol optimization, diagnostic criteria development, and exploration of therapeutic monitoring potential are needed, alongside machine learning integration.

### REFERENCES

1. Davydov V.V., Grebenikova N.M., Smirnov K.Yu., Optical method for monitoring the state of low-transparency fluids containing large inclusions, *Measurement Techniques*. 62 (6) (2019) 519–526.
2. Davydov V.V., Porfiryeva E.V., Davydov R.V., Non-destructive method for monitoring the elasticity of human veins and arteries, *Russian Journal of Nondestructive Testing*. 58 (9) (2022) 847–857.



3. **Davydov V.V., Myazin N.S., Grebenikova N.M., Dudkin V.I.**, Determination of composition and concentration of components in hydrocarbon mixtures during their express analysis, *Measurement Techniques*. 62 (12) (2020) 1090–1098.
4. **Naumova V., Kurkova A., Davydov R., Zaitseva A.**, Method for analyzing tissue oxygen saturation disorders using an optical analyzer of visible and IR spectra, *Proceedings of the 2022 International Conference on Electrical Engineering and Photonics (EExPolytech 2022)*. (2022) 151–153.
5. **Mazing M.S., Zaitseva A.Yu., Kislyakov Yu.Yu., et al.**, Monitoring of human tissue oxygen supply using a non-invasive optical system based on a multichannel integrated spectrum analyzer, *International Journal of Pharmaceutical Research*. 12 (2020) 1974–1978.
6. **Porfiryeva E., Davydov V., Davydov R., Isakova D.**, Features of using esCCO technology for human condition diagnostics, *Proceedings of the 9th IEEE International Conference on Information Technology and Nanotechnology (ITNT)*. (2023).
7. **Margieva T.V., Sergeeva T.V.**, The involvement of endothelial dysfunction markers in the pathogenesis of chronic glomerulonephritis, *Current Pediatrics*. 5 (3) (2006) 22–30.
8. **Margiyeva T.V., Smirnov I.Ye., Timofeyeva A.G., et al.**, Endothelial dysfunction in different forms of chronic glomerulonephritis in children, *Russian Pediatric Journal*. (2) (2009) 34–38.
9. **Khaertynov Kh.S., et al.**, Endothelial dysfunction in patients with COVID-19 coronavirus infection, *The Scientific and Practical Medical Journal*. 22 (2) (2024) 77–83.

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Conference materials

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### **Fluorescent micropatterning of an albumin film with high intensity femtosecond laser pulses**

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**Abstract.** In this study, we performed laser ablation of the solid albumin film, using near-infrared high intensity femtosecond laser pulses. As a result, microstructures with multicolor and excitation-dependent visible fluorescence were produced. We studied fluorescence characteristics of laser-processed protein and characterized its chemical modifications.

**Keywords:** proteins, femtosecond laser pulses, fluorescence, fluorescence patterning, laser microstructuring

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Материалы конференции

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### **Создание флуоресцентных микроструктур в дегидратированной пленке альбумина при помощи высокоинтенсивных фемтосекундных лазерных импульсов**

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**Аннотация.** В настоящей работе продемонстрировано микроструктурирование альбуминовой пленки при помощи остросфокусированного фемтосекундного лазерного излучения ближнего ИК-диапазона. Результатом микроструктурирования стало образование продуктов с многоцветной и зависящей от длины волны флуоресценции. В работе приведены оптические и физико-химические характеристики продуктов лазерного воздействия.

**Ключевые слова:** белки, фемтосекундные лазерные импульсы, флуоресценция, лазерное микроструктурирование

**Ссылка при цитировании:** Астафьев А.А., Шахов А.М., Сырчина М.С., Надточенко В.А. Создание флуоресцентных микроструктур в дегидратированной пленке альбумина при помощи высокоинтенсивных фемтосекундных лазерных импульсов // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2025. Т. 18. № 3.2. С. 284–288. DOI: <https://doi.org/10.18721/JPM.183.257>

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## Introduction

Laser writing of fluorescent micropatterns in organic matrices holds promise for many applications, including counterfeiting, data storage, bioengineering, optical devices and sensors [1–4]. Patterning with ultrashort laser pulses minimizes thermal damage to the material and enables spatially localized patterning and even direct writing of 3-dimensional structures [5]. Biopolymers, e.g., cellulose, are attractive as a target material in fluorescent writing due to their superior biocompatibility [6]. Proteins, another class of natural biopolymers with highly versatile properties, are a promising material with yet unexplored potential for laser writing. Proteins exhibit weak intrinsic visible fluorescence, which can be enhanced by aggregation or by photooxidation of aromatic residues [7–8]. Both mechanisms enable manipulation of fluorescence using laser irradiation. Previously we demonstrated that a model protein – bovine serum albumin (BSA). A is rendered highly fluorescent upon irradiation with femtosecond laser pulses in a solution [9]. Here we examined if femtosecond laser modification of the solid BSA enables direct wiring of fluorescent micropatterns in a protein film and analyzed fluorescent properties of laser-processed protein and their relation to the processing laser parameters. Chemical modifications of the BSA upon laser irradiation were probed using Raman and infrared spectroscopy and the mechanism of laser modification analyzed.

## Materials and methods

**Laser processing of the protein films.** Protein films were obtained by drying a drop of the BSA aqueous solution on a silica glass surface at a room temperature. Femtosecond laser pulses generated by a TETA laser system (Avesta Project, central wavelength 1033 nm, pulse duration 260 fs, repetition rate 10 kHz, pulse energy up to 1  $\mu$ J) were coupled to an optical microscope (Olympus IX71) and focused on the surface of the BSA film with an objective lens (Olympus, NA = 0.75). The beam waist diameter at the focus was estimated as 1.7  $\mu$ m. With corrections for losses and the objective lens transmission the estimated laser fluence  $J$  was related to the input laser power  $P$  as  $J[J/cm^2] = 0.9 \cdot P [mW]$ . Laser fluence in the focal area reached values about 10 J/cm<sup>2</sup>, which caused ablation of the protein films. The BSA film was processed with laser pulses in a square area of 30–100  $\mu$ m width by moving the film relative to the objective lens focal point using a programmable piezoelectric stage (NT-MDT, scanning speed 50  $\mu$ m/s). (Fig. 1, a). Several squares were created in a film with a laser power ranging from 2 to 10 mW and one scanning cycle. Another series of laser-processed squares was created with a laser power fixed at 5 mW and the number of successive cycles varying from 1 to 32.

**Samples characterization.** Fluorescent images and fluorescence emission spectra of the protein film were obtained with a scanning confocal microscope (LSM 980, Zeiss Microscopy) using

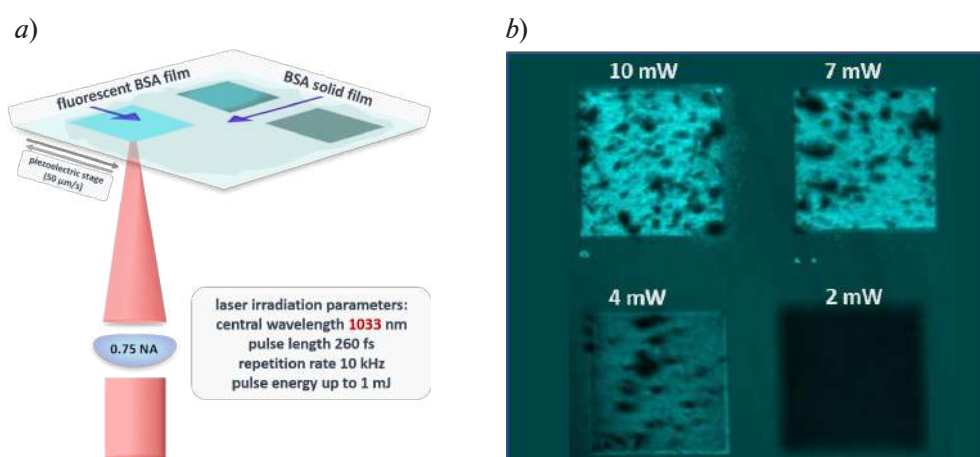


Fig. 1. Experimental setup (a); fluorescent confocal images of micropatterns (b), written in the BSA film by femtosecond laser irradiation with laser powers of 2 mW, 4 mW, 7 mW, 10 mW

fluorescence excitation at 405, 488 and 561 nm. Fluorescence emission spectra were averaged over processed squares. Raman spectra of the BSA were registered locally within the laser processed squares and in unprocessed protein film using Bruker Senterra microscope-spectrometer (laser excitation at 785 nm). Registered Raman spectra were processed and the autofluorescence background was subtracted using Origin Pro 2015 software. Infrared spectra were also registered locally using the Bruker Lumos II Fourier-transform infrared (FTIR) microscope-spectrometer in an attenuated total reflectance mode.

## Results and discussion

Upon laser processing the surface layer of protein film was partially ablated and at the same time the laser-processed squares became fluorescent and were readily observed on the fluorescent microscopy images (Fig. 1, *b*). The fluorescence intensity within the squares increased with the processing laser power and for 10 mW power it was several times stronger than intensity of autofluorescence of the BSA protein (Fig. 2, *a*). The effect of varying the laser power was threshold-like: at the minimal power (2 mW) the film was ablated, but the protein autofluorescence was bleached, and no new fluorescence was generated. As a result, the fluorescence intensity in the processed square became weaker than the autofluorescence background. Above the threshold power the emission spectral shape did not depend on the processing laser power. At the same time emission spectra in the processed squares were somewhat redshifted compared with the autofluorescence spectrum of the BSA. This indicates that autofluorescence and laser-generated fluorescence in the BSA originates from different fluorophores. Emission spectra of processed BSA were excitation-dependent and shifted to the red area with increase of the excitation wavelength from 405 to 561 nm (Fig. 2, *b*). The emission maxima shifted from 540 to more than 600 nm when changing the excitation wavelength from 488 to 561 nm (Fig. 2, *c*). The emission was the brightest under the blue (405 nm) excitation.

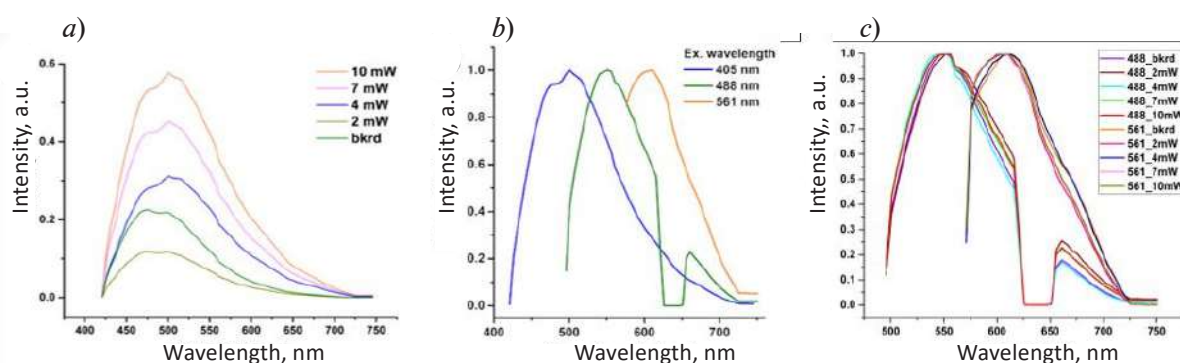


Fig. 2. Averaged fluorescence emission spectra of laser-processed BSA as a function of laser power compared with the background from the unprocessed BSA. Excitation at 405 nm (*a*); comparison of the emission spectra in the laser-processed square under 405, 488 and 561 nm excitation at laser power of 10 mW (*b*); comparison of normalized emission spectra of laser-processed squares at 488 and 561 fluorescence excitation for all laser regimes (*c*)

Multiple scanning cycles of the same area at a fixed laser power led to brighter fluorescence (Fig. 1, *b*), indicating accumulation of fluorescent products of laser irradiation. Fluorescence intensity monotonically increased with a number of cycles. The dependence on the number of cycles was not linear and could be approximated with a function  $I = I_{\text{auto}} + I_0 \ln(N + 1)$ , where  $I_{\text{auto}}$  is autofluorescence intensity of the normal BSA,  $N$  is the number of scanning cycles,  $I_0$  is a constant (Fig. 3, *b*).

FTIR spectra of the protein revealed characteristic amide bands at 3280, 1650, 1535, and 1300  $\text{cm}^{-1}$  as well as vibrational band associated with alkyl and carboxylate groups near 2900, 1450 and 1395  $\text{cm}^{-1}$  (Fig. 4, *a*). Laser-processed BSA exhibited the same bands of similar shape and intensity. The largest difference was a weaker intensity in the OH stretching range (3000–3600  $\text{cm}^{-1}$ ), probably due to evaporation of residual water within the protein film. Similarity of the FTIR spectra demonstrates that the chemical structure of the protein underwent little changes after the laser



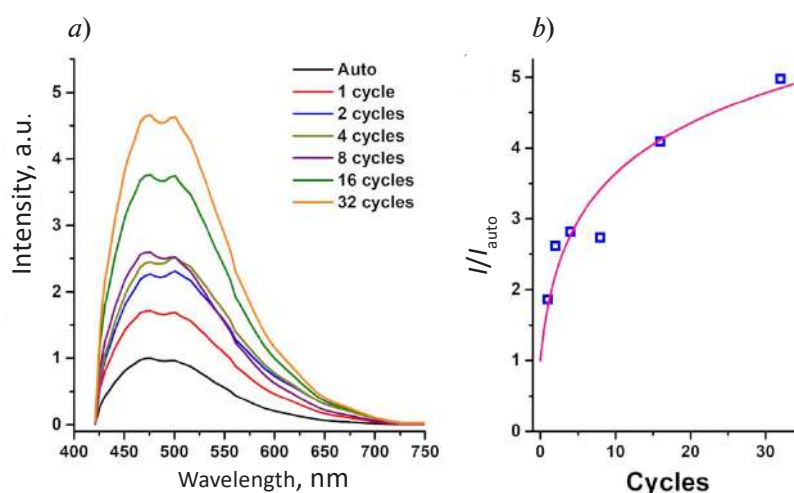


Fig. 3. Fluorescence emission spectra of the laser-processed BSA with a different number of scanning cycles, 5 mW laser power. Autofluorescence spectrum of the unprocessed BSA is presented for comparison (black line). Excitation at 405 nm (a). Ratio of the integral fluorescence intensity in the processed square to the autofluorescence intensity of unprocessed BSA protein as a function of the number of scanning cycles (squares) and its fit with a logarithmic function (b)

processing. More specifically, unaltered maxima and shapes of the Amide I and III bands suggest that the secondary structure of the protein was not significantly altered. Similarly, Raman spectra of normal and laser-processed proteins demonstrated that no conspicuous new vibration bands appeared after the laser irradiation (Fig. 4, b). In particular, absence of characteristic G and D bands of carbon near  $1580$  and  $1310\text{ cm}^{-1}$  indicates that no appreciable carbonization of the protein occurred.

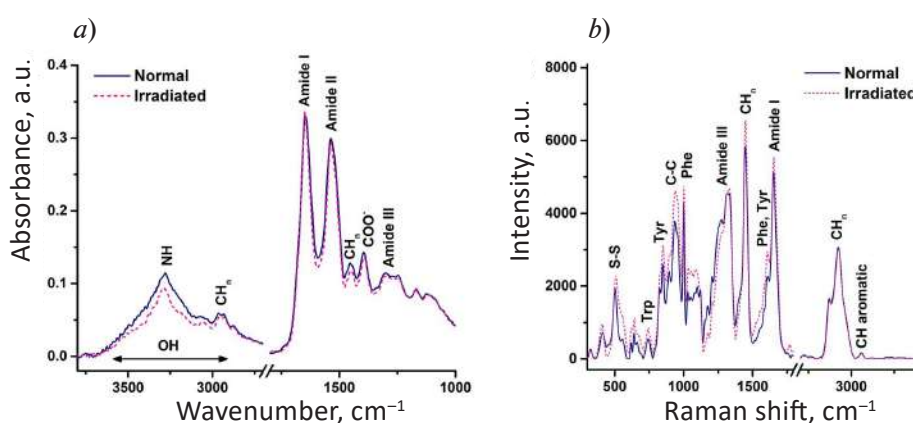


Fig. 4. Comparison of the FTIR (a) and Raman (b) spectra of the normal BSA protein and laser-processed BSA (at 10 mW)

A possible mechanism of fluorescent patterning of an organic material, as demonstrated for cellulose, is a generation of fluorescent carbon dots through laser-induced thermal carbonization [6]. In our work FTIR and Raman analysis excludes large-scale carbonization of the protein and does not support carbonization mechanism of fluorescence generation. Thus, fluorescence enhancement resulted from relatively minor changes in chemical composition or physical characteristics of the BSA. We hypothesize that these changes might include densification of the protein as a result of the laser ablation, leading to enhancement of its nonconjugated fluorescence [10]. Laser-induced oxidation of the aromatic residues of the protein mediated by nonlinear absorption of laser pulses, in particular production of fluorescent kynurenine and N-formylkynurenine from tryptophan, offers another possible mechanism [8].

## Conclusions

We demonstrated that femtosecond laser ablation of the solid protein film produces microstructures with multicolor and excitation-dependent visible fluorescence. Processing laser power and exposure enable control of the fluorescence intensity. Intensities several times stronger than the autofluorescence background can be achieved, so that micropatterns can be readily discerned on fluorescent images. Infrared and Raman analysis indicate only minor changes in chemical structure of the protein as a result of laser irradiation.

## REFERENCES

1. Guo Y., Gao Y., Wang Y., et al., Rapid in situ photochemical synthesis of carbon dots in polymer coating by infrared CO<sub>2</sub> laser writing for color tunable fluorescent patterning, Chemical Engineering Journal. 504 (2025) 158749.
2. Hu J., Guo R., Zhu S., et al., Full-color and high-resolution femtosecond laser patterning of Perovskite quantum dots in polyacrylonitrile matrix, Adv. Funct. Mater. 34 (2024) 2407116.
3. Chen W., Gao J., Tian J., Zhang J., In situ femtosecond-laser-induced fluorophores on surface of polyvinyl alcohol for H<sub>2</sub>O/Co<sup>2+</sup> sensing and data security, Sensors. 21 (2021) 7755.
4. Kim E., Kyhm J., Kim J.H., et al., White light emission from polystyrene under pulsed ultraviolet laser irradiation, Sci.Rep. 3 (2013) 3253.
5. Wen X., Ouyang W., Chen Z., et al., Ultrahigh-resolution ( $\lambda/10$ ) femtosecond laser writing of polymer-encapsulated multicolor perovskite patterns beyond the diffraction limit, Adv. Funct. Mat. (2025) 2505625.
6. Guo Y., Wang Q., Li H., et al., Carbon dots embedded in cellulose film: programmable, performance- tunable, and large-scale subtle fluorescent patterning by in situ laser writing, ACS Nano. 16 (2022) 2910–2920.
7. Niyangoda C., Miti T., Breydo L., et al., Carbonyl-based blue autofluorescence of proteins and amino acids, PLOS ONE. 12 (5) (2017) e0176983.
8. Reid L.O., Roman E.A., Thomas A.H., Dantola M.L., Photooxidation of tryptophan and tyrosine residues in human serum albumin sensitized by pterin: a model for globular protein photodamage in skin, Biochemistry. 55 (2016) 4777–4786.
9. Astafiev A.A., Shakhov A.M., Syrchina M.S., Nadtochenko V.A., Fluorescent cell imaging with femtosecond laser pulses-produced protein nanoaggregates, St. Petersburg Polytechnic University Journal. Physics and Mathematics. 17 (3.2) 2024.
11. Lam J.W.Y., Goddard W.A., Tang B.Z., Non-conventional fluorescent biogenic and synthetic polymers without aromatic rings, Polym. Chem. 8 (2017) 1722.

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### Development of a method for increasing the stability of a group frequency standard

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**Abstract.** The paper presents a method for increasing the stability of group frequency standards, the effectiveness of which has been confirmed in the course of mathematical modeling of transient processes in a system consisting of two rubidium and two cesium atomic clocks, upgraded with an automatic gain control (AGC) system. The dynamics of mutual influence between individual frequency standards are described using a system of stochastic differential equations based on Langevin equations. Numerical simulations demonstrate that properly selected AGC parameters and coupling coefficients significantly reduce group signal dispersion and ensure high system stability. The results show a 30–40% improvement in frequency stability compared to conventional single-standard configurations, making this approach particularly valuable for satellite navigation systems and telecommunication networks.

**Keywords:** atomic frequency standard, group frequency standard, automatic gain control, Langevin equations, stochastic differential equations

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## Разработка метода повышения стабильности группового стандарта частоты

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**Аннотация.** В работе представлен метод повышения стабильности групповых стандартов частоты эффективность которого подтверждена в ходе математического моделирования переходных процессов в системе, состоящей из двух рубидиевых и двух цезиевых атомных часов, модернизированной системой автоматической регулировки усиления (АРУ). Динамика взаимного влияния отдельных стандартов частоты описана с помощью системы стохастических дифференциальных уравнений на основе уравнений Ланжевена. Численное моделирование показало, что правильно подобранные параметры АРУ и коэффициенты связи позволяют снизить дисперсию группового сигнала на 30–40% и обеспечить высокую устойчивость системы, что имеет важное значение для спутниковых навигационных систем и телекоммуникационных комплексов.

**Ключевые слова:** квантовый стандарт частоты, групповой стандарт частоты, регулировка усиления, уравнения Ланжевена, стохастические дифференциальные уравнения, стабильность частоты

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## Introduction

The development of high-precision frequency standards represents a critical challenge for modern navigation and telecommunication systems. Atomic frequency standards (AFS) based on rubidium and cesium atoms currently serve as the foundation for time synchronization in global navigation satellite systems (GLONASS, GPS) and telecommunication networks [1–5]. However, the growing demands for accuracy and reliability require new approaches to enhance their performance.

Recent research demonstrates that group frequency standards (GFS) combining multiple atomic clocks offer significant advantages over single-device configurations [6–9]. By implementing collective operation principles, GFS can achieve improved stability while maintaining system redundancy. This approach becomes particularly valuable for critical applications where continuous operation is essential.

The proposed technological solution focuses on developing a GFS architecture with enhanced control algorithms.

This research builds upon existing work in atomic clock technology [10–12] while introducing novel control methodologies for group operation. The developed solutions address current limitations in frequency stability and reliability, offering practical implementations for next-generation systems.

### Modeling of stochastic processes in a group frequency standard

The development of a comprehensive mathematical model for group frequency standards represents a critical step in understanding and optimizing their performance. At the core of our approach lies a system of stochastic differential equations derived from Langevin formalism, specifically adapted to describe the complex dynamics of multiple coupled atomic frequency standards (AFS). This modeling framework captures both the deterministic behavior of individual standards and the stochastic nature of their interactions, providing a powerful tool for analyzing and improving system stability.

On the physical level, a group of multiple coupled atomic frequency standards (AFS) can be understood as an ensemble of oscillators whose outputs are interconnected through a shared synchronization mechanism. The coupling arises from common reference distribution networks, digital phase comparison circuits, and feedback loops that exchange phase and frequency information between standards. Such interaction enables mutual stabilization, as fluctuations in one oscillator can be compensated by corrections derived from the others. In practice, the adjustment of the coupling coefficients  $k_{ij}$  can be realized through programmable digital controllers, where the weighting of individual frequency contributions is adaptively tuned. This may include modifying filter parameters, adjusting phase-locked loop gains, or implementing software-defined algorithms that dynamically reallocate synchronization strength between standards depending on their short- or long-term stability characteristics.

Each atomic frequency standard in the ensemble is characterized by two fundamental components: a base frequency  $\omega_0$  representing its ideal, noise-free operation, and time-dependent stochastic deviations  $\delta\omega(t)$  that account for various noise processes. These deviations arise from multiple physical sources, including quantum noise inherent in atomic transitions, thermal fluctuations in oscillator circuitry, environmental disturbances such as temperature variations and electromagnetic interference, and long-term aging effects in the atomic resonance cells. The complete temporal evolution of each standard's frequency output is governed by a modified Langevin equation that incorporates several key terms.

The temporal evolution of each standard's frequency output is governed by the modified Langevin equation (1):

$$\frac{d\omega_i}{dt} = -\gamma_i(\omega_i - \omega_0) + \sum_{j \neq i} k_{ij}(\omega_j - \omega_i) + F_i(t), \quad (1)$$

where  $\gamma_i$  is the relaxation constant, characterizing the tendency of the AFS to a given value  $\omega_0$ ;  $k_{ij}$  are the coefficients of mutual influence, describing synchronization between AFS;  $F_i(t)$  is the noise component, modeling random disturbances, such as white or flicker noise.

To complete the physical description, we introduce an additional equation to account for phase noise effects, which are particularly critical for applications requiring precise timing synchronization. The phase noise component  $\xi_i(t)$  captures several important phenomena including the Dick effect in atomic interrogation processes, phase noise in local oscillators, and quantization effects in digital control systems. The spectral characteristics of phase noise typically follow a power-law dependence, encompassing white phase noise at high frequencies through to random walk phase noise at lower frequencies. To take into account phase noise, an additional equation is introduced (2):

$$\frac{d\phi_i}{dt} = \omega_i + \xi_i(t), \quad (2)$$

where  $\xi_i(t)$  represents the phase noise. The introduction of the automatic gain control system (AGC) is carried out by means of a nonlinear term  $G(\omega_i)$ , described by the logistic function (3):



$$G(\omega_i) = \frac{A}{1 + \exp[-B(\omega_i - \omega_{opt})]}, \quad (3)$$

where  $A$  and  $B$  are the control parameters, and  $\omega_{opt}$  is the optimal frequency value. This function provides several important advantages for system stabilization. From a practical perspective, the AGC system corresponds to an electronic feedback loop that continuously regulates the correction strength applied to frequency deviations. Physically, AGC can be implemented in analog circuitry through voltage-controlled amplifiers or, more commonly in modern designs, via digital signal processing modules embedded in the control unit. The parameters  $A$  and  $B$  may be adjusted during system calibration or dynamically in operation:  $A$  reflects the maximum corrective action that can be applied, while  $B$  determines how sensitively the correction responds to small deviations. The parameter  $\omega_{opt}$  is maintained as the target operating frequency, typically set to the nominal atomic transition frequency of the rubidium or cesium standard and stabilized via digital phase-locked loops. The sigmoidal shape ensures smooth, adaptive correction that automatically adjusts to the magnitude of frequency deviations, preventing the overcorrection that can lead to instability. The parameters  $A$ ,  $B$ , and  $\omega_{opt}$  control different aspects of the AGC performance:  $A$  determines the maximum correction strength (typically 0.1–1.0 Hz/s),  $B$  sets the sensitivity to deviations (with optimal values between 5–15), and  $\omega_{opt}$  represents the target operating point for each standard. In the context of our simulations,  $\omega_{opt}$  corresponds to the fundamental atomic transition frequency that defines the reference for each standard. Specifically, for rubidium-87 clocks this value is 6,834 GHz, while for cesium-133 clocks it is 9,192 GHz. To simplify numerical analysis, the equations are expressed in normalized frequency units where  $\omega_{opt}$  is scaled to unity, allowing for direct comparison of rubidium and cesium standards within the same modeling framework. This adaptive control mechanism is particularly effective at maintaining stability against both sudden disturbances and gradual drifts.

The numerical implementation of this comprehensive model requires careful consideration of several factors. Time step selection represents a critical compromise between computational efficiency and numerical accuracy, with our simulations typically using steps of 0.1–1 milliseconds to properly resolve the fastest system dynamics while remaining computationally tractable for long-duration simulations. We employ the Euler-Maruyama method as our primary integration technique, chosen for its good balance between implementation simplicity and adequate accuracy for stochastic systems. Verification against higher-order methods like the Milstein scheme confirms that numerical errors remain below 1% for our parameter ranges.

Special attention is given to the accurate generation of noise processes with proper spectral characteristics. We implement a multi-rate approach where different noise components are generated at appropriate time scales and then combined. White noise terms are updated at each time step, while correlated noise processes like flicker noise use specialized generation algorithms to maintain correct spectral properties across the simulation duration. This approach ensures faithful reproduction of the physical noise processes without excessive computational overhead.

The complete model enables detailed investigation of group frequency standard behavior under various operating conditions and forms the basis for optimizing system parameters before physical implementation. Through systematic parameter studies and sensitivity analysis, we can identify optimal configurations that maximize stability while maintaining robust performance against disturbances and component variations. This modeling framework thus serves as both an analytical tool for understanding fundamental behavior and a practical engineering tool for system design and optimization.

## Results and discussion

The numerical analysis of our group frequency standard model yielded significant insights into the system's performance characteristics and stability improvements. Using the Euler–Maruyama method for stochastic integration, we obtained comprehensive time series data for all four atomic standards in the ensemble (two rubidium and two cesium). This approach allowed us to capture both the deterministic dynamics and stochastic fluctuations with high fidelity, providing a robust foundation for statistical analysis.

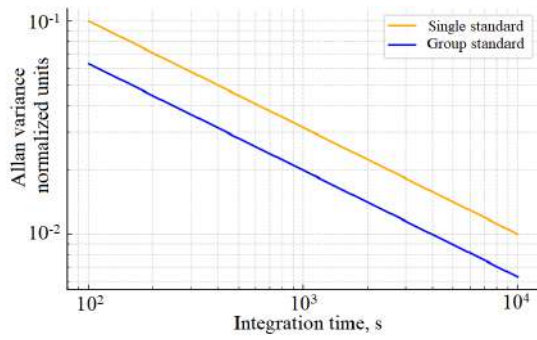


Fig. 1. Dispersion of frequency deviations as a function of integration time of a single atomic frequency standard (orange graph) and a group frequency standard (blue graph)

The calculated statistical characteristics revealed several important aspects of system behavior. The mean frequency values showed excellent convergence to the nominal frequency, with deviations remaining below  $5 \cdot 10^{-14}$  for optimal parameter sets. Dispersion analysis demonstrated a remarkable 35–40% reduction in variance compared to single-standard operation, particularly noticeable at integration times between  $10^2$  and  $10^4$  seconds. This effect is illustrated in Fig. 1, which shows the variance of frequency deviations as a function of integration time for both single-standard and group configurations. The group operation consistently demonstrates lower dispersion, with the most pronounced differences emerging in the intermediate integration intervals. The autocorrelation functions exhibited significantly faster decay in the

group configuration, indicating more effective noise averaging and reduced long-term correlations.

Power spectral density analysis (Fig. 2) provided particularly compelling evidence of the system's advantages. The yellow curve representing a single atomic standard shows characteristic  $1/f$  noise dominating at lower frequencies, with white noise components visible at higher frequencies.

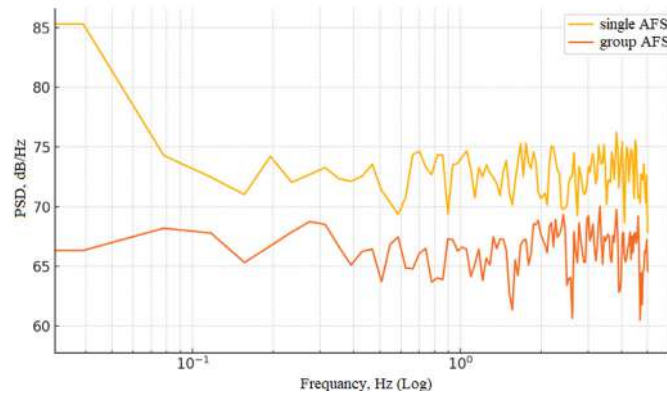


Fig. 2. Mathematical modeling of the power spectral density of a single atomic frequency standard (yellow graph) and a group frequency standard (orange graph)

In contrast, the orange curve for the group standard demonstrates substantial noise suppression across the entire spectrum.

The automatic gain control (AGC) system proved instrumental in achieving these results. Our parametric studies revealed that optimal AGC settings ( $A = 0.45 \pm 0.05$ ,  $B = 12 \pm 2$ ) provided the best compromise between rapid correction and system stability. The logistic function implementation effectively prevented overcorrection while maintaining tight control of frequency deviations, particularly during transient events and mode transitions.

Analysis of the mutual influence coefficients yielded several important findings. The Rb-Rb coupling ( $k_{12}$ ) showed optimal performance in the range of 0.18–0.22, providing strong short-term stabilization. Cs-Cs coupling ( $k_{34}$ ) performed best at 0.27–0.32, enhancing long-term stability. The cross-coupling between Rb and Cs standards ( $k_{13}$ ,  $k_{24}$ ) demonstrated an interesting asymmetry: values of 0.12–0.15 for  $\text{Rb} \rightarrow \text{Cs}$  and 0.08–0.12 for  $\text{Cs} \rightarrow \text{Rb}$  produced the most stable operation, reflecting the different noise characteristics and stability profiles of the two standard types.

The relaxation constants  $\gamma$  proved less sensitive to variation, with optimal values clustering around  $8 \cdot 10^{-4} \text{ s}^{-1}$  for Rb standards and  $6 \cdot 10^{-4} \text{ s}^{-1}$  for Cs standards. This difference accounts for the inherently different response characteristics of the two atomic systems. The system showed particular sensitivity to the ratio between relaxation constants and coupling coefficients, with the  $\gamma/k$  ratio between 0.003–0.005 providing optimal dynamics.

Comparative analysis against single-standard operation revealed consistent 15–20% improvements in Allan deviation across all measured time scales. The most significant enhancements appeared in the  $10^3$ – $10^5$  second range, where the group configuration reduced frequency instability by up to 22%. Fig. 3 presents the Allan deviation curves obtained from numerical simulations.

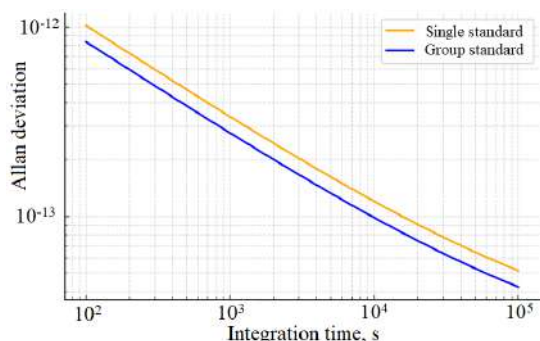


Fig. 3. Allan deviation for a single atomic frequency standard (orange graph) and a group frequency standard (blue graph)

The group configuration demonstrates a uniformly lower deviation curve compared to the single-standard reference, with the relative improvement reaching its maximum in the  $10^3$ – $10^5$  s interval. This confirms that the ensemble approach is particularly advantageous in the long-term stability regime relevant for satellite navigation and telecommunication applications. This corresponds exactly to the critical operational window for satellite navigation systems and other precision timing applications.

The failover characteristics proved particularly impressive. Simulation of single standard failures showed system recovery times below 50 milliseconds, with frequency deviations never

exceeding  $1 \cdot 10^{-14}$  during transitions. This robust performance stems from the adaptive nature of both the coupling network and AGC system, which automatically redistribute timing responsibilities when detecting an out-of-spec standard.

These results collectively demonstrate that our group frequency standard architecture successfully combines the complementary strengths of rubidium and cesium standards while mitigating their individual weaknesses. The 15–20% stability improvement over single-standard operation, combined with excellent failover characteristics and noise suppression, confirms the practical viability of this approach for demanding applications in satellite navigation, telecommunications, and scientific instrumentation. The comprehensive numerical analysis provides clear guidance for physical implementation and parameter optimization in real-world systems.

## Conclusion

The proposed physical and mathematical modeling of transient processes in a group frequency standard based on rubidium and cesium atomic clocks, utilizing an automatic gain control system, demonstrates the potential of this approach. The developed model, based on a system of stochastic differential equations, accounts for both deterministic and stochastic processes affecting synchronization stability.

Numerical simulations confirm the feasibility of achieving high stability and reducing group signal dispersion through system parameter optimization. Further research may include experimental validation of the model and the development of real-time algorithms for integration into modern satellite navigation and communication systems.

## REFERENCES

1. Zhang A., Tariq A., Qudsoos A., et al., Spatio-temporal analysis of urban expansion and land use dynamics using google earth engine and predictive models, *Scientific Reports*. 15(1) (2025) 6993.
2. Petrov A.A., Zaletov D.V., Davydov V.V., Shapovalov D.V., Peculiarities of Constructing a Scheme for Formation of a Microwave Excitation Signal in a Cesium Atomic Clock, *Journal of Communications Technology and Electronics*. 66 (3) (2021) 295–299.
3. Lukashev N.A., Moroz A.V., Compact microwave frequency standard on Hg-199 ions for navigation systems, *Journal of Physics: Conference Series*. 1236 (1) (2019) 012068.
4. Grevtseva A., Rud V., Method of processing velocity increase of measuring results of quantum frequency standard parameters for information transfer velocity increase in satellite communication systems, *Ceur Workshop Proceedings*. 2667 (2020) 15–18.
5. Petrov A.A., Grebenikova N.M., Some Directions of Quantum Frequency Standard Modernization for Telecommunication Systems, *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*. 11118 LNCS (2018) 641–648.

6. Yi X., Yang S., Dong R., et al., Architecture and Algorithm Design of Navigation Satellite Robust Ensemble Clock System, IEEE Sensors Journal. 24 (10) (2024) 17054–17066.
7. Yi X., Yang S., Dong R., et al., A composite clock for robust time–frequency signal generation system onboard a navigation satellite, GPS Solutions. 28 (1) (2024) 6.
8. Ouyang M., Zhu X., Yi R., Lyu D., Using Various Analysis Center Products to Assess the Time-Frequency Transfer Performance of GPS/Galileo/BDS PPPAR Methods, Remote Sensing. 15 (1) (2023) 92.
9. Shavshin A.V., Improving microwave output in rubidium-87 atomic frequency standard with new automatic gain control, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 16 (3.2) (2023) 428–433.
10. Yang Y., Yang Y., Chen J., et al., Pseudo-stable constellation bias error of BDS-3 and its high-precision prediction, Cehui Xuebao Acta Geodaetica Et Cartographica Sinica. 50 (12) (2021) 1728–1737.
11. Song L., Liu J., Wang L., et al., A comparative study on different machine learning approaches with periodic items for the forecasting of GPS satellites clock bias, Scientific Reports. 15 (1) (2025) 2709.
12. Li J., Zhu J., Ruan R., et al., Application and accuracy analysis of raw one way inter-satellite link observations of BDS-3 full operational constellation, Scientific Reports. 15 (1) (2025) 14438.

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## **Terahertz lasing in open plane-parallel metal-dielectric resonator with graphene**

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**Abstract.** Terahertz amplification and lasing regimes in open plane-parallel metal-dielectric resonator with population inverted (active) graphene are studied theoretically. Terahertz lasing arises at the Fabry–Perot resonance in the open-side metal-dielectric substrate of graphene in the vicinity of the reststrahlen band edge of GaAs superstrate due to photon-phonon interaction in GaAs.

**Keywords:** terahertz, lasing, graphene, inversion, Fabry–Perot resonance

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Материалы конференции

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## **Терагерцовая лазерная генерация в открытом плоскопараллельном металлодиэлектрическом резонаторе с графеном**

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**Аннотация.** Теоретически исследованы режимы усиления и генерации терагерцового излучения в открытом плоскопараллельном резонаторе с графеном с инверсной населенностью. Терагерцовая генерация возникает на частоте резонанса Фабри-Перо в металлизированной только с одной стороны подложке графена вблизи края полосы остаточных фоновых лучей в покровном GaAs слое вследствие фотон-фононного взаимодействия в GaAs.

**Ключевые слова:** терагерц, лазер, графен, инверсия, Фабри-Перо резонанс

**Финансирование:** РНФ 00114-22-24 «Возбуждение, усиление и нанофокусировка терагерцовых плазменных волн в желобковых волноводах на основе графена».

**Ссылка при цитировании:** Морозов М.Ю., Машинский К.В., Попов В.В. Терагерцовая лазерная генерация в открытом плоскопараллельном металлодиэлектрическом резонаторе с графеном // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2025. Т. 3.2 № 18. С. 296–300. DOI: <https://doi.org/10.18721/JPM.183.259>

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## Introduction

Terahertz (THz) lasers are in demand for THz imaging systems, medical diagnostics, and monitoring systems [1]. Graphene, being a natural two-dimensional material with unique properties such as a zero band gap and linear energy spectrum of charge carriers originally synthesized in [2, 3], can become a possible candidate for creating miniature THz lasers.

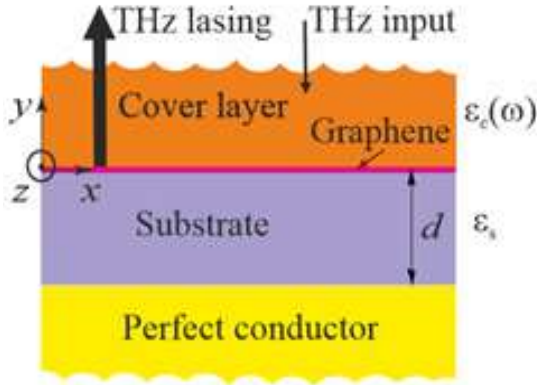


Fig. 1. Structure under consideration

In this paper, we theoretically study the THz amplification and lasing regimes in open parallel-plane metal-dielectric resonator with population inverted (active) graphene. The structure under consideration is schematically shown in Fig. 1. Graphene is deposited on a dielectric hBN substrate of thickness  $d$  screened by ideal conductor at the bottom, which forms a one-side perfect mirror of the Fabry–Perot resonator. No second mirror exists on the other side of the hBN substrate, so that the Fabry–Perot resonator is partially open. Graphene is covered with semi-infinite (in our theoretical model) GaAs superstrate. We consider that THz wave with TEM polarization incident normally upon graphene from inside GaAs cover layer and

reflects back being amplified due to its interaction with active graphene. The inverted carrier distribution in graphene is assumed to be created by optical illumination [4]. We show that THz lasing arises at the Fabry–Perot resonance in the hBN substrate in the vicinity of the reststrahlen band edge of GaAs superstrate due to photon-phonon interaction in GaAs.

## Materials and methods

Solving the Maxwell equations with conventional electromagnetic boundary conditions in the graphene plane and on the perfect conductor plane, we obtain the power reflection coefficient of the incident TEM wave:

$$R = \left| \frac{Y_{\text{ch}} - Y_{\text{load}}}{Y_{\text{ch}} + Y_{\text{load}}} \right|^2, \quad (1)$$

where  $Y_{\text{ch}}$  and  $Y_{\text{load}}$  are the characteristic admittance of the incident TEM mode in GaAs and the admittance of the terminal load (including graphene and dielectric substrate screened by the perfect conductor), respectively. These admittances are defined as

$$Y_{\text{ch}} = \frac{k_{\text{yc}}}{\omega \mu_0}, \quad Y_{\text{load}} = \sigma(\omega) + i \frac{k_{\text{ys}}}{\omega \mu_0} \text{ctg}(k_{\text{ys}} d), \quad (2)$$

where  $\omega$  and  $\mu_0$  are the angular frequency and magnetic constant, respectively,  $\sigma(\omega)$  is the dynamic conductivity of active graphene [5], and

$$k_{\text{yc}} = \sqrt{\epsilon_c(\omega)} \frac{\omega}{c}, \quad k_{\text{ys}} = \sqrt{\epsilon_s} \frac{\omega}{c}, \quad (3)$$

are the normal-to-graphene-plane components of the wavevector of TEM mode in the graphene cover layer (GaAs) and in the substrate, respectively, with  $c$  being the speed of light,  $\epsilon_c = 4.5$  is the dielectric constant of the substrate (hBN), and

$$\varepsilon_c(\omega) = \varepsilon_\infty \frac{\omega_{LO}^2 - \omega^2}{\omega_{TO}^2 - \omega^2}, \quad (4)$$

is the dielectric function of GaAs [6], where  $\omega_{LO} = 2\pi \cdot 8.76$  THz and  $\omega_{TO} = 2\pi \cdot 8.05$  THz are the longitudinal (LO) and transverse (TO) optical phonon frequencies in GaAs, which are the high frequency and the low frequency edges of the reststrahlen band, respectively, and  $\varepsilon_\infty$  is the dielectric constant at an infinite frequency.

### Results and discussion

Let us first analyze the possibility of lasing in open plane-parallel metal-dielectric resonator with graphene but without superstrate. In Fig. 2, *a* we present reflection spectrum in the structure with  $\varepsilon_c = 1$  for the quasi-Fermi energy value in graphene 35 meV, the mean free time of the charge carriers in graphene 0.3 ps, and charge carriers temperature 300 K. One can see a series of peaks corresponding to the Fabry–Perot resonances in the substrate. The incident wave is amplified due to interaction with active graphene but no lasing occurs. The absence of lasing in such structure can be explained as follows. According to Eq. (1), to obtain lasing regime one needs to realize matching of the characteristic admittance of the incident TEM mode in vacuum  $Y_{ch} = Y_0 \approx 2.65$  mS and the admittance of the terminal load  $Y_{load}$ . The free-space admittance  $Y_0$  is a real valued quantity, hence, the total admittance matching  $Y_0 + Y_{load} = 0$  can be fulfilled only at the Fabry–Perot resonances in the substrate, where the admittance of the terminal load becomes also the real-valued quantity  $Y_{load}(\omega_{res}) = \text{Re}\sigma(\omega_{res})$ . However, the free-space admittance is far greater than the graphene conductivity in THz frequency range, hence the sum of the free-space admittance and the admittance of the terminal load at the Fabry–Perot resonances in the desired THz frequency range is always positive  $Y_0 + \text{Re}\sigma(\omega_{res}) > 0$  (as can be seen from Fig. 2, *b*).

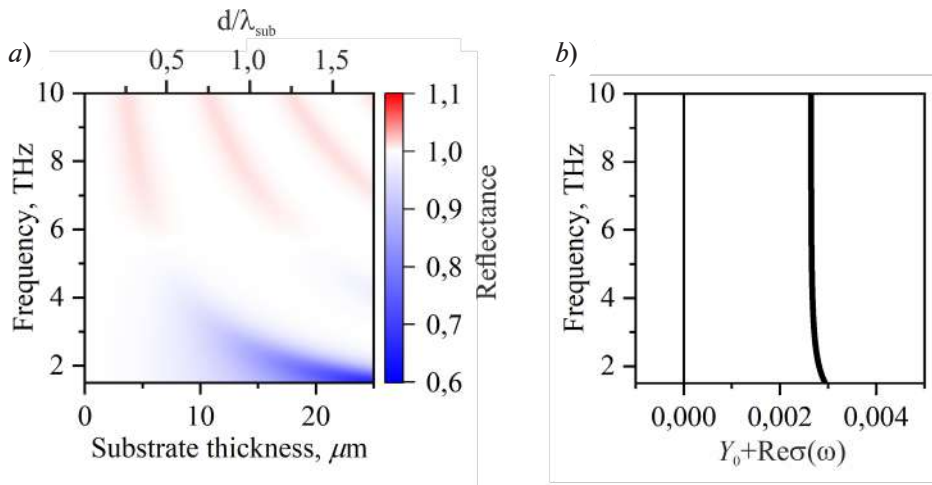


Fig. 2. Reflection spectrum in dependence on frequency and the substrate thickness  $d/\lambda_{sub}$ , where  $\lambda_{sub}$  is the wavelength of the TEM wave in the substrate, in the structure with  $\varepsilon_c = 1$  (*a*). The sum of the free-space admittance and the admittance of the terminal load at the Fabry–Perot resonances,  $Y_0 + \text{Re}\sigma(\omega)$ , in dependence on frequency for the structure with  $\varepsilon_c = 1$  (*b*)

Now, let discuss the possibility of the lasing regime in open plane-parallel metal dielectric resonator with graphene covered by GaAs superstrate, taking into account the photon-phonon interaction in GaAs. Fig. 3, *a* shows the reflection resonances corresponding to the Fabry–Perot resonances in hBN substrate. In the vicinity of the high frequency edge of GaAs phonon reststrahlen band  $\omega \geq \omega_{LO}$  (at about 8.8 THz) the dielectric function of the GaAs becomes very small (but positive) leading to drastic decrease of the characteristic admittance  $Y_{ch} = \sqrt{\varepsilon_c(\omega)} Y_0$ . Hence, the THz lasing condition,  $Y_{ch} + Y_{load} = 0$ , can be fulfilled (see Fig. 3, *b*). Because of this, one can see the high quality resonances corresponding to THz lasing in Fig. 3, *a*, which occur near the high frequency edge of GaAs reststrahlen band (at frequency about 8.8 THz).

We also note that THz lasing emerge at the Fabry–Perot resonances for the substrate thickness values nearly equal to  $d = (2n - 1) \cdot \lambda_{\text{sub}} / 4$ , where  $\lambda_{\text{sub}}$  is the wavelength of the TEM wave in the substrate and  $n$  is the integer. Hence, graphene is located in the vicinity of the antinode of the standing wave in the substrate.

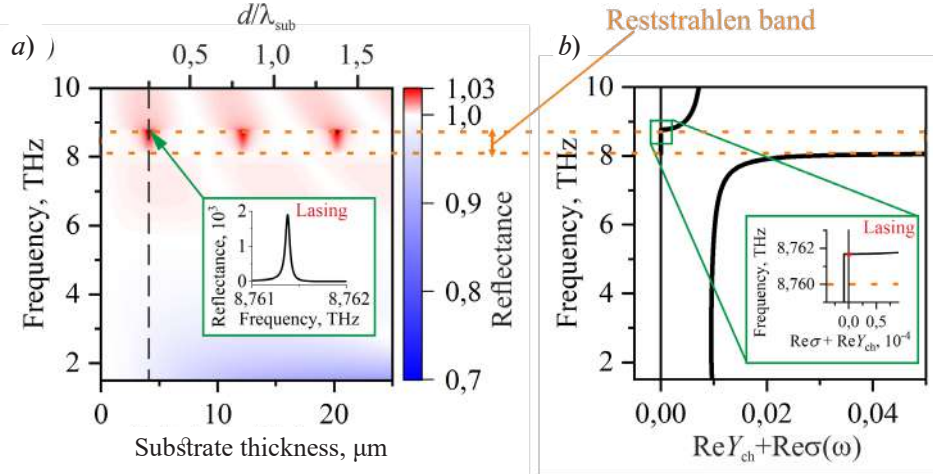


Fig. 3. Reflection spectrum in dependence on frequency and the substrate thickness for the structure with graphene covered by semi-infinite GaAs. The inset represents the cross-section of the raster map for  $d = 4.2$  mm (corresponding to THz lasing) (a).

The sum of the characteristics admittance and the admittance of the terminal load at the Fabry–Perot resonances,  $\text{Re} Y_{\text{ch}} + \text{Re} \sigma(\omega)$ , in dependence on frequency for the structure with graphene covered by semi-infinite GaAs. The inset represents the frequency range in the vicinity of the high frequency edge of GaAs reststrahlen band indicating (by red point) the THz lasing condition (b)

### Conclusion

Terahertz amplification and lasing in open plane-parallel metal-dielectric resonator with population inverted are studied theoretically. Terahertz lasing arises at the Fabry–Perot resonances in the substrate in the vicinity of the reststrahlen band edge of GaAs superstrate due to sharp decrease of the characteristic admittance of GaAs.

### REFERENCES

1. Li X., Li J., Li Y., et al., High-throughput terahertz imaging: progress and challenges, *Light: Science & Applications*. 12 (2023) 233.
2. Novoselov K.S., Geim A.K., Morozov S.V., et al., Electric field effect in atomically thin carbon films, *Science*. 306 (2004) 666.
3. Novoselov K.S., Geim A.K., Morozov S.V., et al., Two-dimensional gas of massless Dirac fermions in graphene, *Nature*. 438 (2005) 197
4. Ryzhii V., Ryzhii M., Otsuji T., Negative dynamic conductivity of graphene with optical pumping, *J. Appl. Phys.* 101 (2007) 083114.
5. Dubinov A.A., Aleshkin V.Ya., Mitin V., et al., Terahertz surface plasmons in optically pumped graphene structures, *J. Phys.: Condens. Matter*. 23 (2011) 145302.
6. Vassant S., Marquier F., Greffet J.J., et al., Tailoring GaAs terahertz radiative properties with surface phonons polaritons, *Applied Physics Letters*. 97 (2010) 161101.

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## Subterahertz 2 Gbit/s wireless channel with frequency-driven beam steering

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**Abstract.** In this work, we report on a subterahertz wireless channel with frequency-driven beam steering in reflected light as a blockage mitigation tool, which is in demand by the next-generation wireless networks with user mobility support. Blockage-preventing switching between user devices via frequency-selective reflecting surface is demonstrated for 2 Gbit/s indoor channel with carrier frequencies in the spectral band 134–158 GHz.

**Keywords:** 6G, wireless channel, subterahertz, indoor, intelligent reflecting surface

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Материалы конференции

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## Субтерагерцовый беспроводной канал 2 Гбит/с с частотно-управляемой разверткой пучка

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**Аннотация.** В этой работе мы сообщаем о субтерагерцовом беспроводном канале с частотно-управляемой разверткой пучка в отраженном свете как о средстве смягчения эффекта блокировок, востребованном в сетях связи нового поколения с поддержкой мобильности пользователя. Нами продемонстрирована возможность коммутации между пользовательскими устройствами с предотвращением блокировок с помощью частотно-селективной отражающей поверхности для внутреннего канала со скоростью 2 Гбит/с и несущими частотами в спектральном диапазоне 158–134 ГГц.

**Ключевые слова:** 6G, беспроводной канал, субтерагерцовый диапазон, внутри помещения, интеллектуальная отражающая поверхность



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## Introduction

Next generation wireless communication networks are expected to utilize spectra of the sub-terahertz (sub-THz) band (100–300 GHz) to increase data transfer rate and reduce latency. Standardization of spectral bands for sub-THz and even terahertz (THz) communications is already underway [1]. However, sub-THz and THz waves are subjects to significant atmospheric absorption [2], making them nearly impractical to use in outdoor cellular network deployments. But indoors, where distances are short and typically do not exceed a few tens of meters, deployment of such networks seems quite feasible utilizing highly directional channels. Their use results in the appearance of line-of-sight blockage and user micromobility issues [3, 4], making wireless connection essentially less stable. The issues can be fixed in the reflection-aided channels equipped with intelligent reflecting surfaces (IRSs). Generally speaking, IRS enables creation of virtual line-of-sight path and, depending on deployment condition and application scenario, can be used for dynamic beam steering or static beamforming through non-specular reflections of carrier signals. In this work, we report on the use of our previously designed and fabricated frequency-selective IRS [5] for real-time beam steering as a blockage mitigation tool in a sub-THz indoor high-speed channel. IRS is presented array of the  $36 \times 36$  log-periodic spiral antennas with static phase-configured via three different unit cells repeated in each row. IRS exhibit in-reflection phase shifts within  $0\text{--}350^\circ$  at the operational angles of incidence up to  $75^\circ$  with beamwidth, side lobe and cross-polarization levels of  $4^\circ$ ,  $-13$  dB and  $-26$  dB, respectively. Details of our experimental studies are provided below.

## Materials and Methods

Referring to Fig. 1, the core of the experimental setup is the transmitter (Tx) module, which can generate modulated signals with carrier frequencies from 134 GHz to 158 GHz and output powers of up to 20 dBm. The modulation type is adjustable. Either quadrature amplitude modulation with 16 states or amplitude shift keying with 4 states (ASK-4) can be implemented by controlling in-phase (I) and quadrature (Q) inputs of IQ mixer incorporated in the Tx module. Baud rates of up to 3 GHz are supported by both the IQ mixer and the digital-to-analog converter (DAC) controlling its I and Q states. Due to the limitations on the receiver (Rx) module side, we fix the modulation to ASK-4 and the baud rate to 1 GHz in our experiments. The limitations of the Rx module are caused by the lack of a suitable sub-THz heterodyne source at our disposal. At the same time, on the Tx module side, the modulation frequency and the number of amplitude states are basically limited by the capabilities of the DAC operated in a stand-alone test mode.

Fig. 2 shows a detailed block diagram of the experimental setup. Generated sub-THz ASK-4 signal is emitted into a free space in the form of an 8 deg wide Gaussian beam. The beam is further incident on an IRS panel, whose frequency-selective reflective properties are used to feed signals with carrier frequencies of 135.6 GHz and 152.4 GHz into two distanced Rx modules based on our previously designed and fabricated the Schottky diode detectors [6]. Switching of the carrier frequencies is maintained at Tx automatically if blockage of a currently active Tx-IRS-Rx path occurs. The employed threshold algorithm with an Rx signal strength as input parameter enables real-time feedback functioning. Time series of the Rx signal strength are logged by a digital oscilloscope with a 1 GHz analog bandwidth.

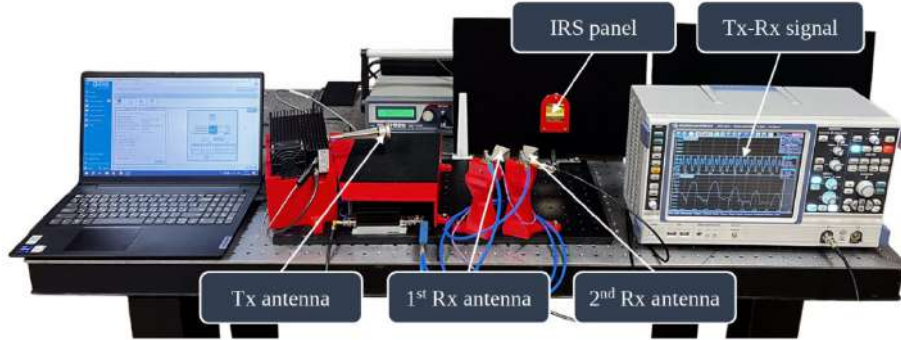


Fig. 1. Photograph of a sub-THz wireless channel with frequency-driven beam steering

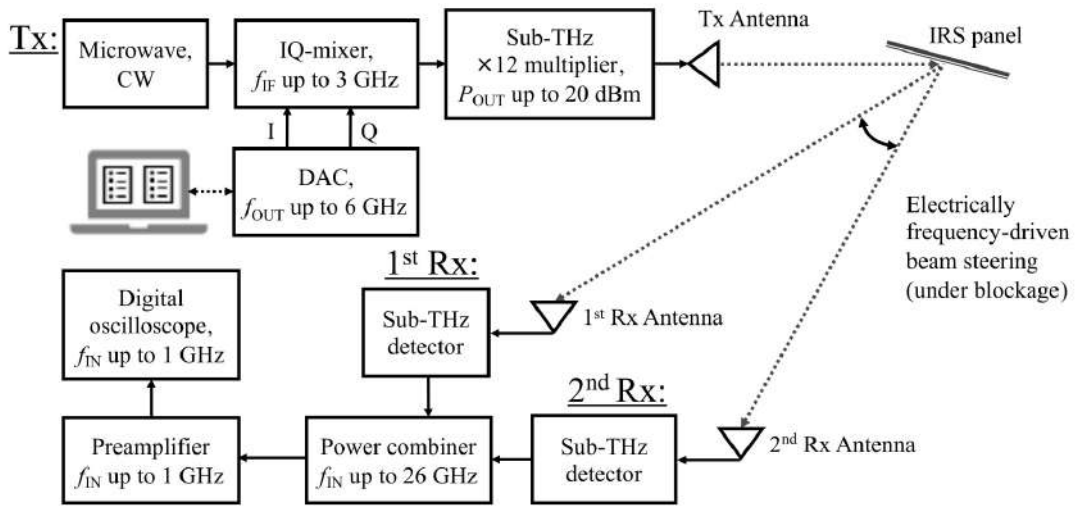


Fig. 2. Block diagram of a sub-THz wireless channel with frequency-driven beam steering

### Results and discussion

Fig. 3 shows the oscillograms of the received signal on the first Rx module at a frequency of 135.6 GHz and on the second Rx module at a frequency of 152.4 GHz, the data rate is 2 Gbit/s using only one IQ mixer input, with the potential to reach 4 Gbit/s using both IQ mixer inputs. It is possible to achieve a data rate of 12 Gbit/s if the DAC is handled through a Firepower Management Center (FMC) hardware interface by an external field-programmable gate array (FPGA) introduced additionally into the developed setup. The time series of the first and second Rx modules exhibit the same data transfer rate but have different waveforms. This is due to the fact that on the Tx side of the module, the DAC component has difficulty generating

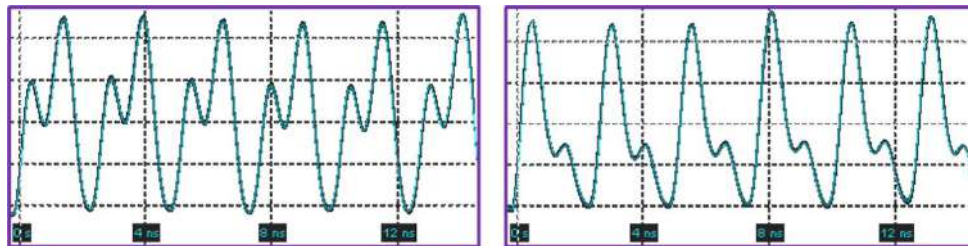


Fig. 3. Oscillograms of the received signal on the first (a) and second Rx modules (b) via frequency-driven beam steering at 135.6 GHz and 152.4 GHz respectively

time series that determine the signal modulation, since it requires a high-performance FPGA for efficient operation. Timely recognition of blockage in the sub-THz channel between the IRS and one Rx, achieved by the threshold algorithm, allows for fast switching to the second sub-THz channel between the IRS and another Rx, which demonstrates the implementation of blockage-preventing detection.

### Conclusion

We implement the IRS panel and the detector diodes of the Rx modules in accordance with our recently reported designs. All electronic and optical components are assessed individually and as a part of the Tx-IRS-Rx assembly. In the end, our experiments successfully demonstrate blockage-preventing switching between user devices in real time via frequency-driven beam steering in a 2 Gbit/s indoor channel with carrier frequencies in the spectral band 134-158 GHz.

### REFERENCES

1. Kürner T., Hosako I., Spectrum and Standardization for THz Communications. Handbook of Radio and Optical Networks Convergence, Singapore: Springer Nature Singapore. (2024) 1141–1163.
2. Recommendation ITU-R P.676-13, Attenuation by atmospheric gases and related effects. URL: <https://www.itu.int/rec/R-REC-P.676-13-202208-I/en.html>. Accessed Mar. 31, 2025.
3. Shurakov A., Moltchanov D., Prikhodko A., et al., Empirical blockage characterization and detection in indoor sub-THz communications, Computer Communications. 201 (2023) 48–58.
4. Petrov V., Moltchanov D., Koucheryavy Y., Jornet J.M., Capacity and outage of terahertz communications with user micro-mobility and beam misalignment, IEEE Transactions on Vehicular Technology. 69 (4) (2020) 6822–6827.
5. Shurakov A., Razakova A., Lvov A., et al., Compact Log-Periodic Single-Port Planar Antennas for D-Band Monolithic RIS Panels, IEEE Antennas and Wireless Propagation Letters. 24 (1) (2025) 88–92.
6. Shurakov A., Belikov I., Prikhodko A., et al., Membrane-integrated planar Schottky diodes for waveguide mm-Wave detectors, Microwave & Telecommunication Technology. 3 (2021) 34.

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## Spectral and technological studies of polyurethane films for flexible sub-THz antennas

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**Abstract.** Efficient antenna solutions are demanded by variety of applications nowadays. As a part of subterahertz (sub-THz) electronics, they are of use in modern wireless modules and systems, providing opportunities for an ultra-high speed data transfer, remote sensing, energy harvesting, etc. The appearance of robust flexible antennas and metasurfaces can substantially widen the scope of potential application of sub-THz wireless technologies, bringing them to practical use cases. This study focuses on the properties of polyurethane and hydrogel polyurethane films in the context of their spectral characteristics and technological robustness. The thicknesses of the films are  $0.18 \pm 0.01$  mm and  $0.15 \pm 0.01$  mm. Calibrated quartz handle-wafers are used to mount them into the optical path of the employed sub-THz reflectometer. At 130–160 GHz, we measure complex permittivities of  $2.95 (1 + 0.01i)$  and  $3.15 (1 + 0.01i)$ , making both films well-suited for designs of planar antennas on quartz. Hydrogel polyurethane film, however, does not demonstrate selectivity to acetone-assisted lithographic processes, leaving polyurethane film as the only candidate for cleanroom fabrication.

**Keywords:** subterahertz, reflection spectrum, dielectric film, polyurethane, hydrogel polyurethane, complex permittivity, flexible antenna, cleanroom fabrication

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Материалы конференции

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## Спектральные и технологические исследования полиуретановых пленок для гибких суб-ТГц антенн

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**Аннотация.** В этом исследовании основное внимание уделяется свойствам полиуретановых и гидрогелевых полиуретановых пленок в контексте их спектральных характеристик и технологичности. В диапазоне частот 130–160 ГГц измерены комплексные диэлектрические проницаемости пленок  $2.95 (1 + 0.01i)$  и  $3.15 (1 + 0.01i)$ , что делает обе пленки хорошо подходящими для проектирования планарных антенн на кварце. Однако гидрогелевая полиуретановая пленка не демонстрирует селективности к литографическим процессам с использованием ацетона, что делает полиуретановую пленку единственным возможным выбором для производства с использованием процессов чистой зоны.

**Ключевые слова:** субтерагерцовый диапазон, спектр отражения, диэлектрическая пленка, полиуретан, гидрогель полиуретана, комплексная диэлектрическая проницаемость, гибкая антенна, производство в чистой зоне

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## Introduction

Mastering the subterahertz (sub-THz) range makes it possible to expand the boundaries of the application of modern wireless modules and systems for an ultra-high speed data transfer, remote sensing, energy harvesting etc. [1]. On that ground, the development of the robust antenna designs is the key issue. In the process of development of new antenna solutions, it becomes clear that the inflexibility of systems due to form factor and weight is a crucial aspect. In terms of designing and manufacturing a flexible antenna, the attention is focused on conductive and isolating materials exhibiting superior properties with the possibility to significantly reduce fabrication cost and/or enhance (or not to compromise at least) the overall radiophysical properties of the design. The isolating substrate acts as a mechanical holder and is assessed on the basis of its dielectric and elastic properties. Together with the resistivity of conductive elements, it contributes to the antenna performance, ageing in deformation cycles. This research is focused on the properties of polyurethane and hydrogel polyurethane films in the context of their spectral characteristics and technological robustness as a platform for flexible planar antennas and antenna arrays operating above 100 GHz. Polyurethane is suitable for antenna applications due to its high mechanical



strength and wear resistance, wide temperature range stability, good dielectric properties, chemical resistance to oils, solvents and moisture, is lightweight, and exhibits excellent adhesion to a variety of materials, making it a durable and versatile choice for flexible sub-THz antennas.

### Materials and methods

To distinguish the relative permittivity of the chosen quartz substrates, the quartz material under the test (MUT) is represented by a two-inch diameter wafer. The thickness of the MUT is 500  $\mu\text{m}$ . In order to evaluate the permittivity of the MUT, we assess the reflective properties of the material. The optical paths between 130–160 GHz transmitter (Tx) and receiver (Rx) with respect to MUT are identical and equal to Fraunhofer distance (FD).

Once the dielectric properties of quartz substrates are assessed, we apply polyurethane films on their surfaces. One side of the film has adhesive layer adhering to the quartz substrate and was smoothed out during application. After that the film was cut to size and shape of the substrate. The thicknesses of the polyurethane and hydrogel polyurethane films under study measured by micrometer are  $0.18 \pm 0.01$  mm and  $0.15 \pm 0.01$  mm. Thus, two quartz handle-wafers are used to mount them one by one into the optical path of the employed sub-THz reflectometer during measurements [2]. The measurements are conducted in two polarizations in the far-field.

### Results and discussion

For frequency range of 130–160 GHz and angles of incidence within 30–60 deg, we fit measured spectra of the quartz wafers by reflectances derived from their frequency-dependent characteristic matrices (CMs) [3] and are compared with the predictions of Fresnel equations (FEs). For the two wafers, we acquire complex permittivities of  $4.159 (1 + 0.01i)$  and  $4.532 (1 + 0.015i)$ , consistently measured for both transverse electric (TE) and transverse magnetic (TM) modes. The quartz substrates are enumerated to ensure correct interpretation of the obtained reflection spectra of structures. The measured spectra  $R_{\text{TE}}$  and  $R_{\text{TM}}$  with fit-functions CM and FE are provided in Fig. 1.

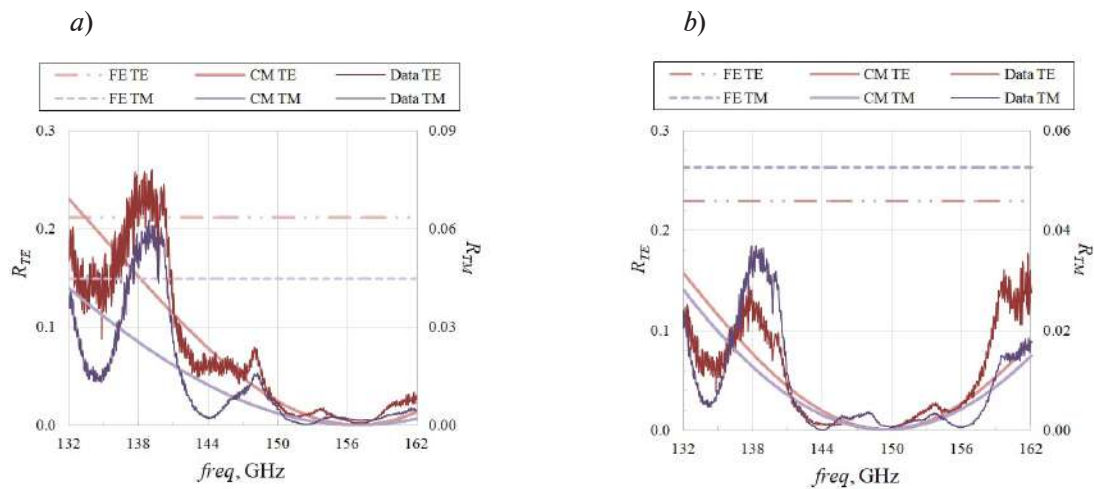


Fig. 1. Reflection spectra of first quartz substrate (a) and second quartz substrate (b) at the angle of incidence of 45 deg

Once the quartz handle-wafers are evaluated, we proceed with the second iteration: the measurements of the reflectance spectra of two bilayer structures quartz/polyurethane and quartz/hydrogel polyurethane. Examples of the measured spectra are provided in Fig. 2.

The spectral measurements are conducted in the same configurations as when measuring the reflectance spectra of quartz, and the CM method is used as a permittivity extraction tool again. Thus, the CM fit-functions depicted in Fig. 1 achieve an average accuracy of 10–20% of the values of the real and imaginary parts of the dielectric permittivity. The extracted complex permittivities of polyurethane film and hydrogel polyurethane film are  $2.95 (1 + 0.01i)$  and  $3.15 (1 + 0.01i)$ , respectively. This potentially makes both films well-suited for designs of planar antennas and antenna arrays on quartz, as such values improve phase-amplitude characteristics.

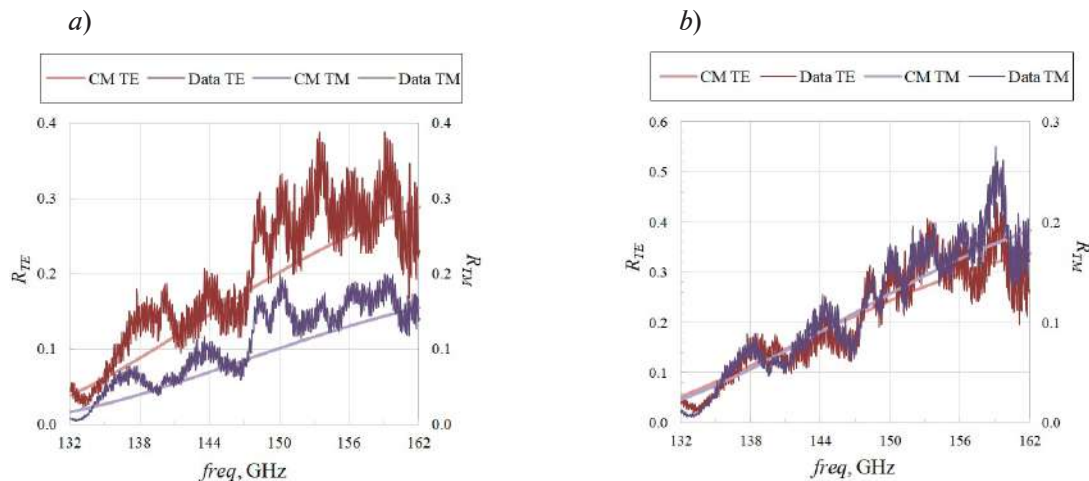


Fig. 2. Reflection spectra of quartz/hydrogel polyurethane (a) and quartz/polyurethane (b) sandwiches measured at the angle of incidence of 30 deg

We further assess technological robustness of the films under study and find out that hydrogel polyurethane does not demonstrate selectivity to acetone-assisted lithographic processes, whereas the polyurethane does. Thus, polyurethane film seems to be the only candidate for cleanroom fabrication. Nevertheless, it has poor adhesive properties of the surface that leads to the increase in complexity of fabrication process. The issue can be solved by structuring surface's roughness with mechanical treatment or by integration of additional adhesive polymer layers such as poly-methyl methacrylate (PMMA).

We plan to use the film to implement an antenna array with 1.5k–2.5k elements similar to that reported by us in [4] in the future.

### Conclusion

In this paper, we report on the reflective and technological properties of bilayer structures quartz/polyurethane and quartz/hydrogel polyurethane. Reflectometer-based measurement setup is used for the sub-THz spectral studies of the samples. At 130–160 GHz, the experimental values of complex permittivities of polyurethane film and hydrogel polyurethane film are  $2.95 (1 + 0.01i)$  and  $3.15 (1 + 0.01i)$ , respectively. We also conclude that the polyurethane film is suitable for the fabrication of flexible reflectarrays in lift-off cleanroom processes. This should be interesting to developers of low-cost flexible sub-THz antennas.

### REFERENCES

1. Kirtania S.G., Elger A.W., Hasan M.R., et al., Flexible antennas: A review, *Micromachines*. 11 (9) (2020) 847.
2. Rozhkova P.V., Prikhodko A.N., Shurakov A.S., Goltzman G.N., Polyethylene-on-quartz platform for subterahertz reconfigurable reflective surfaces, *St. Petersburg State Polytechnical University Journal. Physics and Mathematics*. 17 (3.1) (2024) 363–366.
3. Born M., Wolf E., *Principles of Optics*, Cambridge University Press. (2019).
4. Razakova A.A., Prikhodko A.N., Lvov A.V., et al., Subterahertz circularly polarized 1k-pixel reflective surface for 6G applications, *St. Petersburg State Polytechnical University Journal. Physics and Mathematics*. 17 (3.1) (2024) 345–348.

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## **A comparative study of near-field blockages in 14 GHz and 140 GHz indoor wireless channels**

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**Abstract.** Further increase in the volume and speed of data transfer requires the use of the subterahertz frequency range as the next stage in the evolution of wireless communication systems. Problems emerge due to large propagation losses of subterahertz signals in the atmosphere and a drop in the output power and sensitivity of subterahertz transceivers. This leads to the necessity of highly directional communication channels. Such channels will rely on the use of antenna arrays in both the base station and the user equipment. Given the inherent limitation to relatively small coverage areas, the deployment of subterahertz systems in indoor environments will emerge as a key aspect of their practical implementation. It is expected that line-of-sight channel blockages by users in crowded premises will significantly affect the communication stability. Signal scattering effects are to be different from those observed at microwaves. Moreover, near-field wireless operation becomes possible and probable. In this paper, we perform a comparative study of near-field blockages in 14 GHz and 140 GHz indoor wireless channels. Different trajectories of the blocking user are studied. A diffraction model describing dynamics of the blockage process is parameterized. The results obtained allow one to enhance the existing cluster models of subterahertz channels and to determine the available time budget for communication systems with real-time blockage avoidance.

**Keywords:** subterahertz, 6G network, indoor deployment, channel blockage, near-field diffraction, signal time series, signal loss

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Материалы конференции

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## Сравнительное исследование ближнепольных блокировок в беспроводных каналах с несущими 14 ГГц и 140 ГГц внутри помещений

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**Аннотация.** Для дальнейшего увеличения объемов и скорости передачи данных необходимо освоение субтерагерцового диапазона, требующего использования высоконаправленных каналов связи из-за значительных потерь на распространение. Ключевым сценарием становятся помещения, где на устойчивость связи влияет блокировка каналов прямой видимости, а распространение сигнала характеризуется ближнепольными эффектами, отличающимися от микроволнового диапазона. В этой статье мы проводим сравнительное исследование блокировок в ближнем поле в беспроводных каналах внутри помещений на частоте 14 ГГц и 140 ГГц. Изучаются различные траектории блокирующего пользователя, параметризуется аналитическая дифракционная модель, описывающая динамику процесса блокировки сигнала. Полученные результаты позволяют уточнить существующие кластерные модели субтерагерцовых каналов и определить доступный временной бюджет для систем связи с упреждающим методом предотвращения блокировки в реальном времени.

**Ключевые слова:** субтерагерц, сеть 6G, развертывание внутри помещений, блокировка канала, дифракция в ближнем поле, временной ряд сигнала, ослабление сигнала

**Финансирование:** Исследование осуществлено в рамках Программы фундаментальных исследований НИУ ВШЭ.

**Ссылка при цитировании:** Ершова М.И., Львов А.В., Шерстов В.А., Приходько А.Н., Гольцман Г.Н., Шураков А.С. Сравнительное исследование ближнепольных блокировок в беспроводных каналах с несущими 14 ГГц и 140 ГГц внутри помещений // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2025. Т. 18. № 3.2. С. 310–314. DOI: <https://doi.org/10.18721/JPM.183.262>

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### Introduction

At the moment the development of wireless communications is widely conducted and oriented to raising data rate and connection reliability. Increasing throughput is a cornerstone of next-generation wireless networks. Transition to subterahertz (sub-THz) frequencies poses significant challenges, primarily due to huge atmospheric propagation losses and an essential reduction in transceiver output power, which require the use of ultra-directional transceiver systems. In the pursuit of ensuring a stable wireless connection, it is imperative to implement mechanisms that can proactively detect obstructions that arise when the line-of-sight (LoS) is impeded by the human body. Information about the characteristic signal oscillations that occur immediately before blockage and are associated with the diffraction phenomenon near the object can be used for proactive detection methods [1]. In accordance with the standard approaches to modeling



communication channels at the system level, deterministic ray tracing methods are selected, supplemented by emulation of certain stochastic components. Based on them, diffraction models are presented that describe the effect of the human body on the transmission channel when it is blocked [2, 3]. This paper provides an addition to existing models using the classical description of diffraction at the edge of a half-plane using Fresnel integrals [4].

### Experiment Methodology

In order to assess the received signal level during the dynamic blockage, two experimental setups were employed, operating at carrier frequencies of 14 GHz and 140 GHz. The setups are similar to those detailed by us in [5]. The difference is that the 14 GHz setup does not have final frequency multiplication stage as compared to the 140 GHz setup. The antennas terminating transmitters (Tx) and receivers (Rx) are physically different but have similar beamwidths of 8–10°. The trajectories of the blocking user under study are a straight line and a circle (both are 1.8 m long), while the height and the length of the Tx-Rx LoS are 1.5 m and 1.1 m, respectively. The blocking user intersects the LoS at the midpoint with an average speed of  $u_x = 0.63$  m/s.

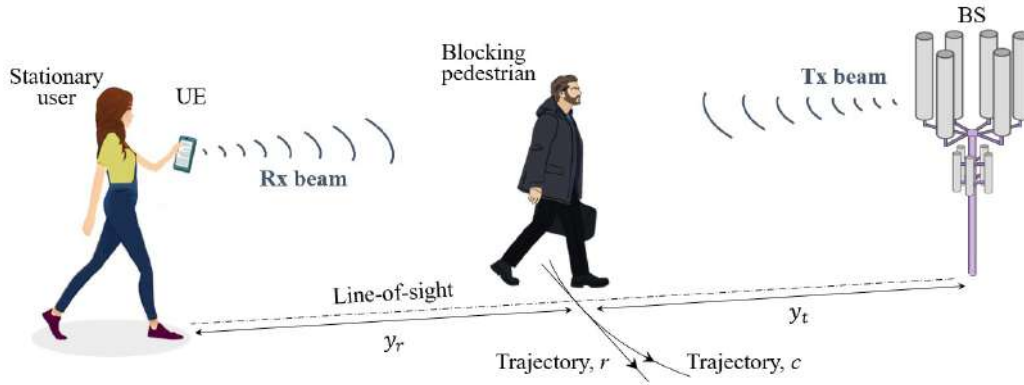


Fig. 1. Geometries of the experiments

Geometry of the experiments is detailed in Fig. 1. And analytical geometry-dependent diffraction models of the dynamic blockage process are shown in Fig. 2, *a*, *b*. Illustrated knife-edge diffraction models are parameterized and compared against the Rx signals,  $P_{exp14}$  and  $P_{exp140}$ , obtained in the experiments at  $f = 14$  GHz, 140 GHz. Approximation curves,  $P_{fit,1}$ , are determined directly using Fresnel integrals (1)–(4) described below, treating the human body as an infinite vertical opaque strip 0.2 m wide,  $\Delta v$ , in a horizontal plane and the experiment geometry as measured, i.e., Tx/Rx coordinates relative to the LoS and user trajectory intersection point  $y_r = y_t = 0.55$  m (5):

$$C(v) = \int_0^v \cos(t^2) dt, \quad S(v) = \int_0^v \sin(t^2) dt, \quad (1)$$

$$I(v, \Delta v) = \frac{1}{2} \left\{ \left[ 1 - C\left(v + \frac{\Delta v}{2}\right) + C\left(v - \frac{\Delta v}{2}\right) \right]^2 + \left[ 1 - S\left(v + \frac{\Delta v}{2}\right) + S\left(v - \frac{\Delta v}{2}\right) \right]^2 \right\}, \quad (2)$$

$$v(t) = \frac{v_1 + v_2}{2}, \quad \Delta v(t) = v_1 - v_2, \quad (3)$$

where

$$v_m(t) = \sqrt{\frac{2f}{c} \left( \frac{1}{y_t} + \frac{1}{y_r} \right)} \left( \frac{u_x t y_t}{y_t + y_r} - \Delta x_m \right), \quad m = 1, 2, \quad (4)$$

$$P_{fit,m}(t) = 10 \lg I(v, \Delta v) - I_0 | y_t = y_r. \quad (5)$$



Here  $c$  is the speed of light. In contrast,  $P_{fit,2}$  are determined using the LoS lengths,  $y_r$  and  $y_p$ , and shift factor,  $I_0$ , as fitting coefficients. The fitting is successful in the initial phase of the blockage of interest with the LoS lengths of 0.2 m and 0.36 m for rectilinear ( $r$ ) and curvilinear ( $c$ ) trajectories, respectively.

## Results and discussion

An assessment of the time signatures in the signal dynamics is made, since for the development of next-generation stable wireless links it is important to determine the actually available time budget that allows avoiding connection loss when routing a radio signal under blockage conditions. In the experiments at 14 GHz, the pre-blocked state is not expressed, it lasts 400 ms and is followed by a slow signal drop by 1.5 dB. Even though, we observe a bit error rate of 8% in the quadrature amplitude modulation (QAM) scheme with 64 states. At 140 GHz, the signal attenuations are significantly higher and reach 13–17 dB. Fig. 2,  $c$ ,  $d$  provides statistics on the signal temporal metrics.

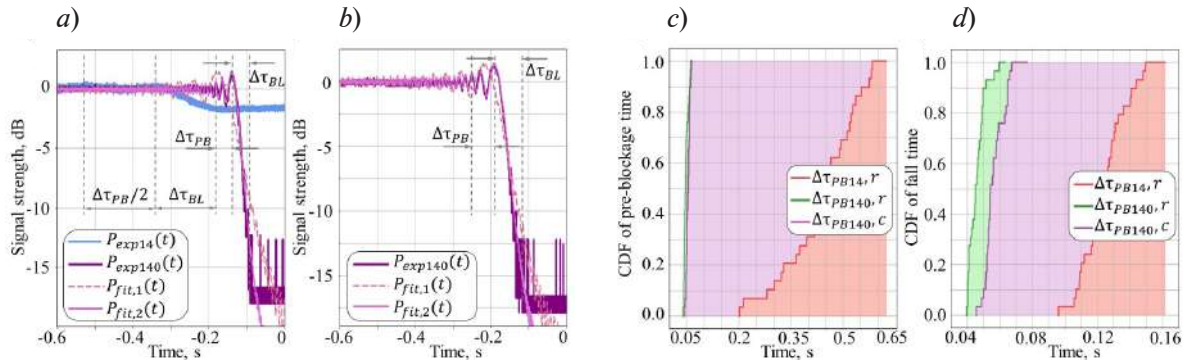


Fig. 2. Parameterized blockage model for rectilinear trajectory (a), curvilinear trajectory; cumulative distribution function (CDF) (b) for pre-blockage time (c), signal fall time (d)

Based on the results of a series of 60 independent measurements, it was found that the average time of the pre-blocked state,  $\Delta t_{PB}$ , is 51 and 54 ms for rectilinear and curvilinear trajectories, respectively, and the fall time,  $\Delta t_{BL}$ , is 52 and 57 ms, respectively. The parameterized analytical diffraction blockage model fits experimental data  $P_{exp140}$  well, providing a normalized root-mean-square error of only 2.6–4.4% for both studied trajectories. As an analytical model, it requires minimal computational resources while maintaining high accuracy, enabling integration into high-fidelity cluster models of sub-THz communication channels.

## Conclusion

This study presents a comparative analysis of near-field blockage effects in indoor wireless channels at 14 GHz and 140 GHz. Despite the modest 1.5 dB attenuation at 14 GHz causing an 8% bit error rate for 64 QAM, blockage at 140 GHz leads to severe signal degradation with 13–17 dB attenuation. To characterize the behavior of the near-field signal, a parameterized diffraction model based on Fresnel integrals was developed. At the same time, the analytical model agrees well with the experimental data, demonstrating a root-mean-square error of only 2.6–4.4%. Key time characteristics, such as the pre-blocked state time (51–54 ms) and the signal fall time (52–57 ms), were determined for different trajectories of the blocking user. These results enable accurate time budget estimation for proactive blockage detection in next-generation communication systems. The obtained results can be integrated into cluster models of subterahertz channels, which helps to enhance the design procedure and performance analysis of stable wireless networks with directive data links.

## REFERENCES

1. **Khakimov A., et al.**, A New Blockage Detection Approach for 6G THz Systems. International Conference on Next Generation Wired/Wireless Networking, Cham: Springer Nature Switzerland. (2023) 181–193.
2. **Mukherjee S., et al.**, Scalable modeling of human blockage at millimeter-wave: A comparative analysis of knife-edge diffraction, the uniform theory of diffraction, and physical optics against 60 GHz channel measurements, IEEE Access. 10 (2022) 133643–133654.
3. **Tataria H., et al.**, Standardization of propagation models for terrestrial cellular systems: A historical perspective, International Journal of Wireless Information Networks. 28 (2021) 20–44.
4. **Hecht E.**, Optics, Pearson Education India. (2012).
5. **Shurakov A., et al.**, Empirical blockage characterization and detection in indoor sub-THz communications, Computer Communications. 48 (2023) 201–58.

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## Low-loss reflective X-band phase shifter with wide phase control range

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**Abstract.** Nowadays, one of the important tasks driven by the actual society needs is the development of effective technical solutions in the field of reflective surfaces and antenna arrays for modern microwave wireless networks. They are necessary to enhance network coverage and communication stability on the way of the operating frequency increase. Their use is beneficial in highly directive wide-band radio channels vulnerable to blockage and micromobility effects. In this work, we propose a low-loss reflective X-band phase shifter with wide phase control range which can be effectively used as a part of field-programmable reflectarray for radio signal routing. Our study focuses on the influence of the errors in geometrical parameters arising during the fabrication process on the radiophysical properties of the phase shifter based on a log-periodic antenna integrated with diode. For such a design, we demonstrate geometry-defined reflection losses of less than 1 dB, and the corresponding phase control range approaching 330° with a tolerable absolute geometry deviation of up to 90 μm.

**Keywords:** microwave devices, reflective antenna, reflection coefficient, varactor diode

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## Отражательный фазовращатель X-диапазона с низкими потерями и широким диапазоном регулировки фазы

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**Аннотация.** Совершенствование отражающих поверхностей и антенных решеток для беспроводных СВЧ систем представляет собой важную научно-техническую задачу. Ее решение должно позволить расширить зону покрытия, повысить стабильность связи и обеспечить эффективную работу в условиях роста рабочих частот. Особую актуальность приобретают решения для высоконаправленных широкополосных радиоканалов, где существенное влияние оказывают эффекты блокировки сигнала и микромобильности.

В данной работе представлена конструкция фазовращателя X-диапазона с широким диапазоном регулировки фазы и низкими потерями на отражение на основе логопериодической антенны, интегрированной с диодом. Основное внимание уделено исследованию влияния погрешностей изготовления геометрических параметров на радиофизические характеристики фазовращателя. Продemonстрировано, что предложенная геометрия антенны обеспечивает потери на отражение не более 1 дБ при диапазоне регулировки фазы до 330°. При этом допустимое отклонение геометрических параметров, не приводящее к заметному ухудшения характеристик, достигает 90 мкм.

**Ключевые слова:** СВЧ устройства, отражательная антенна, коэффициент отражения, варакторный диод

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### Introduction

The development of radio access networks, in accordance with consumer demand for increased network capacity, poses urgent tasks for the scientific and technical community to develop fundamental and technical solutions in the field of antenna-feeder devices. An important part of this class of devices, which is of direct interest for use in microwave networks, are reflective antennas based on the theory of phased array antennas, i.e. with the ability to reflect an incident electromagnetic wave at a given angle, as well as with the ability to control the direction of reflection [1]. The basic unit of such antennas is a unit cell [2], in which the phase shift control allows you to control the direction of the reflected beam [3].

Numerical modeling and analytical calculations of antenna devices are undoubtedly an important design stage, however, in any case, the model represents an ideal structure without taking into account the errors that inevitably arise during manufacturing [4]. This work highlights issues related to the control of geometric parameters of antenna devices, the effect of deviation of these parameters from the nominal value on the radio frequency (RF) characteristics of the final manufactured devices both individually and as part of the antenna array. We develop our earlier reported ideas [5] and implement a low-loss reflective X-band phase shifter with wide phase control range. The details are provided below.

### Design and fabrication

The initial phase of antenna array development involved numerical modeling of unit cells using the finite element method (FEM) in an electromagnetic (EM) simulation environment. Each cell is designed as a 7.5×7.5×1.524 mm parallelepiped comprising back-metallized FSD888T substrate ( $\epsilon_r = 3.55$ ) carrying a log-periodic planar spiral antenna structure as shown in Fig. 1, *a*. The spiral outer and inner arc radii  $R_i$  and  $r_i$  are defined by Eq. (1), with initial radius  $R_0 = 0.285$  mm and growth rate  $\tau = 0.7$ .

$$R_{i+1} = R_i \tau, r_i = R_i \sqrt{\tau}. \quad (1)$$

A diode was incorporated between the spiral arms to enable phase control by externally applied voltage. A simplified diode model was used for the initial performance evaluation. During simulation, the diode capacitance,  $C_{var}$ , was varied to analyze its effect on the phase shift of the reflected wave at 10 GHz. Using Floquet port analysis, the following characteristics were obtained for s-polarization: complex reflection coefficient's magnitude,  $\Gamma = \text{mag}(S_{11})$ , and phase,  $\varphi = \text{arg}(S_{11})$ . The results are given in Fig. 1, *b*.



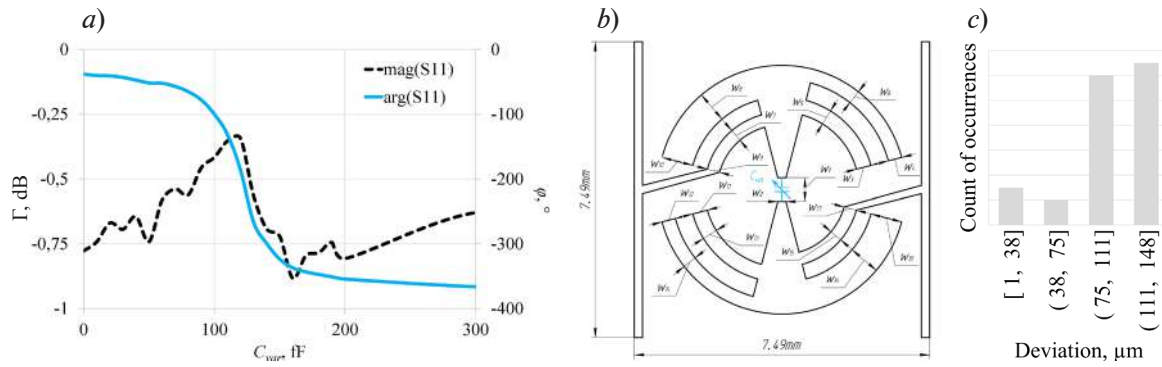


Fig. 1. Dependence of the magnitude and phase of the complex reflection coefficient on the spiral load capacitance (a). Unit cell design and deviations measurements (b). Histogram of the measured deviations of critical dimensions from their nominals (c)

Referring to Fig. 1, a, the proposed design exhibits geometry-defined reflection losses of below 1 dB with the corresponding phase control range of up to 330°. The dissipative losses in the cell are not considered at the current simulation stage.

Based on the EM model, technical drawings were generated for sample production. The samples were fabricated using direct mechanical structuring on a MITS Eleven Lab computer-driven milling machine. After the fabrication, critical dimensions  $\Delta w_i$  and  $\Delta r_i$  were measured using a Nikon SMZ745T optical microscope, equipped with an image processing system, at multiple positions as illustrated in Fig. 1, b. A statistical analysis of size deviations from nominal values was performed, revealing the absolute geometry deviation equal to 100  $\mu\text{m}$  (Fig. 1, c). Fabricated sample cell was further equipped with a BAT2402LS Schottky diode by Infineon [6] and bias lines wiring as shown in Fig. 2, a. Conductive paste and solder were used to integrate the parts.

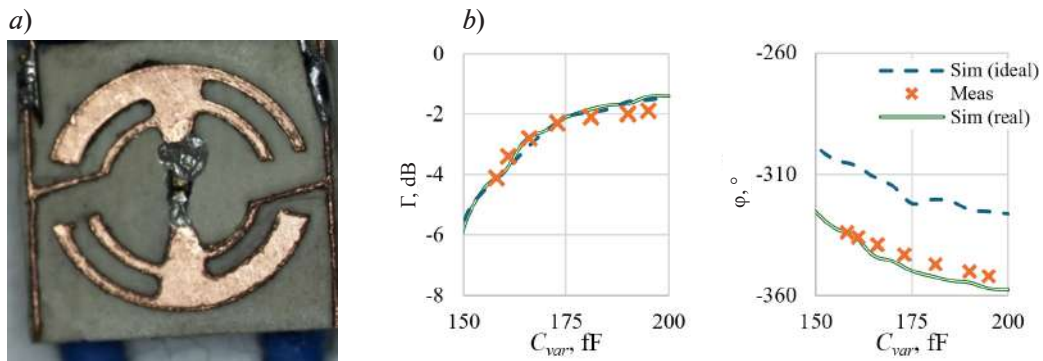


Fig. 2. Fabricated sample cell (a). Measured (Meas) magnitude and phase of the complex reflection coefficient compared with the model predictions without (Sim (ideal)) and with size deviations (Sim (real)) due to fabrication errors (b)

Following geometric inspection, we characterized radiofrequency (RF) response of the manufactured cells by measuring the magnitude and phase of the complex reflection coefficient. The measurements were performed using a Planar C4220 vector network analyzer (VNA) in single-port mode. Sample cell was installed in a holder, made using 3D-printer, ensuring precise alignment parallel to the waveguide port with a controlled gap of 1–1.5 mm. The holder was mounted at the output of a coaxial-to-waveguide junction (JCW) with a 10×23 mm waveguide cross-section, operating in the 8–12 GHz frequency range. The VNA was set to an output power of 0 dBm, and measurements were conducted across the JCW's operational bandwidth. The measurement results are presented in Fig. 2, b for a frequency of 10 GHz.

## Results and discussion

To ensure measurement accuracy, we performed full single-port calibration (SOL: Short-Open-Load) of the VNA, applied an electrical delay of 250 ps (corresponding to the 75 mm waveguide length) to compensate for port connector misalignment and eliminate phase deviations caused by waveguide propagation of the probing 10 GHz signal.

We compare experimental results with an advanced model incorporating the diode imperfections (series resistance of 8 Ohm, capacitance tuning range of 40 fF) and the finite copper conductivity ( $5.8 \times 10^7$  S/m). As shown in Fig. 2, *b*, the good agreement between measurements and EM simulations is achieved. We also observe additional losses of 1.5–6 dB as compared with a simplified simulation shown in Fig. 1, *b*. This is due to the dissipative losses, the impact of the bias line termination, and the spill-over loss between the sample and the JCW. But one should keep in mind that the use of a varactor diode with wider capacitance tuning range (e.g., from 25 to 250 fF ensured by MACOM's MAVR-011020-1411) enables a phase control range of up to 330°.

## Conclusion

We developed ideal and real models of a phase shifter that account for manufacturing geometry deviations. The modeled device provides a phase control range of up to 330° with an insertion loss of 1.5 to 6 dB. To validate the models, an experimental prototype was fabricated, its geometrical parameters were measured, and based on this data, simulation was performed in an RF CAE system. We observe that the mean size deviations equal 100 μm in both the antenna arcs' length and width have minimal impact on the magnitude and phase profiles of the reflected probing 10 GHz signal. Numerical analysis indicates that using a diode with 3 Ohm series resistance could significantly reduce reflection losses. The developed antenna geometry is robust and suitable for direct mechanical fabrication, making these findings valuable for low-cost X-band antenna development.

## REFERENCES

1. Dai L., Wang B., Wang M., et al., Reconfigurable intelligent surface-based wireless communications: Antenna design, prototyping, and experimental results, IEEE access. 8 (2020) 45913–45923.
2. Montori S., Chiappesi E., Marcaccioli L., et al., 1-bit RF-MEMS-reconfigurable elementary cell for very large reflectarray, In: Proceedings of IEEE 10th Mediterranean Microwave Symposium, Guzelyurt, Northern Cyprus. (2010) 98–101.
3. Hansen R.C., Phased array antennas, John Wiley & Sons, New Jersey. (2009).
4. Yakimov A.N., Modeling of the influence of production errors on the radiation of microwave antennas, Reliability and quality of complex systems. 3 (2023) 74–82.
5. Shurakov A., Razakova A., Lvov A., et al., Compact Log-Periodic Single-Port Planar Antennas for D-band Monolithic RIS Panels, IEEE Antennas and Wireless Propagation Letters. 24 (1) (2025) 88–92.
6. Infineon. BAT24-02LS RF Schottky diode. URL: [https://www.infineon.com/dgdl/Infineon-BAT24-02LS-DS-v02\\_00-EN.pdf](https://www.infineon.com/dgdl/Infineon-BAT24-02LS-DS-v02_00-EN.pdf) Accessed: Mar, 27, 2025

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## УСЛОВИЯ ПУБЛИКАЦИИ СТАТЕЙ

в журнале «Научно-технические ведомости  
Санкт-Петербургского государственного политехнического университета.  
Физико-математические науки»

### 1. ОБЩИЕ ПОЛОЖЕНИЯ

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С 2008 года журнал издавался в составе сериального издания "Научно-технические ведомости СПбГПУ". **Сохраняя преемственность и продолжая научные и публикационные традиции сериального издания «Научно-технические ведомости СПбГПУ», журнал издавали под двойными международными стандартными сериальными номерами ISSN 1994-2354 (сериальный) 2304-9782.** В 2012 году он зарегистрирован как самостоятельное периодическое издание **ISSN 2304-9782** (Свидетельство о регистрации ПИ № ФС77-52144 от 11 декабря 2012 г.). С 2012 г. начат выпуск журнала в двуязычном оформлении.

Издание входит в Перечень ведущих научных рецензируемых журналов и изданий (перечень ВАК) и принимает для печати материалы научных исследований, а также статьи для опубликования основных результатов диссертаций на соискание ученой степени доктора наук и кандидата наук по следующим основным научным направлениям: **Физика, Математика, Механика**, включая следующие шифры научных специальностей: 1.1.8., 1.1.9., 1.3.2., 1.3.3., 1.3.4., 1.3.5., 1.3.6., 1.3.7., 1.3.8., 1.3.11., 1.3.19.

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