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# INFLUENCE OF STIMULATED INTERBAND EMISSION ON TERAHERTZ PHOTOLUMINESCENCE IN *n*-TYPE GALLIUM ARSENIDE LAYERS

*N. Yu. Kharin*[1]✉, *V. Yu. Panevin*[1], *P. A. Petruk*[2], *M. Ya. Vinnichenko*[1],
*N. I. Norvatov*[1], *F. V. Fedorov*[3], *D. A. Firsov*[1]

[1] Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russia;

[2] State University of New York at Stony Brook, Stony Brook, USA;

[3] Alferov University of RAS, St. Petersburg, Russia

✉ kharin.nikita66@gmail.com

**Abstract.** In the paper, a possibility of increasing the terahertz (THz) radiation intensity under optical interband pumping in the epitaxial GaAs layer doped with shallow donors has been studied. An increase in the intensity of THz radiation was achieved by implementation of conditions for stimulated interband radiation in the near-IR range, which depopulated intensively the donor ground state. The photoluminescence spectra of the samples were measured by Fourier spectrometer. Photoluminescence spectra were recorded in the near-IR and THz ranges in the sub- and post-threshold working conditions of radiation generation in the near-IR range. In the THz spectra, a change in behavior of the dependence of the radiation intensity on pumping was observed. The change was due to a decrease in the radiative lifetime of electrons at the impurity level.

**Keywords:** photoluminescence, terahertz radiation, impurity transition, epitaxial layer, bulk semiconductor, stimulated emission

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# ВЛИЯНИЕ СТИМУЛИРОВАННОГО МЕЖЗОННОГО ИЗЛУЧЕНИЯ НА ТЕРАГЕРЦОВУЮ ФОТОЛЮМИНЕСЦЕНЦИЮ В СЛОЯХ АРСЕНИДА ГАЛЛИЯ *n*-ТИПА

*Н. Ю. Харин*[1]✉, *В. Ю. Паневин*[1], *А. Д. Петрук*[2], *М. Я. Винниченко*[1],
*И. А. Норватов*[1], *В. В. Федоров*[3], *Д. А. Фирсов*[1]

[1] Санкт-Петербургский политехнический университет Петра Великого, Санкт-Петербург, Россия;

[2] Университет штата Нью-Йорк в Стоуни Брук, г. Стоуни Брук, США;

[3] Академический университет им. Ж.И. Алфёрова РАН, Санкт-Петербург, Россия

✉ kharin.nikita66@gmail.com

**Аннотация.** В работе исследована возможность увеличения интенсивности терагерцового (ТГц) излучения при оптической межзонной накачке в эпитаксиальном слое GaAs, легированном мелкими донорами, за счет реализации условий для стимулированного межзонного излучения ближнего инфракрасного (ИК) диапазона, интенсивно опустошающего основное состояние донора. Получены спектры фотолюминесценции в ближнем ИК и ТГц диапазонах в до- и постпороговом режимах генерации излучения ближнего ИК диапазона. В ТГц спектрах наблюдается изменение характера зависимости интенсивности излучения от накачки, связанное с уменьшением излучательного времени жизни электронов на примесном уровне.

**Ключевые слова:** фотолюминесценция, терагерцовое излучение, примесный переход, эпитаксиальный слой, объемный полупроводник, стимулированное излучение

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## Introduction

Fabrication of optoelectronic devices operating in the terahertz (THz) range is the subject of much attention from researchers. This is because THz radiation has a wide scope of application. The absorption spectra of various organic substances have distinct characteristics in the THz range [1], allowing to monitor the state of the aatmosphere, analyze gases, and detect the objects concealed by packaging. This radiation can be used in security systems, biology, medicine [2]. Observation of spectral lines in the THz spectral range using heterodyne techniques for studying the radiation of the Universe can provide new insights into the composition and origin of the Solar System [3].

A quantum cascade laser is a sophisticated, compact and sufficiently powerful semiconductor source of THz radiation [4–6], but it is rather complex and costly to produce, which limits its potential applications. For this reason, a major challenge in fundamental research lies in developing novel physical principles for generation of THz radiation in semiconductors.

A promising approach to developing semiconductor sources of THz radiation consists in using impurity-assisted optical transitions of charge carriers, since the binding energy of shallow impurities in semiconductors lies in the THz range. THz radiation sources with interband

Издатель: Санкт-Петербургский политехнический университет Петра Великого.

optical pumping at impurity transitions of charge carriers in doped bulk semiconductors were first described for *n*-GaAs and *p*-Ge [7], as well as *n*-GaN [8]. As for donor semiconductors, the THz radiation studied in [8] was associated with the transitions of nonequilibrium electrons from the conduction band and excited donor states to the ground state of the donor during interband optical pumping. The depopulation of the donor ground state, which is finite for THz electron transitions, occurred due to interband radiative electron-hole recombination occurring spontaneously between the donor ground state and the valence band. THz radiation of this nature has also been detected and investigated in structures with GaAs/AlGaAs quantum wells [9].

The intensity of THz radiation in the described generation mechanism is determined by the depopulation rate of the final state for THz electron transitions.

Thus, an increase in the depopulation rate of the impurity ground state should lead to an increase in the intensity of THz radiation. Intense depopulation of the impurity ground state can be induced using stimulated interband emission in the near-infrared (IR) range at transitions from the donor ground state to the valence band. The conditions for generating such stimulated emission should be achieved in the structure we consider.

Using such a mechanism of efficient depopulation of the final state for optical transitions has been discussed earlier to increase the intensity of impurity THz photoluminescence in laser nanostructures with doped GaAs/AlGaAs quantum wells [10, 11], as well as in diode structures with vertically coupled InGaAs/AlGaAs quantum dots [12], where stimulated interband emission between the ground-state levels electrons and holes in quantum dots were used to increase the intensity of mid-IR emission associated with intraband transitions of charge carriers between the levels in quantum dots.

This paper investigates the effect of stimulated emission in the near-IR range on the characteristics of THz radiation arising from impurity transitions of nonequilibrium electrons in epitaxial layers *of n*-GaAs under interband optical pumping.

## Methods and materials

The study focuses on a structure with an epitaxial gallium arsenide (GaAs) layer doped with silicon donors.

The sample was obtained by molecular beam epitaxy on a semi-insulating GaAs substrate, with the concentration of the doping silicon donor impurity was $1.0{\cdot}10^{16}$ cm$^{-3}$. The growth temperature was 620–630 °C, the Ga : As flux ratio was 1 : 3 during the growth of epitaxial layers. The epitaxial layer was located in a waveguide for near-IR emission produced by layers of an $Al_xGa_{1-x}As$ solid solution with a composition gradient $x$. The thickness of the epitaxial layer was 0.52 μm. A high-finesse resonator with total internal reflection was used to generate stimulated near-IR emission; the resonator was constructed from cleaved faces of a sample pre-polished to a thickness of about 100 μm.

Three types of samples were used in the experiments: with a total internal reflection resonator (size 0.4 × 0.4 mm), without a resonator (geometric size 5 × 5 mm) and a substrate with epitaxial layers removed.

The samples were soldered with indium to a copper plate, which was pressed against the copper cold finger of the Janis PTCM-4-7 closed-cycle optical cryostat, which allows smoothly varying the sample temperature in the range from 4 to 320 K.

A Horiba Jobin Yvon FHR 640 monochromator with a holographic diffraction grating of 1200 gr/mm was used to study the photoluminescence spectra in the near IR range. A CCD array was used as a radiation detector. Nonequilibrium charge carriers were excited by radiation from a semiconductor laser (frequency-doubled Nd:YAG in a nonlinear $LiIO_3$ crystal, radiation wavelength 532 nm).

Measurements of photoluminescence spectra at a low excitation level were carried out with a laser operating in continuous mode. A high-power pulsed laser with the same radiation wavelength was used to excite stimulated near-IR radiation. The pulse repetition rate was 8 kHz, pulse duration was 250 ns.

The same lasers were used to study photoluminescence in the THz range. The spectra were recorded using a Bruker Vertex 80v vacuum Fourier spectrometer operating in step-scan mode. The detector was a silicon bolometer cooled by liquid helium. A filter made of polyethylene coated with diamond powder was installed at the entrance of the bolometer, with transmission in the photon energy range from 6 to 100 MeV. The spectrometer used a PET beam splitter, the entrance window of the spectrometer was made of white polyethylene; it was additionally shielded with black polyethylene to prevent the pump radiation from entering the measuring system of the setup. The signal from the bolometer was extracted from the noise using the SR830 lock-in amplifier, then sent to a computer to process the interferogram and obtain the spectrum.

## Results and discussion

Fig. 1 shows the photoluminescence spectra of a structure with a resonator and a substrate in the near-IR range for different optical pumping intensities at $T = 4$ K. A continuous pumping mode was used, that is, the excitation level did not reach the threshold for the onset of stimulated near-IR emission in a structure with a resonator.

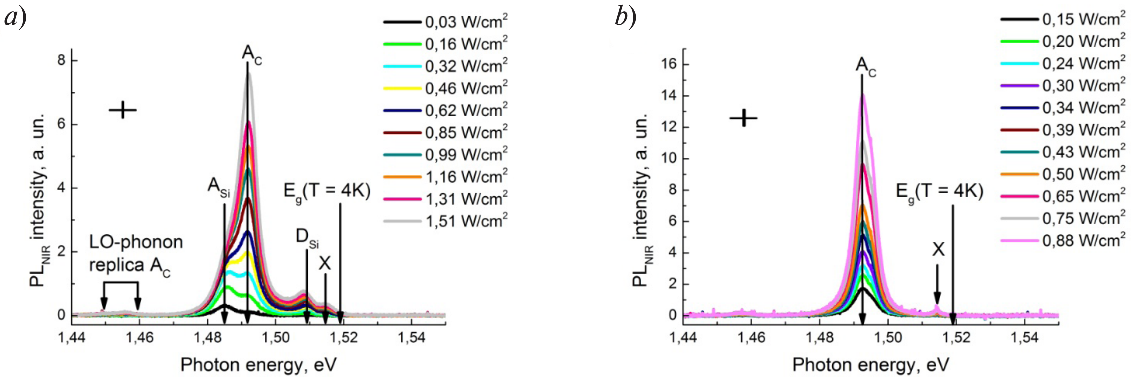

Fig. 1. Photoluminescence spectra in near-IR range at different optical pumping intensities for structure with resonator (*a*) and for substrate (*b*). Measurement temperature $T = 4$ K

Several features can be observed in the photoluminescence spectra of the epitaxial layer (see Fig. 1,*a*). Notice that optical transitions are not observed in the spectra of structures with a resonator and the spectra of the substrate at a photon energy equal to the GaAs band gap (1.519 eV for $T = 4$ K) due to low temperature and exciton excitation. The emission line at an energy of 1.514 eV, denoted as as $X$ in the spectra, corresponds to the energy of a free exciton in GaAs [13] and is clearly visible in all photoluminescence spectra. The peak at an energy of 1.509 eV, denoted as $D_{Si}$, is absent in the photoluminescence spectra of the substrate (see Fig. 1,*b*), so we can assume that this peak is associated with the epitaxial layer and corresponds to transitions involving a silicon donor. This interpretation is also supported by a significant broadening of the exciton line in the spectra of the epitaxial layer, compared with a similar line in the spectra of the substrate. The exciton line in the photoluminescence spectra of the epitaxial layer is significantly widened due to the relatively high level of ionized impurities present [14].

The spectral distance between the $D_{Si}$ peak and the GaAs band gap is about 10 MeV, which is consistent with the spectrum of THz radiation we observed (see below). The emission peak at an energy of 1.493 eV, denoted as $A_C$, is apparently associated with an uncontrolled carbon acceptor impurity that appears during the growth of GaAscontaining semiconductor structures and substrates [15].

The emission line at an energy of 1.485 eV, denoted as $A_{Si}$, is likely associated with the inclusion of an amphoteric silicon impurity in our structure as an acceptor. The binding energy of the silicon acceptor impurity in our structure found from the photoluminescence spectra is equal to 35 MeV, which is consistent with the literature data [16]. This line is absent in the spectra of the substrate (see Fig. 1,*b*), which is further evidence for the origin of this spectral characteristic: it is associated with doping. Notably, this line merges with a high-intensity carbon peak with an increase in the pumping level, and is practically indistinguishable in the spectra under intense excitation. This is probably related to the low concentration of silicon acceptors in our structure. Barely discernible features in the spectra in the range from 1.450 to 1.460 eV can be classified as phonon replicas associated with carbon acceptors in our structure [17].

Fig. 2,*a* shows data on photoluminescence in the near-IR range obtained at high levels of pulsed optical pumping. When a certain threshold pumping intensity is reached, the $D_{Si}$ emission line associated with the silicon donor impurity in our structure begins to prevail in intensity over the other emission lines.

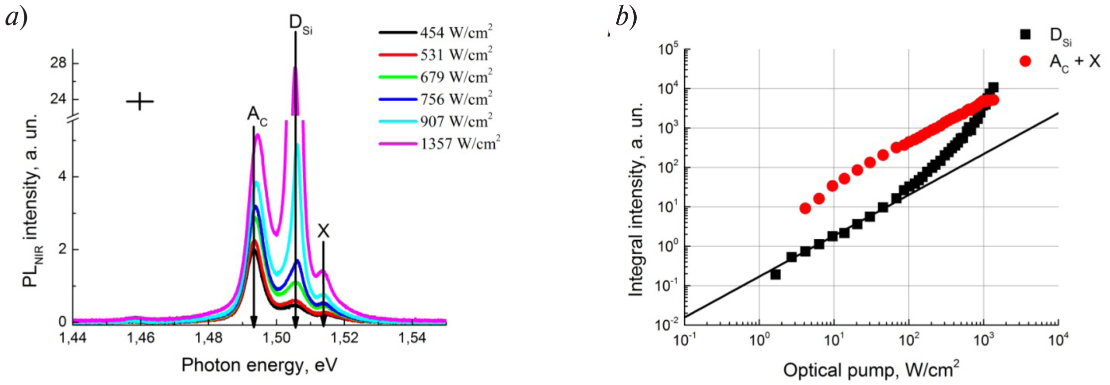

Fig. 2. Photoluminescence spectra in the near-IR range at different optical pumping powers for structure with resonator (*a*), as well as their processing: dependences of integral intensity of individual peaks on optical pumping intensity (*b*)
Measurement temperature *T* = 4 K

We approximated an experimental spectrum with three singularities (see Fig. 2,*a*) by three Lorentz profile. The areas of the individual profiles corresponded to the integral emission intensity of each peak. Thus, we obtained the dependences of the integral photoluminescence signal in the near IR range for individual peaks on the pumping intensity (shown in Fig. 2,*b*). The threshold nature of the dependence for the $D_{Si}$ emission line associated with silicon donors in our structure indicates the onset of stimulated emission. The threshold intensity of optical excitation, determined from the obtained dependence, is about 100 W/cm².

Fig. 3 shows the THz photoluminescence spectra for samples with and without a resonator. A wide emission line is observed in the spectra obtained for a sample with an epitaxial layer but without a resonator (see Fig. 3,*a*) in the photon energy range from 15 to 30 MeV. We observe the same emission line in the substrate spectrum (black curve in Fig. 3,*a*). Thus, this line can be associated with intracenter transitions between the states of the carbon acceptor impurity or with transitions from the main acceptor state to the valence band. This line is present both in

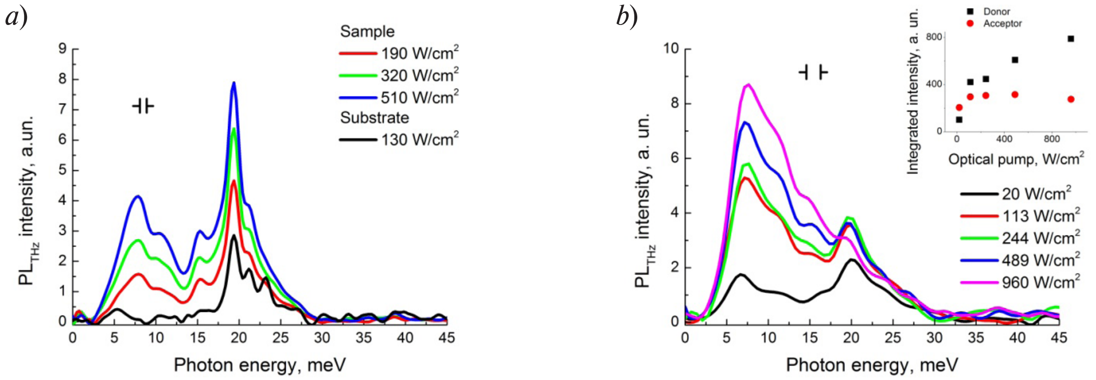

Fig. 3. Photoluminescence spectra in the THz range for substrate (black curve) and for structure without resonator (colored curves) at different optical pumping intensities (*a*), spectra for structure with resonator also at different optical pumping intensities (b).
*Inset:* dependences of integral emission intensity of spectral bands associated with donors and acceptors on the pumping level
Measurement temperature *T* = 4 K

the emission spectra of epitaxial layers and in the substrate spectrum. The energy of these transitions is consistent with the literature data [16]. The emission band in the photon energy range of 5–13 MeV is not observed in the substrate spectrum and, therefore, this band may be associated with the presence of a silicon donor impurity in the epitaxial layers of gallium arsenide. As the optical pumping power increases, the intensity of the lines associated with both donors and acceptors increases monotonically.

The THz photoluminescence spectra of a sample with a resonator (see Fig. 3, *b*) show that the ignition of stimulated near-IR emission at pumping intensities exceeding 100 $W/cm^2$ leads to a change in the nature of the dependence of the THz photoluminescence intensity on the pump level. The spectra in Fig. 3,*b* can be approximated by two Lorentz profiles. The inset to Fig. 3,*b* shows the dependences of the integral intensity of radiation for these two bands on the intensity of optical pumping that we have obtained. Evidently, the intensity of the emission band in the photon energy range from 5 to 13 MeV associated with donors continues to grow after the stimulated emission threshold, while the band from 15 to 30 MeV associated with acceptors exhibits a behavior close to saturation.

Such dependences of emission intensity associated with transitions involving donor and acceptor states confirm the hypothesis about the influence of stimulated near-IR emission on the intensity of optical transitions in the THz spectral region. Stimulated near-IR emission in our experiments occurs with the participation of donor states. When the stimulated emission threshold is reached, the donor states begin to depopulate more intensively, since the radiative lifetime of electrons at the main donor level decreases. Electron transitions from the conduction band to the donor level accompanied by emission of THz photons are more intense and begin to prevail over THz radiation associated with acceptor impurities. After the start of stimulated emission in the near IR range, THz radiation associated with electron transitions from the acceptor ground-state level to the valence band experiences saturation. This can be explained by the stabilization of the concentration of holes in the valence band with an increase in the pump level after the start of stimulated emission in the near IR range.

## Conclusion

The study established that stimulated near-IR emission, occurring under interband optical pumping of an epitaxial *n*-GaAs layer placed in an optical waveguide and a total internal reflection resonator, significantly affects the intensity of optical transitions of electrons from the conduction band to impurity states, increasing the intensity of THz radiation associated with impurity transitions.

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## THE AUTHORS

**KHARIN Nikita Yu.**
*Peter the Great St. Petersburg Polytechnic University*
29 Politechnicheskaya St., St. Petersburg, 195251, Russia
kharin.nikita66@gmail.com
ORCID: 0000-0002-2220-881X

**PANEVIN Vadim Yu.**
*Peter the Great St. Petersburg Polytechnic University*
29 Politechnicheskaya St., St. Petersburg, 195251, Russia
pvyu@rphf.spbstu.ru
ORCID: 0000-0003-4424-1722

**PETRUK Anton A.**
*State University of New York at Stony Brook*
100 Nicolls Rd, Stony Brook, New York, 11794-2350, USA
ianton583@gmail.com
ORCID: 0000-0003-1824-9173

**VINNICHENKO Maxim Ya.**
*Peter the Great St. Petersburg Polytechnic University*
29 Politechnicheskaya St., St. Petersburg, 195251, Russia
mvin@spbstu.ru
ORCID: 0000-0002-6118-0098

**NORVATOV Ilya I.**
*Peter the Great St. Petersburg Polytechnic University*
29 Politechnicheskaya St., St. Petersburg, 195251, Russia
norv2@mail.ru
ORCID: 0000-0002-0048-7512

**FEDOROV Vladimir V.**
*Alferov University of RAS*
8/3 Khlopin St., St. Petersburg, 194021, Russia
burunduk.uk@gmail.com
ORCID: 0000-0001-5547-9387

**FIRSOV Dmitry A.**
*Peter the Great St. Petersburg Polytechnic University*
29 Politechnicheskaya St., St. Petersburg, 195251, Russia
dmfir@rphf.spbstu.ru
ORCID: 0000-0003-3947-4994

## СВЕДЕНИЯ ОБ АВТОРАХ

**ХАРИН** Никита Юрьевич – *инженер Высшей инженерно-физической школы Санкт-Петербургского политехнического университета Петра Великого.*
195251, Россия, г. Санкт-Петербург, Политехническая ул., 29
kharin.nikita66@gmail.com
ORCID: 0000-0002-2220-881X

**ПАНЕВИН** Вадим Юрьевич – *старший преподаватель Высшей инженерно-физической школы Санкт-Петербургского политехнического университета Петра Великого.*
195251, Россия, г. Санкт-Петербург, Политехническая ул., 29
pvyu@rphf.spbstu.ru
ORCID: 0000-0003-4424-1722

**ПЕТРУК** Антон Дмитриевич – *PhD, студент Университета штата Нью-Йорк в Стоуни Брук.*
USA, 100 Nicolls Rd, Stony Brook, NY 11794-2350
ianton583@gmail.com
ORCID: 0000-0003-1824-9173

**ВИННИЧЕНКО** Максим Яковлевич – *кандидат физико-математических наук, доцент Высшей инженерно-физической школы Санкт-Петербургского политехнического университета Петра Великого.*
195251, Россия, г. Санкт-Петербург, Политехническая ул., 29
mvin@spbstu.ru
ORCID: 0000-0002-6118-0098

**НОРВАТОВ** Илья Алексеевич – *стажер-исследователь Высшей инженерно-физической школы Санкт-Петербургского политехнического университета Петра Великого.*
195251, Россия, г. Санкт-Петербург, Политехническая ул., 29
norv2@mail.ru
ORCID: 0000-0002-0048-7512

**ФЕДОРОВ** Владимир Викторович – *кандидат физико- математических наук, старший научный сотрудник лаборатории возобновляемых источников энергии Санкт-Петербургского академического университета РАН им. Ж. И. Алфёрова.*
194021, Россия, г. Санкт-Петербург, ул. Хлопина, 8, к. 3
burunduk.uk@gmail.com
ORCID: 0000-0001-5547-9387

**ФИРСОВ** Дмитрий Анатольевич – *доктор физико-математических наук, профессор Высшей инженерно-физической школы Санкт-Петербургского политехнического университета Петра Великого.*
195251, Россия, г. Санкт-Петербург, Политехническая ул., 29
dmfir@rphf.spbstu.ru
ORCID: 0000-0003-3947-4994

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