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Optical characterization and surface plasmon polariton mode simulation of GaN/InGaN nanowires on Ag/AlO$_x$ film for plasmonic nanolasers

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Abstract. Plasmonic nanolasers based on semiconductor nanowires are presently attracting wide interest due to the breaking in the light diffraction limit and the deep subwavelength mode operation. In this work, we synthesize and investigate the optical properties of GaN nanowires with InGaN quantum wells as the core element of plasmonic nanolasers. The results of modeling the electric field intensity distribution for propagating modes and dispersion curve of surface plasmon polaritons in the studied nanowires placed on the AlO$_x$-coated atomically flat Ag film confirm the formation of hybrid plasmonic modes and the viability of these structures for subwavelength light confinement and nanolaser applications.

Keywords: InGaN, GaN, nanowires, nanoplasmonics, nanolasers, molecular beam epitaxy, photoluminescence, numerical simulations

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Материалы конференции
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Оптические свойства и моделирование поверхностных плазмон поляритонов GaN/InGaN нитевидных нанокристаллов на пленках Ag/AlO_x для создания плазмонных нанолазеров

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Аннотация. Данная работа посвящена синтезу и исследованию оптических свойств гетероструктурных нитевидных нанокристаллов InGaN/GaN как потенциально ключевых элементов плазмонных нанолазеров. Представлены результаты моделирования распределения электрического поля и дисперсионных кривых поверхностных плазмон-поляритонов в исследуемых нитевидных нанокристаллах, размещенных на атомарно гладкой серебряной подложке с покрытием из оксида алюминия. Полученные результаты открывают возможность для создания экстремально малых по своим размерам источников когерентного излучения.

Ключевые слова: InGaN, GaN, нитевидные нанокристаллы, наноплазмоника, нанолазеры, молекулярно-пучковая эпитаксия, фотолюминесценция, численное моделирование

Финансирование: Эксперименты по синтезу нитевидных нанокристаллов проводились при финансовой поддержке Российского научного фонда (проект № 24-79-00104). Исследования структурных свойств полученных образцов были выполнены при поддержке Санкт-Петербургского государственного университета, шифр проекта 122040800254-4. А.А. Харченко благодарит Министерство науки и высшего образования РФ (проект FSRM-2023-0010) за поддержку оптических исследований. Численное моделирование гибридных наноструктур выполнено при поддержке Министерство науки и высшего образования РФ (Государственное задание № 0791-2023-0004).

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Introduction

Semiconductor nanowires (NWs) are promising structures for creating micro- and nanolasers due to their inherent high crystal quality and large aspect ratio. However, the size of semiconductor lasers is limited by the diffraction limit, which obstruct them to use in many optoelectronic applications. A promising route to overcome this limitation is the integration of NWs with a metal-dielectric system. Such hybrid structures enable the realization of plasmonic nanolasers operating at the deep subwavelength scale [1]. Among them, NWs based on ternary InGaN compounds occupy a special niche, capable of emitting in the entire visible range and having a gain of about 10^4 cm^{-1} [2].

In this work, we synthesize and study the optical properties of GaN NWs with embedded InGaN quantum wells (QWs) which demonstrated room temperature photoluminescence at 545 nm. Numerical simulations were conducted to analyze the dispersion curve and propagation modes of surface plasmon polaritons (SPPs) in the NW/AlO_x/Ag heterostructure. The results demonstrate that these NWs placed on an AlO_x-coated ultra-smooth Ag film are well-suited for nanolaser fabrication.

Materials and Methods

The GaN NWs with InGaN QWs were grown directly on p-type Si(111) substrates using Riber Compact 12 molecular beam epitaxy setup, equipped with Ga, In, Al effusion cells, and a nitrogen plasma source. Prior to growth, the substrates were heated up to a temperature of 920 °C and annealed for 20 min to remove the native oxide. The substrate temperature was then lowered to 600 °C, after which nitrogen plasma was activated and applied for 20 minutes to form a thin Si_xN_y layer. At the next stage, Al was deposited onto the formed layer in the absence of nitrogen. Next, the substrate temperature was increased to 865 °C, the nitrogen plasma was ignited, and the Ga source was opened to grow of GaN NWs. After the 17h of growth, the Ga source was closed, and the substrate temperature was decreased to 580 °C. Then the In, Ga, Al sources were opened and closed in the required order to form 15 periods of InGaN QWs/(Al,Ga)N barriers.

Photoluminescence (PL) was excited by a He-Cd laser operating at a wavelength of 325 nm. The diameter of the focused laser spot on the sample was 125 μm. The total optical power incident on the sample was amounted to 11.3 mW. Detection was performed using a single-channel silicon photodetector in combination with synchronous amplification. Measurements were carried out on an array of NWs, with the excitation area encompassing a large number of individual nanostructures. Therefore, the recorded PL spectra represent ensemble-averaged optical properties of the sample. The measurements were performed at room temperature. The structural properties of the samples were examined by scanning electron microscopy (SEM) on a Supra 25 microscope.

Modeling the dispersion curve of SPP for the Ag/AlO_x/InGaN was performed via finite elements method in COMSOL Multiphysics software. The hybrid system was simulated using a 2D layered model with the following sequence: a 300-nm-thick Ag layer, a 5-nm-thick AlO_x layer, an InGaN layer (thickness equal to the NW diameter), and a top air cladding. The in-plane length of the structure was 1 μm. The optical constants of InGaN and AlO_x were adopted from Refs. [3, 4]. Distribution of the electric field intensity in the Ag/AlO_x/NW cross section for the propagating SPP mode was calculated using the finite-difference method in the frequency domain using the Ansys Lumerical software.

Results and Discussion

Figure 1, *a* shows typical SEM images of the grown InGaN/GaN NW array. Measurements revealed an average NW diameter of 58 nm and a height of 1.3 μm. Structurally, 15 periods of axial InGaN QWs and (Al,Ga)N barriers were formed on the top of the NW (see Fig. 1, *b*).

Figure 1, *c* demonstrates room temperature PL spectrum of the NW array. The sample has a bright PL with two maxima corresponding to a short wavelength peak (361 nm) and a long wavelength peak (545 nm). We attribute the short wavelength peak of PL with bulk GaN area of NW and long wavelength peak with InGaN QWs, respectively.

For the fabrication of the InGaN NW-based plasmonic nanolaser, the NW should be transferred to a plasmonic substrate (see Fig. 2, *a*) featuring an atomically flat Ag surface coated with a

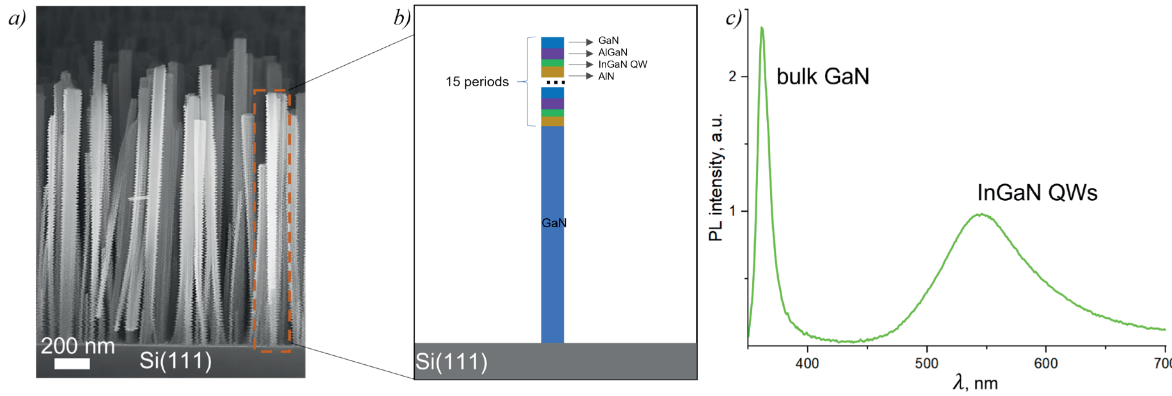

Fig. 1. Typical cross-section SEM image of synthesized NW array (*a*); schematic image of the single NW (*b*); room-temperature PL spectra of the NW array (*c*)

5 nm thick low-refractive-index layer (AlO_x or SiO_x) [2, 5]. Furthermore, strong exciton-plasmon interaction requires spectral overlap between the nanowire emission and the SPP dispersion in the semiconductor/dielectric/metal system [6]. To verify this, the modeling the dispersion curve of SPP were performed. A clear overlap was observed between the calculated Ag/AlO_x/InGaN SPP dispersion and the PL spectrum of the InGaN QWs in the energy range of 2.0–2.5 eV, indicating efficient energy transfer from the synthesized heterostructured NWs to surface plasmon modes (see Fig. 2, *b*).

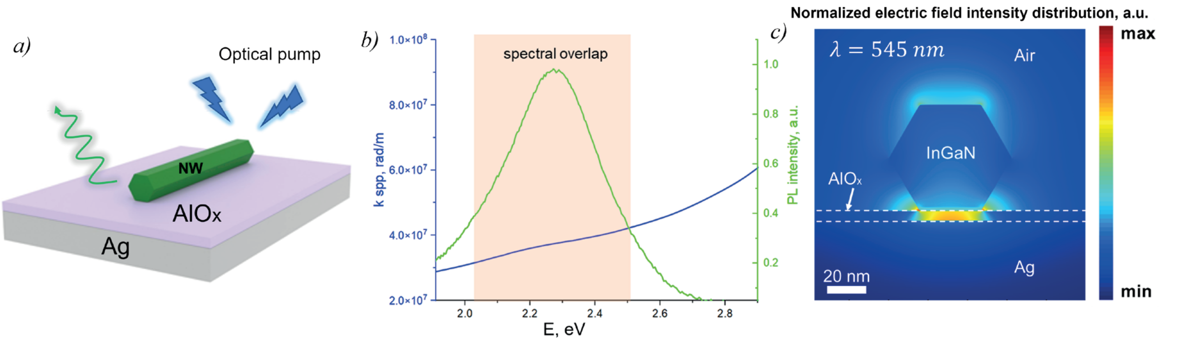

Fig. 2. Schematic illustration of the plasmonic nanolaser design (*a*); calculated dispersion relation of Ag/AlO_x/InGaN SPP and spectral overlap with InGaN QWs emission (*b*); distribution of the electric field intensity in the cross section view for the propagating SPP mode (*c*)

As a result, the excitation of the SPPs in such hybrid structures manifests itself the localization of the electric field in a thin dielectric layer [2, 7]. Figure 2, *c* shows the distribution of the electric field intensity in the cross section view for the propagating SPP mode. As expected, a significant part of the intensity is concentrated in the 5 nm thick AlO_x layer, which is unattainable in the case of a fully dielectric waveguide for the above PL of InGaN QWs.

Conclusion

In summary, we synthesized heterostructured GaN NWs with InGaN QWs by molecular beam epitaxy. The observed photoluminescence of these structures and the results of numerical simulation showed that these NWs can be used as an element of plasmonic nanolasers. Thus, the demonstrated capabilities may be of interest for the creation of components of photonic integrated circuits and other applications related to the localization of light on the nanometer scale.

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