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Optical properties of disk microresonators based on wide-bandgap III-N materials

S.D. Komarov [1] ✉, A.G. Vainilovich [2], G.A. Feigin [1], A.V. Sakharov [3], A.E. Nikolaev [3], K.A. Ivanov [1], E.I. Moiseev [1], N.V. Kryzhanovskaya [1], E.V. Nikitina [4], A.F. Tsatsulnikov [3], E.V. Lutsenko [2], A.E. Zhukov [1]

[1] National Research University Higher School of Economics, St. Petersburg branch, St. Petersburg, Russia;
[2] Institute of Physics of the NAS of Belarus, Minsk, Belarus;
[3] Ioffe Institute, St. Petersburg, Russia;
[4] Alferov University, St. Petersburg, Russia
✉ skomarov@hse.ru

Abstract. Fabrication, optical study, and mode modeling of III-N microdisk resonators with InGaN/GaN quantum wells on Al_2O_3 are presented. It is shown that the created epitaxial structures have high optical quality, and the microresonators support high-Q whispering gallery modes.

Keywords: III-N, WGM microresonators, InGaN/GaN quantum wells, microdisk lasers

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Материалы конференции
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Оптические свойства дисковых микрорезонаторов на основе широкозонных III-N материалов

С.Д. Комаров [1] ✉, А.Г. Войнилович [2], Г.А. Фейгин [1], А.В. Сахаров [3], А.Е. Николаев [3], К.А. Иванов [1], Э.И. Моисеев [1], Н.В. Крыжановская [1], Е.В. Никитина [4], А.Ф. Цацульников [3], Е.В. Луценко [2], А.Е. Жуков [1]

[1] Национальный исследовательский университет «Высшая школа экономики», Санкт-Петербургский филиал, Санкт-Петербург, Россия;
[2] Институт физики им. Б.И. Степанова НАН Беларуси, г. Минск, Беларусь;
[3] Физико-технический институт им. А.Ф. Иоффе РАН, Санкт-Петербург, Россия;
[4] Академический университет им. Ж.И. Алфёрова РАН, Санкт-Петербург, Россия
✉ skomarov@hse.ru

Аннотация. Проведено исследование оптических свойств и моделирование мод III-N микродисковых резонаторов с квантовыми ямами InGaN/GaN на подложке Al_2O_3. Показано, что созданные эпитаксиальные структуры обладают высоким оптическим качеством, а микрорезонаторы поддерживают высокодобротные моды шепчущей галереи.

Ключевые слова: III-N, МШГ, квантовые ямы InGaN/GaN, микродисковые лазеры

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Introduction

Microdisk lasers based on III-N semiconductor materials are promising candidates for use as compact and efficient radiation sources in optoelectronic and photonic integrated circuits due to a combination of their unique characteristics [1]. III-N materials feature a wide direct bandgap, high thermal stability of their characteristics, and significant chemical and mechanical durability, enabling the development of light-emitting devices operating across a broad wavelength range and capable of functioning in harsh environmental conditions [2–4]. Resonators of disk shape support the propagation of high-quality whispering gallery modes (WGMs), allowing lasers with such resonators to achieve ultralow lasing thresholds [5]. Moreover, these lasers have a small footprint, low power consumption, and offer high modulation frequencies [1]. In this study, the design and fabrication of epitaxial structures with InGaN/GaN quantum wells on an Al_2O_3 substrate were carried out. Microscale disk resonators were formed from these structures, and their optical properties were investigated using photoluminescence (PL) spectroscopy.

Materials and Methods

A heterostructure with an active region in the form of $In_{0.1}Ga_{0.9}N$/GaN quantum wells (QWs) was grown on an Al_2O_3 (0001) substrate using metalorganic vapour-phase epitaxy (MOVPE). The growth process started with a low-temperature GaN nucleation layer, followed by the deposition of a 3 μm thick GaN buffer layer ensuring full surface planarization. The active region was then formed, consisting of three 5 nm thick $In_{0.1}Ga_{0.9}N$ QWs separated by 100 nm thick GaN barriers. A 30 nm thick GaN capping layer was then grown as the final step. Disk microresonators with diameters ranging from 1 to 12 μm were fabricated via plasma chemical etching through a Ni mask. Figure 1 shows scanning electron microscopy (SEM) images of the formed microresonators. The spatial distribution of mode intensity in the fabricated disk resonators was simulated using the finite element method (FEM).

The photoluminescence study was performed under optical pumping in continuous wave excitation mode at room temperature using a He Cd laser (λ = 325 nm). Laser beam was focused on the sample surface into an 8 μm spot with a 5× UV objective. The PL signal was collected by the same objective and recorded using a SOL Instruments MS 5004i monochromator and a Sol Instruments HS 101H CCD camera.

Results and Discussion

The PL spectra obtained from different regions of the samples with grown epitaxial heterostructure exhibit negligible variation, which indicates a high degree of their homogeneity. These spectra

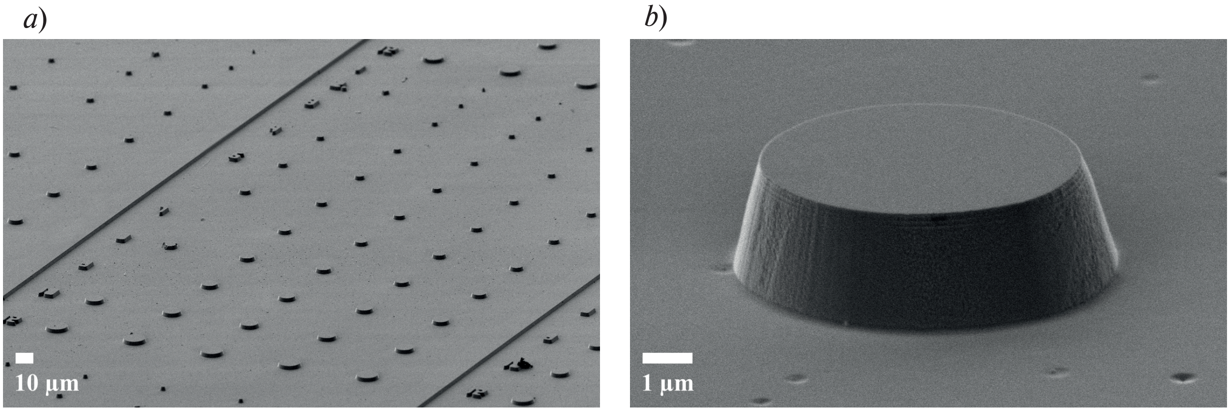

Fig. 1. SEM images of an array of formed disk resonators (*a*) and a single 6 µm diameter resonator (*b*)

feature two PL bands at wavelengths of 365 nm and 415 nm, corresponding to emission from GaN layers and $In_{0.1}Ga_{0.9}N$ quantum wells, respectively (Fig. 2, *a*). In the PL spectra of the microresonators, multiple intensity maxima are observed within the QW emission band, spaced by a few nanometers. Specifically, in the PL spectrum of the 6 µm-diameter resonator, shown in Fig. 2, *b,* these maxima are ~3 nm apart.

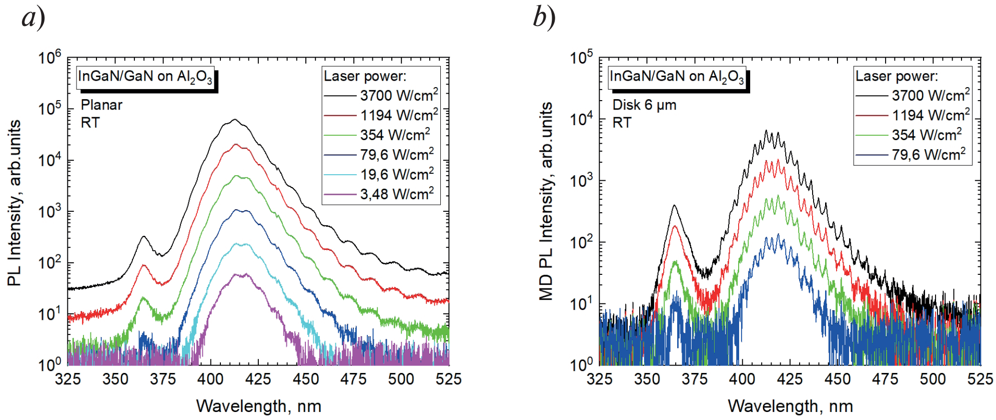

Fig. 2. PL spectra of the planar epitaxial heterostructure (*a*) and a single 6 µm diameter resonator (*b*)

For microdisks of all diameters, the distance between the maxima closely matches the WGM free spectral range, corresponding to the respective resonator sizes. The integrated PL intensity of the quantum wells exhibits a linear dependence on the optical pump power over a wide range for both planar heterostructures and fabricated disk microresonators of all diameters (Fig. 3, *a*).

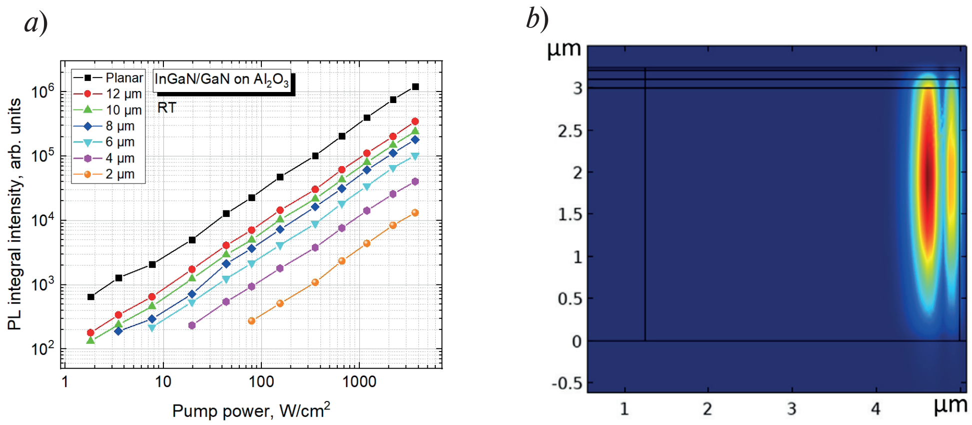

Fig. 3. Dependences of integrated PL intensity of the QWs on pump power (*a*) and a spatial distribution of WGM in 10 µm diameter resonator (*b*)

This indicates the predominance of the radiative recombination mechanism and, as a consequence, the high quality of the obtained structures [6]. However, laser emission was not achieved in the fabricated resonators. The calculated spatial distribution of WGM in the formed microresonators is presented on Fig. 3, *b*. The obtained modeling results indicate strong mode leakage into the buffer layer, with a calculated Γ factor of only 0.2%. This is attributed to insufficient optical confinement in the structure, which is likely the reason for the absence of lasing.

Conclusion

This study demonstrates that the fabricated heterostructure on Al_2O_3 substrate have high quality and uniformity, while the disk microresonators created from this structure support the propagation of high-quality whispering gallery modes. Additionally, spatial intensity distribution modeling of the modes in the investigated resonators was performed to further optimize the heterostructures for laser applications. The obtained results are an important step in the advancement of technologies for the development of nitride-based microdisk lasers. Subsequently, taking into account the significant leakage of modes into the buffer layer, the vertical confinement in the epitaxial structure will be improved by introducing additional buffer layers with a low refractive index. This change is expected to enable laser generation under optical pumping.

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THE AUTHORS

KOMAROV Sergey D.
skomarov@hse.ru
ORCID: 0000-0002-7025-3527

FEIGIN Grigorii A.
gafeygin@edu.hse.ru
ORCID: 0009-0007-9304-6401

NIKOLAEV Andrey E.
aen@mail.ioffe.ru
ORCID: 0000-0001-6522-4484

MOISEEV Eduard I.
emoiseev@hse.ru
ORCID: 0000-0003-3686-935X

NIKITINA Ekaterina V.
mail.nikitina@mail.ru
ORCID: 0000-0002-6800-9218

LUTSENKO Evgenii V.
e.lutsenko@ifanbel.bas-net.by
ORCID: 0000-0003-2333-7776

VAINILOVICH Aliaksei G.
a.vainilovich@ifanbel.bas-net.by
ORCID: 0009-0009-5699-2751

SAKHAROV Alexei V.
val.beam@mail.ioffe.ru
ORCID: 0000-0002-9976-999X

IVANOV Konstantin A.
kivanov@hse.ru
ORCID: 0000-0003-2165-1067

KRYZHANOVSKAYA Natalia V.
nkryzhanovskaya@hse.ru
ORCID: 0000-0002-4945-9803

TSATSULNIKOV Andrey F.
andrew@beam.ioffe.ru
ORCID: 0000-0002-5078-8946

ZHUKOV Alexey E.
zhukale@gmail.com
ORCID: 0000-0002-4579-0718

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