Conference materials
UDC 538.975
DOI: https://doi.org/10.18721/JPM.183.126

Growth of GaN nanowires with InN inserts by PA-MBE

V.O. Gridchin [1, 2, 3] ✉, A.M. Mintairov [4], T. Shugabaev [1, 2], V.Yu. Axenov [4], A.S. Vlasov [4], V.V. Lendyashova [1, 2], K.P. Kotlyar [1, 2, 3], I.A. Eliseev [4], A.I. Khrebtov [2], R.R. Reznik [2], V.Yu. Davydov [4], G.E. Cirlin [1, 2, 3]

[1] Alferov University, St. Petersburg, Russia;
[2] St. Petersburg State University, St. Petersburg, Russia;
[3] Institute for Analytical Instrumentation RAS, St. Petersburg, Russia;
[4] Ioffe Institute, St. Petersburg, Russia
✉ gridchinvo@gmail.com

Abstract. For the first time, the growth details and photoluminescence properties of ultra-thin InN insertions embedded in GaN nanowires are presented. The InN insertions embedded in GaN nanowires exhibit photoluminescence in the range of 2.9–3.35 eV, where the most intense emission line at 3.17–3.23 eV is tentatively attributed to monolayer-thick InN insert based on comparative spectral analysis. These findings can be promising for the development of single-photon sources and Wigner quantum dots operating from cryogenic to elevated temperatures.

Keywords: InN, GaN, MBE, quantum dots, nanowires

Funding: The growth experiments were carried out under the support of the Russian Science Foundation (project no. 23-79-00012). Optical measurements were carried out with the support of the State Assignment of the Russian Ministry of Science and Higher Education (No. FFUG-2024-0018). For structural property measurements the authors acknowledge St. Petersburg State University for a research project No. 129360164.

Citation: Gridchin V.O., Mintairov A.M., Shugabaev T., Axenov V.Yu., Vlasov A.S., Lendyashova V.V., Kotlyar K.P., Eliseev I.A., Khrebtov A.I., Reznik R.R., Davydov V.Yu., Cirlin G.E., Growth of GaN nanowires with InN inserts by PA-MBE, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 18 (3.1) (2025) 139–142. DOI: https://doi.org/10.18721/JPM.183.126

Материалы конференции
УДК 538.975
DOI: https://doi.org/10.18721/JPM.183.126

Рост нитевидных нанокристаллов GaN с вставками InN с помощью МПЭ-ПА

В.О. Гридчин [1, 2, 3] ✉, А.М. Минтаиров [4], Т. Шугабаев [1, 2], В.Ю. Аксенов [4], А.С. Власов [4], В.В. Лендяшова [1, 2], К.П. Котляр [1, 2, 3], И.А. Елисеев [4], А.И. Хребтов [2], Р.Р. Резник [2], В.Ю. Давыдов [4], Г.Э. Цырлин [1, 2, 3]

[1] Академический университет им. Ж.И. Алфёрова РАН, Санкт-Петербург, Россия;
[2] Санкт-Петербургский государственный университет, Санкт-Петербург, Россия;
[3] Институт аналитического приборостроения РАН, Санкт-Петербург, Россия;

[4] Физико-технический институт им. А.Ф. Иоффе РАН,
Санкт-Петербург, Россия
✉ gridchinvo@gmail.com

Аннотация. Представлены результаты по росту и фотолюминесцентным свойствам InN вставок в GaN нитевидных нанокристаллах. Установлено, что такие InN вставки демонстрируют фотолюминесценцию в диапазоне 2,9–3,35 эВ, при этом наиболее интенсивная линия излучения при 3,17–3,23 эВ связывается с излучением от монослойных InN вставок на основании сравнительного спектрального анализа. Полученные результаты могут представлять интерес для создания источников одиночных фотонов и вигнеровских квантовых точек, способных работать в диапазоне от гелиевых до более высоких температур.

Ключевые слова: InN, GaN, MBE, квантовые точки, нитевидные нанокристаллы

Финансирование: Ростовые эксперименты выполнены при поддержке Российского Научного Фонда (проект номер 23-79-00012). Оптические измерения выполнены при поддержке Государственного задания Министерства науки и высшего образования Российской Федерации (номер FFUG-2024-0018). Исследования структурных свойств выполнены при поддержке СПбГУ, шифр проекта 129360164.

Ссылка при цитировании: Гридчин В.О., Минтаиров А.М., Шугабаев Т., Аксенов В.Ю., Власов А.С., Лендяшова В.В., Котляр К.П., Елисеев И.А., Хребтов А.И., Резник Р.Р., Давыдов В.Ю., Цырлин Г.Э. Рост нитевидных нанокристаллов GaN с вставками InN с помощью МПЭ-ПА // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2025. Т. 18. № 3.1. С. 139–142. DOI: https://doi.org/10.18721/JPM.183.126

Introduction

III-N wurtzite materials (AlN, GaN, InN) attract wide attention for fabrication novel two-dimensional optoelectronic structures. Of particular interest is the ultra-thin InN inserts (1 ML thick) embedded in GaN matrices. These structures exhibit photoluminescence at 3.2 eV which is substantially higher than the InN bulk band gap [1]. Theoretical studies predict that thin InN/GaN heterostructures can host topological insulator states [2], potentially enabling new opto-topological electronic applications. Furthermore, combined with the strong piezoelectric fields of III-N wurtzite materials, these structures may exhibit Wigner crystallization when InN is confined as quantum dot (QD) within GaN matric [3].

However, a growth of high-quality InN-based heterostructures remains challenging due to the relatively low growth temperature and the high lattice-mismatch between InN and other III-N materials (GaN, AlN) [4]. To overcome these limitations, we investigate the InN/GaN heterostructures through the nanowire (NW) growth. Due to a very efficient relaxation of elastic stress on strain-free sidewalls, NW heterostructures can be grown in lattice-mismatched system without structural defects or with largely reduced dislocation density compared to epi-layers [5].

In this work, the growth details and photoluminescence properties of ultra-thin InN inserts embedded in GaN NWs are presented. We demonstrate that the InN inserts within GaN nanowires exhibit photoluminescence in the 2.9–3.35 eV with the most intense line at 3.17–3.23 eV which assigns to monolayer-thick InN inserts based on comparative spectral analysis.

Materials and Methods

Growth experiments were carried out on one-side polished *n*-type Si substrates with resistivity of 0.002–0.004 Ohm·cm in a Riber Compact 12 plasma-assisted molecular beam epitaxy (PA-MBE) system. The surface orientation of the substrate was (111) with a 4° miscut toward the [110] direction. The MBE chamber equipped with Addon RF-N 600 plasma source and Knudsen cells of Ga and In. Prior to loading into the growth chamber, the substrate was etched in a 47.5%

hydrofluoric acid solution for 40 seconds, followed by a 60 second washing in deionized water. After that, the substrate was thermally cleaned in the MBE growth chamber at 855 °C for 20 min. Then, the substrate temperature was decreased to 620 °C. Next, the nitrogen plasma was ignited at a source power of 350 W with nitrogen flow of $4.4 \cdot 10^{-6}$ Torr, and the substrate was nitridated for 20 min to form Si_xN_y thin layer. At the next stage, Al was deposited onto the formed layer for 6 seconds in the absence of nitrogen plasma, nominally corresponding to ~2 ML coverage. After that, the substrate temperature was increased to 805 °C, the nitrogen plasma was ignited at the same parameters, and the Ga source was opened to grow of GaN NWs. This procedure allowed one to achieve the N-polar GaN NWs. The beam equivalent pressure of Ga corresponded to $1.5 \cdot 10^{-7}$ Torr. After a 18h of growth, the Ga source was closed, and the substrate temperature was decreased to 425 °C. The In source was opened with beam equivalent pressure of $1 \cdot 10^{-7}$ Torr for 25.9 sec to grow a thin InN insertion. Following the formation of the InN insertion, a 20 nm GaN cupping layer was grown at the same substrate temperature. The beam equivalent pressure of Ga in this case corresponded to $1 \cdot 10^{-7}$ Torr. It should be noted that the substrate temperature was measured using an Optris CT Laser 3MH1 pyrometer calibrated on the 7×7 to 1×1 surface reconstruction of the Si(111) substrate.

Morphological properties were studied using a Carl Zeiss Supra 25 scanning electron microscopy (SEM) system. Micro-PL measurements were carried out using a setup based on Horiba LabRAM HREvo UV-VIS-NIR-Open spectrometer. The spectra were excited by the 325 nm (3.81 eV) line of a He-Cd laser (Kimmon Koha IK5751I-G). To control the sample temperature, it was mounted in a Linkam THMS600 closed-cycle He cryostat (CRYO Industries of America). A long-working-distance objective (Mitutoyo Plan UV 80×, NA = 0.55) was used to focus the laser beam and collect the PL signal from the sample area of ~0.5 µm in diameter. To prevent damage and heating effects on the nanostructures, the incident laser power was limited to 60 µW. The spectra were measured using excitation power density ~0.5 W/cm² and spectral resolution 2–10 meV.

Results and Discussion

The NWs were synthesized through a self-induced mechanism, where NW nucleation occurs due to the lattice mismatch between the epitaxially growing material and the substrate. Figure 1, *a* demonstrates a representative SEM image of the grown InN/GaN NW array. The NW density is only ~10^8 cm^{-2}, which is unusually small for III-N NW growth, and was achieved by exploiting the high substrate growth temperature, where the Ga desorption from the Si surface becomes significant [37]. The NWs have hexagonal shape with a mean lateral sizes D ~ 40 nm and lengths ranging from 100 to 500 nm.

Figure 1, *b* presents integrated PL spectra measured in a region of 30×30 µm region on a squire grid with a step of 1 µm at 5K. The inclusions show PL intensity maps for the ranges 3.34–3.30 eV, 3.23–3.17 eV and 3.15–2.90 eV. We attribute most intense PL (in the range 3.23–3.17 eV) to 1 ML thick InN inserts embedded in GaN nanowires which is in good agreement with previously published data showing the emission from a 1 ML InN quantum well embedded in a GaN layer at ~3.2 eV [6, 7]. Other PL bands may originate from thicker inserts, which will be discussed in detail in subsequent works.

a) *b*)

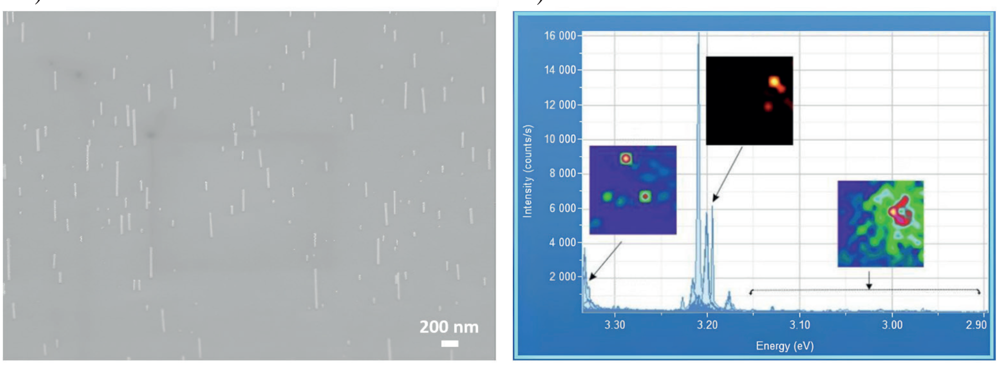

Fig. 1. Representative SEM image of grown InN/GaN nanowires (*a*). Integrated PL spectra measured in a 30×30 µm region on a squire grid having a step 1 µm at 5K (*b*). The inclusions show PL intensity maps for the ranges 3.34–3.30 eV, 3.23–3.17 eV and 3.15–2.90 eV

Conclusion

In summary, our study reveals that InN inserts embedded in GaN nanowires demonstrate distinct photoluminescence at 2.9–3.35 eV and a dominant peak at 3.17–3.23 eV. We attribute the latter dominant peak to monolayer-thick InN inserts based on comparative spectral analysis. Notably, these quantum-confined systems can be promising for single-photon emitters and Wigner quantum dots with operational capabilities ranging from helium temperatures to elevated temperature regimes.

REFERENCES

1. **Pan W., Dimakis E., Wang G.T., Moustakas T. D., Tsui D.C.,** Two-dimensional electron gas in monolayer InN quantum wells, Applied Physics Letters. 105 (21) (2014) 213503.
2. **Barettin D., Auf der Maur M., Pecchia A., Zhang Y., Willatzen Y., Wang Z.L.,** Piezoelectric tunability and topological insulator transition in a GaN/InN/GaN quantum-well device, Journal of Physics: Materials. 4 (3) (2021) 034008.
3. **Mintairov A.M., Axenov V.Yu., Lebedev D.V., Vlasov A.S., Frolov A.S., Ponamarev E.V., Stolyarov V.S.,** Dirac anyons in magnetophotoluminescence spectra of Wigner quantum dots: Molecular versus puddle states, Physical Review B. 111(4) (2025) 045410.
4. **Ivanov S.V., Shubina T.V., Komissarova T.A., Jmerik V.N.,** Metastable nature of InN and In-rich InGaN alloys, Journal of crystal growth. 403 (2014) 83–89.
5. **Dubrovskii V.G., Cirlin G.E., Kirilenko D.A., Kotlyar K.P., Makhov I.S., Reznik R.R., Gridchin V.O.,** Instantaneous growth of single monolayers as the origin of spontaneous core–shell $In_xGa_{1-x}N$ nanowires with bright red photoluminescence, Nanoscale Horizons. 9 (2024) 2360–2367.
6. **Kusakabe K., Imai D., Wang K., Yoshikawa A.,** InN/GaN short-period superlattices as ordered InGaN ternary alloys, physica status solidi (c). 13 (5–6) (2016) 205–208.
7. **Dimakis E., Nikiforov A.Yu., Thomidis C., Zhou L., Smith D.J., Abell J., Kao C.-K., Moustakas T.D.,** Growth and properties of near-UV light emitting diodes based on InN/GaN quantum wells, physica status solidi (a). 205 (5) (2008) 1070–1073.

THE AUTHORS

GRIDCHIN Vladislav O.
gridchinvo@gmail.com
ORCID: 0000-0002-6522-3673

MINTAIROV Alexander M.
amintairov@mail.ioffe.ru

SHUGABAEV Talgat
talgashugabaev@mail.ru
ORCID: 0000-0002-4110-1647

AXENOV Valerii Yu.
axenov.v@gmail.com

VLASOV Alexey S.
vlasov@scell.ioffe.ru

LENDYASHOVA Vera V.
erilerican@gmail.com
ORCID: 0000-0001-8192-7614

KOTLYAR Konstantin P.
konstantin21kt@gmail.com
ORCID: 0000-0002-0305-0156

ELISEEV Ilya A.
zoid95@yandex.ru

KHREBTOV Artem I.
khrebtovart@mail.ru

REZNIK Rodion R.
moment92@mail.ru
ORCID: 0000-0003-1420-7515

DAVYDOV Valery Yu.
valery.davydov@mail.ioffe.ru

CIRLIN George E.
george.cirlin@mail.ru
ORCID: 0000-0003-0476-3630

Received 13.08.2025. Approved after reviewing 18.08.2025. Accepted 01.09.2025.