PHYSICAL MATERIALS TECHNOLOGY

Conference materials
UDC 538.975
DOI: https://doi.org/10.18721/JPM.161.227

Physical properties of GaN nanowires with core-shell InGaN/GaN insertions grown by PA-MBE on Si substrate

D.N. Bondarenko[1,2]✉, V.O. Gridchin[1,2,3], K.P. Kotlyar[1], R.R. Reznik[1,2,3], D.A. Kirilenko[4], A.I. Baranov[2], A.S. Dragunova[2,5], N.V. Kryzhanovskaya[5], A.A. Maksimova[2], G.E. Cirlin[1,2,3,4]

[1] St. Petersburg State University, St. Petersburg, Russia;
[2] Alferov University, St. Petersburg, Russia;
[3] IAI RAS, St. Petersburg, Russia;
[4] Ioffe Institute, St. Petersburg, Russia;
[5] HSE University, St. Petersburg, Russia
✉ bondarenko.dariya.spb@gmail.com

Abstract. An approach to the fabrication of LED structure based on GaN nanowires with thick core-shell InGaN insertions with high indium content is studied. The results of optical measurements demonstrate the photoluminescence from the InGaN insertions in the green spectrum at room temperature. The study of electrical properties shows typical diode dependence. The results can be crucial for the development of light-emitting diodes on Si substrates.

Keywords: GaN/InGaN nanowires, micro light-emitting diodes, plasma-assisted molecular beam epitaxy, thick core-shell InGaN insertions.

Funding: The samples were grown under financial support of Ministry of Science and Higher Education of the Russian Federation (state task № 0791-2020-0003). Optical studies of grown samples were done under financial support of Russian Science Foundation grant №19-72-30010. Structural and electro-physical properties were studied under financial support of St. Petersburg State University under research grant № 92591131.

Citation: Bondarenko D.N., Gridchin V.O., Kotlyar K.P., Reznik R.R., Kirilenko D.A., Baranov A.I., Dragunova A.S., Kryzhanovskaya N.V., Maksimova A.A., Cirlin G.E., Physical properties of GaN nanowires with core-shell InGaN/GaN insertions grown by PA-MBE on Si substrate, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 16 (1.2) (2023) 179–184. DOI: https://doi.org/10.18721/JPM.161.227

Материалы конференции
УДК 538.975
DOI: https://doi.org/10.18721/JPM.161.227

Физические свойства нитевидных нанокристаллов GaN с вставками структуры «core-shell» InGaN/GaN, выращенных методом МПЭ с плазменной активацией на подложке Si

Д.Н. Бондаренко[1,2✉], В.О. Гридчин[1,2,3], К.П. Котляр[1], Р.Р. Резник[1,2,3], Д.А. Кириленко[4], А.И. Баранов[2], А.С. Драгунова[2,5], Н.В. Крыжановская[5], А.А. Максимова[2], Г.Э. Цырлин[1,2,3,4]

[1] Санкт-Петербургский государственный университет, Санкт-Петербург, Россия;
[2] Санкт-Петербургский академический университет имени Ж. И. Алферова РАН, Санкт-Петербург, Россия;
[3] Институт аналитического приборостроения РАН, Санкт-Петербург, Россия;
[4] Физико-технический институт имени А. Ф. Иоффе РАН, Санкт-Петербург, Россия;
[5] Национальный исследовательский университет «Высшая школа экономики», Санкт-Петербург, Россия

✉ bondarenko.dariya.spb@gmail.com

Аннотация. Исследован подход к созданию светоизлучающей структуры на основе нитевидных нанокристаллов GaN с объемными вставками структуры «core-shell» InGaN с высоким содержанием индия. Результаты оптических измерений демонстрируют фотолюминесценцию вставок InGaN в зеленом спектре при комнатной температуре. Изучение электрических свойств показывает типичную диодную зависимость. Результаты могут иметь решающее значение для разработки светоизлучающих диодов на кремниевых подложках.

Ключевые слова: нитевидные нанокристаллы GaN/InGaN, микросветоизлучающие диоды, молекулярно-пучковая эпитаксия с плазменной активацией, объемные вставки структуры «core-shell» InGaN

Финансирование: Экспериментальные образцы были синтезированы при финансовой поддержке Министерства науки и высшего образования Российской Федерации (государственное задание № 0791-2020-0003). Оптические исследования выращенных образцов выполнены при финансовой поддержке гранта РНФ №19-72-30010. Структурные и электрофизические свойства изучены при финансовой поддержке СПбГУ в рамках исследовательского гранта № 92591131.

Ссылка при цитировании: Бондаренко Д.Н., Гридчин В.О., Котляр К.П., Резник Р.Р., Кириленко Д.А., Баранов А.И., Драгунова А.С., Крыжановская Н.В., Максимова А.А., Цырлин Г.Э. Физические свойства нитевидных нанокристаллов GaN с вставками структуры «core-shell» InGaN/GaN, выращенных методом МПЭ с плазменной активацией на подложке Si // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2023. Т. 16. № 1.2. С. 179−184. DOI: https://doi.org/10.18721/JPM.161.227

Introduction

Nowadays, a particular interest of researchers is directed to the creation of micro light-emitting diodes (LEDs) based on InGaN ternary compounds [1]. Among the unique properties of these direct band gap semiconductors, the ability to tune the emission wavelength from the near UV to near IR by changing the chemical composition is highlighted [1]. However, the synthesis of homogeneous InGaN layers in a wide chemical range leads to the internal strains and phase separation («miscibility gap») due to the large lattice mismatch between InN and GaN [2]. In addition, the lack of lattice-matched substrates relative to InGaN remains as an unsolved problem of the synthesis of InGaN layers with high crystalline quality. As was shown earlier, one of the methods for solving these challenges is the synthesis of nanowires (NWs) [3]. Among advantages of NWs, the possibility of obtaining practically defect-free structures on substrates with different lattice parameters and different thermal expansion coefficients [4]. This advantage allows using low cost and high availability silicon wafers as the substrates for NWs growth. Another advantage of NWs is the possibility to circumvent of «miscibility gap» and obtain InGaN solid solution with any required chemical composition [5]. Generally, InGaN NWs with a high In content are grown in spontaneously formed core-shell structure [6]. In these regards, an approach to the creation of thick core-shell InGaN active area embedded in GaN NWs can be a promising way to obtain high efficiency visible LEDs. In addition, the quantum confinement Stark effect can be negligible due to the using of thick core-shell active area.

In this work, we study the structural and optoelectronic properties of GaN NWs with the thick core-shell InGaN active region grown on n-Si (111) substrates by plasma-assisted molecular beam epitaxy (PA-MBE).

Materials and Methods

The GaN/InGaN NWs were grown by molecular-beam epitaxy using a Riber Compact 12 MBE setup equipped with Ga, In, Mg, and Si effusion cells and a nitrogen plasma source. We used n-Si(111) substrates with 0.002-0.004 Ω·cm electrical resistivity. The pretreatment of the substrates, necessary for the removal native silicon oxide layer, was carried out using an aqueous solution of hydrofluoric acid. After processing, the substrates were transferred to a growth chamber and heated to a temperature of 950 °C for thermal treatment. Next, the temperature was lowered to a value of 600 °C, and a Ga source was opened for 15 seconds to form droplets on the substrate surface. Then the substrate temperature was raised to 820 °C. After stabilization of the temperature, a nitrogen plasma source with a power of 450 W was ignited, the flux of which was set at 0.4 sccm. At this stage, the effusion cells of Ga and Si were simultaneously opened to form GaN NWs with n-type conductivity. After that, the substrate temperature was decreased to the formation of InGaN active area. Finally, GaN doped by Mg were grown for obtaining p-type conductivity. Total growth time was 17h. The morphological properties of the sample were studied using scanning electron microscopy (SEM supra 25 Zeiss).

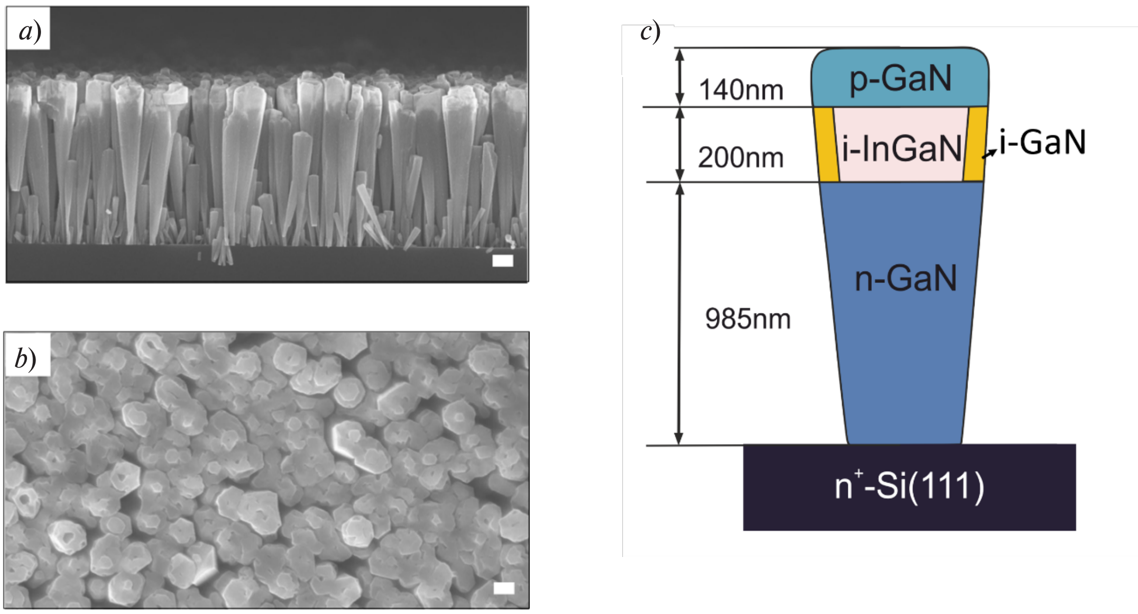

Fig. 1. SEM images of GaN/InGaN NWs: cross-section view (*a*), plane view (PV) (*b*) and schematic image of the NW structure (*c*). The scale bars correspond to 200 nm

The study of optical properties of GaN/InGaN NWs was realized using the photoluminescence (PL) method at the room temperature. To excite the PL, a helium-cadmium (He-Cd) metal-vapor laser with a wavelength of 325 nm and a power of 15.5 mW was used. The microstructure and chemical composition of grown NWs were studied by high-angle annular dark-field scanning transmission electron microscopy (HAADF-STEM, JeolJEM-2100FTEM) with energy-dispersive X-ray (EDX) spectroscopy techniques (XFlash 6TI30, Bruker). The electrical properties of the NWs were studied by measuring the current–voltage (I-V) curves at room temperatures.

Results and Discussion

Fig. 1 shows SEM images of the obtained GaN/InGaN NWs in two views: a cross-section view (*a*) and a plane view (*b*), as well as a schematic image of the NW structure (*c*).

As can be seen from Fig. 1, the morphology of the grown structures is close-packed GaN/InGaN NWs with an average length of 1.7 μm and the diameters at the base and top of about 100 nm and 300 nm, respectively. Also, it can be seen that the sample consists of both separated and partially coalesced NWs.

The typical PL spectrum is shown in Fig. 2. The results of the PL measurements showed that the sample has a PL spectrum in the visible region (450–650 nm) with a maximum nearly 536 nm. The full width at half maximum is about 67 nm.

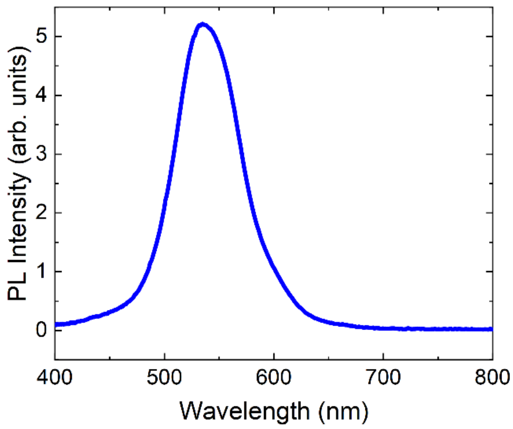

Fig. 2. Typical photoluminescence spectrum of the GaN/InGaN NWs

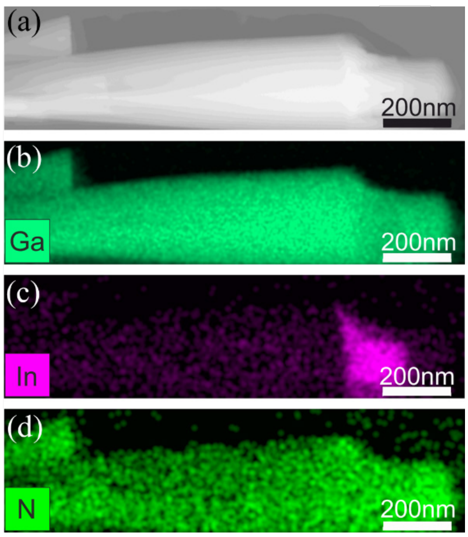

Fig. 3. HAADF-STEM image of an GaN/InGaN NWs (*a*); the Ga distribution along the NW (*b*); the In distribution along the NW (*c*)

Fig. 3 shows HAADF-STEM image of a single GaN/InGaN NW and the Ga, In distribution along the NW. As can be seen from these results, the InGaN insert exhibits core–shell structure with lateral and vertical sizes about 230 nm and 200 nm, respectively. In accordance with the PL and TEM measurements, the In content in the NWs is about 30%.

To measure the I-V curves the aluminium ohmic bottom contacts were formed on the n-Si substrate. Next, face top contacts were formed on the p-GaN NWs by coating Ag paste (Fig. 4, *a*). Fig. 4, *b* presents the results of the measurements of I-V curves. As can be seen from the figure, the sample demonstrates typical diode dependence with the opening voltage of about 6V. High opening voltage is apparently related to the Schottky barrier on p-GaN/Ag interface [7].

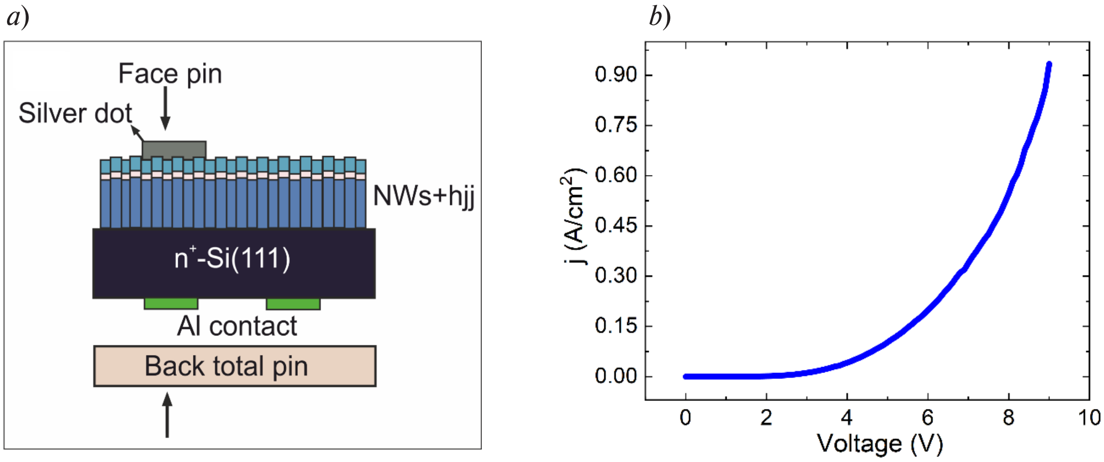

Fig. 4. Scheme of an LED based on an array of GaN/InGaN NWs on the *n*-Si(111) substrate (*a*); the current-voltage curve of GaN/InGaN NWs LED (*b*)

Conclusion

The experimental results of the growth of the n-GaN/i-InGaN/p-GaN nanowires on the n-Si(111) substrate by the PA-MBE method were presented. It was shown that the photoluminescence of the obtained nanostructure is observed in the visible green region with a maximum of the PL spectrum at about 536 nm. STEM studies showed, that the InGaN inserts have a spontaneously formed core–shell structure with In content in the core about 30 %. The presented results can be promising for creation of green LEDs grown on silicon substrates.

Acknowledgments

The samples were grown under financial support of Ministry of Science and Higher Education of the Russian Federation (state task 0791-2020-0003). Optical studies of grown samples were done under financial support of Russian Science Foundation grant 19-72-30010. Structural and electro-physical properties were studied under financial support of St. Petersburg State University under research grant 92591131.

REFERENCES

1. **Bui H.Q.T., Velpula R.T., Jain B., Aref O.H., Nguyen H.-D., Lenka T.R., Nguyen H.P.T.,** Full-Color InGaN/AlGaN Nanowire Micro Light-Emitting Diodes Grown by Molecular Beam Epitaxy: A Promising Candidate for next Generation Micro Displays, Micromachines. 10 (8) (2019) 492.
2. **Ho I., Stringfellow G.B.,** Solid phase immiscibility in GaInN, Applied Physics Letters. 69 (18) (1996) 2701—2703.
3. **Yan R., Gargas D., Yang P.,** Nanowire photonics, Nature Photonics. 3 (10) (2009) 569.
4. **Dubrovskii V.G., Cirlin G.E., Ustinov V.M.,** Semiconductor nanowhiskers: Synthesis, properties, and applications, Semiconductors. 43 (12) (2009) 1539—1584.

5. **Roche E., Andre Y., Avit G., Bougerol C., Castelluci D., Rйveret F., Gil E., Mйdard F., Leymarie J., Jean T., Dubrovskii V. G., Trassoudaine A.,** Circumventing the Miscibility Gap in InGaN Nanowires Emitting from Blue to Red, Nanotechnology. 29 (46) (2018) 465602.

6. **Gridchin V.O., Kotlyar K.P., Reznik R.R., Dragunova A.S., Kryzhanovskaya N.V., Lendyashova V.V., Kirilenko D.A., Soshnikov I.P., Shevchuk D.S., Cirlin G.E.,** Multi-colour light emission from InGaN nanowires monolithically grown on Si substrate by MBE, Nanotechnology. 32 (33) (2021) 335604.

7. **Picozzi S., Continenza A., Satta G., Massidda S., Freeman A. J.,** Metal induced gap states and Schottky barrier heights at non–reactive GaN/noble-metal interfaces, Physical Review B. 61 (24) (2000) 16736.

THE AUTHORS

BONDARENKO Daria N.
bondarenko.dariya.spb@gmail.com
ORCID: 0000-0003-4537-069X

GRIDCHIN Vladislav O.
gridchinvo@yandex.ru
ORCID: 0000-0002-6522-3673

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

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

KIRILENKO Demid A.
Kirilenko@mail.ioffe.ru
ORCID: 0000-0002-1571-209X

BARANOV Artem I.
baranov_art@spbau.ru
ORCID: 0000-0002-4894-6503

DRAGUNOVA Anna S.
anndra@list.ru
ORCID: 0000-0002-0181-0262

KRYZHANOVSKAYA Natalia V.
nataliakryzh@gmail.com
ORCID: 0000-0002-4945-9803

MAKSIMOVA Alina A.
deer.blackgreen@yandex.ru
ORCID: 0000-0002-3503-7458

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

Received 11.10.2022. Approved after reviewing 14.11.2022. Accepted 14.11.2022.