Semiconductor Physics, Quantum Electronics & Optoelectronics, 2021. V. 24, No 4. P. 407-412.

Hetero- and low-dimensional structures

Electron transport in AlGaN/GaN HEMT-like nanowires: Effect of depletion and UV excitation

A.V. Naumov[1], V.V. Kaliuzhnyi[1*], S.A. Vitusevich[2], H. Hardtdegen[2], A.E. Belyaev[1]

[1]*V. Lashkaryov Institute of Semiconductor Physics, National Academy of Sciences of Ukraine,*
41, prospect Nauky, 03680 Kyiv, Ukraine
[2]*Electronic Sensors Group, IBI-3, Forschungszentrum Juelich, Juelich, Germany*
[*] *Corresponding author e-mail: vladkaliuzh@gmail.com*

Abstract. In this work, we have investigated the features of electron transport in AlGaN/GaN transistor-like heterostructures with nanowires of different width. These nanostructures are studied extensively because of their great electronic and sensing advantages for electronic biosensor applications. We study the depletion effects and impact of ultraviolet excitation on the electron transport in sets of nanowires of different width from 1110 down to 185 nm. We have found significant difference in electrical characteristic's behavior between wide (1110…480 nm) and narrow (280…185 nm) nanowires and have observed regions related to space-charge-limited transport for the narrowest nanowires. Also, we obtained evident dependence of nanowire's current-voltage characteristics on the wavelength and energy of UV excitation. External UV excitation allows us to control the depletion widths in nanowires and effectively tune space-charge-limited transport.

Keywords: gallium-nitride, nanowire, electron transport.

https://doi.org/10.15407/spqeo24.04.407
PACS 62.23.Hj, 72.20.-i, 72.25.-b

Manuscript received 14.07.21; revised version received 24.08.21; accepted for publication 10.11.21; published online 23.11.21.

1. Introduction

One-dimensional semiconductor nanowires (NWs) are one of the best candidates for electronic biosensors and are promising elements in modern nanoelectronics from the viewpoint of downscaling the microelectronic devices [1–3]. The nanoscale NWs fabricated on the base of low-dimensional quantum heterostructures have advantages of high integral compactness, high-speed quasi-ballistic electron transport, and high quantum localization of charge carriers in the conduction channel, thus providing a wide range of size-dependent electronic and electrical characteristics management. Besides, NWs have a large surface-to-volume ratio for efficient detection of targets in biosensing at the atomic and molecular level. However, understanding the processes of quantum electron transport in NW biosensors is still insufficient, because their interfaces are extremely sensitive to surrounding materials and environment conditions [1, 4].

The very recent technological achievements in NW structures and their studies reveal the following critical peculiarities different from their bulk counterparts: considerable non-uniformity of all parameters across NWs, including electron mobility and concentration, essential role of interface states, large depletion regions near interfaces, *etc*. It is expected that these phenomena will be dependent on bias/current conditions because of electrical heating, electron injection, charging defects, filling factor and so on. Therefore, NWs are ideal objects for fundamental studies of nonlinear transport effects and their applications. Nanowire field-effect transistors (NW-FETs) are promising candidates to boost progress in device scaling beyond the limitations of planar MOS transistor technology [5].

In Ref. [6], the significant performance enhancement of GaN nanowire UV photodetectors through effective coupling of Pt nanoparticles based on the localized surface plasmon resonance effect was demonstrated.

In Ref. [7], the influence of the growth technique, doping, and crystal polarity on the kinetics of photo-generated charges in GaN was studied using a combination of contact potential difference and photocurrent (PC) measurements. It was found that the processes and corresponding time scales involved in the decay of charge carriers generated at and close to the GaN surface *via* photo-excitation are independent of the growth technique, doping (*n*-/*p*-types), and crystal polarity. Hence, the transfer of photogenerated charges from band states back to surface states proceeds always by hopping *via* shallow defect states in the space-charge region (SCR) close to the surface.

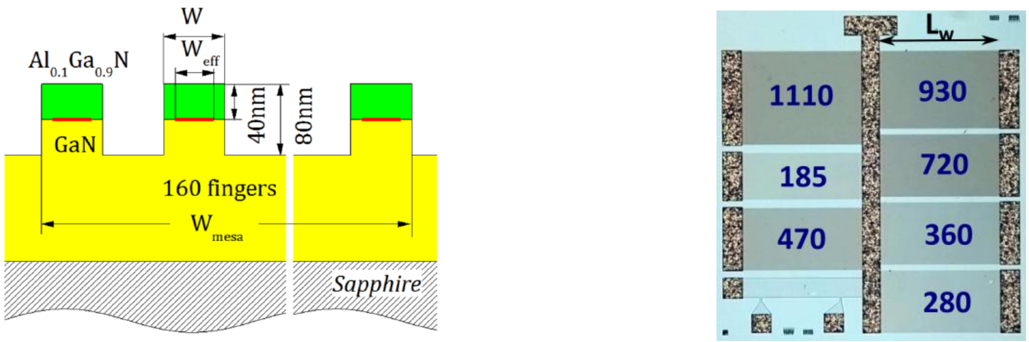

Fig. 1. Experimental NW-samples details: layers structure (a) and microphoto of NWs sets (b). On the microphoto (b): 7 sets of NWs ($W = 185…1110$ nm) and Hall-bar structure for magneto-transport measurements (at the bottom/left); common electrical contact (“Source”) at the middle part of photo and electrical contacts (“Drain”) for each set of NWs at the edges of the photo.

In this study, we performed electrical characterization of AlGaN/GaN HEMT-like heterostructures with nanowires to investigate the features of electron transport in these structures. Photoexcitation with ultraviolet (UV) light was used to influence on charge carriers and consequently on electron transport in NW heterostructures.

2. Experimental samples and methods

The experimental samples with AlGaN/GaN nanowires were grown by top-down technique. First, the AlGaN/GaN HEMT-like heterostructures were grown using metal organic vapour phase epitaxy on (0001) Al_2O_3 substrate and consisted of 3-µm-thick GaN buffer followed by 40-nm-thick $Al_{0.1}Ga_{0.9}N$ barrier layer. Then, the nanowires were fabricated on prepared heterostructures by using the electron beam lithography and Ar^+-ion beam etching. The etching depth was close to 80 nm, and thus NWs include the heterojunction AlGaN-GaN with 2DEG channel.

Seven different sets of nanowires were prepared (Fig. 1): each set consisted of 160 wires in parallel with the length 620 µm and different width W (185, 280, 360, 470, 720, 930 and 1110 nm).

This length of NWs (620 µm) was chosen to exclude the effect of the contact resistance on the total NWs resistance. Ohmic electrical contacts were made by deposition of Ti/Al/Ni/Au layers and the consequent annealing at 900 °C for 30 s.

Current-voltage characteristics, both dc and pulse, were obtained using Keithley 2600 and 2400 series source-measure units. The Stirling cooling system and vacuum chamber were used for temperature changing down to 70 K. Different types of light emitting diodes (LED) were used as a source of visible and UV radiation: blue-green LED (511 nm) and blue LED (470 nm) as test illumination; a set of UV LEDs with narrow spectrum and peak wavelengths of 405, 377, 370 and 365 nm. All LEDs had the similar optical power close to 1 mW. The spectral range of them did not excite interband transitions.

Since electric characteristics of NWs have strong dependence on external illumination and external conditions [8], the experimental set-up with closed dark vacuum chamber was used to exclude impact of external environment onto NW samples. The samples were mounted on heat-spreading plate.

Here, we have presented experimental results for two sets of NW samples, named S1a and S1b, one of them (S1b) was treated by gamma radiation to investigate/illustrate the effect of small doses [9] (improvements of structural and electrical properties of samples after irradiation with small doses of gamma-quants $\sim 10^6$ rad).

3. Results and discussion

At the first stage of our investigations, NW samples were characterized by the current-voltage measurements under the dark conditions and room temperature. Fig. 2 demonstrates current-voltage characteristics (CVCs) for initial (S1a) and gamma-irradiated (S1b) samples.

The CVC curves for both samples show similar overall character. They reveal linear behavior in the range of small voltages (up to approximately 1 V). After this, at high voltages, they become nonlinear and show power law dependence of current. For S1a sample, the narrowest conducting wire with $W = 280$ nm shows $V^{2.5}$ dependence. Wider wires tend to decrease the power values: 2.2, 1.6 and 1 for $W = 360$, 470 and 1110 nm, respectively. The situation is quite different for the gamma irradiated sample S1b. Here, the thinnest wire with $W = 185$ nm already conducts the current at voltages > 1V, and has the power law dependence $V^{2.3…3.2}$ in the high-voltage range. Next, 280-nm-wide wire has the power value close to 1.6, and other NWs have the value close to unity.

Next, we measured conductance of NWs within the linear current region of CVCs ($V < 0.1$). The conductance G has linear dependence on nanowire width W (Fig. 3) for S1a and S1b samples. Extrapolation of $G(W)$ to zero conductance gives the width of wire that already cannot conduct electrical current, the so-called “critical width” W_c. We estimated W_c to be approximately 200 nm for S1a, and 170 nm – for S1b sample. So, we can introduce the effective width $W_{eff} = W - W_c$ for conductive parts of nanowires.

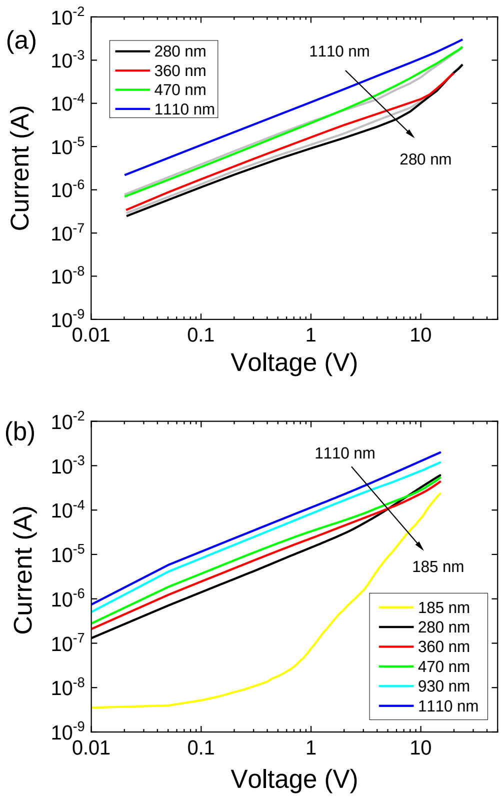

Fig. 2. DC current-voltage characteristics of AlGaN/GaN NW samples measured at room temperature in the dark conditions. (a) Initial sample S1a; (b) γ-irradiated sample S1b. The CVC curves correspond to different widths of nanowires *W* from 1110 down to 185 nm. In the case of S1a, nanowire with *W* = 185 nm is nonconductive and not presented at the graph.

It is known that GaN material has a large surface potential [10, 11], and thus carrier depletion regions near the surface W_{depl} can be expected. Indeed, these depletion effects were observed in various experimental works [12, 13] and even recently directly measured with Kelvin probe force microscopy [14]. We consider our critical width W_c correspond to the overall thickness of depletion regions on both sides of nanowire ($W_c = 2W_{depl}$). Thus, NWs with $W < 170$ nm in case of S1b ($W < 200$ nm in case of S1a) are completely depleted. The difference between two samples we explain by the influence of gamma irradiation and improvement of defect structure of S1b sample and, accordingly, decreasing of depletion regions near the side surfaces.

Besides, we carried out electrical characterization of NWs at temperature sweeping from 300 down to 77 K. For each temperature (step value ~ 50 K) CVCs were measured under the dark conditions. The depletion width W_c under the same conditions trends to decrease (from 170 down to 120 nm) with lowering the temperature to 100 K (Fig. 4).

The next stage of our work was to investigate the features of electron transport in these nanostructures under the influence of external photoexcitation with UV light. For these purposes, we used the sample S1b that has conductive wires of all widths including the most interesting thinnest 185-nm nanowire. We used blue light LED (λ = 460…480 nm) and a set of UV LEDs with a narrow spectrum and the peak wavelengths 405, 370 and 365 nm. All LEDs had the similar optical power close to 1 mW. The radiation of the LEDs spectral range could not excite interband transitions. Initially, the time- and UV-wavelength-dependences of current were studied (Fig. 5).

Under illumination, the current values increase approximately 1.5 times as compared to the dark case. The character of current dependence on UV light wavelength is close to the linear one (inset in Fig. 5a). Time dependence of current relaxation (Fig. 5b) shows two-exponential character, consisting of two parts – fast (approximately 0.5 s) and then slow decay of current after illumination is switched off.

The following step was to investigate W_c dependence on the wavelength of UV photoexcitation. The samples were placed into closed dark vacuum chamber and illuminated by UV light of various wavelengths. Between measurements with different wavelengths, the samples were left under the dark conditions at least 6 hours to reach full relaxation.

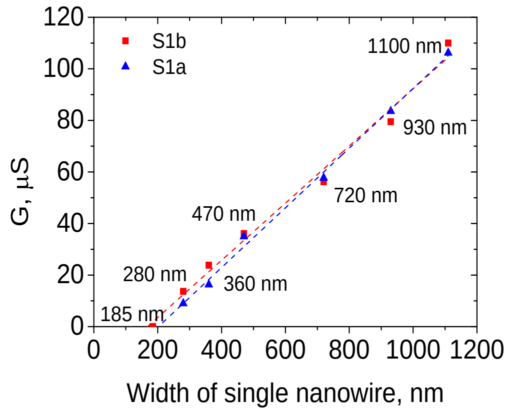

Fig. 3. Plot of NWs conductance as a function of their width: *G*(*W*). Triangles – sample S1a, $W_c = 200$ nm; squares – sample S1b, $W_c = 170$ nm.

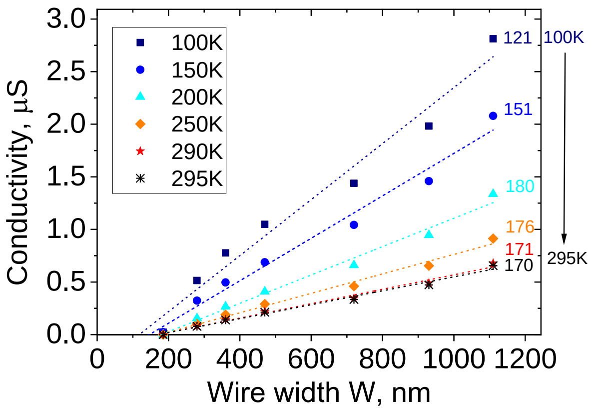

Fig. 4. Dependence of conductance of NWs (per one nanowire) on their width *G*(*W*), and determined values of W_c for dark conditions for all temperatures. Sample S1b.

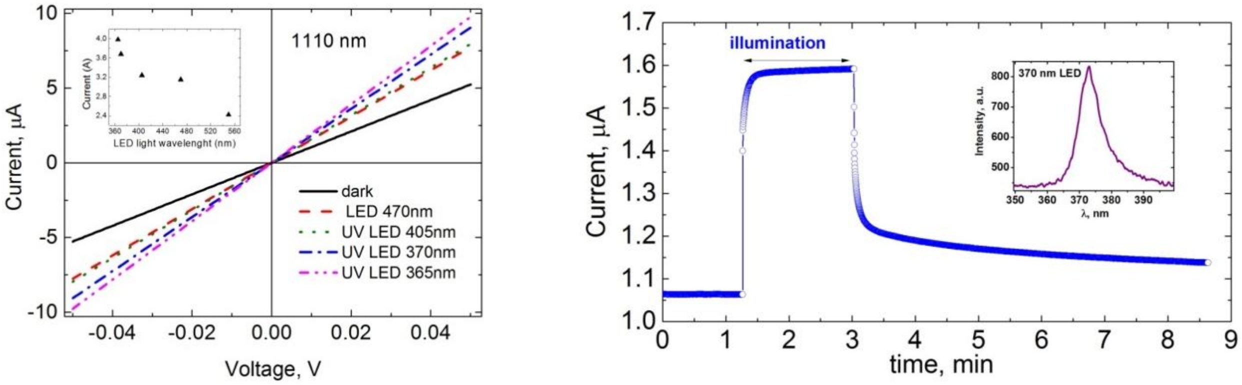

Fig. 5. (a) The dependence of current-voltage characteristics on LED wavelength for NW with $W = 1110$ nm. Inset: Current at 0.2 V *vs* LED wavelength. (b) Time-trace of current flow before and after relatively short-time illumination with UV LED 370 nm. On the inset: characteristic spectrum of 370 nm UV LED. $T = 300$ K.

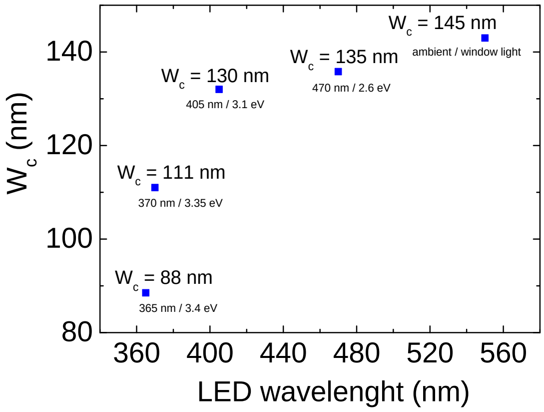

Fig. 6. The critical width W_c as a function of the LED illumination wavelength. $T = 300$ K.

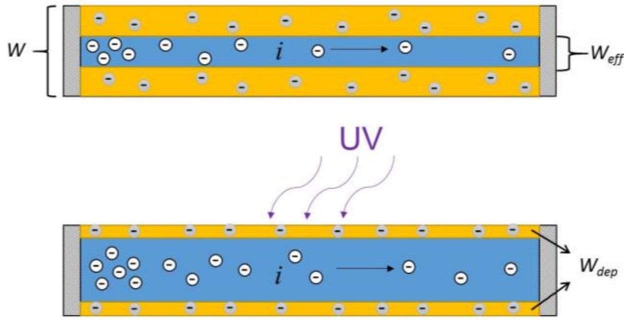

Fig. 7. Illustration for change of depletion width under UV excitation.

Fig. 6 shows the summary data on critical width W_c and UV photoexcitation wavelength. With decreasing the UV wavelength and, respectively, with increasing the energy of photons W_c was decreased down to approximately 90 nm at 365-nm UV LED.

General explanation of this effect is based on Fermi level pinning at the surface (NW's edges in our case) in the presence of relatively deep surface states. This pinning causes the band bending near the surface and space charge redistribution. We consider that critical width W_c in our case corresponds to depletion widths at both edges of NWs, thus NWs with $W < 170$ nm are totally depleted and nonconductive. External UV photoexcitation releases electrons from deep states/traps and accordingly decreases the width of depletion region. As result, the current grows in the conductive 2DEG channel (Fig. 7).

The most interesting result was obtained for the set of narrowest NWs with $W = 185$, 280 nm at high voltages (Fig. 8). As we mentioned above, CVCs have nonlinear character after 1 V, and show power law current dependence. This characteristic power dependence corresponds to the space-charge-limited current (SCLC) regime [15].

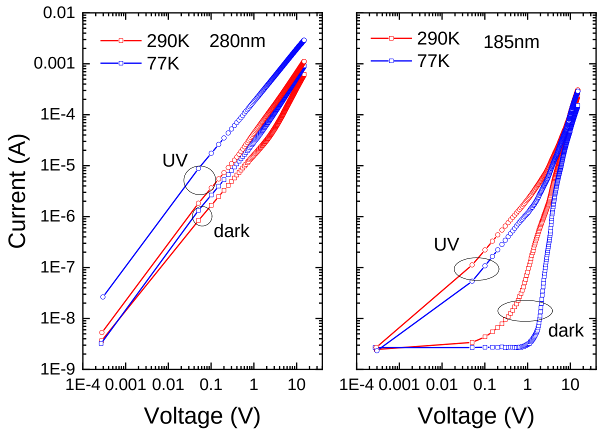

Fig. 8. DC current-voltage characteristics measured at the temperatures 290 and 77 K under the dark conditions and UV LED illumination (370 nm) for nanowires with $W = 280$ nm (a) and $W = 185$ nm (b). Sample S1b.

The critical voltage at which the SCLC regime is achieved strongly depends on the ratio between depletion and the conductive channel width. The smaller the ratio the larger the critical voltage. This feature is clearly seen for the sample with narrowest width of 185 nm under the dark conditions and UV LED illumination (370 nm).

4. Conclusions

In conclusion, we used sub-band-gap ultraviolet excitation to investigate more deeply electron transport processes in nitride based NWs and obtained evident dependence of NWs CVCs on wavelength and intensity of UV excitation. External UV excitation allows us to control the depletion widths in NW samples and effectively tune space-charge-limited transport. We suggest that the features of the electric current found in NWs are of general character and the results obtained are promising for the development of novel devices for nanoelectronic, photonic and biosensing applications.

Acknowledgements

This work is supported by BMBF Project 01 DK 13016, DAAD Project A/14/02428 and by National Academy of Sciences of Ukraine (Project No. 6/20-H). A. Naumov gratefully acknowledges for support FP7 project MCA-IRSES-294949 at Riga Photonics Centre of University of Latvia. The authors are grateful to V. Kochelap and V. Korotyeyev for valuable discussions.

References

1. Dasgupta N.P., Sun J., Liu C. *et al.* 25th anniversary article: Semiconductor nanowires – synthesis, characterization, and applications. *Adv. Mater.* 2014. **26**. P. 2137–2184. https://doi.org/10.1002/adma.201305929.
2. Barrigon E., Heurlin M., Bi Z., Monemar B., Samuelson L. Synthesis and application of III–V nanowires. *Chem. Rev.* 2019. **119**. P. 9170–9220. https://doi.org/10.1021/acs.chemrev.9b00075.
3. Chen C.-P., Ganguly A., Lu C.-Y. *et al.* Ultrasensitive *in situ* label-free DNA detection using a GaN nanowire-based extended-gate field-effect-transistor sensor. *An. Chem.* 2011. **83**, No 6. P. 1938–1943. https://doi.org/10.1021/ac102489y.
4. Yang P., Yan R., Fardy M. Semiconductor nanowire: what's next? *NanoLett.* 2010. **10**. P. 1529–1536. https://doi.org/10.1021/nl100665r.
5. Gačević Ž., López-Romero D., Mangas T.J., Calleja E. A top-gate GaN nanowire metal–semiconductor field effect transistor with improved channel electrostatic control. *Appl. Phys. Lett*. 2016. **108**. P. 033101. https://doi.org/10.1063/1.4940197.
6. Zhang X., Liu Q., Liu B. *et al.* Giant UV photoresponse of a GaN nanowire photodetector through effective Pt nanoparticle coupling. *J. Mater. Chem. C.* 2017. **5**. P. 4319–4325. https://doi.org/10.1039/C7TC00594F.
7. Winnerl A., Pereira R.N., and Stutzmann M. Photo-induced changes of the surface band bending in GaN: Influence of growth technique, doping and polarity. *J. Appl. Phys.* 2017. **121**. P. 205307. https://doi.org/10.1063/1.4983846.
8. Pfüller C., Brandt O., Grosse F. *et al.* Unpinning the Fermi level of GaN nanowires by ultraviolet radiation. *Phys. Rev. B*. 2010. **82**. P. 045320. https://doi.org/10.1103/PhysRevB.82.045320.
9. Kurakin A.M., Vitusevich S.A., Danylyuk S.V. *et al*. Mechanism of mobility increase of the two-dimensional electron gas in AlGaN/GaN heterostructures under small dose gamma irradiation. *J. Appl. Phys*. 2008. **103**. P. 083707. https://doi.org/10.1063/1.2903144.
10. Kočan M., Rizzi A., Lüth H., Keller S., Mishra U.K. Surface potential at as-grown GaN(0001) MBE layers. *phys. status solidi (b).* 2002. **234**. P. 773–777. https://doi.org/10.1002/1521-3951(200212)234:3<773::AID-PSSB773>3.0.CO;2-0.
11. Himmerlich M., Lymperakis L., Gutt R. *et al.* GaN(0001) surface states: Experimental and theoretical fingerprints to identify surface reconstructions. *Phys. Rev. B.* 2013. **88**. P. 125304. https://doi.org/10.1103/PhysRevB.88.125304.
12. Sanford N.A., Robins L.H., Blanchard P.T. *et al.* Studies of photoconductivity and field effect transistor behavior in examining drift mobility, surface depletion, and transient effects in Si-doped GaN nanowires in vacuum and air. *J. Appl. Phys.* 2013. **113**. P. 174306. https://doi.org/10.1063/1.4802689.
13. Gassoumi M., Grimbert B., Gaquiere C., Maaref H. Evidence of surface states for AlGaN/GaN/SiC HEMTs passivated Si_3N_4 by CDLTS. *Semiconductors*. 2012. **46**. P. 382–385. https://doi.org/10.1134/S1063782612030104.
14. Henning A., Klein B., Bertness K.A. *et al.* Measurement of the electrostatic edge effect in wurtzite GaN nanowires. *Appl. Phys. Lett.* 2014. **105**. P. 213107. https://doi.org/10.1063/1.4902873.
15. Sydoruk V.A., Zadorozhnyi I., Hardtdegen H. *et al.* Electronic edge-state and space-charge phenomena in long GaN nanowires and nanoribbons. *Nanotechnology.* 2017. **28**. P. 135204. https://doi.org/10.1088/1361-6528/aa5de3.

Author and CV

Andrii Naumov defended his PhD thesis in Physics in 2006. He is researcher at the V. Lashkaryov Institute of Semiconductor Physics, NAS of Ukraine and Assistant professor at AGM University of Science and Technology, Cracow, Poland. He is the author of more than 15 publications. The area of interests includes semiconductor devices (III-nitrides, GaN/AlGaN HEMT, RTD, nanowire heterostructures); aluminum superconducting nanowires, topological materials. E-mail: naumov_av@ukr.net. https://orcid.org/0000-0002-7688-9737.

Vladyslav Kaliuzhnyi defended his MSc thesis in Physics and Astronomy in 2019 at the Taras Shevchenko National University of Kyiv. He is junior researcher and PhD student at the Department of electric and galvanomagnetic properties of semiconductors of the V. Lashkaryov Institute of Semiconductor Physics, NAS of Ukraine. The area of scientific interests includes physics of semiconductor materials and devices (HEMTs and HEMT-like structures, III-nitrides), modeling of properties. https://orcid.org/0000-0003-2084-6938.
E-mail: vladkaliuzh@gmail.com

Svetlana Vitusevich got PhD degree in physics and mathematics in 1991 from Institute of Semiconductor Physics, NASU; the Dr. Sc. degree in 2006 from the Supreme Attestation Commission of Ukraine and Dr. Habil. degree in 2006 from Technical University of Dortmund, Germany. Since 2017, she is full Professor at the Institute of Semiconductor Physics, NASU and at Forschungszentrum Juelich, Germany. She is author of more than 240 publications and 9 patents. Her research interests include transport and noise properties of novel device structures for future information technologies. https://orcid.org/0000-0003-3968-0149.
E-mail: s.vitusevich@fz-juelich.de

Hilde Hardtdegen obtained PhD degree in Chemistry in 1988 in RWTH Aachen University, Institute of Inorganic Chemistry, Germany. She is the section leader of “Applied nanomaterials” at the Ernst Ruska Centre, Forschungszentrum Juelich, Germany. She has more than 230 publications. Her scientific interests include characterization of nanomaterials for different applications such as in the fields of information technology and energy. https://orcid.org/0000-0003-0445-6489.
E-mail: h.hardtdegen@fz-juelich.de.

Alexander Belyaev obtained PhD degree in semiconductor physics and dielectrics in 1980, the Dr. Sc. degree in 1991, he is Professor from 1999. He is the Head of the Department of electric and galvanomagnetic properties of semiconductors at the V. Lashkaryov Institute of Semiconductor Physics, NAS of Ukraine. Alexander Belyaev is the author of more than 220 publications. The area of his scientific researches is transport and optical properties in quantum multi-layer hetero-structures and low-dimensional systems and their application in UHF devices.
https://orcid.org/0000-0001-9639-6625.
E-mail: belyaev@isp.kiev.ua

Електронний транспорт у нанодротах на основі AlGaN/GaN HEMT: вплив збіднення та УФ збудження

А.В. Наумов, В.В. Калюжний, С.А. Вітусевич, H. Hardtdegen, О.Є. Беляєв

Анотація. У цій роботі досліджено властивості електронного транспорту у транзисторних гетероструктурах AlGaN/GaN з нанодротами різної ширини. Такі структури широко вивчаються для застосування в електронній біосенсориці завдяки їх електронним та сенсорним перевагам. Досліджено явище збіднення та вплив ультрафіолетового збудження на електронний транспорт у наборах нанодротів різної ширини від 1110 до 185 нм. Виявлено значну відмінність у поведінці електричної характеристики між широкими (1110…480 нм) та вузькими (280…185 нм) нанодротами та спостережено області, що відповідають транспорту, обмеженому просторовим зарядом у випадку найтонших нанодротів. Також отримано явну залежність вольт-амперної характеристики нанодротів від довжини хвилі та енергії УФ збудження. Зовнішнє УФ збудження дозволяє керувати шириною збідненої зони у нанодротах і, таким чином, оперативно налаштовувати транспорт, обмежений просторовим зарядом.

Ключові слова: нітрид галлію, нанодріт, електронний транспорт.