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Technological and Structural Solutions for High-Frequency, High-Power, and Optoelectronic Gallium Nitride Devices

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Abstract
The advantages and disadvantages of using gallium nitride (GaN) in comparison with other semiconductor materials of microelectronics are described. It is shown that the high thermal, chemical, and radiation resistance of GaN makes it possible to manufacture devices operating at elevated temperatures and under extreme conditions, while high thermal conductivity simplifies cooling of the active region. The combination of high electron mobility and a high breakdown electric field makes GaN suitable for manufacturing high-power, high-frequency, and high-temperature transistors. Design solutions and technological methods for forming GaN-based devices are presented.

Keywords: gallium nitride, technology, device structure, sensor, modeling.

الملخص
يتم في هذا البحث استعراض مزايا وعيوب استخدام نيتريد الغاليوم (GaN) مقارنةً بغيره من مواد أشباه الموصلات المستخدمة في الإلكترونيات الدقيقة. ويُبيَّن أن المقاومة الحرارية والكيميائية والإشعاعية العالية لنيتريد الغاليوم تُمكّن من تصنيع أجهزة تعمل عند درجات حرارة مرتفعة وفي ظروف قاسية، في حين تسهم الموصلية الحرارية العالية في تبسيط عملية تبريد المنطقة الفعّالة. كما أن الجمع بين الحركة العالية للإلكترونات وشدة مجال الانهيار الكهربائي المرتفعة يجعل نيتريد الغاليوم مادة مناسبة لتصنيع الترانزستورات عالية القدرة وعالية التردد وعالية التحمل الحراري. وتُعرض في البحث الحلول التصميمية والأساليب التكنولوجية الخاصة بتشكيل الأجهزة المعتمدة على نيتريد الغاليوم.
الكلمات المفتاحية: نيتريد الغاليوم، التكنولوجيا، بنية الأجهزة، المستشعرات، النمذجة.

Introduction

Promising materials with a wide range of practical applications include structures based on semiconductor nitrides. Heterostructures based on gallium nitride (GaN) and its solid solutions possess physical properties that provide electronic devices with optical, power, and frequency characteristics, enabling their application in various fields of semiconductor electronics [1]. The application range of this material in optoelectronics is wide and includes blue–green light-emitting diodes, near-ultraviolet LEDs, white light sources based on the "chip–phosphor" system, active media of laser diodes, and others [2].
GaN-based structures are promising not only in optoelectronics, but also for the development of components for power and microwave electronics, such as Schottky diodes and high-electron-mobility transistors, as well as devices operating under harsh radiation conditions.

Characteristics of Gallium Nitride

Compared with other semiconductor materials, gallium nitride exhibits high thermal, chemical, and radiation resistance, which allows it to be used in devices operating at elevated temperatures and in unfavorable environments [3]. High thermal conductivity simplifies cooling of the active region, while the combination of high electron mobility and a high breakdown electric field makes GaN suitable for manufacturing high-power, high-frequency, and high-temperature transistors [4].

The direct nature of interband transitions, wide bandgap energy, and the formation of isomorphic solid solutions with aluminum and indium nitrides enable a significant expansion of the operating spectral range of light-emitting and photodetecting devices fabricated on its basis [5].

The advantages of GaN application in microelectronics include:

- high specific output power density.
- high operating temperature (transistors remain functional at temperatures up to 500–600 °C [6]).
- application in low-noise transistors in the frequency range from 1 GHz to 25 GHz [7,8].
- possibility of creating hybrid and monolithic integrated circuits based on GaN transistors [9].
- lower on-state resistance compared with conventional transistors, resulting in reduced power consumption [10].
- cost reduction of GaN devices through the use of high-resistivity silicon substrates Si (111);
- high radiation resistance of devices [11].

Despite the large number of advantages, GaN-based device structures also have several disadvantages, the main ones being:

- high requirements for efficient heat removal from the active structure;
- the need to grow GaN epitaxial structures on substrates with mismatched lattice and thermal expansion parameters due to the lack of commercially available native GaN substrates [12,13].

For transistors, a significant problem of GaN technology is drain current instability with increasing drain voltage (current collapse effect). In addition, degradation of high-frequency characteristics (transconductance dispersion) and mismatch between pulsed output and input signals (gate or drain lag effects) have been observed. These instability effects are associated with material defects and trap states located both at the surface (gate–drain and gate–source regions) and in the bulk of the GaN buffer layer [14]. Surface passivation of completed transistor structures using thin SiNx dielectric films has been proposed as an effective method to mitigate these effects [15].

Technology

Epitaxial GaN structures on sapphire, SiC, and Si (111) substrates are grown using metal–organic chemical vapor deposition (MOCVD), molecular beam epitaxy (MBE), and hydride vapor phase epitaxy (HVPE). Despite the impressive results achieved to date, the technology for forming initial AlGaN/GaN epitaxial structures on sapphire, SiC, and Si (111) substrates by heteroepitaxy is still far from perfect. Structures grown by MOCVD, MBE, and HVPE methods exhibit a high density of defects (from 10^6 to 10^9 cm^{-2}). The presence of defects affects long-term device operation, especially under conditions of high voltages and elevated temperatures. More than 30 companies worldwide are manufacturers of GaN substrates, the main ones being European companies Imec, Epigan, Novagan, and Azzurro; Asian companies Dowa, Nttat, and Powdec; and North American companies Kyma, Translucent, and Dow Corning.

Heteroepitaxy leads to the formation of mechanical stresses due to lattice constant mismatch. Differences in the thermal expansion coefficients of the substrate and the epitaxial layer result in stress during cooling of the structure to room temperature, which may cause wafer bowing or cracking.

From the standpoint of commercial application, the most promising option is the use of silicon as a substrate. One of the methods suitable for growing gallium nitride layers on silicon substrates is hydride vapor phase epitaxy (HVPE) [16]. At present, this method is the only one implemented on an industrial scale. Unfortunately, only a few companies possess the technology for producing gallium nitride substrates. Conventional process conditions do not guarantee high-quality HVPE on silicon substrates, as they cannot prevent the chemical reaction between gallium and silicon at temperatures above 1170 K caused by silicon diffusion into the growing layer. It was shown in [17] that the use of buffer (nucleation) layers significantly reduces mismatch effects in the GaN/Si system. In particular, epitaxial GaN layers with a thickness of 0.3 μm free of cracks were obtained.

Considerable interest is attracted by hybrid technology combining standard silicon technology with GaN technology [17].

In all cases, crystal formation is carried out exclusively by dry (plasma-chemical) etching. High ion-density plasma sources, such as electron cyclotron resonance and inductively coupled plasma sources, are used, in which a high ion flux ensures efficient breaking of GaN bonds. Doping of GaN with n-type and p-type impurities is performed by implantation of Si^+ and Mg^+ ions followed by high-temperature annealing at temperatures above 1320 K [18, 19].

Structural Solutions

At present, various types of gallium nitride–based microwave transistors have been implemented worldwide, confirming the prospects of this class of devices.

The development of AlGaN/GaN heterojunction field-effect transistors with Schottky gates is one of the main directions in microwave semiconductor electronics. The key element of such a structure is the two-dimensional electron gas region in a quantum well located directly beneath the heterojunction. Electron mobility in this region reaches 2000 $cm^2/V{\cdot}s$, while the carrier concentration is about 10^{13} cm^{-2}. The HEMT structure is shown in Fig.1. The buffer layer improves the parameters of the two-dimensional electron gas and prevents electron transfer to surface states and bulk defects. The developed HEMT designs make it possible to achieve output power exceeding 8 W at a frequency of 4 GHz [20]. Figure.2 shows the GaN HEMT device structure described in [21].

A typical GaN-based HEMT design forms the basis for many promising chemical and biological sensors, pressure sensors, and similar devices.

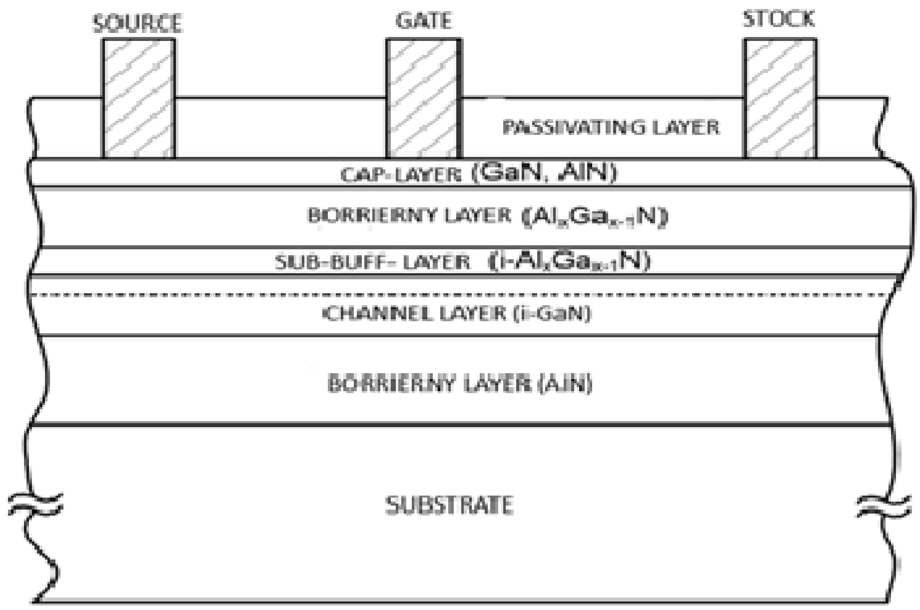


Fig. 1. Typical GaN HEMT structure

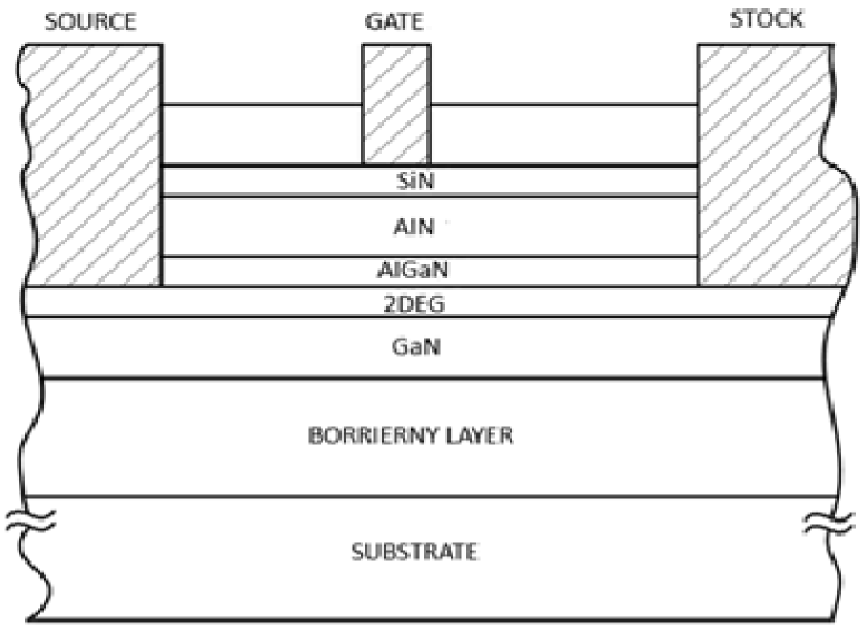


Fig. 2. GaN HEMT with an insulated gate

A gallium nitride (GaN)–based light-emitting diode (LED) is shown in Fig. 3. Several design variants of LED chips exist. For LEDs based on classical AIII–BV compound semiconductors, such as GaAs and InP, a typical chip design includes contact pads located on the top surface of the structure. In this case, light extraction is also performed through the surface, since the substrate is opaque to the radiation generated in the active region of the structure. This type of chip design is referred to as a *face-up* configuration, or a surface-emitting chip.

At present, the vast majority of commercial GaN-based LED chips are grown on monocrystalline sapphire substrates. The use of a substrate that is transparent to radiation and electrically insulating enables the implementation of a *flip-chip* LED configuration. In this design, both contact pads are located on the same side of the structure, while the generated light is extracted from the opposite side through the transparent sapphire substrate. A significant advantage of this approach is the possibility of mounting the chip onto a carrier board without wire bonding, which is highly favorable for large-scale industrial production.

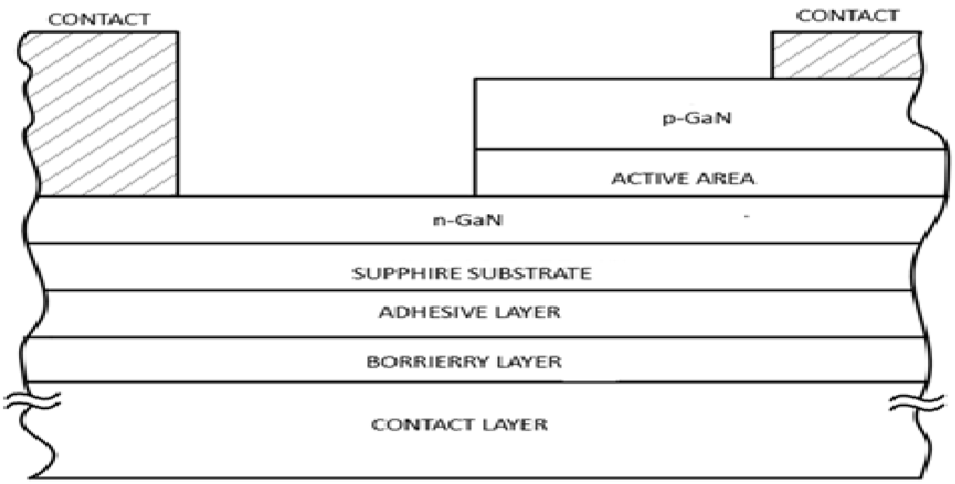
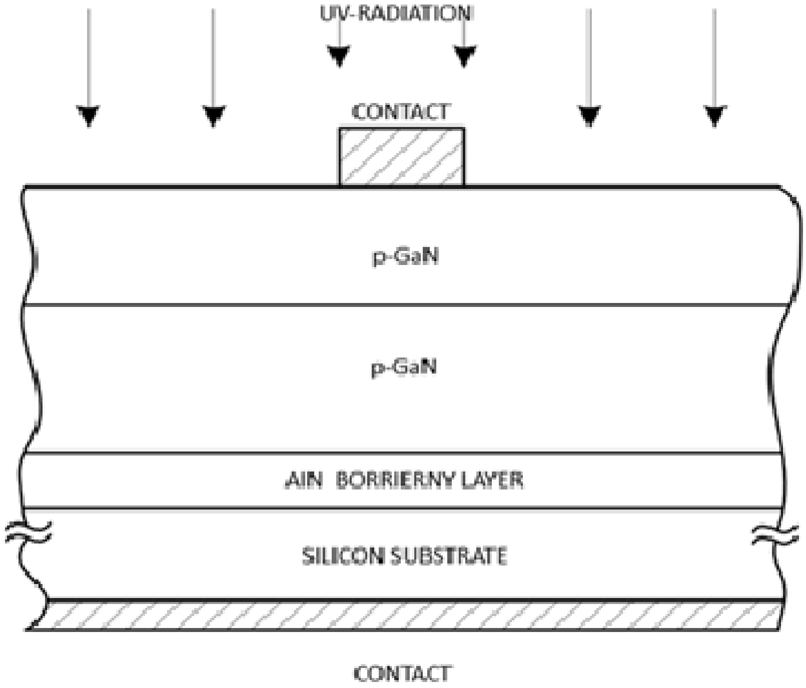


Fig. 3. GaN-based LED.

Under high-current operating conditions, efficient heat dissipation from the LED chip becomes critically important. In this regard, flip-chip LEDs significantly outperform face-up LEDs. In face-up structures, the sapphire substrate separates the chip from the heat sink; due to the low thermal conductivity of sapphire, this configuration impedes effective heat transfer [22].

Since GaN is a highly promising semiconductor material for the development of radiation-hardened microwave (RF and microwave) electronic components intended for military and space applications, it is also widely used in the fabrication of various types of sensors. These include ultraviolet (UV) radiation sensors (Fig. 4), infrared (IR) radiation sensors, and ionizing radiation (IR) detectors [23]. The enhanced resistance of GaN to ionizing radiation makes it a particularly attractive material for the development of long-lifetime solar cells for spacecraft applications. Fig. 5 presents, as an example, the device structure of a solar cell and its power conversion unit.



. Fig. 4. Ultraviolet radiation sensor

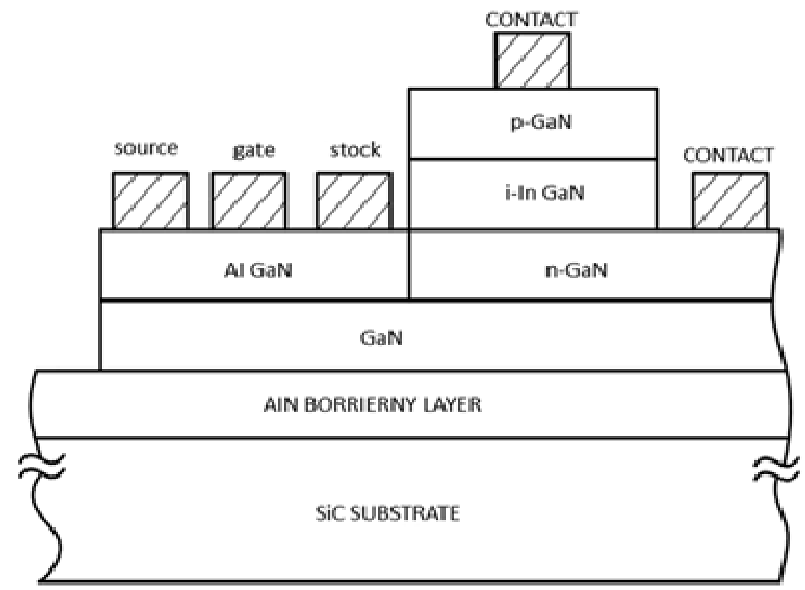


Fig. 5. Solar cell power converter.

Computer Modeling of GaN-Based Device Structures

To develop advanced electronic devices and systems, it is essential to employ modern computer-aided design (CAD) tools, particularly device–technology simulation systems. Such systems enable numerical evaluation of the impact of various structural and technological design choices on the performance characteristics of the devices under development, thereby significantly reducing the cost and scope of experimental investigations.

Most contemporary CAD tools for device–technology simulation were originally developed primarily for silicon-based technologies. The models used for silicon devices have been extensively validated and allow highly accurate calculation of both static and dynamic characteristics. However, when transitioning to wide-bandgap semiconductor materials, particularly gallium nitride (GaN), these models cannot be directly applied. In recent years, a large number of specialized models have been developed for the simulation of devices based on wide-bandgap materials.

The Silvaco software suite includes the Blaze module, which enables the simulation of devices fabricated using advanced semiconductor materials. This module incorporates a library of binary, ternary, and quaternary semiconductor compounds. Blaze features built-in models for both graded and abrupt heterojunctions and supports the simulation of binary device structures such as MESFETs, HEMTs, and HBTs. All measurable DC, AC, and transient characteristics of a device can be obtained through simulation. The calculated DC parameters include threshold voltage, gain, leakage currents, breakdown voltage, breakdown current, and other key characteristics. The results of modeling GaN-based device structures are presented in studies [24-30].

Conclusion

The conducted analysis and previously obtained results demonstrate that, in comparison with other semiconductor materials, gallium nitride (GaN) possesses significant advantages as a base material for the fabrication of power, high-frequency, and optoelectronic devices.

The high thermal, chemical, and radiation resistance of GaN enables its use in structures operating at elevated temperatures and under extreme environmental conditions. Furthermore, its relatively high thermal conductivity facilitates efficient heat dissipation from the active region. The combination of high electron mobility and a strong electric breakdown field makes GaN particularly suitable for the fabrication of high-power, high-frequency, and high-temperature transistors.

References

1.Jayant Baliga B. Fundamentals of Power Semiconductor Devices 2008th // Springer, 1069p.

2.Turkin A. N. Nitrid galliya kak odin iz perspektivnyh materialov v sovremennoj optoehlektronike // Komponenty i tekhnologii. 2011. №5. (in Russ.).

3.Ansel'm A. I. Vvedenie v teoriyu poluprovodnikov // Moskva, 1978, 618 s. (in Russ.).

4.LED Lighting, LED Technology, SiC & GaN Power, RF Solutions | Cree, Inc [site]. URL : http://www.cree.com/ (date of access: 05.12.2017).

5.30-W/mm GaN HEMTs by field plate optimization / Y.-F. Wu, A. Saxler, M. Moore [et al.] // IEEE Electron Devices Lett. 2004. № 11 (25). P. 117–119.

6.Evalution of the temperature stability of AlGaN/GaN heterostructure FETs / I. Daumiller, C. Kirchner, M. Kamp [et al.] // IEEE Electron Device Lett. 1999. № 9. P.440–450.
7.Lu W., Kumar V., Piner E.L., Adesida I. DC, RF, and microwave noise performance of AlGaN-GaN field effect transistors dependence of aluminum concentration // IEEE Trans. Elec. Devices. 2003. № 4 (50). P. 1069–1074.
8.Adesida I., Lu W., Kumar V. – 6 Int. Conf. on Solid_State and IC Technology Proc., 2001, p.1163–1168.
9.Wide bandgap semiconductor devices and MMICs for RF Power Applications (Invited) / J. W. Palmour [et al.] // IEDM. 2001. P. 385–391.
10.High voltage RF operation of AlGaN/GaN heterostructure FETs / M. Kuzuhara, H. Miyamoto, Y. Ando [et al.] // Phys. Stat. Sol. 2003. № 1 (200). P. 161–167.
11.Danilin V. N., Dokuchaev Yu. P., Zhukova T. A., Komarov M. A. Moshchnye vysokotemperaturnye i radiacionnostojkie SVCh-pribory novogo pokoleniya na shirokozonnyh geteroperekhodnyh strukturah AlGaN/GaN // Obzory po ehlektronnoj tekhnike. Ser.1. SVCh-tekhnika. 2001. vyp.1. (in Russ.).
12.Ammono [site]. URL : https://www.ammono.com/ (date of access: 05.12.2017).
13.Технологическая компания «Тринитри» [site]. URL : http://www.trinitri.ru/ (date of access: 04.12.2017).
14.Binari S. C., Klein P. B., Kazior T. E. Trapping Effects in GaN and SiC Microwave FETs // Proceedings of the IEEE. 2002. № 6 (90). P. 1048–1058.
15.Reduction of current collapse in AlGaN/GaN heterostructure FETs / J. S. Lee, J. W. Kim, J. H. Lee [et al.] // Electron. Lett. 2003. № 9 (39). P. 750–752.
16.Osobennosti hlorid-gidridnoj ehpitaksii nitridnyh materialov na podlozhke kremniya / M. G. Mynbaeva, A. A. Golovatenko, A. I. Pechnikov [i dr.] // Fizika i tekhnika poluprovodnikov. 2014. № 11 (48). S. 1573–1577. (in Russ.).
17.Chung J. W. et al. GaN-on-Si Technology, A New Approach for Advanced Devices in Energy and Communications // Proc. of the European Solid-State Device Research Conf. 2010 (ESSDERC). 2010. P. 52–56.
18.Taking S. AlN/GaN MOS-HEMTs Technology // Glasgow Theses Service, 2012. 175 p.
19.Tekhnologiya izdelij integral'noj ehlektroniki / L. P. Anufriev, S. V. Bordusov [i dr.] pod red. akademika NAN Belarusi A. P. Dostanko i chlena-korrespondenta NAN Belarusi L. I. Gurskogo // Minsk : «Integralpoligraf». 2009. 379 s. (in Russ.).
20.Shchuka A. A. Nanoehlektronika : uchebnoe posobie / M.: BINOM. Laboratoriya znanij, 2012. 342 s. (Nanotekhnologii). (in Russ.).
21.Parikh P., Mishra U., Wu Y. Insulating gate AlGaN/Gan HEMT // United States Patent. 2007. № 7,230,284.
22.Sravnenie svojstv svetodiodnyh kristallov AlGaInN vertikal'noj i flip-chip konstrukcii s ispol'zovaniem kremniya v kachestve platy-nositelya / L. K. Markov [i dr.] // Fizika i tekhnika poluprovodnikov. 2013. № 3 (47). S. 386–391. (in Russ.).

23.Gromov D. V., Matveev Yu. A., Nazarova G. N. Issledovanie vliyaniya ioniziruyushchih izluchenij na harakteristiki geterostrukturnyh polevyh tranzistorov na nitride galliya // Institut ehkstremal'noj prikladnoj ehlektroniki NIYAU «MIFI»; Nacional'nyj issledovatel'skij yadernyj universitet «MIFI». MEHS -2012. Moskva, 2012. (in Russ.).

24.Konstruktivno-tekhnologicheskie osobennosti sensornyh ustrojstv na osnove shirokozonnyh poluprovodnikov / V. S. Volchyok [i dr.] // Doklady BGUIR. 2015. № 7(93). S. 99–105. (in Russ.).

25.Volchyok V. S., Dao Din' Ha, Lovshenko I. Yu., Stempickij V. R. Konstruktivno-tekhnologicheskie osobennosti sensornyh ustrojstv na osnove shirokozonnyh poluprovodnikov // Doklady BGUIR. 2015. № 7(93). S. 99–105. (in Russ.).

26.Volchyok V. S., Stempickij V. R. Optimizaciya konstrukcii tranzistora s vysokoj podvizhnost'yu ehlektronov, obespechivayushchej snizhenie vliyaniya ehffekta samorazogreva // SVCh-tekhnika i telekommunikacionnye tekhnologii (KryMiKo'2016). 2016. S. 1600–1606. (in Russ.).

27.Volchek V., Dao Dinh Ha, Stempitsky V., Tran Tuan Trung. Suppression of the self-heating effect in AlGaN/GaN high electron mobility transistor by diamond heat sink layers // 2016 International Conference on Advanced Technologies for Communications (ATC). 2016. P. 264–267.

28.Volchyok V. S., Stempickij V. R. Optimizaciya konstrukcii AlGaN/GaN HEMT, obespechivayushchaya snizhenie vliyaniya ehffekta samorazogreva s ispol'zovaniem teplootvodyashchih ehlementov na osnove grafena // Nitridy galliya, indiya i alyuminiya – struktury i pribory. 2017. S. 122–123. (in Russ.).

29.Volchyok V. S., Stempickij V. R. Ehlektricheskie i chastotnye svojstva tranzistora s vysokoj podvizhnost'yu ehlektronov s grafenovymi teplootvodyashchimi ehlementami // Sovremennye problemy radioehlektroniki. 2017. S. 500–503. (in Russ.).

30.Volcheck V. S., Stempitsky V. R. Suppression of the self-heating effect in GaN HEMT by few-layer graphene heat spreading elements // J. Phys.: Conf. Ser. 2017. Vol. 917.