Technical Physics, 2026, Vol. 71, No. 2

07

Effects of carrier-substrate type on resistive and optical properties of AlGaAs/GaInAs light-emitting infrared diodes

© A.V. Malevskaya, N.A. Kalyuzhnyy, R.A. Salii, F.Y. Soldatenkov, D.A. Malevskii, V.M. Andreev

Ioffe Institute,
194021 St. Petersburg, Russia
e-mail: amalevskaya@mail.ioffe.ru

Received May 6, 2025
Revised September 30, 2025
Accepted October 6, 2025

Investigations of various designs of light-emitting infrared (840 nm) diodes based on AlGaAs/GaInAs heterostructures with multiple quantum wells, grown by metalorganic vapor-phase epitaxy, have been carried out. The decrease of optical radiation losses in light-emitting diodes has been achieved by including multilayer combined reflectors into the design by transferring thin layers of the heterostructure onto a carrier-substrate based on a semiconductor material (Si, GaAs) or metal (Cu, Au). Analyzed was the influence of device designs on the light-emitting diodes characteristics. Maximum efficiency values of 46 % at a current density of 10−20 A/cm^2 were achieved in devices on a GaAs carrier-substrate. The decrease of resistive losses and increase of optical power up to 730 mW at an operating current of 1.2 A were achieved in devices on a metal currier-substrate.

Keywords: infrared light-emitting diode, AlGaAs/GaInAs heterostructure, currier-substrate.

DOI: 10.61011/TP.2026.02.62886.107-25

Introduction

The field of application of infrared (IR) light-emitting diodes (LEDs) affects various spheres, both scientific and household: medical diagnostics, optical sensors in wireless devices, night vision systems, etc. [1–3]. The optical power of the emitters is increased by developing highly efficient heterostructures with multiple quantum wells [4,5], integrated structural reflectors [6], as well as when modifying the post growth complex, aimed at forming built-in rear reflectors that ensure effective output of radiation generated in the active region [7–10].

The embedded reflectors with a wavelength of $<$ 900 nm should be formed in IR LEDs directly between the active region of the heterostructure and the GaAs substrate absorbing radiation in this wavelength range. The reflector is embedded by transferring thin layers of the heterostructure onto a carrier substrate [11,12]. The influence of device designs with different carrier substrate materials on the characteristics of IR LEDs is analyzed: the serial resistance of the device, efficiency at different operating currents, and the optical power of the emitters.

The issues of manufacturing IR LEDs on semiconductor carrier substrates (Si) with optical radiation power of 180−280 mW at current 200−300 mA are covered in Ref. [8–9]. However, the current dependences of optical power show a slight increase in power with an increase in current to values exceeding 150 mA, which indicates high resistive losses and does not allow high-power devices.

The main objective of the study is to analyze resistive losses when using various materials as a carrier substrate (GaAs semiconductors, Si or Au, Cu metals, etc.) and when varying the methods of transferring thin layers of heterostructure, as well as optimizing the resistive and optical properties of IR LEDs at different operating currents.

1. Formation of IR LEDs on semiconductor and metal carrier substrate

AlGaAs/GaInAs heterostructures of IR (840 nm) LEDs grown by the method of Metalorganic Vapor Phase Epitaxy on a GaAs *n*-type substrate were studied in this paper. The growth of the heterostructure begins with the crystallization of the sacrificial layer of $Al_{0.9}Ga_{0.1}As$, which has high selectivity during chemical etching of the GaAs growth substrate. The active region of the heterostructure includes six GaInAs quantum wells enclosed between wide-gap barrier $Al_{0.2}Ga_{0.8}As$- and $Al_{0.4}Ga_{0.6}As$-layers of *n*- and *p*-type of conductivity. An $Al_{0.2}Ga_{0.8}As$ layer of *n*-type of conductivity with a thickness of 4−6 μm is formed to reduce the spreading resistance, reducing contact resistance is achieved by forming heavily doped GaAs layers of *n*- and *p*-type of conductivity. The post-growth technology of device manufacturing includes the following stages [13]:

- formation of a point contact of *p*-type of conductivity based on NiCr/Ag/Au layers on the surface of the heterostructure;
- application of a multilayer combined reflector based on SiO_2/NiCr/Ag/Ti/Pt layers;
- transfer of a heterostructure to a carrier substrate (GaAs or Au);
- removal of the growth substrate and sacrificial layer of $Al_{0.9}Ga_{0.1}As$ by selective chemical etching;

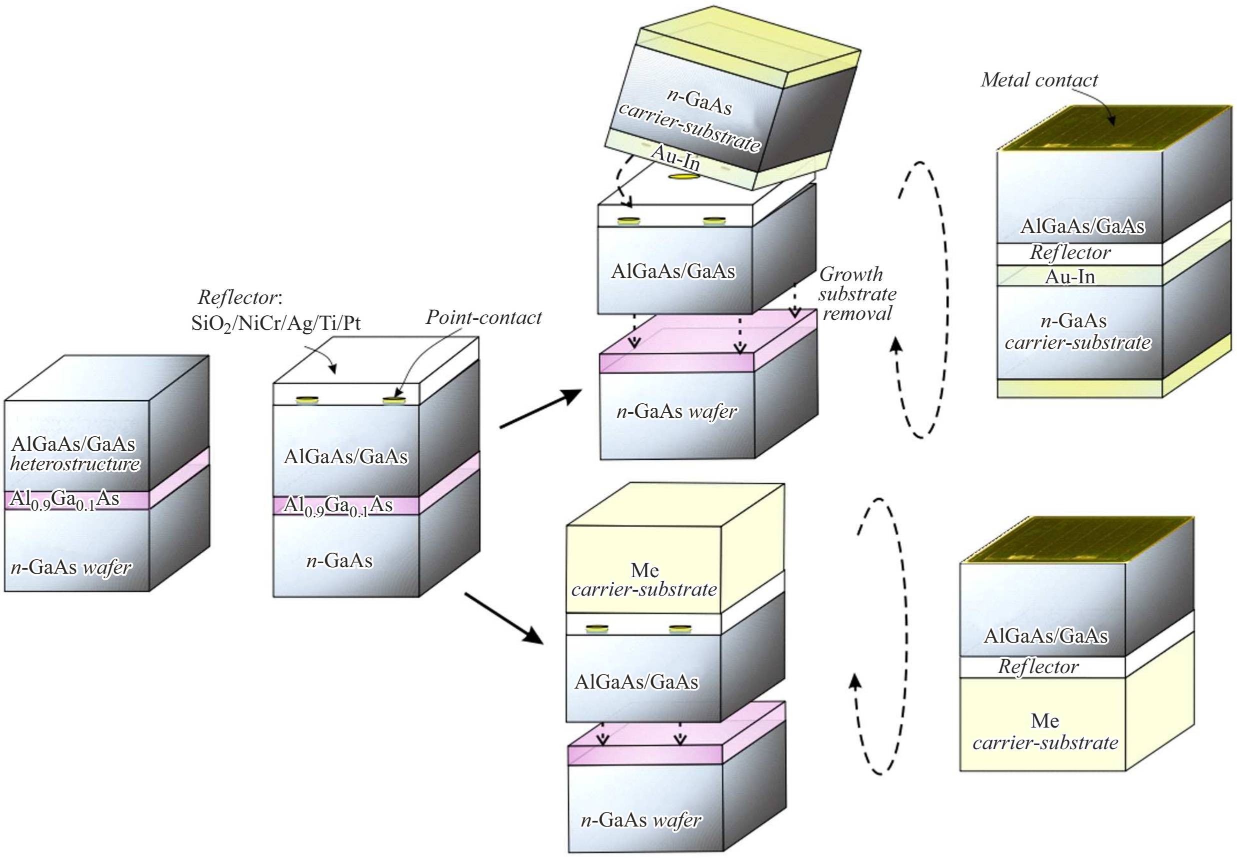

Figure 1. Schematic representation of the stages of formation of an IR LED with a rear combined reflector SiO_2/NiCr/Ag/Ti/Pt on a *n*-GaAs or metal carrier substrate.

- formation of a frontal ohmic contact of *n*-type of conductivity based on Pd/Ge/Au layers;
- texturing of the light-emitting surface.

The resistive losses of the IR LED can be reduced by developing an optimal configuration of ohmic contacts that ensure a minimal contribution to the spreading resistance, specific contact resistance and series resistance of the device as a whole, as well as by optimizing the technology of mounting a carrier substrate made of a material with high electrical conductivity.

GaAs semiconductor carrier substrate is used because its coefficient of thermal expansion is similar to the coefficient of thermal expansion of an epitaxial heterostructure material, which is especially important to prevent degradation of IR LEDs during heating during their manufacture and operation [11]. However, the GaAs carrier substrate is mounted by mechanical docking through the intermetallic compound Au–In, which can lead to the formation of micropores on the heterogeneous boundary of the structure–Au–I*n*-substrate and, accordingly, to an increase in resistive losses [12].

The use of a gold carrier substrate is due to its high electrical conductivity and chemical resistance to environmental influences, while the use of alternative metals reduces the cost of LED crystals. The formation of a metal carrier substrate is carried out by electrochemical buildup of metal directly on the surface of the rear combined reflector of the heterostructure (Fig. 1). The advantage of this technology is the absence of mechanical coupling of the heterostructure and the carrier substrate. However, the difference in the coefficients of thermal expansion of the heterostructure material (AlGaAs/GaInAs) and metals (Cu, Au) can lead to the appearance of microdefects in the heterostructure, which requires a more detailed study of the carrier design and modes of its formation.

The metal carrier substrate was formed by electrochemical deposition of gold from a cyanide electrolyte in two stages: at a cathode current density of $0.01\,\mathrm{mA/mm^2}$ at the initial stage of nucleation to ensure high adhesion to the surface of the structure and at an operating current density of $0.08-0.1\,\mathrm{mA/mm^2}$ to form a monolithic support substrate with a thickness of $60-80\,\mu$m.

After the formation of the carrier substrate, the GaAs growth substrate and the sacrificial layer $Al_{0.9}Ga_{0.1}As$ are removed, followed by sputtering of the frontal ohmic contact. Due to the difference in the coefficients of thermal expansion of the heterostructure material and the metal carrier substrate, it is necessary to minimize the thermal effect on the LED crystal. The use of a Pd/Ge/Au contact system with a low resistivity $\sim 10^{-6}\,\Omega\cdot\mathrm{cm}^2$ to a GaAs

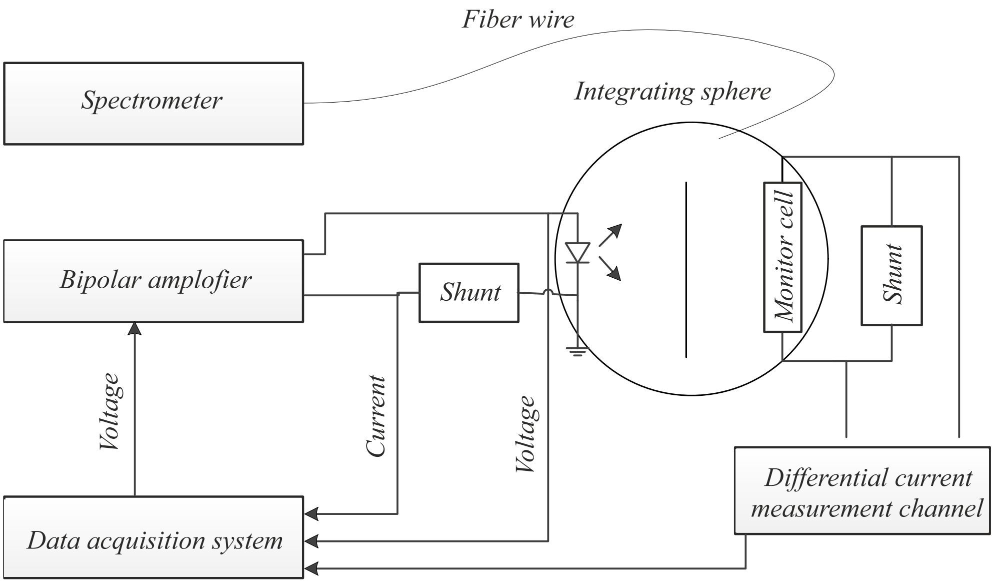

Figure 2. Block diagram of an installation for measuring the efficiency, IV and power-current characteristics of LEDs.

contact layer of *n*-type of conductivity at low ignition temperatures of $\sim 185\,^\circ$C prevents thermal degradation of IR LEDs [14].

The reduction of resistive losses of IR LEDs was achieved by increasing the thickness of the contact bus-bars to $2-4.5\,\mu$m by electrochemical deposition of contact materials based on Ag/Ni/Au layers. When designing devices on a metal carrier substrate, the main task is to increase the efficiency of LEDs at high currents, which leads to the need to form contact bus-bars with a larger cross-sectional area ($4.5\,\mu$m thick with a width of $8\,\mu$m). In LED designs on a GaAs carrier substrate designed to operate at low currents, the main task is to reduce optical losses, which is achieved by reducing the degree of shading of the light-emitting surface when forming contact bus-bars with a smaller cross-sectional area ($2\,\mu$m thick with a width of $7\,\mu$m).

According to the results of the study, two types of IR (840 nm) LED crystals with an area of 1 mm^2 were produced on carrier substrates made of GaAs ($400-450\,\mu$m thick) and Au ($60-80\,\mu$m thick), they were installed on ceramic heat-dissipating bases. The optical element is formed in the form of a silicone hemisphere on the light-emitting surface of the LED to increase the output of radiation from the crystal [11].

2. Methodology for studying the characteristics of LED crystals

To analyze the influence of designs and methods of manufacturing IR LEDs on the characteristics of developed devices, measurements of current-voltage and optical power-current characteristics, current dependences of efficiency were performed, values of serial and shunting *p*-*n*-junction resistance were calculated. Measurements in quasi-constant mode at low current density ($10^{-7}-10^{-1}$ A/cm^2) were carried out using a Keithley 2400 measuring source to set current and register voltage, as well as an AKIP V7/78 voltmeter to register the current signal from the control photodetector. Measurements at high current density (up to 100 A/cm^2) were carried out in pulse mode (single pulse duration $10-100\,\mu$s, off-duty ratio > 1000) using a digital data input/output system for recording current, voltage the investigated LED and the signal from the control photodetector. The voltage sweep of the IR LED was carried out using a bipolar amplifier. To reduce the influence of the angular divergence of LED radiation, measurements were carried out in an integrating sphere (Fig. 2). The luminescence spectra were recorded with a spectrometer with a sensitivity range of $350-1100$ nm (Fig. 3, *a*).

Additionally, the electroluminescence method was used to detect local defects using a camera with sensitivity in the wavelength range $350-1050$ nm. The uniform distribution of the electroluminescence of the IR LEDs over the entire area of the LED crystal indicates the absence of defects on the surface, as well as the optimal choice of the configuration of the frontal ohmic contact and the parameters of the $\mathrm{Al_{0.2}Ga_{0.8}As}$-layer of spreading (Fig. 3, *b*).

3. The effect of resistive losses on the efficiency and optical power of IR LEDs

To estimate the series resistance of the IR LED, the current-voltage (IV) characteristic were measured (Fig. 4) and the idealized IV characteristic (at $Rs = 0\,\Omega$) was approximated. The measurement results showed that during monolithic electrochemical build-up of a metallic (Au)

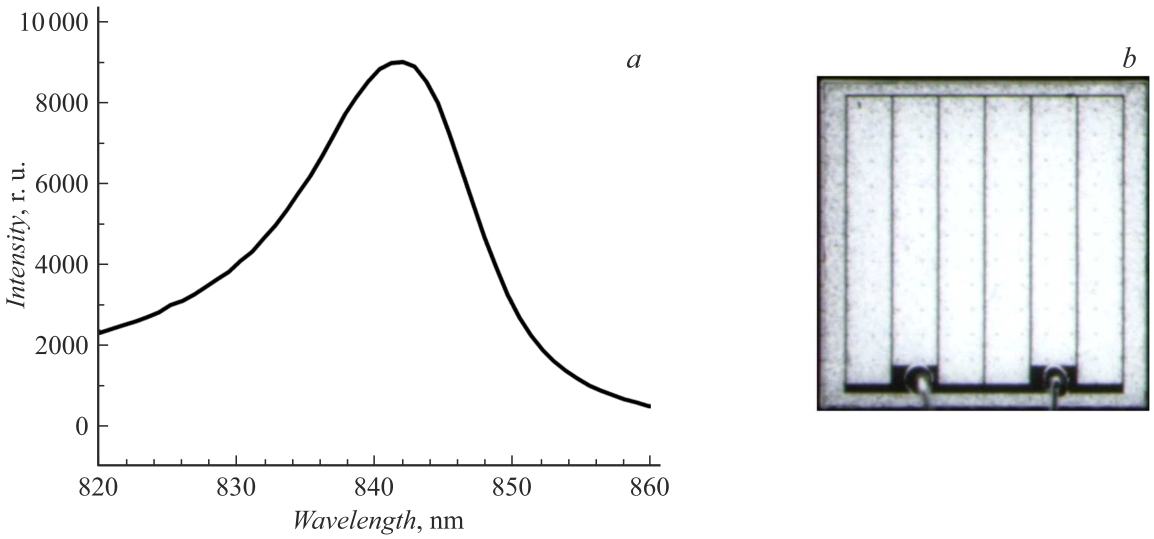

Figure 3. Spectral characteristic of an IR (840 nm) LED crystal with a size of 1×1 mm (*a*) and the distribution of electroluminescence (*b*).

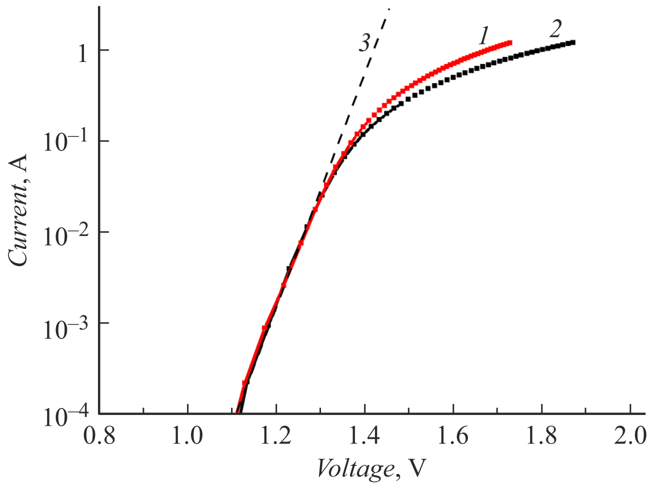

Figure 4. IV characteristics of IR (840 nm) LEDs on a carrier substrate made of Au (*1*) or GaAs (*2*); approximation of an idealized IV characteristics (*3*).

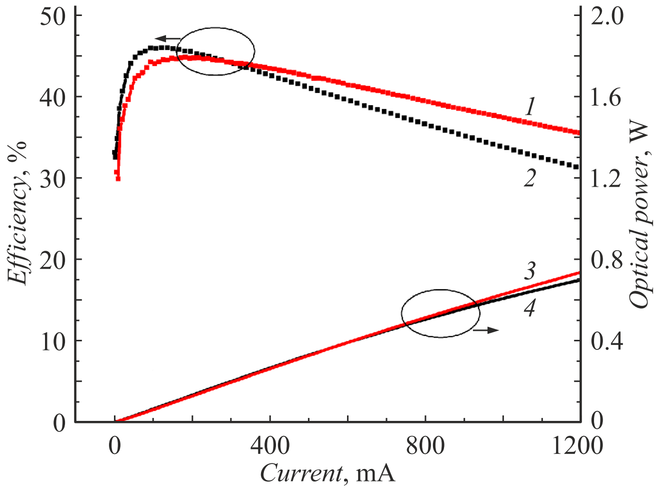

Figure 5. Current dependences of efficiency and optical power of IR (840 nm) LEDs on a carrier substrate made of Au (*1*, *3*) or GaAs (*2*, *4*).

carrier substrate onto the surface of a heterostructure with a reflector, the sequential resistance of the LED area is $1\,\mathrm{mm}^2$ is $Rs = 0.24\,\Omega$. When the heterostructure and the GaAs carrier substrate are mechanically joined via the Au–In connection, the series resistance of the devices increases to $Rs = 0.36\,\Omega$. Thus, the use of a metal carrier substrate reduces resistive losses and allows for more efficient conversion of electric power at high currents ($> 100-200$ mA).

To analyze the effect of series resistance on the characteristics of IR LEDs, current dependences of efficiency and optical power were measured for two types of device designs (Fig. 5). The maximum efficiency values $\eta = 46\,\%$ were achieved in IR LEDs ($1\,\mathrm{mm}^2$) on a GaAs carrier substrate at current density of $10-20\,\mathrm{A/cm}^2$ and $\eta = 37\,\%$ in LEDs on a gold carrier substrate at a current density of $100\,\mathrm{A/cm}^2$.

The advantage of the gold substrate in the high current range ($100-120\,\mathrm{A/cm}^2$) contributes to the increase in efficiency by 5 %. In the range up to $20\mathrm{A/cm}^2$, slightly lower efficiencies were recorded for such LEDs (by 1 %–2 %) compared to LEDs on a GaAs carrier. This is due to the stresses transmitted from the gold carrier to the AlGaAs/GaInAs heterostructure, with the formation of microdefects, as well as the configuration of the frontal ohmic contact with an increased cross-sectional area of the contact bus-bars, which leads to a decrease in resistive losses at high current densities, but at the same time leads to a slight increase in optical losses, which affects a drop in efficiency.

Conclusion

Research and development of various designs of IR (840 nm) LEDs with an integrated multilayer combined reflector, made by transferring thin layers of AlGaAs/GaInAs heterostructure onto a carrier substrate made of metal or semiconductor material, has been performed. At low current densities, resistive losses do not affect the efficiency of the devices, which made it possible to achieve maximum efficiency values of 46 % at current densities 10–20 A/cm^2 in devices on a GaAs carrier substrate. A decrease in resistive losses and an increase in optical power to 730 mW at an operating current of 1.2 A were obtained in devices on a metal carrier substrate.

The possibilities of obtaining IR LEDs operating in various current ranges were studied. Each type of device studied can have its own field of application. Highly efficient LEDs made on a GaAs carrier substrate can be used in low-power optoelectronic devices. Powerful LEDs ($P_{rad} > 700$ mW) on a metal carrier substrate can be widely used, for example, for IR illumination and in security systems.

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] M. Vasilopoulou, A. Fakharuddin, F.P. Arquer, D.G. Georgiadou, H. Kim, A.R. Yusoff, F. Gao, M.K. Nazeeruddin, H.J. Bolik, E.H. Sargent. Nat. Photon., **15**, 656 (2021). DOI: 10.1038/s41566-021-00855-2

[2] A.G. Entrop, A. Vasenev. Energy Proc., **132**, 63 (2017). DOI: 10.1016/j.egypro.2017.09.636

[3] M. Kitamura, T. Imada, S. Kako, Y. Arakawa, Y. Jpn. J. Appl. Phys., **43**, 2326 (2004). DOI: 10.1143/JJAP.43.2326

[4] L. Han, M. Zhao, X. Tang, W. Huo, Zh. Deng. J. Appl. Phys. V, 127, (2020). DOI: 10.1063/1.5136300

[5] Y. Yu, X. Qin, B. Huang, J. Weia, H. Zhou, J. Pan, W. Chen, Yun Qi, X. Zhang, Z. Ren. Vacuum, **69**, 489 (2003). DOI: 10.1016/S0042-207X(02)00560-2

[6] Su-Chang Ahn, Byung-Teak Lee, Won-Chan An, Dae-Kwang Kim, In-Kyu Jang, Jin-Su So, Hyung-Joo Lee. J. Korean Phys. Soc., **69** (1), 91 (2016). DOI: 10.3938/jkps.69.91

[7] H.-J. Lee, G.-H. Park, J.-S. So, Ch.-H. Lee, J.-H. Kim, L.-K. Kwac. Infrared Phys. Technol., **118**, 103879 (2021). DOI: 10.1016/j.infrared.2021.103879

[8] H.-J. Lee, I.-K. Jang, D.-K. Kim, Y.-J. Cha, S.W. Cho. Micromachines, **13**, 695 (2022). DOI: 10.3390/mi13050695

[9] H.-J. Lee, G.-H. Park, J.-S. So, J.-H. Kim, H.-G. Kim, L.-K. Kwac. Current Appl. Phys., **22**, 36 (2021). DOI: 10.1016/j.cap.2020.12.002

[10] E.F. Shubert. *Light-Emitting Diodes* (second edition) (Cambridge University Press, 2006)

[11] A.V. Malevskaya, N.A. Kalyuzhnyy, D.A. Malevskii, S.A. Mintairov, A.M. Nadtochiy, M.V. Nakhimovich, F.Y. Soldatenkov, M.Z. Shvarts, V.M. Andreev. Semiconductors, **55** (8), 686 (2021). DOI: 10.1134/S1063782621080121

[12] N.A. Kalyuzhnyy, A.V. Malevskaya, S.A. Mintairov, M.A. Mintairov, M.V. Nakhimovich, R.A. Salii, M.Z. Shvarts, V.M. Andreev. Sol. Energy Mater. Sol. Cells, **262**, 112251 (2023). DOI: 10.1016/j.solmat.2023.112551

[13] A.V. Malevskaya, N.A. Kalyuzhnyy, R.A.Salii,, F.Yu.Soldatenkov, M.V.Nakhimovich, D.A.Malevskii. Pis'ma v ZhTF, **50** (18), 22 (2024) (in Russian). DOI:10.61011/PJTF.2024.18.58625.19946

[14] A.V. Malevskaya, F.Yu. Soldatenkov, R.V. Levin, N.A. Kalyuzhnyy, M.Z. Shvarts. Vacuum, **233**, 114030 (2025). DOI: 10.1016/j.vacuum.2025.114030

Translated by E.Ilyinskaya