UDC 621.315.592

Photoelectric laser radiation converter $\lambda = 1064$ nm based on GaInAsP/InP

© K.A. Gavrilov[1], V.V. Evstropov[1], N.A. Kalyuzhnyy[1], M.A. Mintairov[1], S.A. Mintairov[1,¶], A.M. Nadtochiy[2], M.V. Nakhimovich[1], E.V. Pirogov[2], R.A. Salii[1], M.Z. Schwarts[1]

[1] Ioffe Institute,
194021 St. Petersburg, Russia
[2] Alferov University,
194021 St. Petersburg, Russia
[¶] E-mail: mintairov@scell.ioffe.ru

Received April 30, 2025
Revised September 8, 2025
Accepted November 11, 2025

InAsP and GaInAsP layers were grown on InP substrates using the metal-organic vapor-phase epitaxy method. The studies conducted using the photoluminescence, X-ray diffractometry, and energy-dispersive X-ray spectroscopy methods allowed us to determine the conditions for growing $Ga_{0.26}In_{0.74}As_{0.5}P_{0.5}$ layers with $\Delta a/a = 2000$ ppm and a band gap of 1.04 eV (absorption edge 1190 nm). Based on these layers, a laser radiation photoconverter structure for $\lambda = 1064$ nm was grown. The measurements and calculations made it possible to predict the efficiency of such a structure at a level of 40 % at a laser radiation incident power density of $\lambda = 1064$ nm up to 30−50 W/cm^2.

Keywords: laser photoconverter, MOVPE, spectral characteristics, mathematical modeling.

DOI: 10.61011/SC.2025.08.62597.7973

Recently, the task of transmission of energy over long distances by a laser beam has become increasingly relevant and finds a number of practical applications. In particular, powerful and efficient solid-state lasers based on yttrium garnet with a wavelength of $\lambda = 1064$ nm, are optimally suited for this. The laser photoconverter (LPC), designed for $\lambda = 1064$ nm, was first created in 1981 [1]. It was an InP/GaInAsP/InP heterostructure grown by liquid-phase epitaxy and had an efficiency of ~ 43 % at an incident laser power of 4.85 mW [1]. At that time, the general level of technology did not allow the implementation of the concept of laser wireless energy transmission, which began to develop actively only at the beginning of the 21st century in connection with NASA projects [2]. To date, the best GaInAsP-based LPC has an efficiency of ~ 41 % at an incident radiation power of 1.67 W [3]. Also, silicon structures were proposed for $\lambda = 1064$ nm LPC and the conversion efficiency of ~ 38.8 % (incident power density 1.3 W/cm^2) was demonstrated [4]. However, this result was achieved using a very complex surface texturing procedure, and the peak power of the converted radiation was insufficient for wireless power transmission systems. It should be noted that to date, the metamorphic InGaAs LPC technology has been developed, which allows for an efficiency of up to 50 % at an incident power density of > 10 W/cm^2 [5,6]. At the same time, the technology of monolithic GaInAsP/InP LPC lattice parameter-matched has a greater potential than the technology of metamorphic InGaAs LPC, due to the leakage currents inherent in perfect crystals compared to metamorphic layers.

Theoretical estimates of efficiency for GaInAsP-based LPC with a band gap of $E_g = 1.16$ eV (corresponding to $\lambda = 1064$ nm) reach 75 % with a photocurrent density of 103 A/cm^2, which is equivalent to the incident radiation power of 1.16 kW/cm^2 [7]. Thus, studies for creating highly effective GaInAsP-based LPC are relevant.

The LPC heterostructure was created in this study based on the system of GaInAsP/InP materials. The technology of metalorganic vapor phase epitaxy (MOVPE) using a horizontal low-pressure reactor was applied for epitaxial growing. Phosphorus hydrides (PH_3) and arsenic hydrides (AsH_3) were used as sources of group V atoms. Trimethylgalium (TMGa) and trimethylindium (TMIn) were used as sources of group III atoms, silane (SiH_4) was used as a source of n-type impurity, and diethylzine (DEZn) was used as a source of a p-type impurity.

Epitaxial experiments for growing $InAs_xP_{1-x}$ layers on InP substrates were conducted with the ratio of molar fluxes of V and III group atoms in the gas phase ~ 70 and 260. The position of the peaks in the photoluminescence (PL) spectra made it possible to calculate arsenic concentrations in the layers (Figure 1, a) using data on the parameters of $A^{III}In^{V}$ zones of semiconductors and their solid solutions [8]. It is important to note that layers with a similar composition had a higher peak intensity at a high ratio of V/III (Figure 1, a). The $InAs_{0.45}P_{0.55}$ layers were obtained with the ratio of the molar fluxes of arsenic atoms to the total flux of group V atoms (As/V) equal to 0.043. An order of magnitude higher concentration of arsenic atoms in the solid phase compared to the gas phase is explained by the fact that phosphine does not decompose completely at

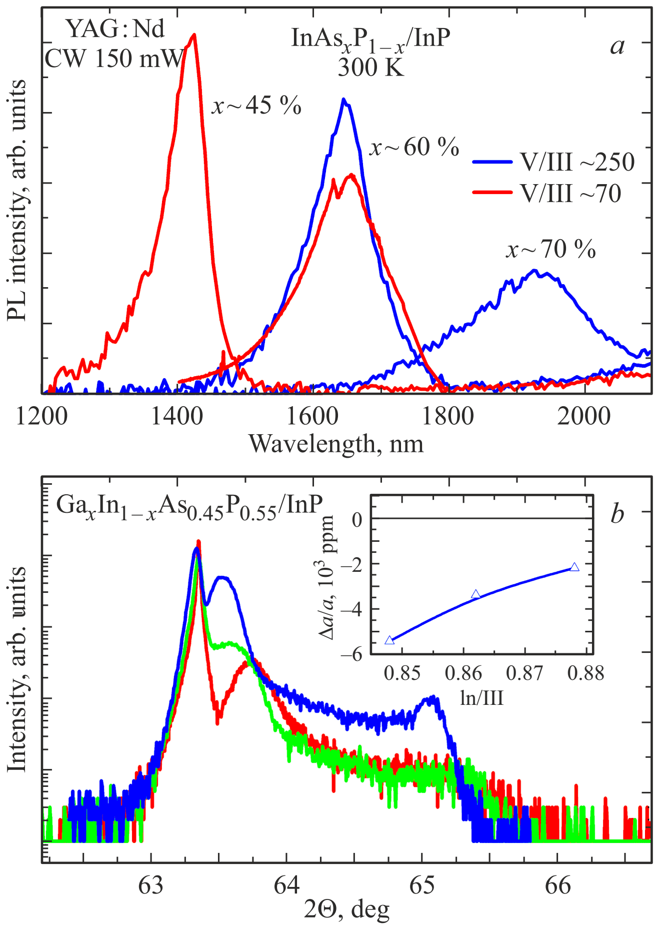

Figure 1. *a* — photoluminescence spectra at room temperature for InAsP layers of various compositions grown on InP substrates at a ratio of V and III groups in the gas phase ~ 70 (red lines) and ~ 250 (blue lines); *b* — X-ray rocking curves of $Ga_xIn_{1-x}As_{0.45}P_{0.55}$ layers grown on InP substrates at various temperatures the ratio of indium atoms to group III atoms in the gas phase (in the inset, the mismatch of the layers of $Ga_xIn_{1-x}As_{0.45}P_{0.55}$ depends on the In/III ratio).

growth temperatures, which reduces the concentration of atomic phosphorus above the growth surface.

Experiments for growing $Ga_xIn_{1-x}As_{0.45}P_{0.55}$ layers on InP substrates were carried out with different ratios of molar fluxes of indium atoms to the total flux of group III atoms in a gas phase (In/III). Measurements of X-ray (XRD) rocking curves (Figure 1, *b*) allowed establishing the dependence of the mismatch of the epitaxial layers and the substrate ($\Delta a/a$) on the ratio In/III (Figure 1, *b*, see insert) and obtaining layers mismatching with the substrate by only -2000 ppm. The data presented in Ref. [8] allow estimating the composition of the solid solution ($\Delta a/a = -2000$ ppm) as $Ga_{0.23}In_{0.77}As_{0.45}P_{0.55}$ with a band gap of 1.06 eV (absorption edge 1170 nm).

Studies of the layer with $\Delta a/a = -3400$ ppm (Figure 2, *b*, green line) by electron microscopy showed that the layer had a raised surface due to relaxation of elastic stresses (Figure 2, *a*).

The compositions in the grown $Ga_xIn_{1-x}As_yP_{1-y}$ layers were determined by energy-dispersive X-ray (EDX) spectroscopy measurements of the layer with $\Delta a/a = -3400$ ppm (Figure 2,*b*, green line), corresponding, according to previous experiments, to a solid solution of $Ga_{0.25}In_{0.75}As_{0.45}P_{0.55}$, (Figure 2, *b*). The atomic concentrations in the layer, determined using X-ray spectroscopy, correspond to a solid solution of $Ga_{0.28}In_{0.72}As_{0.5}P_{0.5}$, having a calculated mismatch of $\Delta a/a = -3500$ ppm. Thus, we can talk about a good matching between the experimental data obtained from PL studies using PL, XRD, and EDX methods. The concentrations of arsenic and phosphorus atoms determined by the EDX method made it possible to determine a solid solution with $\Delta a/a = -2000$ ppm (Figure 2, *b*, blue line) as $Ga_{0.26}In_{0.74}As_{0.5}P_{0.5}$ with a band gap of 1.05 eV (absorption edge 1190 nm).

On the basis of this layer, the LPC structure was grown, consisting of *p*-$Ga_{0.26}In_{0.74}As_{0.5}P_{0.5}$ layers sequentially deposited on a *p*-InP substrate, acting as a rear potential barrier of a 4 μm thick base, doped with zinc atoms, *n*-$Ga_{0.26}In_{0.74}As_{0.5}P_{0.5}$ emitter 200 nm thick, doped with silicon atoms, *n*-InP wide-band window 150 nm thick and n^{++}-InGaAs of the contact layer with a thickness of 30 nm. An LPC was made from the grown structure using a simplified technology without an antireflective coating. For this purpose, contacts were applied to the back and front sides of the structure by electrochemical deposition of nickel, and in the area not covered by the contact, the n^{++}-InGaAs layer was removed by chemical etching.

The measured spectrum of the external quantum efficiency (EQE) of LPC in the range of 1000–1100 nm does not exceed 50–55 % (Figure 3, *a*, red triangles), and the EQ is 52 % at a wavelength of 1060 nm (corresponds to a spectral sensitivity of (*SR*) 0.45 A/W), which is primarily due to the lack of an antireflective coating. The absorption edge corresponds well to the calculated band gap of the absorbing layers $Ga_{0.26}In_{0.74}As_{0.5}P_{0.5}$ (Figure 3, *a*). To estimate the coefficient of collecting photogenerated media from photo assets using the methodology described in Ref. [9].

The calculated EQE spectrum (Figure 3, *a*, red line) agrees well with the experimental one for the values of the diffusion lengths of the non-basic charge carriers: $L_p = 240$ nm, $L_n = 1800$ nm for the emitter and base, respectively. The low value of the diffusion length in the base (more than 2 times less than the thickness) causes incomplete collection of the photogenerated media and is probably due to defects due to misalignment of the photoactive layers with the substrate. The calculated spectrum of internal quantum efficiency (Figure 3, *a*, blue line) does not exceed 80–85 %, and the quantum efficiency is 72 % at a wavelength of 1060 nm (corresponds to $SR = 0.61$ A/W).

To determine the efficiency of the LPC, its volt-ampere characteristic (VAC) was calculated using the current

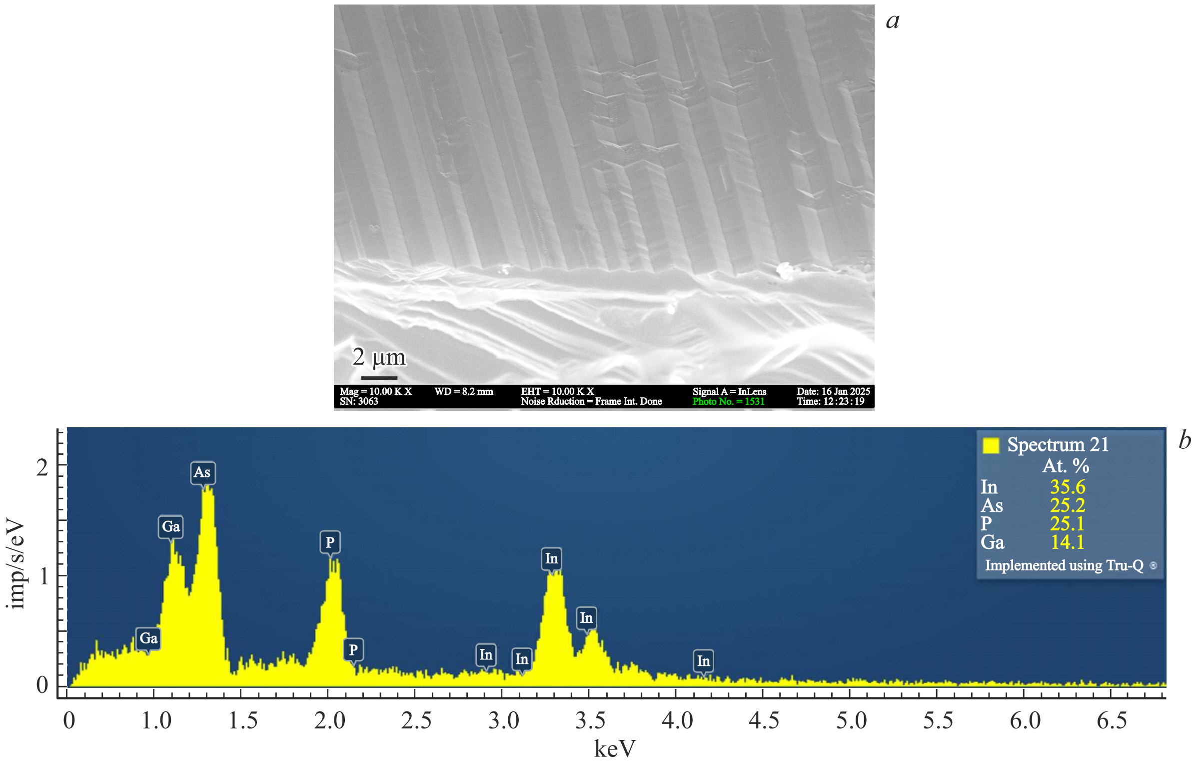

Figure 2. *a* — image of the sample surface of the $Ga_{0.28}In_{0.72}As_{0.5}P_{0.5}$layer obtained by electron microscopy; *b* — energy dispersion spectrum of excited X-ray radiation of the $Ga_{0.28}In_{0.72}As_{0.5}P_{0.5}$ layer.

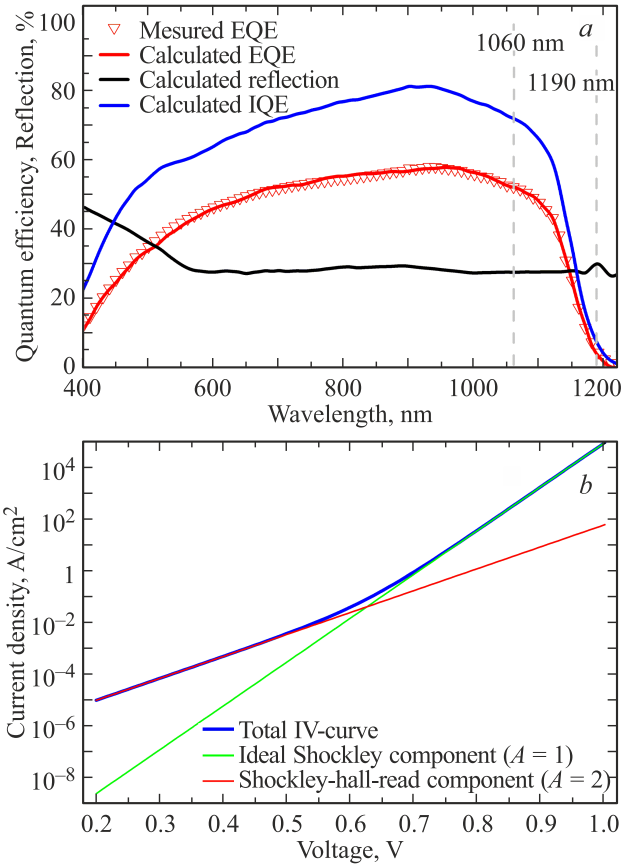

Figure 3. *a* — measured EQE spectrum of LPC based on $Ga_{0.26}In_{0.74}As_{0.5}P_{0.5}$ (red triangles), as well as calculated spectra of EQE (red line), reflection (black line) and internal quantum efficiency (blue line); *b* — dark non-resistive VAC of LPC based on $Ga_{0.26}In_{0.74}As_{0.5}P_{0.5}$ calculated by the current invariant method.

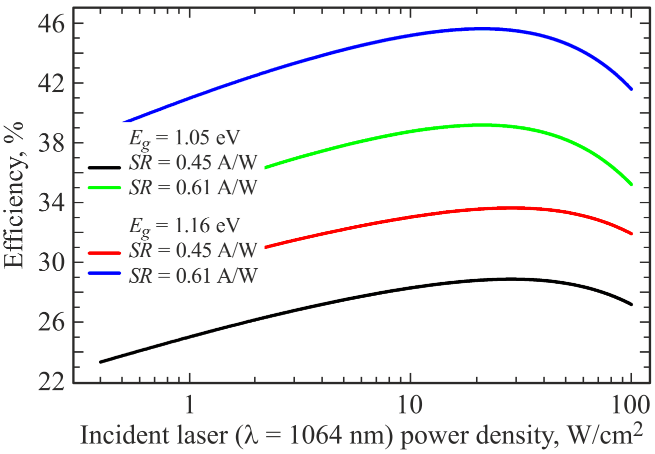

Figure 4. Calculated dependences of the efficiency of LPC based on $Ga_{0.26}In_{0.74}As_{0.5}P_{0.5}$ on the incident power density of laser radiation with $\lambda = 1064$ nm at a series resistance of 0.01 Ohm · cm: black line — $E_g = 1.05$ eV, $SR = 0.45$ A/W; green line — $E_g = 1.05$ eV, $SR = 0.61$ A/W; red line — $E_g = 1.16$ eV, $SR = 0.45$ A/W; blue line — $E_g = 1.16$ eV, $SR = 0.61$ A/W.

invariant model [10], which makes it possible to give a reliable (the model has been experimentally confirmed) estimate for the saturation currents of the two-diode photoconverter model [11], knowing the band gap absorbing material. Such a VAC is shown in Figure 3, *b*, and the saturation current densities were: $J_{01} = 7 \cdot 10^{-13}$ A/cm^2 and $J_{02} = 2 \cdot 10^{-7}$ A/cm^2 for diffusion and recombination mechanisms of dark current flow, respectively.

The production of LPC from a grown structure with the application of a face contact grid will result in the appearance of a series resistance of the device ~ 0.01 Ohm · cm [12,13]. This allows estimating the efficiency of the structure without an antireflective coating (at $SR = 0.45$ A/W) at the level of 29 % when converting laser radiation with $\lambda = 1064$ nm and an incident power density of 30–50 W/cm^2 (Figure 4, black line), and applying an antireflection coating will increase the efficiency (Figure 4, green line) to ~ 40 % (at $SR = 0.61$ A/W).

A further increase in the efficiency of the LPC can be achieved by fully matching the GaInAsP absorbing layers with the substrate in terms of the lattice parameter. This should lead to an increase in the diffusion lengths of the non-basic charge carriers and an increase in *SR*. Moreover, the efficiency will increase if the band gap of the GaInAsP absorbing layers is increased to 1.16 eV, which will allow for lower saturation currents and, as a result, a higher no-load voltage. The values of saturation currents were estimated using the invariant method. The material with $E_g = 1.16$ eV had the following saturation current densities: $J_{01} = 1 \cdot 10^{-14}$ A/cm^2 and $J_{02} = 2 \cdot 10^{-8}$ A/cm^2 for diffusion and recombination mechanisms, respectively. At the same time, if we preserve the LPC structure and assume that the diffusion lengths of the minor charge carriers will not change when the absorbing layer $E_g = 1.16$ eV is grown (i.e., the spectrum of the external quantum output is preserved), then the calculated efficiency values are 34 % at $SR = 0.45$ A/W, which corresponds to the absence of an antireflective coating (Figure 4, red line) and 46 % at $SR = 0.61$ A/W, which corresponds to the presence of an antireflective coating (Figure 4, blue line).

Funding

The study was carried out with the financial support of the Ministry of Science and Higher Education of the Russian Federation (subject FFUG-2024-0026). A.M. Nadtochiy thanks the Ministry of Science and Higher Education of the Russian Federation for financial support (project FSRM-2023-0010), E.V. Pirogov thanks the Ministry of Science and Higher Education of the Russian Federation (project FSRM-2023-0006).

Acknowledgments

The authors would like to express their gratitude to I.P. Soshnikov for measurements using electron microscopy and EDX methods.

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] H.D. Law, W.W. Ng, K. Nakano, P.D. Dapkus, D.R. Stone. IEEE Electron Dev. Lett., **2** (2), 26 (1981). DOI: 10.1109/EDL.1981.25327

[2] H. Liu, Y. Zhang, Y. Hu, Z. Tse, J. Wu. Power Electron. Drives, **6** (41), 167 (2021). DOI: 10.2478/pead-2021-0010

[3] J.J. Yin, Y.R. Sun, A.C. Wang, S.Z. Yu, J.S. Wang, Q.X. Fu, J. Qin, Y.H. Han, W. Zhang, S.M. Zhang, C. Xue, J.R. Dong. IEEE Electron Dev. Lett., **43** (8), 1291 (2022). DOI: 10.1109/LED.2022.3183833

[4] M.A. Green, J. Zhao, A. Wang, S.R. Wenham. IEEE Electron Dev. Lett., **13**, 317 (1992).

[5] N.A. Kalyuzhnyy, V.M. Emelyanov, V.V. Evstropov, S.A. Mintairov, M.A. Mintairov, M.V. Nahimovich, R.A. Salii, M.Z. Shvarts. Sol. Energy Mater. Sol. Cells, **217**, 110710 (2020). DOI: 10.1016/j.solmat.2020.110710

[6] C. Pellegrino, H. Helmers, J. Ohlmann, O. Höhn, D. Lackner. In: 2023 13th Eur. Space Power Conf. (ESPC), Elche, Spain: IEEE, Oct. 2023, pp. 1–4. DOI: 10.1109/ESPC59009.2023.10298134

[7] V.M. Andreev. Sovrem. elektron., **6**, 28 (2014). (in Russian).

[8] I. Vurgaftmana, J.R. Meyer, L.R. Ram-Mohan. J. Appl. Phys., **89** (11), 5815 (2001).

[9] C.A. Mintairov, V.M. Andreev, V.M. Yemelyanov, N.A. Kalyuzhny, N.K. Timoshina, M.Z. Schwartz, V.M. Lantratov. FTP, **44** (8), 1118 (2010). (in Russian).

[10] M.A. Mintairov, V.V. Evstropov, S.A. Mintairov, M.V. Nakhimovich, R.A. Salii, M.Z. Shvarts, N.A. Kalyuzhnyy. Sol. Energy Mater. Sol. Cells, **264**, #112619 (2024). DOI: 10.1016/j.solmat.2023.112619

[11] P. Wurfel. *Physics Of Solar Cells: From Principles To New Concepts* (Weinheim, Wiley-VCH, 2005).

[12] M.A. Mintairov, V.V. Evstropov, N.A. Kalyuzhny, S.A. Mintairov, N.H. Timoshina, M.Z. Schwartz, V.M. Lantratov. FTP, **46** (8), 1074 (2012). (in Russian).

[13] H. Helmers, E. Oliva, M. Schachtner, G. Mikolasch, L.A. Ruiz-Preciado, A. Franke, J. Bartsch. Progr. Photovolt.: Res. Appl., **32**, 636 (2024).

Translated by A.Akhtyamov