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Metamorphic InGaAs/GaAs heterostructures for radiation-resistant laser power converters

© M.Z. Shvarts, V.M. Emelyanov, P.D. Kornienko, V.R. Larionov, S.A. Levina, S.A. Mintairov, M.V. Nakhimovich, R.A. Salii, N.A. Kalyuzhnyy

Ioffe Institute,
194021 St. Petersburg, Russia
E-mail: shvarts@scell.ioffe.ru

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Solutions are presented for photovoltaic converters based on metamorphic $In_xGa_{1-x}As$ heterostructures with a built-in Bragg reflector. Photovoltaic converters are optimized for efficient operation under power laser radiation with a wavelength of 1000−1100 nm. Experimental estimates of the photovoltaic parameters degradation rate are obtained at converters irradiation with 2 and 4.5 MeV electrons

Keywords: photovoltaic laser power converter, laser radiation, metamorphic heterostructure, radiation resistance.

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Photovoltaic laser power converters (LPCs) are being used more and more often to establish remote (with energy transmission via optical fiber or open channels) power supply of systems and devices. Currently available high-power lasers cover several key spectral wavelength ranges, including those corresponding to the atmospheric transparency bands (for open energy transmission channels) and optical fiber transparency windows (for the corresponding transmission lines). Of the utmost interest are the spectral ranges that are covered both by readily available high-power sources of laser radiation (800−860, 1064 nm, etc.) and by efficient semiconductor LPCs „tuned" to the chosen wavelength of laser radiation and optimized in design and functional parameters for operation at high illumination intensities [1–4].

The need for wireless or fiber-optic power supply for devices (test and diagnostic equipment, etc.) positioned in regions with high levels of radiation exposure, which include outer space and unshielded sites in the proximity of atomic (nuclear) reactors, charged particle accelerators, isotope sources, and other objects, necessitates the development of heterostructures for radiation-resistant LPCs. One effective way to enhance the radiation resistance of LPCs is to reduce the thickness of photoactive layers while maintaining the fraction of absorbed radiation by incorporating a Bragg reflector (BR), which acts as a selective mirror (for radiation with a wavelength corresponding or close to the fundamental absorption edge of the material) and a rear potential barrier for photogenerated carriers, into the structure [5,6]. The results of radiation degradation studies for GaAs LPCs within the 800−860 nm range have been widely reported, since this semiconductor material is used in solar cells on spacecraft [7,8].

$In_xGa_{1-x}As$ subcells with up to 30 % of In are touted as a narrow-band cascade (with photosensitivity up to 1200 nm) of monolithic multi-junction solar cells [9]. However, published data on their radiation resistance are extremely scarce [10,11].

In the present study, we discuss design solutions for LPCs based on metamorphic $In_xGa_{1-x}As$ heterostructures with BR optimized for efficient conversion of high-power laser radiation (LR) with a wavelength of 1000−1100 nm and assess their radiation resistance under irradiation with high-energy (2 and 4.5 MeV) electrons.

Metamorphic $In_xGa_{1-x}As$ heterostructures for LPCs were fabricated by metalorganic vapor-phase epitaxy in a laboratory-scale AIX 200/4 reactor [8,12] (Figure 1). The spectral photosensitivity within the target wavelength range was maximized with an In content of 17−21 %. BRs were formed from 12−18 pairs of $In_xAl_{1-x}As$ and $In_x(GaAl)_{1-x}As$ layers. The thicknesses BR layers were calculated based on the spectral dependences of the refraction index obtained in accordance with the procedure

$In_{0.17}Ga_{0.83}As$-p^+(Zn)	Contact layer
$In_{0.17}AlGaAs$-p(Zn)	"Window"
$In_{0.17}Ga_{0.83}As$-p(Zn) [500 nm]	Emitter
$In_{0.17}Ga_{0.83}As$-n(Si) [450–3000 nm]	Base
$In_{0.17}GaAlAs$-n(Si)	BL
$In_{0.17}Al_{0.83}As$-n(Te)	×18 BR
$In_{0.17}(Ga_{0.88}Al_{0.12})_{0.83}As$-$n$(Te)	
$In_xGa_{1-x}As$-n(Si)	MB
GaAs-n(Si)	Substrate

Figure 1. Schematic diagram of the metamorphic LPC heterostructure for radiation resistance tests: BL — buffer layer, BR — Bragg reflector, and MB — metamorphic buffer.

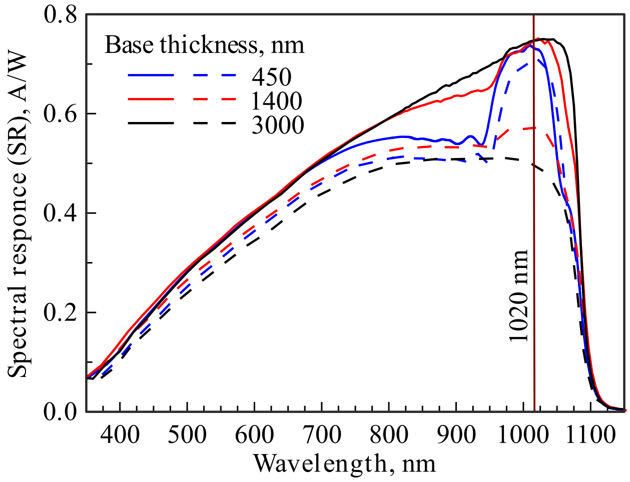

Figure 2. Spectral dependences of photosensitivity of experimental LPC samples based on $In_{0.17}Ga_{0.83}As$ heterostructures with BR and different thicknesses of the base region prior to irradiation with 2 MeV electrons with a fluence of $5 \cdot 14\,e/cm^2$ (solid curves) and after it (dashed curves). The dependences were plotted without account for optical losses due to radiation reflection.

outlined in [13]. It was established that the optimal BR version has InGaAlAs/InAlAs structure a structure based on $In_{0.17}(Ga_{0.88}Al_{0.12})_{0.83}As/In_{0.17}Al_{0.83}As$ materials with a reduced level of absorption of long-wave radiation in the reflector layers and their series resistance reduced due to the use of tellurium as a dopant [14].

The optical processes of transmission and absorption of radiation in photoactive layers, reflection from LPC, and self-absorption in BR were studied within the target wavelength range of 1000–1100 nm. The use of an extremely thin active region was the proposed design solution for the LPC structure with BR that should ensure an increase in radiation resistance.

Structures with an active region in the $In_{0.17}Ga_{0.83}As$ material were grown: emitter, 500 nm; base layer, 3000, 1400, or 450 nm; $In_{0.17}(Ga_{0.88}Al_{0.12})_{0.83}As/In_{0.17}Al_{0.83}As$ BR, 18 pairs of layers. With the chosen composition of the active region, the spectral sensitivity of experimental LPCs was maximized at a wavelength of 1020–1030 nm and reached ~ 0.74 and ~ 0.69 A/W for samples with a base region of 1400–3000 and 450 nm, respectively. The slightly weaker photoresponse of the thin-base LPC is attributable to the incomplete absorption of radiation reflected from the BR. The difference may also be attributed in some degree to the quality of the metamorphic base layers and variations in tuning of the optical BR characteristics in the fabricated structures.

A set of $In_{0.17}Ga_{0.83}As$ LPCs 3×3.4 mm in size with a 2.8×2.8 mm photoreceiving surface, which included current-collecting buses with a width of $5\,\mu m$ and a pitch of $100\,\mu m$, was prepared for radiation resistance tests. Experiments on irradiation of LPCs with 2 and 4.5 MeV electrons were performed through to the maximum fluence of $1 \cdot 16\,e/cm^2$.

Their results, which are presented in Figures 2 and 3, revealed that the LPC based on the heterostructure with a thin active region (450 nm base layer) outperformed the other structures throughout the entire fluence range. The reduction in spectral sensitivity at the target wavelength for the LPC with a thin base was no greater than 15 % at a fluence of $1 \cdot 15\,e/cm^2$, while the corresponding reduction magnitude for samples with base layer thicknesses of 1400 and 3000 nm was 31 and 40 %, respectively. It should be noted that BR loses its importance in providing radiation resistance of LPCs in structures with a thick (3000 nm) base layer: identical degradation dependences of photoelectric parameters were recorded for devices with and without a built-in reflector. All LPC designs demonstrated the same pattern of reduction of the open-circuit voltage with increasing fluence.

The tests revealed that a reduction in thickness of the $In_xGa_{1-x}As$ base in the heterostructure from 3000 to

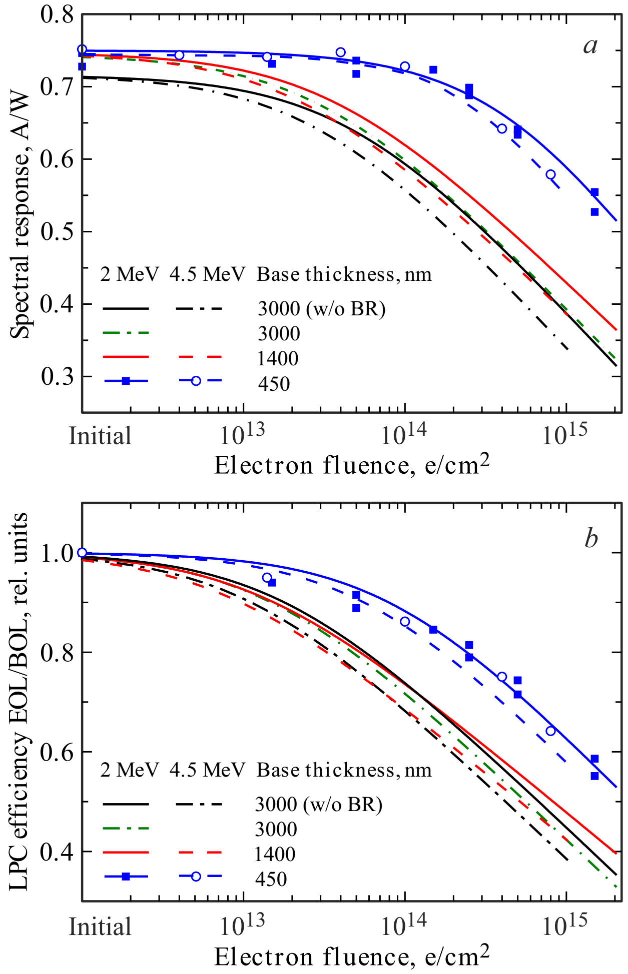

Figure 3. Spectral sensitivity at target wavelength $\lambda = 1020$ nm (*a*) and efficiency at a laser radiation power density of $5\,W/cm^2$ (*b*) for experimental LPC samples based on $In_{0.17}Ga_{0.83}As$ heterostructures with BR as functions of the fluence of electrons with energies of 2 and 4.5 MeV. Experimental points are shown in the dependencies for LPC samples with a base region thickness of 450 nm.

1400 nm does not exert any significant influence on the radiation resistance of the LPC. At the same time, when the LPC base is reduced further to 450 nm, one gains an advantage in spectral sensitivity and efficiency over LPCs with a thick base that is already visible at fluences $> 1 \cdot 13\,e/cm^2$ of electrons with energies of 2 and 4.5 MeV.

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] C. Algora, I. García, M. Delgado, R. Peña, C. Vázquez, I. Rey-Stolle. Joule, **6** (2), 340 (2022). DOI: 10.5281/zenodo.6620474

[2] Y. Zheng, G. Zhang, Zh. Huan, Y. Zhang, G. Yuan, Q. Li, G. Ding, Zh. Lv, W. Ni, Yu. Shao, X. Liu, J. Zu. SSPWT, **1** (1), 17 (2024). DOI: 10.1016/j.sspwt.2023.12.001

[3] 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**, 112551 (2023). DOI: 10.1016/j.solmat.2023.112551

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

[5] M.Z. Shvarts, O.I. Chosta, I.V. Kochnev, V.M. Lantratov, V.M. Andreev. Sol. Energy Mater. Sol. Cells, **68**, 105 (2001). DOI: 10.1016/S0927-0248(00)00349-4

[6] V.M. Emelyanov, N.A. Kalyuzhniy, S.A. Mintairov, M.Z. Shvarts, V.M. Lantratov. Semiconductors, **44**, 1600 (2010). DOI: 10.1134/S1063782610120122

[7] J.M. Raya-Armenta, N. Bazmohammadi, J.C. Vasquez, J.M. Guerrero. Sol. Energy Mater. Sol. Cells, **233**, 111379 (2021). DOI: 10.1016/j.solmat.2021.111379

[8] M. Klitzke, J. Schön, R.H. Van Leest, G.M.M.W. Bissels, E. Vlieg, M. Schachtner, F. Dimroth, D. Lackner. EPJ Photovolt., **13**, 25 (2022). DOI: 10.1051/epjpv/2022024

[9] N. Gruginskie, F. Cappelluti, G.J. Bauhuis, P. Mulder, E. Haverkamp, E. Vlieg, J. Schermer. Progr. Photovolt.: Res. Appl., **28**, 266 (2020). DOI: 10.1002/pip.3224

[10] M. Imaizumi, T. Takamoto, T. Sumita, T. Ohshima, M. Yamaguchi, S. Matsuda, A. Ohi, T. Kamiya. Proc. 3rd World Conf. on PV Energy Conversion, **1**, 599 (2003).

[11] M. Imaizumi, T. Nakamura, T. Takamoto, T. Ohshima, M. Tajima. Progr. Photovolt.: Res. Appl., **25**, 161 (2017). DOI: 10.1002/pip.2840

[12] N.A. Kalyuzhnyy, V.M. Emelyanov, S.A. Mintairov, M.V. Nahimovich, R.A. Salii, M.Z. Shvarts. AIP Conf. Proc., **2298**, 030001 (2020). DOI: 10.1063/5.0032903

[13] V.M. Emelyanov, N.A. Kalyuzhnyy, S.A. Mintairov, M.Z. Shvarts. Opt. Express, **26** (18), A832 (2018). DOI: 10.1364/OE.26.00A832

[14] V.M. Emelyanov, N.A. Kalyuzhnyy, S.A. Mintairov, M.V. Nakhimovich, R.A. Salii, M.Z. Shvarts. Semiconductors, **54** (4), 476 (2020). DOI: 10.1134/S1063782620040053

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