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AlGaAs/GaAs Photovoltaic Converters For High Power Narrowband Radiation

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Abstract. AlGaAs/GaAs-based laser power PV converters intended for operation with high-power (up to 100 W/cm^2) radiation were fabricated by LPE and MOCVD techniques. Monochromatic (λ = 809 nm) conversion efficiency up to 60% was measured at cells with back surface field and low (x = 0.2) Al concentration 'window'. Modules with a voltage of 4 V and the efficiency of 56% were designed and fabricated.

Keywords: laser power converter, GaAs, AlGaAs, heterostructure.
PACS: .88.80.ht, 88.40.hj, 81.15.Kk, 81.15.Lm

INTRODUCTION

Although the mainstream of modern solar photovoltaics is the research and development of multijunction photovoltaic (PV) converters based on III-V structures, the single-junction cells can be still applied efficiently for converting the LED and laser radiation as well as in the solar splitting systems. Nowadays the PV converters exhibit the justified efficiency that is close to the maximum value and can be used in wireless systems for transfer energy by laser beam. According to the previous studies [1-3], the calculated maximum efficiency of the ideal PV cell under the monochromatic illumination is about 70-85%. This value should be multiplied by the factor of 0.8-0.85 in order to estimate the real efficiencies that can be achieved. This study aims at improving the structure of the PV cell based on the AlGaAs/GaAs structure for converting high-power (up to 100 W/cm^2) radiation with a wavelength λ=809 nm.

AlGaAs/GaAs CELLS

The GaAs-based laser power converters were fabricated by liquid phase epitaxy (LPE) and metalorganic chemical vapour deposition (MOCVD).

The AlGaAs/GaAs heterostructure grown by LPE consisted of n-GaAs base, p-GaAs emitter, and wide-gap 'window'. Also, a contact layer is added in the case of high power cells. The PV converters, which are 2 mm x 2 mm to 20 mm x 20 mm in size, have demonstrated the monochromatic (λ = 809 nm) conversion efficiency of 50-56.2% (Figs. 1, 2). The presented PV efficiency values were obtained at Xe flash lamp illumination with gradual elevated irradiation at changing the lamp-to-cell distance. Based on recorded IV and measured J_{sc} value, the incident power density has been quantified via equation:

$$E_{ins}\Big|_{\lambda=809\text{ nm}} = J_{SC} / SR \Big|_{\lambda=809\text{ nm}} . \qquad (1)$$

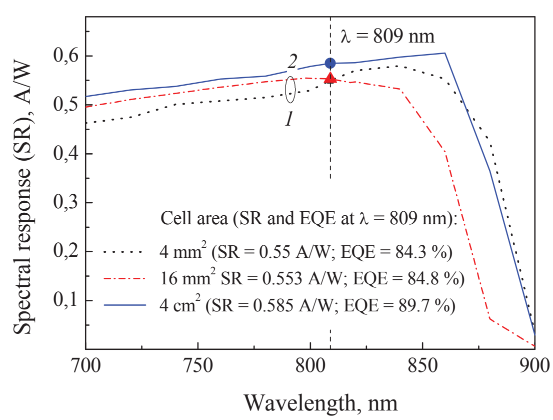

FIGURE 1. Spectral response (*SR*) of LPE photovoltaic converter with (*1*) and without (*2*) a contact layer (EQE, the external quantum efficiency).

Other types AlGaAs-based PV converters grown by MOCVD have been studied. The structure (Fig. 3) includes a photoactive p-n junction based on GaAs. An $Al_{0.3}Ga_{0.7}As$ back surface field layer (Eg = 1.8 eV) was grown between the substrate and n-GaAs base. This layer creates a potential barrier for charge carriers produced by long-wavelength photons and improves the carrier collection in the base. The structure of

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Fig. 3 is different from that of the usual solar cells; the former has significantly lower Al concentration ($x = 0.2$ versus $x = 0.85$) and increased thickness of the 'window' as compared to the latter. The $Al_{0.2}Ga_{0.8}As$ layer grown on the p-GaAs:Zn emitter is used to reduce the rate of surface recombination of charge carriers and acts as an additional region for charge carriers' spreading. The 'window' thickness and doping level were chosen to improve the spreading resistance in the structure. The ohmic losses induced by the lateral currents in the PV converter determine the efficiency maximum position. These losses increase as the squared luminous flux value, so they are particularly significant for photovoltaic structures used as a laser power PV converter.

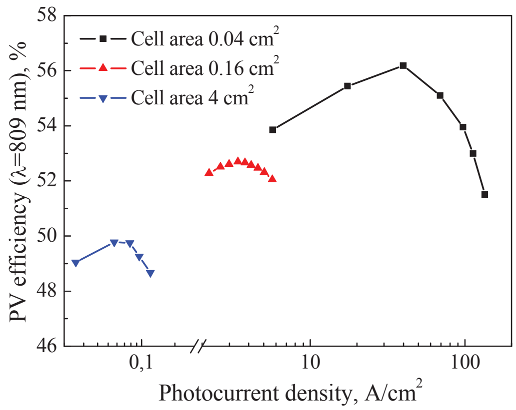

FIGURE 2. Monochromatic efficiency η as a function of current density for LPE photovoltaic converters.

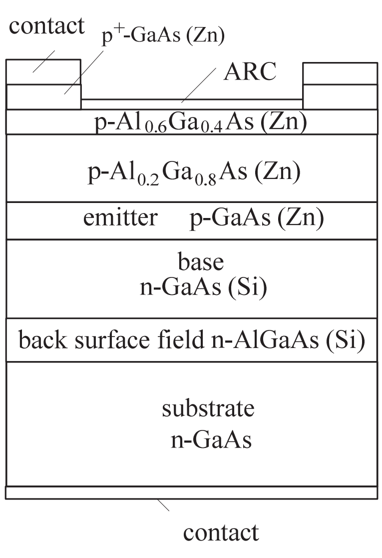

FIGURE 3. Structure of high power PV converters grown by MOCVD.

For optimization of the 'window' and emitter parameters a numerical model [4-6], which is based on (i) calculating the electromagnetic field in a PV structure by means of the Abeles matrices, (ii) solving the diffusion-drift equations by the method of a small parameter, and (iii) using 3D-network distributed equivalent circuits, has been applied. The dependencies of the optimum power ($Vm \cdot Im$) normalized to photogenerated current density in the range of typical 809 nm laser radiation have been calculated with different values of the series resistance (R_s) induced by spreading currents in the 'window' layer (Fig. 4).

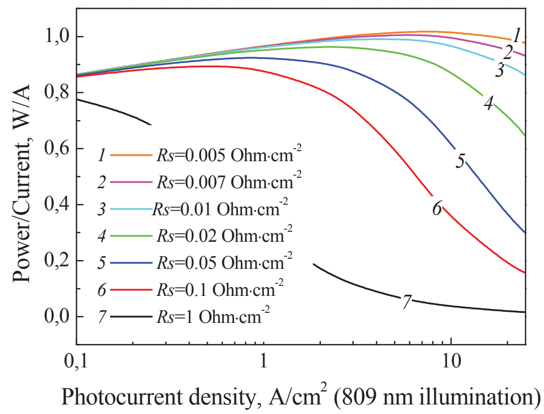

FIGURE 4. Normalized optimum power ($V_m \cdot I_m$) vs. the current density at laser radiation with $\lambda = 809$ nm.

Figure 4 shows that the maximum power is achieved at the series resistance of 0.005 Ohm·cm^{-2} up to photogenerated current density of 4 A/cm^2. The thickness ($h = 350$ nm) and doping level ($p = 2 \cdot 10^{18} cm^{-3}$) of the p-GaAs emitter and parameters of the $Al_{0.2}Ga_{0.8}As$ wide-band gap 'window' ($h = 1000$ nm, $p = 1 \cdot 10^{19} cm^{-3}$) as well as the front contact grid step (100 microns) were chosen to provide the specified value of the series resistance. Further reduction of series resistance gives very weak increase in power for this range of photocurrents. Decreasing the power losses of PV converters at higher photocurrents is possible by varying the parameters of emitter and window layers, but it should be taken into account, that *Im* decreases with increasing layer thickness as well as contact grid density

The wide-band gap $Al_{0.6}Ga_{0.4}As$ layer grown on the $Al_{0.2}Ga_{0.8}As$ window was used as a stop layer for etching the p^+-GaAs contact layer in photoactive regions during post-growth processing of the PV structure. A double-layer TiO_x/SiO_2 anti-reflection coating (ARC) was deposited on the $Al_{0.6}Ga_{0.4}As$ layer. The layer thickness (h=20 nm) is sufficiently small, which allows us to neglect the influence of this layer on the reflectance of the PV converter.

Spectral response (Fig. 5) and IV curves for the AlGaAs/GaAs converter of 3.0 mm x 3.4 mm in size were measured. The following parameters were obtained at the current of 5.9 A/cm^2: V_{oc} = 1.19 V, FF = 83.9%, η = 60.0% (Fig. 6).

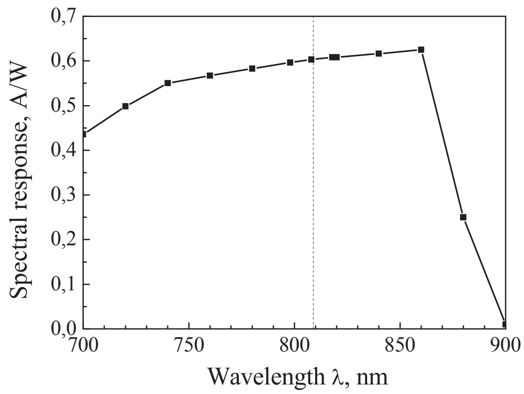

FIGURE 5. Spectral response of MOCVD photovoltaic converter.

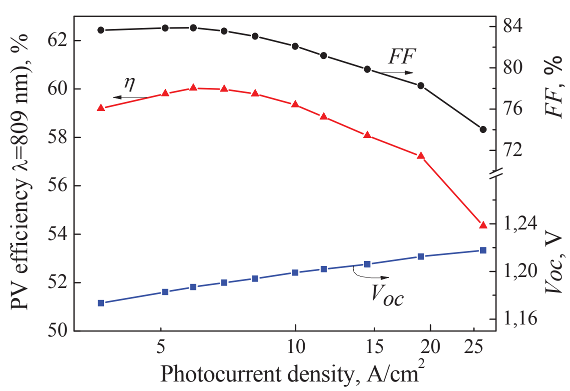

FIGURE 6. Efficiency η, V_{oc} and FF as a function of current density for MOCVD photovoltaic converter.

PV MODULES

Two approaches, namely the conversion of low-density laser radiation and its concentration in 100-1000 times by optical systems can be used in the development of PV modules. In the latter approach the optical losses are increased and the requirements for the cooling systems are higher. Moreover, materials with low degradation properties should be utilized for the fabrication of the concentrators. Meanwhile the photocell size can be significantly reduced in the concentrator modules, which can essentially reduce costs and simplify their technology.

In this study, both the approaches (i.e., without concentration systems and with a quartz lens) to converting the laser radiation have been used. First, the PV module (Fig. 7) with V_{oc} = 4.7 V, FF = 80.5%, η ~ 56.3% at the radiation power density of 4-7 W/cm^2 was fabricated (Fig. 8). Four 3 mm x 3.4 mm GaAs cells grown by MOCVD were connected in series. Such a small prototype module was fabricated for testing under semiconductor laser illumination and for preliminary evaluation of parameters of the above type arrays.

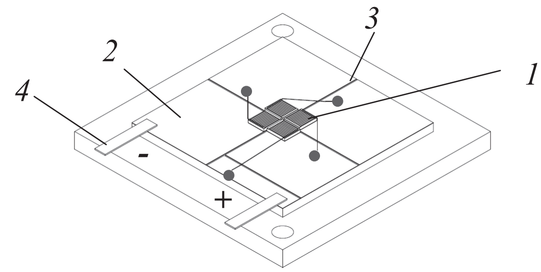

FIGURE 7. Module with 4 PV converters: *1* - PV cell; *2* – conducting coating; *3* – isolation; *4* – contact.

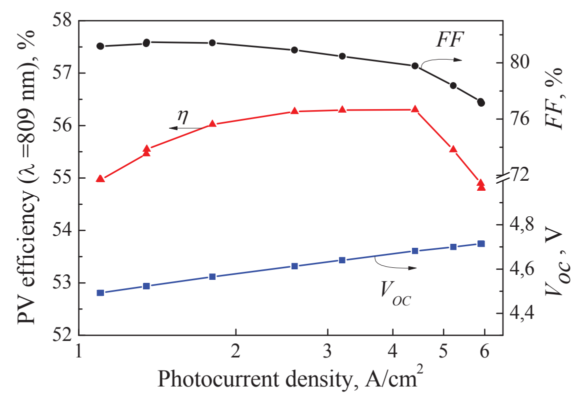

FIGURE 8. Efficiency η, V_{oc} and FF vs. the photocurrent density for a module with 4 PV converters.

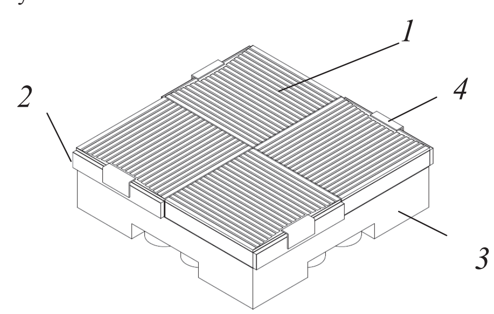

FIGURE 9. Design of PV module with 4 converters: *1* - PV cell (20 mm x 20 mm in size); *2* – metal plate with a dielectric film; *3* – copper base; *4* – contact.

A GaAs-based array of 16 cm^2 built up of 4 cell (20 mm x 20 mm in size each) based on LPE-structures and connected in series has been manufactured as well (Fig. 9). As a module base (*3*) material copper (8 mm in thickness) with high thermal conductivity and good heat sink was used. A radiator (not shown here) was additionally added to the module to increase the efficiency of air cooling. Each PV cell is electrically insulated from each other and from the base by a metal plate with a dielectric film (*2*). The space between the sealed cells (Fig. 9) was not greater than 0.1 mm, which allowed using quite effectively the operation surface for illumination. The estimated optical losses caused by the 0.1-mm gap are ~1%. The location of contacts to the module shown in Fig. 9 allows us to combine several modules together with a minimum spacing. Fig. 10 shows the variation in module efficiency as a function of photocurrent.

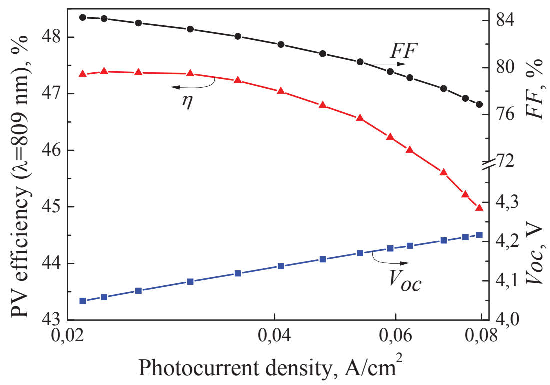

FIGURE 10. Efficiency η, V_{oc} and *FF* vs. the photocurrent density for module with 20 mm x 20 mm converters.

Also, a PV module with a concentrator system based on the matrix consisted of quartz lenses (*1*) and 64 PV cells (*2*) was developed (Fig. 11). The 80 mm x 80 mm matrix contained 64 plano-convex lenses of which eight rows were attached to the quartz substrate (h = 1.5 mm) by glue. The matrix lens size is 100 mm² (i.e. 10 ± 0.015 mm) at the focal distance of 20 mm. The size of the focal spot in the lens was 1.2 mm, which provided high precision (± 0.05 mm) in focusing the laser radiation on the 2 mm x 2 mm photovoltaic converter with photoactive surfaces of 1.6 mm in diameter. The PV cells were mounted on copper heat-sinks (3 mm in thickness). Finally, the 16 submodules are assembled in series-parallel into a 4 V module. The efficient water cooling (*3*) was needed because of high concentration of incoming radiation.

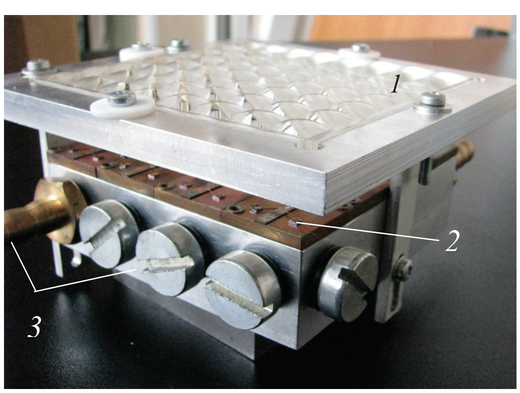

FIGURE 11. Concentrator PV module: *1* – concentrator system; *2* – PV cell; *3* – water-cooled heat removal system.

Fig. 12 presents the efficiency of the array fragment (4 cells out of 64, i.e. one typical submodule). Such submodules (with relatively low PV converters efficiency ~47%) were used to work-out the ways for assembling them in a single array. It should be noted that the assembly of this array is rather complicated due to the required precision in alignment of the focal spots of the lenses with photoactive surfaces of numerous elements. An estimated power of the whole module is presented in Fig. 12.

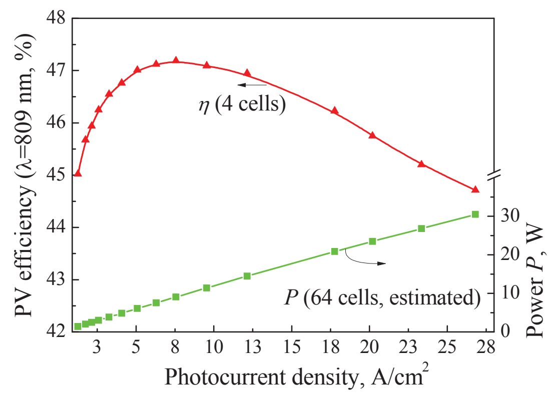

FIGURE 12. Efficiency vs. the photocurrent for a module fragment with 4 converters and whole module power.

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