Increasing the efficiency of optical power input in AlGaAs/GaAs photovoltaic laser converters

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This work is devoted to studying the improvement of optical power input efficiency in AlGaAs/GaAs photovoltaic laser radiation converters by employing prismatic covers. The primary focus is on the design and optimization of a construction that minimizes reflection. It is demonstrated that the use of prismatic covers enhances the external quantum efficiency of the samples.

Keywords: photovoltaic converters, prismatic covers, external quantum efficiency.

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1. Introduction

Laser photovoltaic converters (LPVC) are widely used in many fields of science, technology and medicine [1,2]. PVCs operating in a wavelength range of 800−860 nm are fabricated using AlGaAs/GaAs semiconductor compounds. PVCs based on this heterostructure were first made under the direction of Zh.I. Alferov at Ioffe Institute [3]. Now the achieved laser conversion efficiencies at 809 nm are 60 % [4]. It was shown that an efficiency of 68.9 % at 809 nm may be reached for AlGaAs/GaAs-heterostructure LPVC made by incorporating a silver reflector using a heterostructure-to-substrate transfer technique [5].

Further research efforts for PVC efficiency improvement are focused on ohmic and optical loss reduction, increase in the power of converted radiation that is possible by reducing the front surface grid pitch. However, this solution causes a significant increase in optical loss: a part of radiation is absorbed or reflected by current collecting busbars, thus, affecting the device photocurrent and efficiency. Optical loss due to radiation input can be reduced by formation of a pyramidal inclined profile of current collecting busbars with mirror side faces that reflect radiation towards the PVC photosensitive surface [6]. Another solution to this problem involves the formation of prismatic cover (PC) that generally has a form of a matrix consisting of semicylindrical solid linear lenses with a base width of each of the lenses corresponding to the PVC grid pitch [7]. Principle of operation of such lenses is in redirecting light beams coming onto the grid towards the PVC photosensitive surface by means of light refraction on a concave face.

The objective of this study is to reduce ohmic and optical loss through the development and fabrication of a micro-sized PC for LPVC with a typical photoreceiving surface grid pitch of 50 μm and to investigate the influence of PC on the properties of AlGaAs/GaAs radiation detectors.

2. AlGaAs/GaAs heterostructure

The investigations were performed using an AlGaAs/GaAs heterostructure (see Figure 1), grown by the MOS-hydride epitaxy on *p*-type GaAs substrates [8]. The *p*-Al_xGaAs layer serves as a rear potential barrier. The active region with a heterojunction formed by the basic *p*-GaAs region and *n*-Al_xGaAs → GaAs gradient emitter reduce the potential barrier height, thus, increasing the carrier lifetime. Note that the parameters of the structure's active region used for preparing the test PVC samples were not the best possible in terms of photon absorption in a spectral range of 800−860 nm. These structures served as reference ones for creating inverse PVC with rear reflector and reduced base layer, therefore couldn't have a high energy efficiency. The *n*-Al_xGaAs layer with high aluminum concentration serves as a stop layer for window etching during post-growth treatment and helps reduce the dissipation resistance. The high-doped n^+-GaAs layer is needed to reduce the resistance when forming the front ohmic contact to the PVC surface.

3. Post-growth formation technique

Operations of post-growth formation of the AlGaAs/GaAs heterostructure LPVC include the following steps [9,10]:

– etching of the n^+-GaAs conducting contact layer for opening the PVC photosensitive region;

– formation of antireflection coating (ARC) by magnetron sputtering;

– formation of the front grid to the *n*-type semiconductor (Au(Ge)-Ni-Au);

– deposition of a solid rear ohmic contact to the *p*-type semiconductor layer (NiCr-Ag-Au);

– electrochemical „enhancement“ of the front and rear ohmic contacts;

– formation of a separating mesastructure;

Reflection coefficient for various ARC at 800 nm

Coating material	TiO_x	TiO_x+Si	TiO_x/SiO_2+Si	TiO_x/SiO_2
Reflection coefficient R, %	6.79	2.32	5.93	0.9

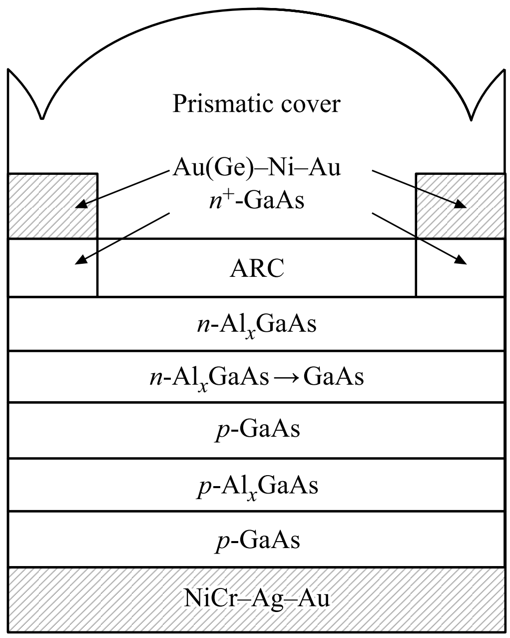

Figure 1. Cross-section diagram of the AlGaAs/GaAs heterostructure PVC.

Generally ARC is formed from a pair of TiO_x/SiO_2 layers [11]. The study is based on the interference of beams reflected at the air–film–substrate interfaces. Material refractive index shall increase at the approach to the substrate.

When using PC based on the Wacker 604 optical silicone compound (refractive index $\sim 1.43-1.39$ in the wavelength range of 350–2000 nm [12]), interference at the Si–film interface shall be considered. Since the SiO_2 film has a refractive index of ~ 1.45, additional optical loss will be induced at the Si–SiO_2 interface. Therefore, for the PC case, only a TiO_x layer (refractive index ~ 2.42) was deposited on the PVC surface to ensure the maximum reduction of reflection loss for the target laser wavelength (see the table).

A grid with a small contact bar pitch is formed on the photoreceiving surface to reduce the spreading resistance and increase the power of converted radiation in PVC. Loss due to photosensitive region shading with 6.5 μm bars spaced at 50 μm is $K = 13$ %.

4. Prismatic cover formation method

PC on the basis of optical silicone was formed using the gallium arsenide matrices. Before fabrication of the matrices, lattice planes shall be identified by treating the rear side of the polished GaAs substrate in a mixture of hydrogen peroxide and aqueous ammonia. The typical post-treatment GaAs surface profile is shown in Figure 2, *a*. After the plane identification, a photoresist mask with the PVC layout is formed on the front face. To make a semicylindrical profile by anisotropic wet etching, place the mask on the front surface of the substrate perpendicular to the etched defects. Etching was performed in $K_2Cr_2O_7$:HBr, and the prepared matrix is shown in Figure 2, *b*. Matrix parameters may be varied: by increasing the etching time, semicylinders with smaller radius of curvature may be formed, and a change of orientation provides an inclined profile.

Findings and discussion

PCs with various radii of refractive surface curvature of the linear lenses were fabricated (Figure 3). The PCs were installed on the PVC surface, alignment of the cylindrical lens matrix and contact bars was checked visually.

The study involved the measurement of the external photoconductive response of LPVC with various types of PC. For PC of types (*b*) and (*c*), no light redirection to the photosensitive region was observed: quantum efficiency was at the level of PVC with the „TiO_x + planar Si“ cover. This is due to differences in the prismatic structure geometries. A profile in Figure 3, *b* has a flat on transition between semicylindrical lenses. As a result, light is not refracted, thus, preventing from reducing optical loss. The profile shown in Figure 3, *c* has asymmetrically inclined faces, due to which the refracted radiation deviates and partially falls onto the contact bar region. According to the obtained data, the study was further performed using type (*a*) cover.

Figure 4, *a* shows the efficiency dependence for a sample with prismatic cover and a sample with two-layer TiO_x/SiO_2 ARC. Figure 4, *b* shows the spectral dependence of the external quantum efficiency of photoconductive response for PVC with two-layer TiO_x/SiO_2 ARC (curve *1*), the sample with single-layer TiO_x ARC and PC on the surface (curve *2*) and calculated dependence for the sample without grid shading (curve *3*). Change of the horizontal component of the external quantum efficiency for the sample with prismatic cover (curve *2*) is induced by the selectivity of Si antireflection properties for different wavelengths.

The design external quantum efficiencies cannot be reached due to reflection loss at the air–Si interface. However, the measurements suggest that employment of PC is an effective method to reduce optical loss due to radiation input for PVC with high density of the front grid, in particular, with bars spaced 50 μm. As mentioned above, the active region of the structures was not designed for full subband radiation absorption, therefore PVCs didn't

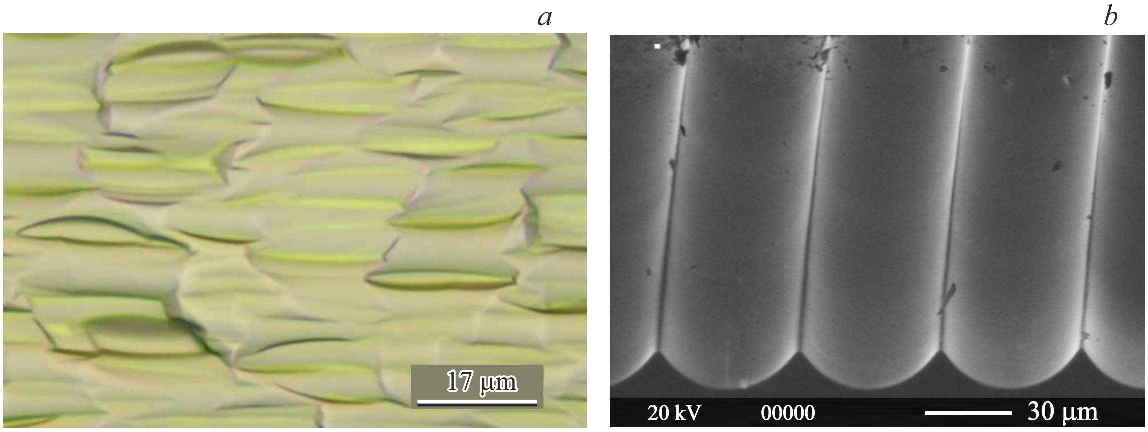

Figure 2. *a* — photo (optical microscope) of the rear surface of the GaAs substrate for identification of crystal-lattice orientation; *b* — image (scanning electron microscope) of the GaAs matrix cross-section.

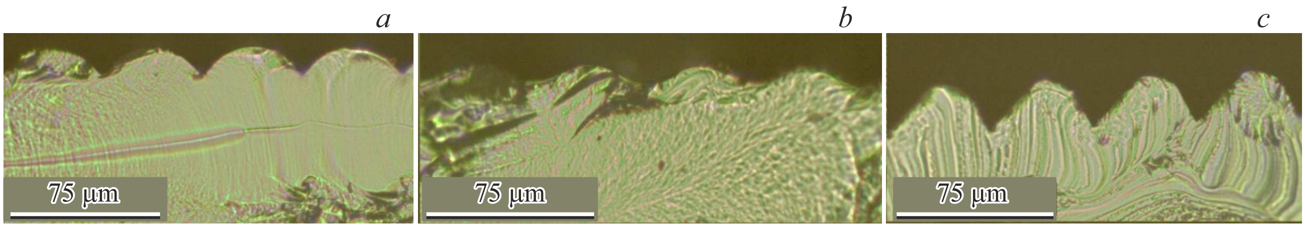

Figure 3. Existing PC profiles: *a* — straight, *b* — gently sloping, *c* — slanted.

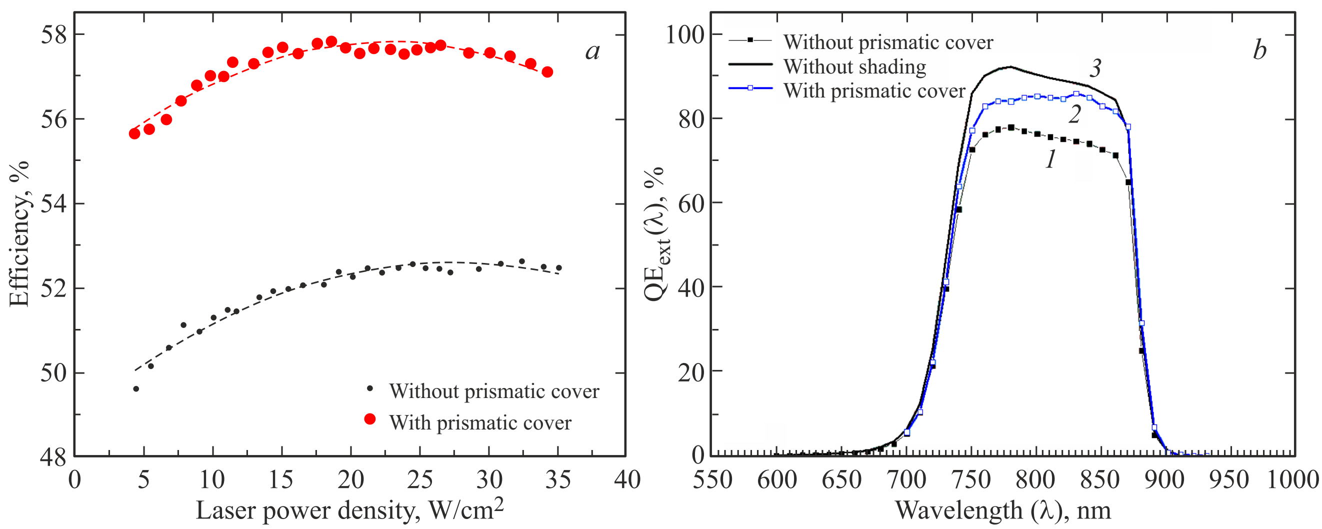

Figure 4. PVC curves: *a* — efficiency vs. power density of LPVC with PC and two-layer ARC, *b* — spectral dependences of the external quantum efficiency of the test samples.

have high efficiency [8]. Nevertheless, PC made it possible to increase the external quantum efficiency of the sample considerably at 800 nm from 76 % to 85 %, providing the growth of PVC efficiency from 52 % (standard two-layer ARC) to values higher than 57 % with laser power density $> 10\,W/cm^2$.

5. Conclusion

A technique used to form silicon PC using GaAs matrices with various chemically etched profiles was studied and developed. The influence of PC profile on the LPVC characteristics was identified. ARC combinations were examined, the minimum reflection coefficients were achieved by applying the two-layer TiO_x/SiO_2 and TiO_x/Si coating.

Formation of PC in the form of a matrix consisting of semicylindrical solid linear lenses made it possible to reduce shading of the photosensitive surface for PVC due to refraction of radiation coming onto the front ohmic contact bar region, to the photosensitive surface, thus, increasing the device efficiency by 5 %.

Conflict of interest

The authors declare no conflict of interest.

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