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High-Efficiency AlGaAs/GaAs Photovoltaic Converters with Edge Input of Laser Light

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Abstract—High-efficiency photovoltaic converters (PVCs) have been developed and fabricated by liquid-phase epitaxy in the AlGaAs–GaAs system with laser light (λ = 850 nm) introduced through the edge surface in parallel to the plane of the *p–n* junction of the device structure. To raise the efficiency of light "capture" by the *p–n* junction, an $Al_xGa_{1-x}As$ waveguide layer is formed, in which the content of aluminum gradually varies from $x = 0.55$ to 0.15 so that the refractive index gradient is created in this layer and light beams are diverted toward the *p–n* junction. When a PVC (having no antireflection coating) is exposed to 0.1- to 0.2-W laser light, an efficiency of 41.5% is obtained. Depositing an antireflection coating on the edge surface of a PVC raises its efficiency to 55%.

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High-power photovoltaic converters (PVCs) of concentrated solar light [1] and high-intensity laser emission [2] are increasingly widely used in solar power engineering and in systems for wireless energy transfer by a laser beam. In recent years, high-efficiency PVCs of high-intensity laser light operating in the photovoltaic mode without application of an external bias have been under active development [3–6].

Figure 1 shows PVCs of two designs: (a) with a conventional input of light perpendicularly to the plane of the *p–n* junction and (b) with edge introduction of light in parallel to the *p–n* junction plane. In the first case, it is necessary to form a system of strip ohmic contacts on the front surface of high-power PVCs. This inevitably leads to an additional optical loss because of the shading of the photoactive surface by the contact grid. In the second variant, light is introduced into the PVC through its edge surface created by cleavage (as this is done in fabrication of plane-parallel edges of a semiconductor laser), or through a photolithographically etched side surface of the PVC chip. The introduction of light in parallel to the *p–n* junction plane can reduce by 5–10% the optical loss for shadowing by strip contacts and diminish the ohmic contact loss by approximately an order of magnitude due to the formation of solid metallic contacts on the front and rear surfaces of the cell. The PVC design with edge input of light, i.e., with a vertical *p–n* junction (Fig. 1b), is widely used in fabrication of silicon PVCs [7]. A theoretical estimate has been made in the case of PVCs based on materials III–V for an AlGaAs–GaAs heterostructure on a *p*-type substrate [8].

The goal of our study was to develop and fabricate by liquid epitaxy high-efficiency PVCs in the AlGaAs–GaAs system with a vertical *p–n* junction, i.e., with introduction of laser light (λ = 850 nm) through the edge surface of a PVC device structure grown on an *n*-type substrate.

Figure 1c shows the structure of the PVC we developed. An important specific feature of the structure is that a wide-bandgap waveguide layer is created, with a gradual variation of the refractive index of the n-$Al_xGa_{1-x}As$ solid solution due to the gradual variation of the Al content in the n-$Al_xGa_{1-x}As$ layer. This results in the light beams introduced into this layer being diverted toward the *p–n* junction. Figure 1c shows calculated trajectories of laser beams in the 100-μm-thick $Al_xGa_{1-x}As$ waveguide layer in which the refractive index varies from $n = 3.2$ in the layer with $x = 0.55$ at the interface with the substrate to $n = 3.5$ in the layer with $x = 0.15$ at the interface with the *n*-GaAs layer. The AlAs concentration gradient in this layer is 0.4 mol %/1 μm. All the beams entering the waveguide region are deviated into the region of the *p–n* junction before reaching the opposite edge of the structure at its length not smaller than 500 μm. At a waveguide layer thickness of 50 μm and AlAs concentration gradient of 0.4 mol %/1 μm, the PVC length at which beams are fully diverted to the *p–n* junction is 360 μm.

Not only the properties of the waveguide layer affect the trajectory of the beams. Also important in this case is angle θ of beam introduction into the waveguide layer. As angle θ is raised from 1° to 40°, the maximum length of the horizontal run of the beams in

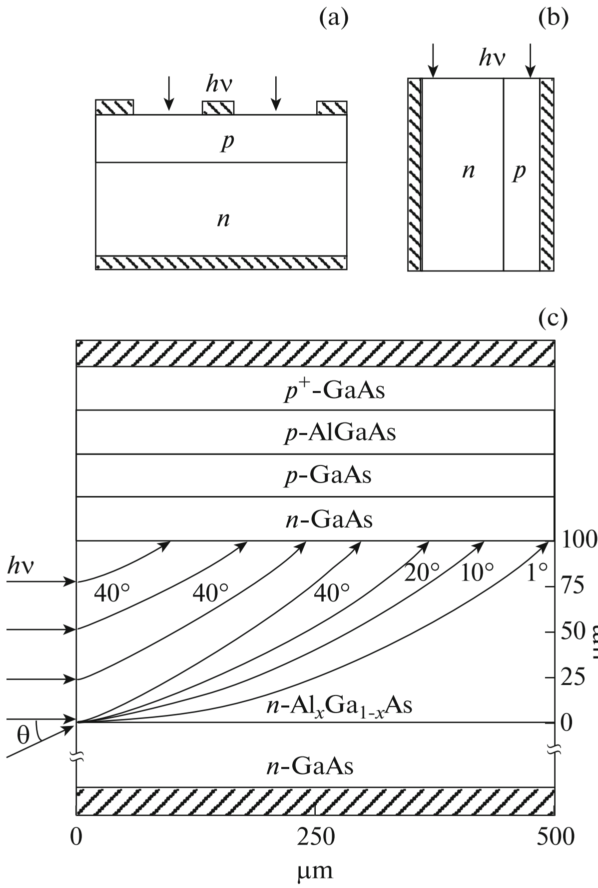

Fig. 1. Schematic image of various PVC designs: (a) with conventional introduction of light, (b) with edge input of light, and (c) that developed in the study with calculated trajectories of light beams in the 100-μm-thick n-AlGaAs waveguide layer at various angles θ of laser light introduction.

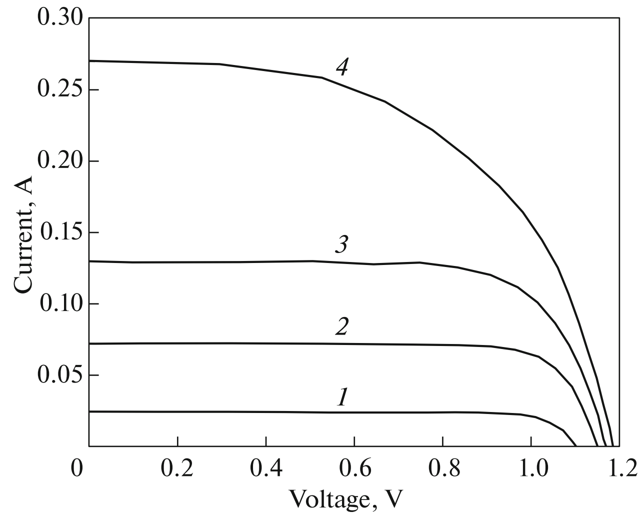

Fig. 2. Family of light current–voltage characteristics of a PVC (having no antireflection coating) under exposure of its edge surface to laser light at a wavelength of 850 nm and power of (*1*) 0.05, (*2*) 0.15, (*3*) 0.28, (*4*) 0.6 W.

the waveguide decreases from 500 to 300 μm at an $Al_xGa_{1-x}As$ layer thickness of 100 μm and from 360 to 190 μm at an $Al_xGa_{1-x}As$ layer thickness of 50 μm (Fig. 1c).

The possibility of fabricating solid ohmic contacts to the top and bottom surfaces of the PVC structure makes it possible to exclude a number of additional technological procedures and minimize the post-growth processing of a structure to obtain PVC and improve the heat removal from high-power PVCs. Also, the ohmic contact loss in a PVC decreases by approximately an order of magnitude because the current-collection area becomes an order of magnitude larger in the case of solid contacts as compared with the current-pickup grid in a PVC with the conventional introduction of light perpendicularly to the p–n junction plane.

To reduce the optical loss, a Ta_2O_5 antireflection coating is deposited on the surface of the illuminated PVC edge. This coating has a minimum reflectance (<1%) in the spectral range of 800–870 nm.

To create the PVC structure shown in Fig. 1c, the following layers were successively grown on an n-GaAs substrate: first, layer n-$Al_xGa_{1-x}As$ with a composition gradient (x = 0.55–0.15); then, an n-GaAs layer, p-GaAs layer; a p-$Al_xGa_{1-x}As$ layer (x = 0.2–0.1); and a p^+-GaAs contact layer. The method of liquid-phase epitaxy used in the study can produce perfect epitaxial layers with thicknesses in the range from several nanometers to hundreds of micrometers in the same process during a comparatively short crystallization time (from seconds to several hours). The layers have a high quality because the growth occurs under the thermodynamic-equilibrium conditions. The crystallization of the n-$Al_xGa_{1-x}As$ gradient layer with thickness of 50 μm (with the aluminum content in the waveguide layer varying from x = 0.55 at the interface with the substrate to x = 0.15 at the heterointerface with the n-GaAs layer) occurred under cooling in the temperature range from 850 to 600°C.

Tin, which has a lower partial vapor pressure than tellurium, was chosen as the donor doping impurity.

Germanium was chosen as the acceptor impurity because it has a lower partial vapor pressure at the epitaxial process temperatures than do magnesium and zinc. To reduce the contact resistance of a PVC, a p^+-GaAs contact layer was grown at the end of epitaxy at growth temperatures of 600–520°C. At a germanium content of 5 at % in the gallium melt, the doping level of the GaAs contact layer was 1×10^{19} cm^{-3}, which provided that a low-resistivity contact was formed.

Figure 2 shows light current–voltage characteristics of the PVC with edge input of light in which the

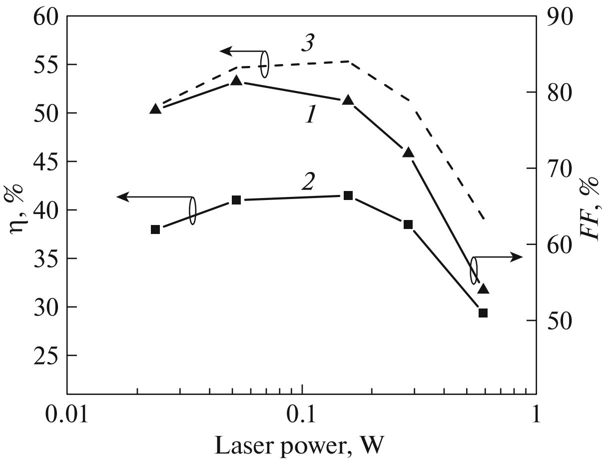

Fig. 3. (*1*) Fill factor (*FF*) of current–voltage characteristics of a PVC and its efficiency (η) (*2*) without and (*3*) with an antireflection coating vs. the laser power in edge input of laser light (λ = 850 nm).

thickness of the waveguide epitaxial layer was 50 μm. Pulsed laser light with wavelength of 850 nm and power varied from 0.05 to 0.6 W was introduced from an optical fiber with a diameter of 50 μm.

The dependences of the PVC efficiency and the fill factor of load characteristics on laser light power are shown in Fig. 3. The maximum efficiency of the photovoltaic conversion of laser light was 41.5% in a PVC having no antireflection coating and 55% in that with an antireflection coating on the edge surface.

Thus, we have simulated the run of beams in a structure with edge introduction of laser light at a linear variation of the aluminum content in the waveguide layer. It was found that, with light introduced at an angle of 1° to the growth plane of the structure having a waveguide thickness of 100 μm, the minimum PVC length should be no less than 500 μm. Raising the light-introduction angle to 40° leads to a decrease in the "effective" PVC length to 300 μm and increases the irradiation power density at the *p*–*n* junction. The method of liquid-phase epitaxy served to grow AlGaAs/GaAs device heterostructures used to fabricate PVCs with solid rear and front contacts and edge introduction of laser light. An efficiency of 55% was provided by a PVC with a 50-μm-thick gradient layer and edge surface with an antireflection coating under exposure to laser light (λ = 850 nm) with power of 0.1–0.2 W. This value is comparable with the maximum efficiency obtained in a PVC with conventional introduction of light perpendicularly to the plane of the *p*–*n* junction.

One way to further raise the efficiency of the AlGaAs photovoltaic converters developed in the study may consist in the possibility of matching the energy gap width of a PVC with the wavelength of incident laser light by changing the content of aluminum in photoactive layers at the *p*–*n* junction.

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