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GaSb Laser-Power (λ = 1550 nm) Converters: Fabrication Method and Characteristics

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Abstract—Photovoltaic converters of laser light with a wavelength of λ = 1550 nm are developed using liquid-phase epitaxy (LPE), metal-organic chemical-vapor deposition (MOCVD), and diffusion from the gas phase into the *n*-GaSb substrate. Photocells with an area of S of 4, 12.2, and 100 mm^2 are fabricated and tested. The characteristics of the samples produced by different methods are compared. The monochromatic efficiency is found to be 38.7% for the best converters (with S = 12.2 mm^2) at a laser power of 1.4 W.

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1. INTRODUCTION

The development of laser-power (λ = 1550 nm) photovoltaic converters (LP PVCs) is promising because of their possible use in terrestrial wireless energy-transfer systems and in the conversion of light transmitted via an optical fiber. They may find application in small-size electronics.

Reports have been published on the development of $In_{0.53}Ga_{0.47}As/InP$ LP PVCs for λ = 1550 nm with an efficiency of 34% [1] and GaInAsP/InP photocells with an efficiency exceeding 45% [2–5]. Another possible material that can be used for the development of monochromatic light converters operating at the given wavelength is gallium antimonide whose absorption edge corresponds to ~1.7 μm. GaSb LP PVCs can be fabricated using experience previously gained in the fabrication of photocells with a single *p*–*n* junction, developed for solar cells and thermophotoelectric generators and produced both by impurity diffusion into a substrate [6–10] and by growth methods: metal-organic vapor phase epitaxy (MOVPE [8, 11]) and liquid-phase epitaxy (LPE [12, 13]). Depending on the size of LP PVCs, their purpose, and laser-light power, each of the above technological methods can exhibit advantages and limitations.

2. PURPOSE OF A LASER-POWER PHOTOVOLTAIC CONVERTER AND CHOICE OF THE METHOD FOR ITS FABRICATION

Practical applications in systems for wireless energy transmission require, depending on the distance between the laser and photovoltaic converter, and on the laser power density, LP PVCs of different sizes. In particular, energy transmission to remote objects requires converters of the largest area, which simplifies laser-beam focusing on their light-sensitive surface. The precision of the guidance system determines the total optical loss by the system. The laser-beam divergence grows with increasing distance to the object. LP PVCs with dimensions of no less than 10 × 10 mm are required to make the system design simpler and to improve general efficiency. Such methods as diffusion from the gas phase or metal-organic vapor-phase epitaxy are preferable for their fabrication, which enables the formation of photocell structures with uniform properties and almost unlimited area. LPE is less promising for the fabrication of large-scale LP PVCs because of the specific features of the method: possible presence of residual amounts of melt on the surface of photocell structures, nonuniform layer thicknesses, and the restriction imposed on the size of the substrates by the dimensions of the growth cassette, etc.

Small-size photocells, for which the fabrication method does not play a key role, will be successfully used in various consumer or industrial devices, in household electronics, or in the case when light is delivered by an optical fiber. Economical parameters will become important in the mass production of LP PVCs, and, therefore, the method of diffusion into a substrate may turn out to be the most convenient, cost-effective, and productive.

Of particular importance for a number of LP PVC applications and, in particular, units on board spacecraft is efficiency and the possibility of converting

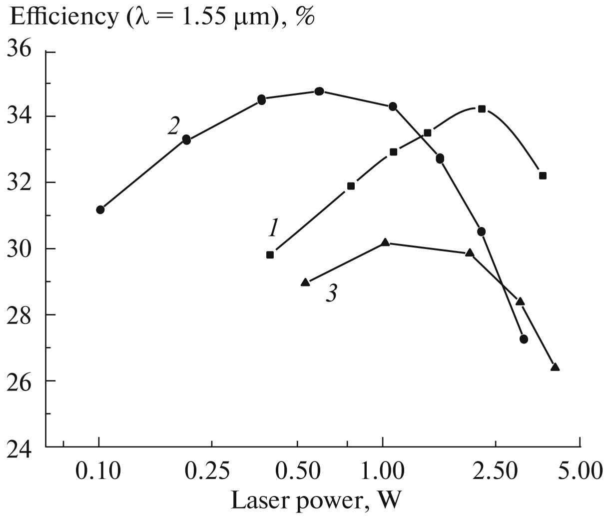

Fig. 1. Monochromatic efficiency (λ = 1550 nm) of a laser-power converter under uniform illumination: S = (*1*) 4 mm^2, (*2*) 12.2 mm^2, (*3*) 100 mm^2.

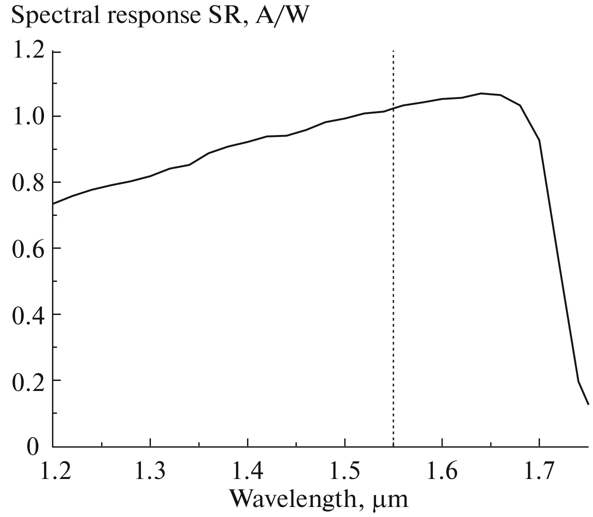

Fig. 2. Spectral response (SR) of a LP PVC produced by a combination of the LPE method and diffusion from the gas phase.

high-density light. The maximum monochromatic efficiencies are reached by using epitaxial-growth techniques. With increasing incident-light power density, the size of the LP PVCs should decrease because the ohmic loss will otherwise increase. Both the methods, MOVPE and LPE, are competitive in terms of the fabrication of small-area concentrator converters. Liquid-phase epitaxy is attractive, compared with MOVPE, due to the low cost of the technological process, simple equipment, and absence of toxic compounds. In turn, metal-organic chemical-vapor deposition enables reproducible fabrication of the most complex epitaxial structures with minimum spread of the photocell parameters, which is particularly important in the voltage- or current-matching of converters upon their assembly into units.

3. SPECIFIC FABRICATION FEATURES AND PARAMETERS OF LASER-POWER PHOTOVOLTAIC CONVERTERS PRODUCED BY DIFFUSION FROM THE GAS PHASE

The simplest way to obtain a single-junction LP PVC is by the diffusion of an impurity into a GaSb substrate, performed in graphite cassettes in LPE installations. A *p*-GaSb emitter was formed and the *p*–*n* junction was buried in the subcontact areas by double-stage doping with zinc from the gas phase across dielectric films. The specific features of the technological processes were described previously [13, 14]. In the case of diffusion-grown LP PVCs (and further for samples produced by the LPE and MOVPE methods) ZnS/MgF_2 films were deposited onto the front surface of the photocells.

To convert high- and low-intensity light, we fabricated and tested under a Xe lamp LP PVCs with areas of S = 4, 12.2, and 100 mm^2 (Fig. 1). The spectral response (SR) at λ = 1550 nm was ~0.99 A/W. An efficiency of η = 34.8% was attained for the best samples (S = 12.2 mm^2) at a laser-light power of ~0.6 W (Fig. 1). The laser power was estimated as I_{sc}/SR (I_{sc} is the short-circuit current). The characteristics of the diffusion LP PVCs were reported in more detail in [14].

4. PARAMETERS AND SPECIFIC FEATURES OF THE FABRICATION OF A LASER-POWER PHOTOVOLTAIC CONVERTER BY EPITAXY FROM THE LIQUID PHASE

Upon the diffusion of an impurity into the substrate, the output characteristics of LP PVCs and their reproducibility are largely determined by the quality of the initial material and its doping level. Another variant of the fabrication technology of GaSb-based converters is through combining epitaxial growth and diffusion, which makes it possible to reduce the influence exerted by the substrate on the efficiency of LP PVCs. The specific features of the LPE growth of device structures are the subject of [12, 15]. The typical spectral response of the photocell is shown in Fig. 2. The characteristics of the photovoltaic converters are shown in Figs. 3 and 4. An efficiency of 38.7% was obtained at a laser-light power of ~1.4 W (Fig. 3).

The additional deposition of a heavily doped n^+-GaSb layer on the rear side of the substrate facilitates the formation of a rear ohmic contact, improves the fill factor (FF) of the current–voltage characteris-

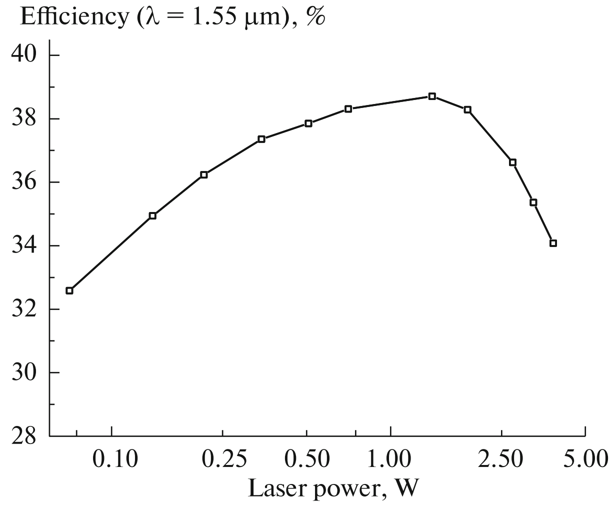

Fig. 3. Monochromatic efficiency ($\lambda = 1550$ nm) of a converter produced by a combination of the LPE method and diffusion from the gas phase ($S = 12.2$ mm^2).

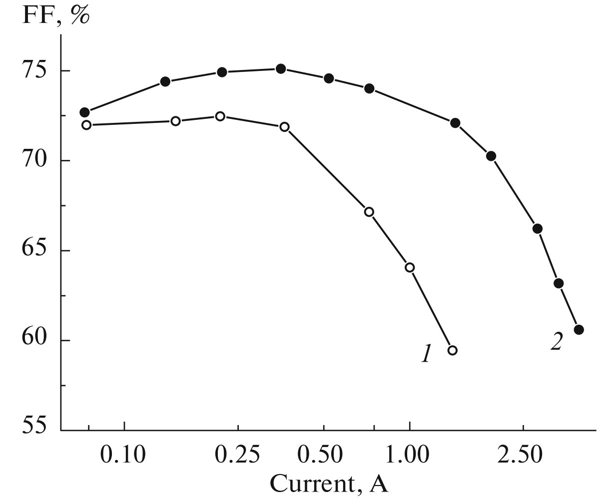

Fig. 4. Fill factor FF of the current–voltage characteristic for converters with (*1*) a buffer layer and a diffusion-grown *p*–*n* junction and (*2*) an additional n^+-GaSb layer on the substrate rear side ($S = 12.2$ mm^2).

tic, and makes it possible to shift the maximum efficiency to higher currents. Comparison of the FF of photocells with a single buffer layer and a diffusion-grown *p*–*n* junction (curve *1*) and converters with a double-sided structure (curve *2*) is illustrated by Fig. 4.

5. PARAMETERS AND SPECIFIC FABRICATION FEATURES OF A LASER-POWER PHOTOVOLTAIC CONVERTER BY THE MOVPE METHOD

The LP PVC heterostructures were grown by the MOVPE method on an AIXTRON AIX200 installation (Germany) with a horizontal reactor. In the growth experiments, the ratio between the trimethylantimony/trimethylgallium (TMSb/TEGa) molar fluxes was set to be 2 at a constant carrier-gas (hydrogen) flow rate of 5.5 L/min. Raising the ratio between the molar fluxes impaired the surface quality. The growth temperature was 600°C. The reactor pressure was maintained at a level of 76 mmHg. The specific features of the technological process were considered in more detail in [16, 17].

The structure of the LP PVC produced by the MOVPE method is shown in Fig. 5. A buffer layer and a rear n^+-GaSb potential barrier were deposited onto an *n*-GaSb substrate. The existence of a concentration gradient of the acceptor impurity in the *p*-GaSb emitter created a drawing electric field, which made it possible to raise the collection probability of carriers generated by light. A wide-gap optical "window" reducing the surface recombination rate was formed on the basis of the *p*-$Al_xGa_{1-x}As_ySb_{1-y}$ quaternary solid solution.

The composition of the solid solution corresponded to $x = 0.82$ and $y = 0.07$, its band-gap width was $E_g = 1.4$ eV. The material of the window should not create additional defects at the interface with the emitter. The high crystal perfection of the deposited $Al_{0.82}Ga_{0.18}As_{0.07}Sb_{0.93}$ solid solution is confirmed by

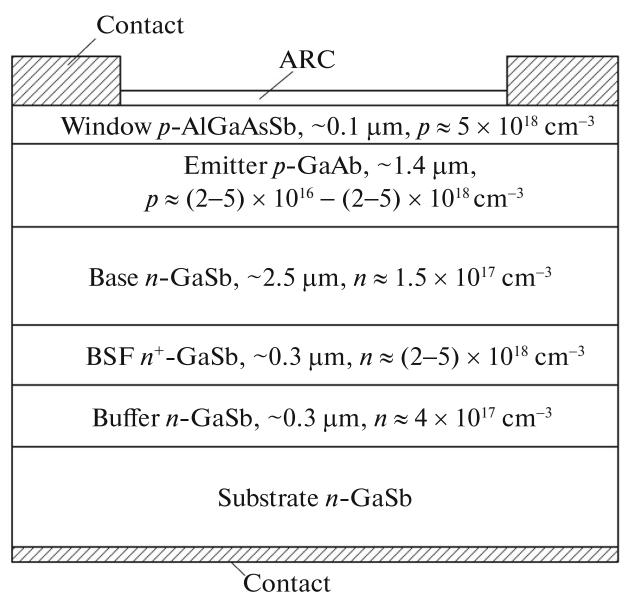

Fig. 5. Structure of a MOVPE-grown GaSb-based LP PVC. ARC is the antireflection coating, and BSF is the back surface field barrier.

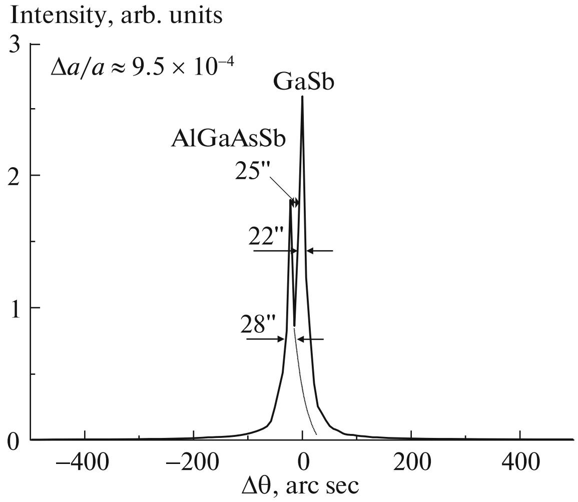

Fig. 6. X-ray diffraction rocking curve for an $Al_{0.82}Ga_{0.18}As_{0.07}Sb_{0.93}$ layer (thickness $d = 1$ μm) grown on a GaSb substrate.

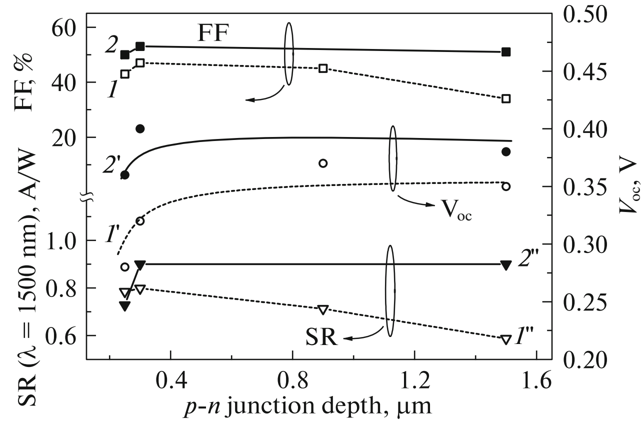

Fig. 7. Dependence of the main parameters of the LP PVCs on the depth of the *p–n* junction. (*1*, *1'*, *1''*) Device having no wide-gap window and (*2*, *2'*, *2''*) devices with an $Al_{0.82}Ga_{0.18}As_{0.07}Sb_{0.93}$ layer.

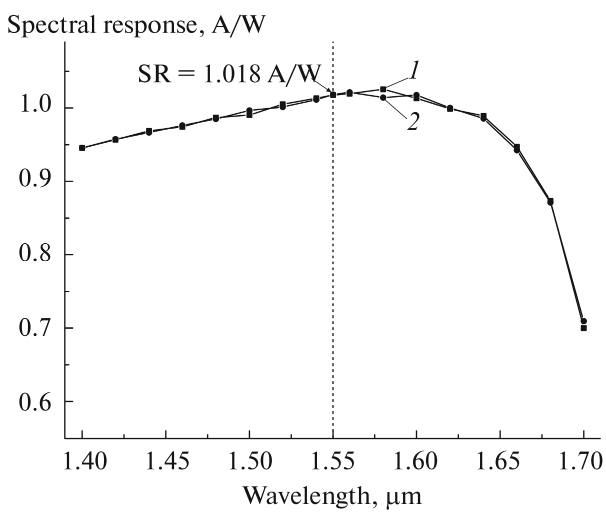

Fig. 8. Spectral response of LP PVCs with an area of 6.25 mm^2, deposited onto *n*-GaSb substrates with *n* of (*1*) ~(2–5) × 10^{17} and (*2*) ~(0.5–1) × 10^{18} cm^{-3}.

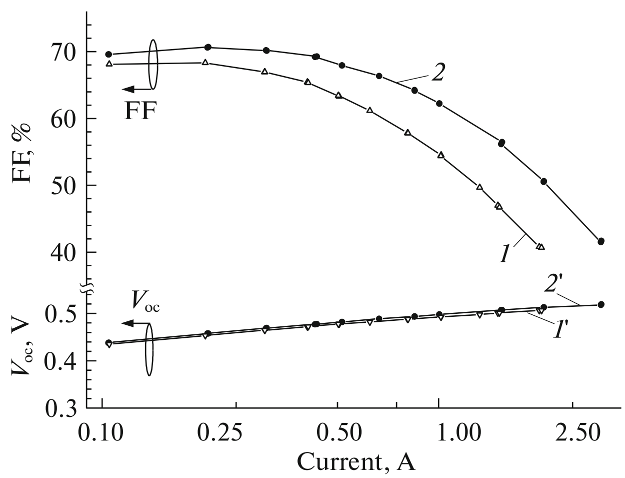

Fig. 9. Dependences of (*1*, *2*) FF and (*1'*, *2'*) V_{oc} on the photocurrent for LP PVCs deposited onto *n*-GaSb substrates with *n* of (*1*, *1'*) ~(2–5) × 10^{17} and (*2*, *2'*) ~(0.5–1) × 10^{18} cm^{-3}.

the close values of the full widths at half-maximum and the peak intensities in the X-ray rocking curve (Fig. 6) for the epitaxial layer and the substrate. Their lattice mismatch $\Delta a/a$ did not exceed 10^{-3}.

The influence exerted by the presence/absence of the layer of the wide-gap optical window and by the depth at which the *p–n* junction lies on the parameters of the LP PVCs is shown in Fig. 7. As expected, deposition of the $Al_{0.82}Ga_{0.18}As_{0.07}Sb_{0.93}$ solid solution leads, due to reduced surface recombination, to a higher spectral response and, consequently, improves the efficiency of the LP PVC. A lack of strict limitations on the small thickness of the *p*-GaSb emitter (~0.3 μm), which are inherent to solar cells and imposed by the requirement of their radiation hardness, makes it possible to raise the thickness to 1.5 μm, with the possible leaks in the *p–n* junction thereby eliminated and the spreading resistance of the layer raised. The thickness of the optical window in the device structure was 0.1 μm.

The spectral response of LP PVCs is shown in Fig. 8. The device structures were grown on *n*-GaSb (100) wafers with various carrier concentrations (curves *1*, *2*). Raising the doping level of the substrate

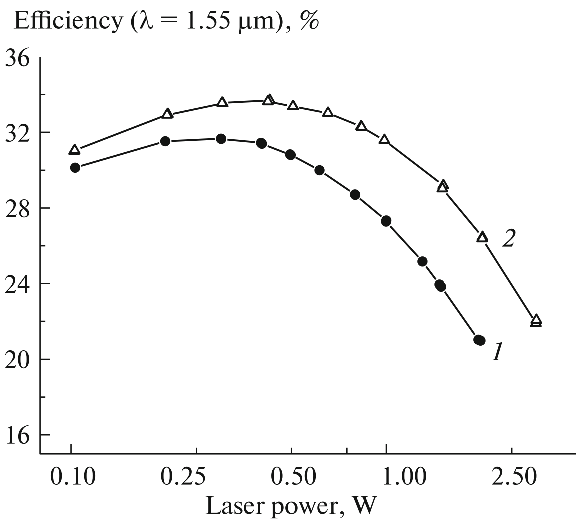

Fig. 10. Dependence of the monochromatic ($\lambda = 1550$ nm) efficiency of a photovoltaic converter with an area of 6.25 mm^2 on the laser power for LP PVCs deposited onto *n*-GaSb substrates with *n* of (*1*, *1*') ~$(2–5) \times 10^{17}$ and (*2*, *2*') ~$(0.5–1) \times 10^{18}$ cm^{-3}.

from $n \sim (2–5) \times 10^{17}$ to ~$(0.5–1) \times 10^{18}$ cm^{-3} facilitates the formation of a low-resistivity rear contact and favors an increase in the fill factor FF of the load characteristic (Fig. 9). At identical response spectra, the monochromatic ($\lambda = 1550$ nm) efficiencies of the converters will be markedly different (Fig. 10).

The MOVPE-grown LP PVCs had a high epitaxial-layer quality and, consequently, a high SR (λ = 1550 nm), but were characterized by FF values insufficient for obtaining the maximum efficiencies and exhibited a rapid drop in efficiency upon raising the illumination intensity. Further optimization of the given converters (as well as the optimization of LP PVCs produced by the diffusion method or by LPE) will be associated with reducing the ohmic loss, which can be done, in particular, by replacing the Cr–Au contact composites with Ti–Pt–Ag [18, 19] and raising the total thickness of the contact from ~1 μm to 3–5 μm.

6. CONCLUSIONS

The diffusion method for the fabrication of GaSb-based laser-power photovoltaic converters (LP PVCs) provides good reproducibility of the layer thicknesses and doping level of the *p*–*n* junction. It is characterized by a low consumption of materials and high output capacity, and, therefore, can be effectively employed both in the fabrication of large-area LP PVCs and in the mass production of photocells under industrial conditions. The possibility of reaching high efficiencies for photocells produced by this method will be largely determined by the quality of the initial substrate material.

Combining liquid-phase epitaxy with the diffusion of zinc from the gas phase enables the reproducible fabrication of high-efficiency (>38.5%) small-size LP PVCs with a vast range of applications, but somewhat complicates the technological cycle of their fabrication.

Under excitation with light with λ = 1550 nm, MOVPE-grown photovoltaic converters that have a wide-gap $Al_{0.82}Ga_{0.18}As_{0.07}Sb_{0.93}$ window ($E_g \sim 1.4$ eV, thickness ~0.1 μm) exhibit a high spectral response. The use of heavily doped *n*-GaSb substrates ($n > 5 \times 10^{17}$ cm^{-3}) leads to an increase in FF and the efficiency.

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