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PHYSICS OF SEMICONDUCTOR DEVICES

Solar Cells Based on Gallium Antimonide

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Abstract—Liquid-phase epitaxy and diffusion from the gas phase have been used to create various kinds of GaSb-based solar cell structures intended for use in cascaded solar-radiation converters. A narrow-gap (GaSb) solar cell was studied in tandem based on a combination of semiconductors GaAs–GaSb (two *p–n* junctions) and GaInP/GaAs–GaSb (three *p–n* junctions). The maximum efficiency of photovoltaic conversion in GaSb behind the wide-gap cells is $\eta = 6.5\%$ (at sunlight concentration ratio of 275X, AM1.5D Low AOD spectrum).

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1. INTRODUCTION

Mechanically stacked cascaded cells (tandems) based on the GaAs–GaSb pair were first fabricated in 1989 [1]. In the last decade, high-efficiency two- and three-junction monolithic concentrator solar cells have been developed thanks to advances in the growth of multilayer III–V heterostructures by metal-organic vapor-phase epitaxy [2–5]. The possibility of further improvement of the efficiency of photovoltaic conversion of mechanically stacked tandems is related to introduction of monolithic two-junction cells into their composition. One of the most promising modifications of such a combined cascaded cell is a tandem based on GaInP/GaAs–GaSb. Addition of a GaSb cell to cascaded solar cells of this kind can raise the efficiency by more than 6%. With narrow-gap Ge cells used in monolithic three-junction solar cells, this gain is mere 3–4%.

This study is concerned with ways to improve the structure of a narrow-gap GaSb solar cell intended for use in mechanically stacked tandem solar light converters with solar cells based on GaAs or GaInP/GaAs as wide-gap components.

2. FABRICATION OF GaSb SOLAR CELLS

Based on the results of our studies aimed at determining the conditions of GaSb layer crystallization from a gallium-enriched melt [6], we developed optimal modes of formation of a solar cell structure by liquid-phase epitaxy (LPE), diffusion, and a combination of these two techniques.

We fabricated solar cell structures by zinc diffusion both directly into an *n*-GaSb substrate [7, 8] and into an epitaxial base layer [9, 10]. The epitaxial growth was performed in graphite cassettes from a gap of width 0.5 mm in the cooling mode at a rate of 0.5–1.0 K min^{-1}. The initial epitaxial temperature was varied within the range 360–510°C, with the cooling interval of 10 to 40°C.

The selectivity of the *p–n* junction was provided by two-stage diffusion of zinc from the gas phase. In the first stage of diffusion, a "shallow" (0.3–0.5 μm) *p–n* junction (photoactive region of the solar cell) was formed. By the subsequent diffusion, the *p–n* junction was "recessed" to 1.0–1.5 μm in areas under the contact grid. The localization of the diffusion processes was provided by the formation of a mask on the substrate surface by deposition of an insulator film of Si_3N_4 (with the thickness exceeding 0.05 μm) or SiO_2 (thickness 0.1–0.2 μm). In the first stage of low-temperature diffusion (450°C), a protective mask of this kind makes it possible to preclude the formation of a *p–n* junction in the peripheral part of the solar cell and thereby to diminish the leakage current. In the second stage of diffusion at a higher temperature (470–480°C), the insulator Si_3N_4 film (with windows opened for the future strip contacts) protects the sample surface from a repeated interaction with the zinc vapor. No shift of the diffusion boundary was observed in the mask-protected photoactive region of the structure. To prevent substrate oxidation, the diffusion was performed in a continuous flow of hydrogen purified with a palladium filter. The single-temperature diffusion technique was employed, i.e., the temperature of the diffusing substance (pure zinc) and the substrate were the same.

The backside ohmic contact to solar cell structures was fabricated by successive deposition of the Au + 12% Ge alloy, Ni, and Au. Cr/Au and Ti/Pt/Au served as front contacts (with the subsequent electrolytic deposition of Au on both sides of the solar cell). The antireflection coating was produced by successive deposition of ZnS/MgF_2 films. The solar cells were 3.5 × 3.5 mm in size and were intended for conversion of concentrated sunlight in a mechanically stacked cas-

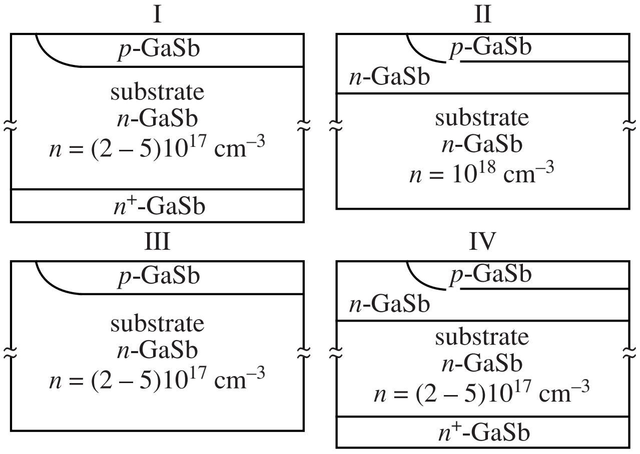

Fig. 1. Variants of GaSb solar cell structures fabricated by combination of LPE and diffusion.

cade with IR-transparent wide-gap single-junction (AlGaAs/GaAs) or two-junction (GaInP/GaAs) solar cells.

Four variants of structures of narrow-gap GaSb solar cells were developed (Fig. 1).

Variant I: diffusion into a substrate with a backside epitaxial n^+-GaSb layer; in this case, the substrate doping level was $n = (2–5) \times 10^{17}$ cm^{-3}.

Variant II: diffusion into the front n-GaSb epitaxial layer; substrate doping level $n \sim 10^{18}$ cm^{-3}.

Variant III: diffusion into the GaSb substrate with a doping level $n = (2–5) \times 10^{17}$ cm^{-3}.

The structure of a solar cell of variant IV comprised a front epitaxial layer with a diffused p–n junction on the front side of the substrate (doping level $n = (2–5) \times 10^{17}$ cm^{-3}); additionally, a heavily doped n^+-layer was crystallized on the backside of the GaSb wafer.

Introduction of the backside n^+–GaSb epitaxial layer (variants I, IV) facilitates the formation of a low-resistance contact and favors an increase in the fill factor (FF) of the current–voltage (I–V) characteristic of the device. Similar consequences lead to an increase in the substrate doping level to $n \sim 10^{18}$ cm^{-3} (variant II). For solar cells of all these types, the p–n junction was formed by two-stage diffusion of zinc from the gas phase.

3. RESULTS OF STUDIES OF GaSb SOLAR CELLS

Figure 2 shows the efficiencies of the GaSb solar cells in Fig. 1 in relation to the intensity of their illumination. The efficiencies were measured under the "upper" single-junction GaAs solar cell, which is transparent to light with wavelengths $\lambda > 0.9$ μm.

As follows from Fig. 2, the solar cells whose structure contains epitaxial layers (curves *1*, *2*, *4*) exhibit higher sunlight conversion efficiencies, compared with the cell fabricated by direct diffusion into a GaSb substrate (curve *3*). For cells of types I and III, the efficiency falls at photocurrent densities $J \gtrsim 3$ A cm^{-2}, whereas for cells of types II and IV, the efficiency continues to grow up to $J = 5–10$ A cm^{-2}. This fact can be attributed to the lower ohmic loss in solar cells fabricated on substrates with an increased doping level or a heavily doped backside layer, which is indicated by the large values of the fill factor of the load characteristic (FF $\geqslant 0.7$) for structures of types II and IV (Fig. 3).

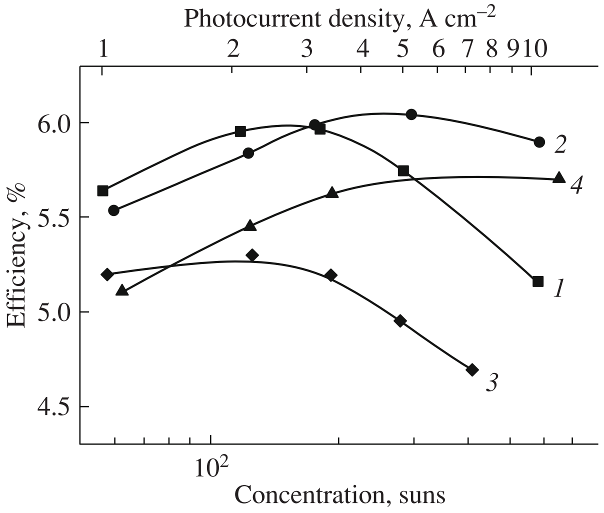

Fig. 2. Efficiency of conversion of concentrated sunlight vs. the concentration ratio for GaSb solar cells of types I–IV (*1*–*4*, respectively). Measurements were performed behind a GaAs "upper" cell. Illumination conditions: AM1.5D low AOD spectrum.

The somewhat lower efficiencies at high values of the FF, obtained with type IV cells, can be attributed to the fact that the p–n junction lies deeper in these cells and, as a result, the photocurrent is lower.

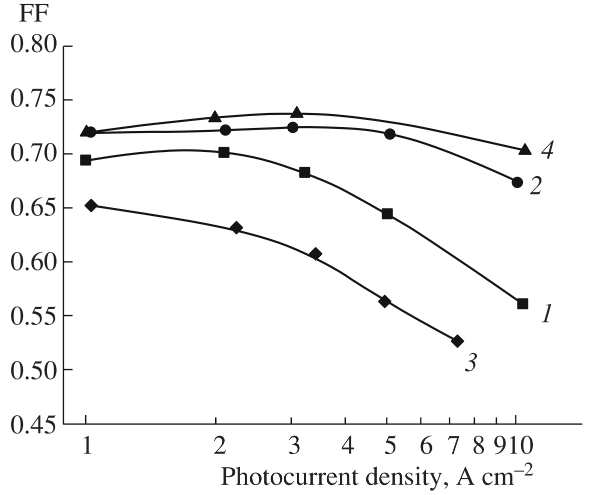

Fig. 3. Fill factor of I–V characteristics vs. the photocurrent density for GaSb solar cells of types I–IV (curves *1*–*4*, respectively).

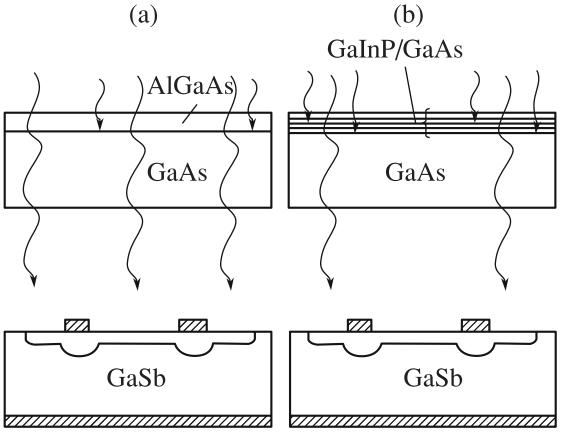

Fig. 4. Schematic of GaSb solar cell exposure through IR-transparent structures of "upper" solar cells: (a) single-junction AlGaAs/GaAs structure and (b) two-junction GaInP/GaAs structure.

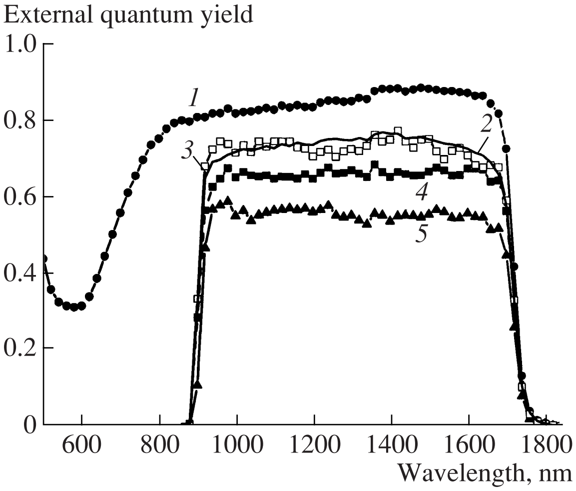

Fig. 5. Spectra of the external quantum yield of a GaSb solar cell: (*1*) without use of wide-gap filters; (*2*) behind the upper GaAs filter (substrate thickness 450 μm, doping level ~10^{17} cm^{-3}); and (*3*–*5*) behind GaInP/GaAs upper filters: (*3*) GaAs substrate thickness $d = 380$ μm, doping level $n = 2 \times 10^{18}$ cm^{-3}; and (*4*, *5*) substrate thicknesses $d = 100$ and 310 μm, respectively, and doping level $n = (2–5) \times 10^{18}$ cm^{-3}.

The GaSb photoelectric converters we developed are intended for use in cascaded solar cells with IR-transparent "upper" cells based on a single-junction AlGaAs/GaAs structure (Fig. 4a) or two-junction GaInP/GaAs structure (Fig. 4b). Two-layer antireflection coatings were fabricated from ZnS/MgF$_2$ for both the "upper" and "lower" cells of the tandem, with the blooming films deposited on both (front and back) sides of the "upper" wide-gap cell to diminish the optical loss.

Figure 5 (curve *1*) shows the photosensitivity spectrum of GaSb photovoltaic converters with a front base layer produced by LPE. Under illumination of this photovoltaic cell through the AlGaAs/GaAs heterostructure, the external quantum yield decreases in the wavelength range 900–1840 nm (Fig. 5, curve *2*) because of the optical loss (reflection and absorption) in the "upper" cell (substrate doping level $n = 2 \times 10^{17}$ cm^{-3}, thickness 450 μm). In this case, the range of photosensitivity wavelengths for the narrow-gap cell is limited to $\lambda = 900–1840$ nm because of the complete absorption of the short-wavelength light ($\lambda < 900$ nm) by the GaAs substrate.

To evaluate the contribution of the narrow-gap photovoltaic converter coupled with a two-junction wide-gap monolithic cell to the total efficiency of the tandem cell [5], we measured the external quantum yield in GaSb behind a filter based on the GaInP/GaAs heterostructure (Fig. 5, curves *3*–*5*). In the mechanically stacked tandem cell, the lower optical loss and the higher photoresponse of the GaSb cell are provided by structures of the "upper" cell with smaller thicknesses (Fig. 5, curve *4*) and lower doping level of the GaAs substrate (Fig. 5, curve *3*).

The values of the photocurrent density in GaSb, listed in the table, also demonstrate that the loss by absorption in the "upper" GaInP/GaAs cell falls as the GaAs substrate thickness is decreased from 310 to 100 μm or its doping level is lowered from (2–5) × 10^{18} cm^{-3} (Fig. 5, curve *5*) to 2 × 10^{16} cm^{-3} (Fig. 5, curve *3*). An increase in the transmittance of the wide-gap two-junction cell leads to a noticeable rise in the photocurrent density to the maximum value of 18.45 mA cm^{-2} for a GaInP/GaAs structure with a lightly doped substrate (Fig. 5, curve *3*).

Photocurrent in a GaSb solar cell in the structure of a cascaded photovoltaic converter with various "upper" cells

Type of the "upper" cell	Photocurrent density, mA cm^{-2}
Without a wide-gap cell	38.76
GaAs (substrate doping level n ~10^{17} cm^{-3}, thickness $d = 450$ μm	18.59
GaInP/GaAs (substrate doping level $n = 2 \times 10^{16}$ cm^{-3}, thickness $d = 380$ μm	18.45
GaInP/GaAs (substrate doping level $n = (2–5) \times 10^{18}$ cm^{-3}, thickness $d = 100$ μm	16.81
GaInP/GaAs (substrate doping level $n = (2–5) \times 10^{18}$ cm^{-3}, thickness $d = 310$ μm	14.00

Note: The data are presented for exposure at 1000 W m^{-2}, AM1.5D Low AOD spectrum.

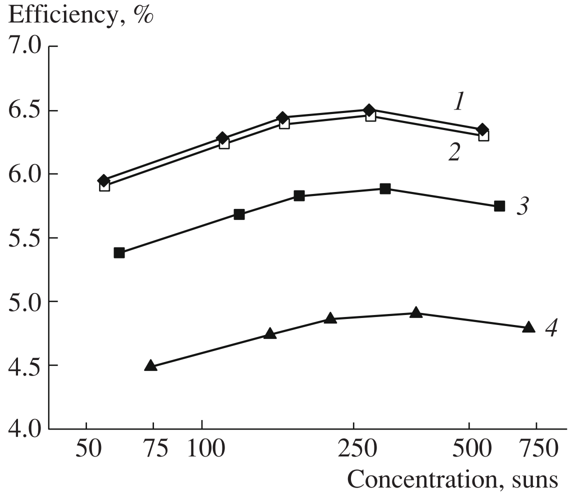

Fig. 6. Conversion efficiency of GaSb solar cells placed behind an “upper” IR-transparent cell based on (*1*) GaAs and (*2–4*) GaInP/GaAs for structures with different doping levels (*n*) and thicknesses (*d*) of the GaAs substrate: (*1*) $n \sim 10^{17}$ cm^{-3}, $d = 450$ μm; (*2*) $n = 2 \times 10^{16}$ cm^{-3}, $d = 380$ μm; (*3*) $n = (2–5) \times 10^{18}$ cm^{-3}, $d = 100$ μm; and (*4*) $n = (2–5) \times 10^{18}$ cm^{-3}, $d = 310$ μm. Measurement conditions: AML.5D Low AOD spectrum.

The maximum values of the solar light conversion efficiency, $\eta = 6.45–6.5\%$ were obtained in GaSb cells in the case of their illumination behind a single-junction GaAs cell (Fig. 6, curve *1*) or a two-junction GaInP/GaAs cell (Fig. 6, curve *2*).

The efficiency of monolithic two-junction GaInP/GaAs solar cells exceeds 30% [5]. If these photovoltaic converters are combined into a tandem cell with the GaSb cells we developed, a total efficiency exceeding 36% can be attained.

4. CONCLUSIONS

A combination of the LPE technique and Zn diffusion from the gas phase was used to fabricate various types of GaSb-based solar cells. It was found that the maximum efficiency is observed for solar cells with an epitaxial front layer and diffusion *p–n* junction. Prospects for raising the efficiency of mechanically stacked tandems with GaSb photovoltaic converters were demonstrated. The influence exerted by parameters of the wide-gap filter based on the two-junction GaInP/GaAs heterostructure on the spectral characteristics and efficiency of the narrow-gap cell was studied. The maximum contribution of the GaSb cell to the total efficiency of the tandem solar cell with GaInP/GaAs was found to be 6.45%. The efficiency of tandem solar cells can be further raised by using a monolithic two-junction cell (e.g., that based on GaInAsSb/GaSb [11]) in the narrow-gap part of the cascade.

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