HIGH CURRENT DENSITY GaAs AND GaSb PHOTOVOLTAIC CELLS FOR LASER POWER BEAMING

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ABSTRACT

AlGaAs/GaAs- and GaSb-based laser power PV converters operating at output photocurrent densities up to 100 A/cm^2 were fabricated. Fill factor values of 0.85-0.87 at laser power density P_{laser}=1.0-50 W/cm^2 and FF=0.80-0.83 at P_{laser}=100-200 W/cm^2 were measured in the GaAs-based cells. Open circuit voltage of the GaAs cells increased from 1.15V at P_{laser}= 5 W/cm^2 to 1.26V at 200 W/cm^2. Efficiency of monochromatic (λ_{laser} =820-850 nm) power conversion increased up to 56% with increasing P_{laser} up to 50 W/cm^2, and further decreased by 3-4% at P_{laser}= 200 W/cm^2. AlGaAs/GaAs converters with internal Bragg reflector ensured the photoresponse increase in the wavelength range of 830-870 nm as well as improvement of radiation resistance. Also, AlGaAsSb/GaSb laser power converters were developed for operation in spectral range of 1300-1680 nm.

1. INTRODUCTION

Laser emission can be effectively converted into electricity by means of the high-current photovoltaic (PV) cells based on semiconductor heterostructures previously developed for conversion of concentrated sunlight [1-4]. Such a conversion can be realized for laser power transmitted through optical fibers [3, 5-7] in the systems of remote power supply. This approach may be useful at power transmission in space: between spacecrafts; from a spacecrafts to earth; from earth to a spacecraft. The main problem in all these cases is the necessity to provide a high PV conversion efficiency of the laser emission in a wide range of the incident power densities at a given wavelength.

One of the promising ways of laser powered system application is arrangement of a laser source directly in space using pumping by solar power. Possible candidates on the role of a space laser are injection lasers based on heterostructures (λ = 800-1680 nm) and iodine lasers (λ = 1315 nm). The conception of placing a laser in space has the following advantage in comparison with terrestrial systems: laser beam does not pass through atmosphere where absorption and scattering are essential. Therefore, beam divergence at the level of 10^{-6}-10^{-7} radians without using the special adaptive systems for correction of atmosphere distortions can be achieved.

Requirements to the systems for laser power conversion are determined by specific features of its characteristics at remote power supply of the objects: continuous mode of operation; relatively high power (1-100 kW); wide range of possible laser power densities and nonuniform distribution of the laser irradiation over PV converter area. These requirements have to be fulfilled at minimum possible area and weight per unit of generated electric power, high reliability and long-term (10-15 year and even more) operation of a system in space.

The purpose of this work is to develop high current density laser power converters intended for operation in PV concentrator modules [8] and in Power-by-Fiber systems. The results of experimental investigations of the AlGaAs/GaAs and GaSb PV cells intended for coupling with AlGaAs/GaAs injection lasers (λ = 800 - 870 nm), InGaAsP/InP lasers (λ = 1550-1680 nm) and iodine lasers (λ=1315 nm) are presented. CW lasers with wavelengths of 820 nm fabricated at the Ioffe Institute [9] were used for testing the developed cells with aperture area of 2 mm^2 at light power densities up to 50 W/cm^2. I-V characteristic measurements under illumination power densities as high as 50-250 W/cm^2 have been carried out using a flash Xe lamp simulator. Also, pulse (τ = 10^{-3} s) iodine laser (λ = 1315 nm) with radiation power up to 10 W was used for GaSb cell illumination [10]. Uniform cell illumination has been ensured in these experiments with pulse iodine laser and flash lamp. Output laser power and external converter photoresponses have been measured using the reference cells calibrated at FhG-ISE, Freiburg.

2. ESTIMATION OF ACHIEVABLE LASER POWER PV CONVERSION EFFICIENCIES

Fig.1 shows theoretical maximum “monochromatic” efficiencies of an idealized PV cell operating at different radiation wavelengths (λ) and photocurrent densities (i_{ph}) [1]. At i_{ph}=10 A/cm^2 theoretical efficiency increases from 63% at λ=1700 nm in GaSb-based cell up to 78% at λ=870 nm in GaAs-based cell.

To estimate the achievable efficiencies, additional optical, recombination and ohmic losses should be taken into account. Optical losses on the free of contact cell surface may be reduced down to 2-3% by using the antireflection coatings. High-power photoconverters should have a contact grid with reduced spacing (50-100 μm) to ensure the efficient photocurrent output. Grid fingers shadowing in these photoconverters is typically about 10% and may be reduced down to 3-4% by using a silicone prismatic cover on the cell surface (Fig. 2, *a*).

Recombination losses in the advanced photoconverters can be reduced down to 3-5% owing to using a high quality epitaxial semiconductor material in the photoactive region. The influence of ohmic losses becomes to be significant at laser power densities higher than 10 W/cm^2.

Taking into account pointed above additional losses in the high-power photoconverters, the values, shown in Fig. 1, have to be multiplied by a factor of 0.80-0.85 to obtain the achievable in practice efficiencies. It means, for instance, that efficiency of 65% is achievable in practical GaAs cells under laser irradiation with wavelengths of 800-870 nm at power densities exceeding 10 W/cm^2.

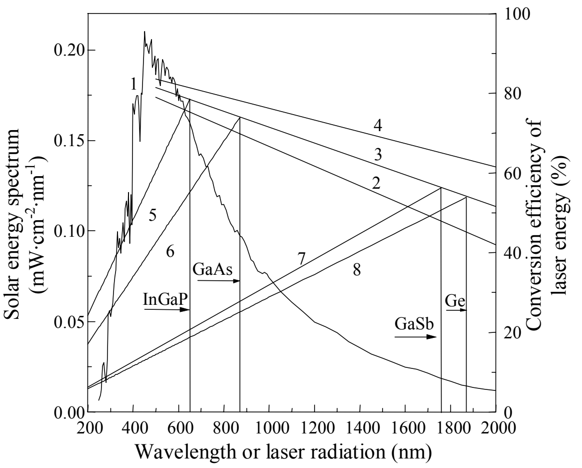

Fig. 1. Curve 1–solar energy spectrum (AM0); lines 2, 3, and 4–plots of maximum magnitudes of the "monochromatic" efficiency of an idealized photoconverter at i_{ph} = 0.1; 1.0 and 10 A·cm^{-2}, respectively, in dependence on the “boundary” wavelength of the semiconductor material; sloped lines 5, 6, 7, 8 - spectral dependences of the conversion efficiency in the idealized photoconverters based on $In_{0.5}Ga_{0.5}P$, GaAs, GaSb and Ge materials at i_{ph} = 1.0 A·cm^{-2}.

3. AlGaAs/GaAs PHOTOCONVERTERS

The structure of the high-power GaAs-based cells grown by LPE or MOCVD consists of (Fig. 2, *a*): *n*-GaAs substrate; *n*-$Al_{0.2}Ga_{0.8}As$ or n$^+$ GaAs BSF layer; *n*-GaAs base (n=3·10^{17} cm^{-3}, Te-doped, 3 µm); *p*-GaAs emitter (p=(0.2-2)·10^{19}cm^{-3}, Mg-, Ge- or Zn-doped, 1.0-1.5 µm); *p*-$Al_{0.85}Ga_{0.15}As$ window (Mg-doped, 0.05 µm). This structure was optimized for operation at more than 50-100 W/cm^2 laser power densities. The cells should have a low sheet resistance, which was ensured by increasing the *p*-GaAs emitter thickness and its doping level keeping sufficient diffusion length for electrons in this layer. These features were realized owing to formation of a built-in electric field in the *p*-GaAs emitter. Acceptor concentration in a top part of this layer was as high as 10^{19} cm^{-3}.

PV cell structures with an internal Bragg reflector (Fig. 2, *b*) were fabricated by MOCVD. An increase in the long-wavelength (λ = 830-870 nm) part of the photoresponse curve was observed in these cells caused by high reflectance (up to 96%) from Bragg reflector in the spectral range of 820-900 nm [11].

Experiments with high laser power density irradiation in the range of 50-200 W/cm^2 were carried out with the cells characterized by designated illumination area of 2 mm^2 (Fig. 3, *b*). The contact grid finger spacing in these cells was 0.1 mm or 0.05 mm; the finger width was 6-10 µm at finger thickness of 2-3 µm. Two-layer ZnS/MgF_2 antireflection coating (ARC) was deposited on the cell surface in the case if no prismatic cover has to be applied (Fig. 2, *b*). One layer of ZnS was used to minimize reflection of photons from the front surface when the prismatic cover is bonded to the cell surface (Fig. 2, *a*).

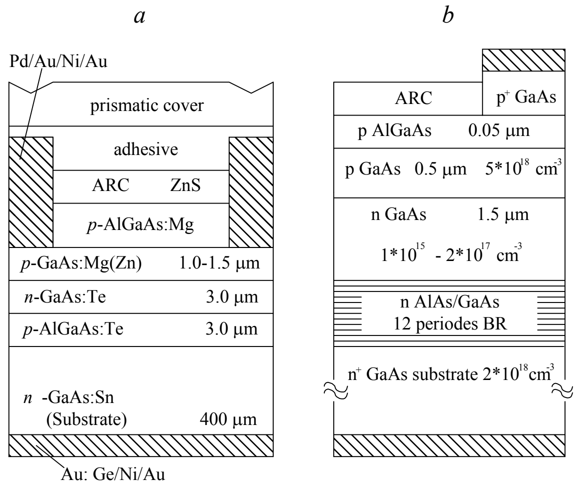

Fig. 2. Heterostructure of the GaAs-based laser power converters: *a*- with prismatic cover, *b* – with internal Bragg reflector.

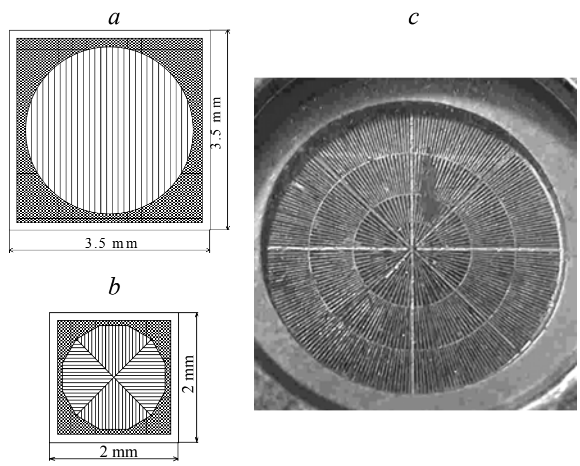

Fig. 3. Top view of the laser power converters with designated illumination area of d_a=6.6 mm^2 (*a*) and 2.0 mm^2 (*b*); PV array with aperture area of 2.45 cm^2 consisting of eight series connected subcell sectors (*c*).

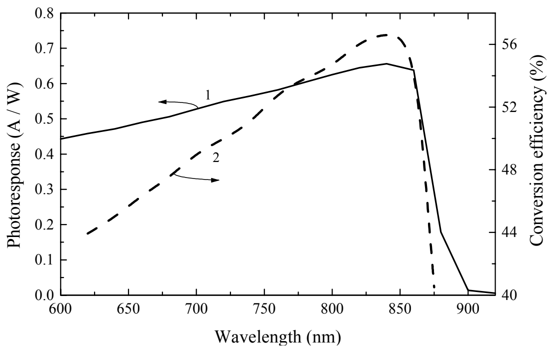

Fig. 4. Spectral photoresponse (curve 1, left axis) and efficiency at I_{ph} = 40 A/cm^2 (curve 2, right axis) of PV converter based on AlGaAs/GaAs heterostructure shown in Fig. 2, *a* (curve 1) and in Fig. 2, *b* (curve 2).

Internal photoresponse of 0.65 A/W at λ = 820-850 nm was achieved in the best cell (Fig. 4). External quantum yield as high as 94-96% at λ = 500-850 nm was measured on the designated illumination area in the test GaAs cells with prismatic cover. Fill factor value decreased from FF=0.86-0.87 at P_{laser} = 5-50 W/cm^2 down to about 0.80 at P_{laser} = 200 W/cm^2. The open circuit voltage increased from 1.1-1.15 V at P_{laser} = 5 W/cm^2 up to 1.2-1.26 V at P_{laser} = 200 W/cm^2. Conversion efficiency of 56% at λ = 820 nm has been obtained at photocurrent density of 30-40 A/cm^2 (Fig. 4, 5) and that of 52% at i_{ph} = 130A/cm^2 (Fig. 5).

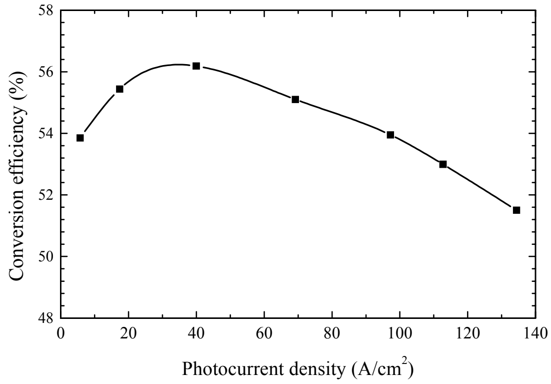

Fig. 5. Conversion efficiency versus photocurrent density for the GaAs cell (d_a = 2 mm^2) irradiated at wavelength of 820 nm (uniform illumination).

GaAs-based array (Fig. 3, *c*) with eight subcell sectors of circular geometry connected in series (d_a = 2.45 cm^2) has been fabricated. V_{oc} = 8.8 V and FF = 0.78 at output current of 1.4 A were measured in this array under concentrated sunlight illumination with water-cooling. Monochromatic efficiency of 46% was estimated in this PV array for λ = 820 nm corresponding to the output electric power of 9.6 W in continuous mode of operation.

Radiation resistance has been improved in the converters with internal Bragg reflector (Fig. 2, *b*) owing to decrease in the base GaAs layer thickness from 3 μm to 1.5 μm without decrease in photoresponse magnitude. It is seen from Fig. 6 that the cells with internal Bragg reflector are characterized by much higher radiation hardness in comparison with those without such a reflector.

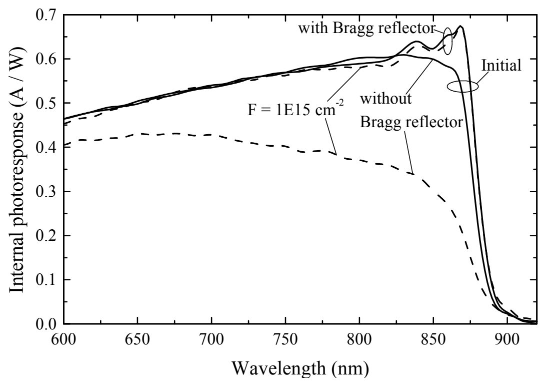

Fig. 6. Internal spectral photoresponse of the PV converters based on AlGaAs/GaAs heterostructures with and without internal Bragg reflector before and after 3.75 MeV electron irradiation with fluence of $1\cdot10^{15}$ cm^{-2}.

This phenomenon was observed in solar cells previously [11], but the influence of Bragg reflector is even more significant for the spectral range of 800-870 nm, corresponding to IR laser radiation.

4. GaSb-BASED PHOTOCONVERTERS

AlGaAsSb/GaSb-based photoconverters for laser power beaming were also developed. External quantum yield as high as 85-90% was measured in the PV cells with GaSb in the photoactive region. These cells were optimized for operation in the couple with lasers radiating in the range of 1550-1700 nm. External photoresponse of 1.2 A/W at λ = 1680 nm was achieved in the cells with epitaxial (LPE) GaSb active region (Fig. 7). The cells with active region fabricated from "bulk" GaSb wafers prepared from ingots grown by the Czochralski technique are characterized by lower photoresponse of 0.8-0.9 A/W at λ = 1300-1700 nm (Fig. 7). Open circuit voltage of 0.57 V and fill factor of 0.75 were measured in GaSb converters at i_{ph} = 65 A/cm^2 (Fig. 8). Efficiency of 49% was achieved in the "epitaxial" GaSb cells (d_a = 2 mm^2) under monochromatic irradiation with wavelength of 1680 nm at photocurrent densities of 60-90 A/cm^2 (Fig. 7, curve 3, Fig. 9, curve 1), slightly decreasing down to η = 48% at i_{ph} = 130 A/cm^2.

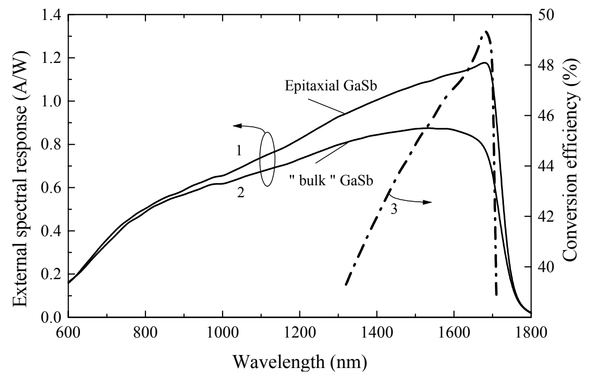

Fig. 7. Spectral photoresponse (curves 1, 2, left axis) and efficiency at i_{ph} = 90 A/cm^2 (curve 3, right axis) for the GaSb cells based on epitaxial (1, 3) or "bulk" (2) material in photoactive region.

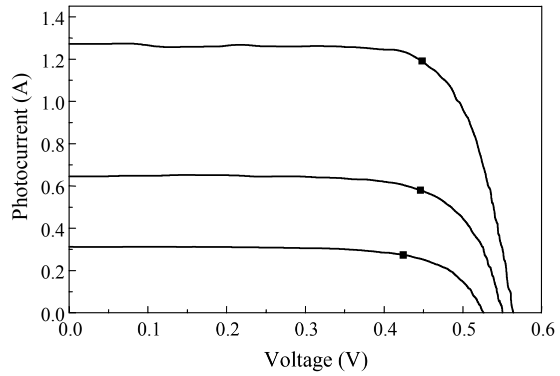

Fig. 8. Illuminated I-V characteristics of the GaSb cells with designated illumination area of 2 mm^2.

Efficiency drop to 45% at λ = 1550 nm (Fig. 7, curve 3, Fig. 9, curve 2) and to 39% at λ = 1315 nm (Fig. 9, curve 3) took place in the GaSb cells at photocurrent density of 90 A/cm^2. The reason for efficiency decrease is a reduction of photoresponse from 1.18 A/W at λ = 1680 nm to 1.1 A/W at λ = 1550 nm and to 0.95 A/W at λ = 1315 nm in "epitaxial" GaSb cells (Fig. 7, curve 1).

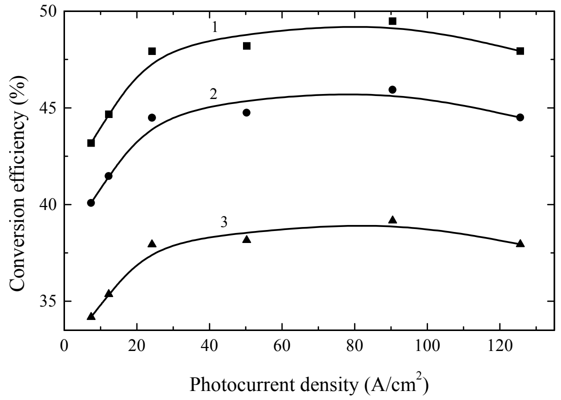

Fig. 9. Conversion efficiencies of the "epitaxial" GaSb PV converter as a function of the photocurrent density at monochromatic irradiation (uniform illumination) with wavelengths: 1 – 1680 nm, 2 – 1550 nm, 3 – 1315 nm.

5. CONCLUSION

Conversion efficiency as high as 56% at λ = 820 nm has been achieved in the GaAs-based laser power converters owing to extremely high photoresponse, open circuit voltage and fill factor in the cells with designated illumination area of 2 mm^2. Efficiency of 52% was obtained in these cells at i_{ph} = 130 A/cm^2 and 56% at i_{ph} = 40 A/cm^2. A high output power GaAs cell array (S = 2.45 cm^2) made of 8 subcell sectors connected in series has been manufactured in this work to achieve the 8.8 V operation goal at output power of 10 W realized under concentrated sunlight illumination.

AlGaAs/GaAs converters with internal Bragg reflector are characterized by much higher radiation hardness, which makes these devices very promising for space-to-space and space-to-Earth laser power beaming applications.

GaSb-based converters ensure the external photoresponse of 1.2 A/W and efficiency of 49% at λ = 1680 nm irradiation and photocurrent densities of 60-90 A/cm^2 and rather high efficiency of 39% at λ = 1315 nm.

There are advantages of using the solar-pumped photodissociative iodine laser (PIL) [10] for power (λ = 1315 nm) transmission from space: – PIL is the gas laser, therefore its active media is free from such kinds of heterogeneity as thermal lenses and heterogeneity refraction, which take place in the active medium of solid-state lasers. – The volume of the active media of a gas laser doesn't have such limitations in sizes as the volume of a solid state laser. Therefore, the laser modules based on PILs with power of 10 kW and more can be created. – It is possible to achieve for a solar-pumped PIL a diffraction limit of a radiation divergence less then $5 \cdot 10^{-6}$ radian, which gives a great advantage for a laser energy transmission.

Usage of the AlGaAsSb or InGaAsP alloys with bandgaps of 0.85-0.9 eV, which are better matched to 1315 nm radiation, will allow achieving the efficiencies of more than 50% under the high power PIL laser.

6. ACKNOWLEDGMENTS

Authors would like to thank N.Timoshina for spectral and I-V characteristic measurements, I.S.Tarasov for fabrication and presenting the injection heterolasers, L.M.Vinogradsky for testing the GaSb cells under iodine laser illumination. Our gratitude to Zh.I.Alferov for support of this work and for fruitful discussions.

The work was supported in part by the Russian Foundation for the Basic Research.

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