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Micro-dimensional GaSb photovoltaic converters of high-power density laser radiation

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Received October 8, 2024
Revised October 31, 2024
Accepted October 31, 2024

Investigations of the manufacturing technology of laser radiation ($\lambda = 1550$ nm) photovoltaic converters, obtained by the two-stage Zn diffusion into *n*-GaSb substrate, with photosensitive region 30 and 80 μm in diameter have been carried out. Methods to reduce optical and ohmic losses of high-power density laser radiation (up to 1.6 kW/cm^2) conversion have been investigated. Laser radiation conversion efficiency more than 38% at photocurrent density $200-550$ A/cm^2 was achieved.

Keywords: photovoltaic converter, laser radiation, diffusion.

DOI: 10.61011/TPL.2025.02.60645.20142

Photovoltaic converters (PVC) of laser radiation (LR) are widely used for wireless transmission of energy to a remote source, including remote power supply for spacecrafts, solar power plants, fiber optic communication lines, and in domestic applications such as wireless charging of devices [1–4]. At the LR wavelength $1500-1700$ nm the minimum optical losses are observed, as well as the minimum dispersion in optical fibers [5]. This substantiates the feasibility of using GaSb-based PVC with spectral sensitivity in the wavelength range $1400-1700$ nm [6,7]. The formation of PVC LR is carried out using different methods: liquid-phase epitaxy technology, gas-phase epitaxy from organometallic compounds, and by diffusion of zinc from the gas phase into the substrate *n*-GaSb [8–12]. The advantages of the diffusion method are technological simplicity of implementation, formation of a gradient field providing separation of charge carriers, high level of doping of near-surface regions providing formation of metal contacts with low specific contact resistance, which is especially important in the fabrication of high-power PVC. At the same time GaSb is characterized by low surface recombination rate, which allows to form photoactive region of PVC without wide-area optical window and corresponds to the possibilities of diffusion method.

Photovoltaic converters of laser radiation are obtained by the method of local diffusion of Zn from the gas phase into the *n*-GaSb substrate to form the photosensitive region with diameters of 30 and 80 μm, which leads to the possibility of power density limit conversion. To maximize the spectral photosensivity at the wavelength of 1550 nm and to reduce ohmic losses due to the spreading resistance along the layer, the formation of the $p-n$-junction in GaSb is carried out in two stages. In the first stage, Zn is diffused through the dielectric mask Si_3N_4 to form a shallow $p-n$-junction at a depth of ~ 500 nm in the 40 or 100 μm diameter PVC region. A dielectric layer Si_3N_4 with a thickness of ~ 100 nm, is deposited by the plasma-activated pyrolysis method, which provides high adhesion of the layer to the GaSb surface and high resistance to diffusion Zn. At the second stage, the diffusion layer is buried to a depth of $1000-1500$ nm along the perimeter of the photosensitive region under the frontal ohmic contact zone through the second mask Si_3N_4. At the same time, the thickness of the Si_3N_4 layer, which is also an illumination coating and provides electrical isolation of the frontal metal contact outside the photosensitive region PVC, is optimized.

Conversion of high laser power density (up to 1.6 kW/cm^2) leads to the necessity of forming low-resistance metal contacts [13]. Earlier contacts to GaSb *p*-type conductivity were formed on the basis of Cr/Au and AgMn/Ni/Au layers. The main disadvantage of these contacts is a high degree of diffusion into the depth of the semiconductor during thermal annealing, which can lead to shunting of $p-n$-junction. The development of a new NiCr/Ag/Au contact system with good adhesion to the semiconductor surface and a low degree of diffusion during thermal annealing provided the formation of a low-resistance ohmic contact, and also contributed to an increase in the yield of good devices and a decrease in leakage currents. The Au(Ge)/Ni/Au contact system is widely applicable to semiconductor materials of *n*-type conductivity. During the development of GaSb-based PVC formation technology, optimization of deposition and thermal annealing modes was carried out. The result of the studies was the achievement of low values of specific contact resistance of the sputtered systems to the semiconductor surface — $(2-3)\cdot 10^{-6}\,\Omega\cdot$cm^2. The above mentioned contact systems are sputtered up to the thickness of $0.2-0.3\,\mu$m, to increase the electrical conductivity of the contacts, they are built up by electrochemical deposition of Ag/Ni/Au layers with the thickness of $2-3\,\mu$m. A mesa-structure of PVC with the size 0.5×1.5 mm is formed by increasing the area of the

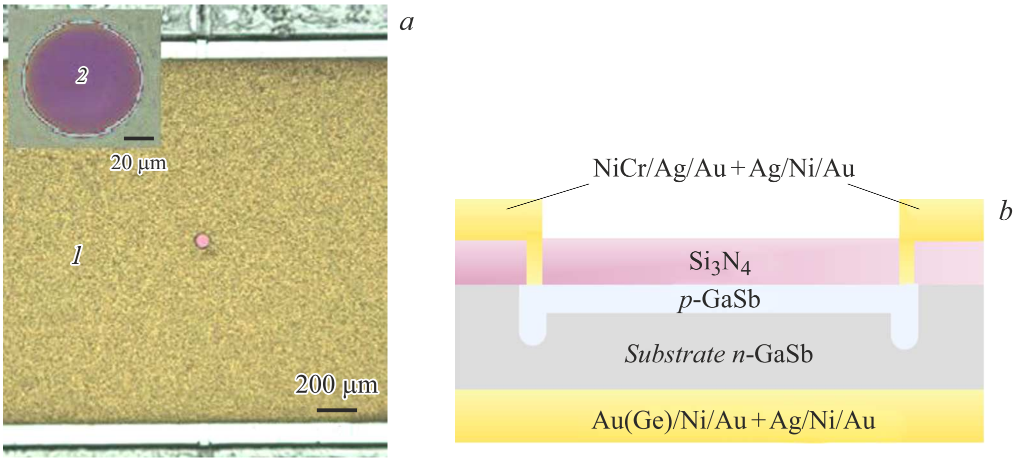

Figure 1. Photograph (*a*) and schematic representation of the cross section (*b*) GaSb-based PVC LR (diameter of the photosensitive region 80 μm). *1* — metal contact, *2* — photosensitive region.

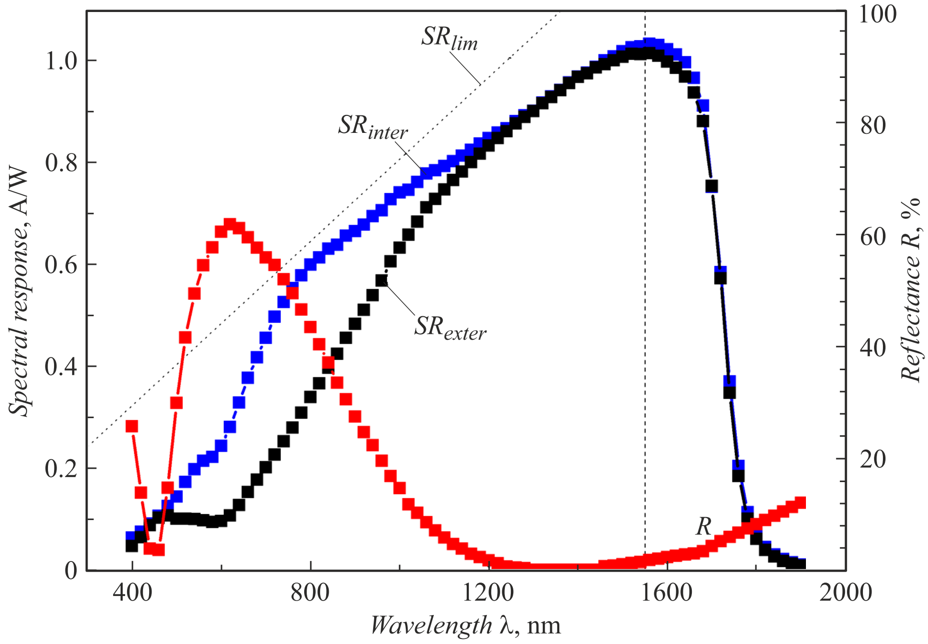

Figure 2. Spectral photosensitivity (SR) of GaSb-based PVC test samples of size 3×3 mm.

peripheral frontal contact, which leads to the improvement of heat dissipation and the possibility of installation and testing of elements (Fig. 1).

The spectral photosensitivity of the PVC was measured on test samples of size 3×3 mm. In the operating wavelength range 1300–1600 nm the values of internal ($SR_{inter.}$) and external (SR_{exter}) photosensitivity of the PVC practically coincide and are equal to 1 A/W, which indicates low optical losses at the LR input. Decrease of the reflection coefficient of the incident radiation to 0–2% was achieved due to optimization of the technology of formation of the anti-reflection coating based on Si_3N_4. The minimum reflectance can be achieved by forming a two-layer anti-reflection coating based on TiO_2/SiO_2, layers optimized for the wavelength of 1550 nm. However, in manufacturing GaSb-based PVC, the anti-reflection coating also serves as a mask for conducting local diffusion of Zn. Studies have shown that the single-layer Si_3N_4 coating is more resistant to diffusion and consequently has an advantage over the double-layer coating. The limiting value of (SR_{lim}) photosensitivity is shown by the dashed line (Fig. 2).

Photovoltaic characteristics of PVC with the diameter of photosensitive area 30 and 80 μm are measured at illumination by continuous laser radiation ($\lambda = 1550$ nm) from optical fiber with diameter 50 μm with numerical aperture 0.22. Fig. 3 shows typical dependences of efficiency, the fill factor of the current-voltage curve and open circuit voltage on photocurrent density for two standard

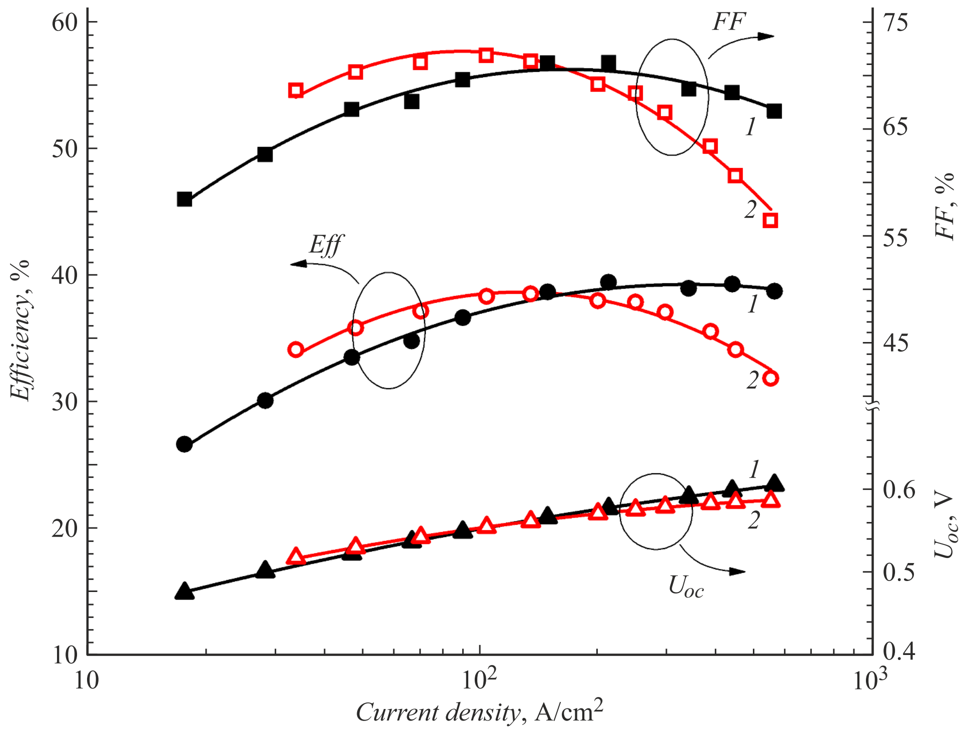

Figure 3. Dependences of efficiency, fill factor (FF) of the current-voltage curve and open circuit voltage (U_{oc}) on the photocurrent density for PVC with photosensitive surface diameters of 30 (1) and 80 μm (2) under continuous LR exposure $(\lambda = 1550\,\text{nm})$.

sizes of PVC. The maximum efficiency values were achieved at photocurrent density 130–200 A/cm^2 and amounted to 39.4 and 38.5% for elements with photosensitive surface diameter 30 and 80 μm respectively. The dependence of the open circuit voltage on the photocurrent density shows that the PVC with a photosensitive area diameter of 80 μm heats up when the photocurrent density increases above 200 A/cm^2. At the same time, the PVC with the diameter of photosensitive area 30 μm is hardly subjected to heating due to essentially lower absolute power, which allows to reach the open circuit voltage of 0.605 V at the photocurrent density $\sim$ 550 A/cm^2.

Thus, the technology of fabrication of photovoltaic converters of laser radiation $(\lambda = 1550\,\text{nm})$ based on GaSb with the diameter of photosensitive window 30 and 80 μm has been developed. Optical losses were reduced by optimizing the technology of formation of diffusion p–n-junction in GaSb, as well as by developing the technology of formation of the antireflection coating on the basis of Si_3N_4, which allowed achieving the external PVC photosensitivity of 1 A/W. The ohmic losses were reduced by creating microsized PVCs due to the decrease in the spreading resistance, as well as by developing new contact systems for GaSb p-type conductivity based on NiCr/Ag/Au + Ag/Ni/Au, which made it possible to convert high LR power density (up to 1.6 kW/cm^2). Previously, we obtained GaSb-based photovoltaic converters operating at incident radiation densities up to 100 W/cm^2, and the efficiency $\sim$ 34% [7,14] was achieved. Research and development work has resulted in PVC LR $(\lambda = 1550\,\text{nm})$ with efficiencies greater than 38% at photocurrent densities as high as 550 A/cm^2.

Conflict of interest

The authors declare that they have no conflict of interest.

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Translated by J.Savelyeva