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Bridge-type contact systems in InGaAs/InP photovoltaic converters

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Methods of reducing resistive losses and capacity of photovoltaic converters of laser radiation ($1.55\,\mu$m) based on InGaAs/InP heterostructures, grown by metalorganic vapor-phase epitaxy, have been carried out. Various contact systems: NiCr/Ag/Au, AgMn/Ni/Au, Cr/Au/Ni/Au and Pd/Ge/Au, Au(Ge)/Ni/Au to InGaAs and InP layers of *p*- and *n*-type conductivity, respectively, have been investigated. Analyzed were the influence of composition and modes of ohmic contacts formation on the contact resistivity and current-voltage characteristics of the devices. Minimum values of specific contact resistivity have been archived by Pd/Ge/Au ohmic contact evaporation on n^+-InGaAs ($\sim 10^{-7}\,\Omega\cdot\text{cm}^2$) and NiCr/Ag/Au on *p*-InGaAs ($-10^{-6}\,\Omega\cdot\text{cm}^2$). A design has been developed for photovoltaic converts with a photosensitive area of $30\,\mu$m in diameter with a bridge-type contact system, which allowed to reduce the $p-n$-junction area in a photocell and, accordingly, its capacity.

Keywords:: InGaAs/InP photovoltaic converter, contact systems, resistive losses.

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Introduction

Photovoltaic converters (PVC) based on A3B5 heterostructures are widely used to convert laser radiation (LR) in the wavelength range of $0.8-1.55\,\mu$m in fiber-optic and atmospheric optical communication lines [1–4]. Photodetectors of high-power short-duration signals with a high (gigahertz) repetition rate are a particularly important category of PVC [5–7]. AlGaAs/GaAs PVC ensuring conversion of high-power LR are the main PVC in the range of $0.8-0.86\,\mu$m [8]. The most popular wavelengths for transmitting information are ~ 1.3 and $\sim 1.55\,\mu$m, which ensure long-range transmission with minimal losses in the transparency windows of fiber-optic communication lines [9]. For this range, it is possible to use InGaAs [10,11] material in the active area of the PVC, which demonstrated the bandwidth of ~ 1.3 GHz ($\lambda = 0.97\,\mu$m) [12] and ~ 8.3 GHz at the level of -3 dB ($\lambda = 0.9\,\mu$m) [13]. $P-i-n$-PVC based on InAs/InGaAs quantum dots have a bandwidth of up to 5.5 GHz ($\lambda = 1.5\,\mu$m) [14]. Another solution is heterostructures grown on InP substrates with an active region based on pseudomorphic InGaAsP quadruple [15] or triple $In_{0.53}Ga_{0.47}As$ solid solutions. Photosensitivity of InGaAs/InP heterostructures can be successfully extended to $2.3-2.4\,\mu$m using metamorphic growth technology [16]. High-speed PVC of mid-infrared spectral range of $1.2-2.4\,\mu$m based on GaSb/GaInAsSb/GaAlAsSb heterostructures with separated sensitive and contact meses connected by a „bridge" frontal contact have a bandwidth of $2-5$ GHz [17].

The main purpose of this work is to study methods for reducing resistive losses and device capacity in the formation of high-speed PVC based on InGaAs/InP heterostructures. To achieve this goal, studies of various contact systems for InGaAs, InP layers of *n*- and *p*-type of conductivity were performed, new designs of devices with „bridge" type contact systems were developed and their influence on the characteristics of the PVC was analyzed.

1. PVC heterostructure

PVCs were manufactured on the basis of InGaAs/InP $p-i-n$-heterostructures grown by the method of MetalOrganic Vapor Phase Epitaxy (MOVPE) on two types of InP substrates:

— heavily-doped substrate of *n*-type of conductivity ($10^{19}\,\text{cm}^{-3}$) (Fig. 1, *a*);

— semi-insulating substrate ($10^{15}\,\text{cm}^{-3}$) (Fig. 1, *b, c*).

The active region of the heterostructure included $p-i-n$-InGaAs layers with *i*-region with a thickness of $\sim 1\,\mu$m enclosed in InP barrier layers of *n*- and *p*-type of conductivity, respectively. Heavily doped contact layers were grown to form low-resistance ohmic contacts. Different compositions of contact layers based on InGaAs and InP of *p*- and *n*-type of conductivity were studied in this paper to analyze the possibility of reducing the contact resistivity and series resistance of devices in general. The contact layer of *p*-type of conductivity was formed on the basis of heavily doped p^+-InGaAs-material with the growth of the heterostructure, the usage of n^+-InGaAs and n^+-InP was considered with the growth of the contact layer of *n*-type of conductivity (Fig. 1, *b, c*).

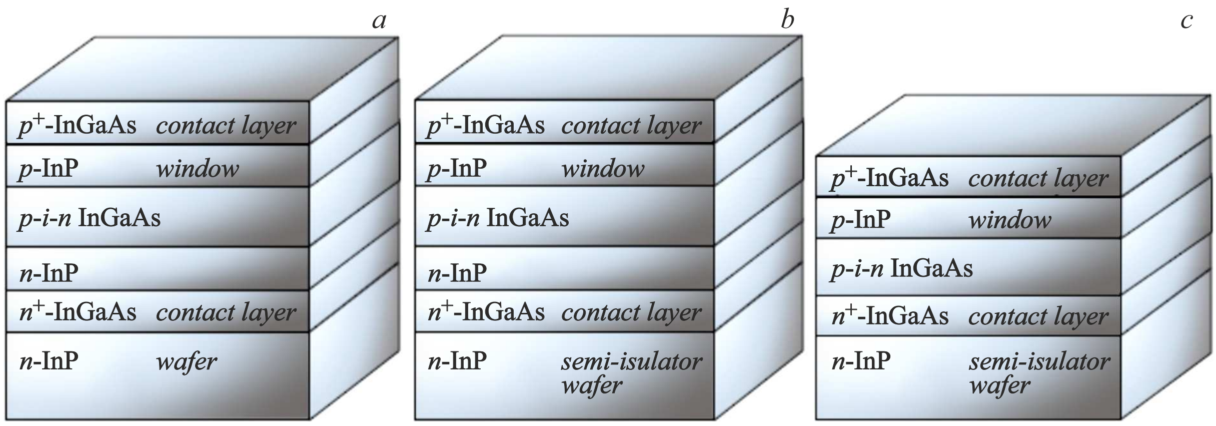

Figure 1. Schematic representation of InGaAs/InP heterostructures on a heavily-doped substrate of *n*-type of conductivity (*a*), semi-insulating substrate with a contact layer of n^+-InGaAs (*b*) and n^+-InP (*c*).

2. Contact systems for layers of *n*- and *p*-type of conductivity

The conversion of high-power optical signals leads to the need to reduce the resistive losses on the spreading resistance, contact resistivity and total series resistance of the device. The main way to reduce resistive losses is to develop and optimize the technology of forming contact systems [18]. GaAs-based semiconductor devices use contact systems based on AgMn/Ni/Au, Cr/Au, Pd/Ge/Au, Au(Ge)/Ni/Au layers [19,20]. Their application in PVC based on InGaAs/InP heterostructures require additional studies to identify the effect of the composition and annealing modes of contacts on the photovoltaic characteristics of devices.

Contact systems for the manufacture of InGaAs/InP power lines with different contact pad topologies were studied in this paper (Fig. 2). A continuous Au(Ge)/Ni/Au contact was formed on the back of the instrument structure during the manufacture of PVC on a heavily doped InP substrate of *n*-type (Fig. 1, *a*). In the manufacture of chips from a structure on a semi-insulating InP substrate (Fig. 1, *b, c*), the contact pad to a layer of *n*-type conductivity (n^+-InP or n^+-InGaAs), as well as the contact pad to the upper layer of the *p*-type was formed on the front side of the PVC.

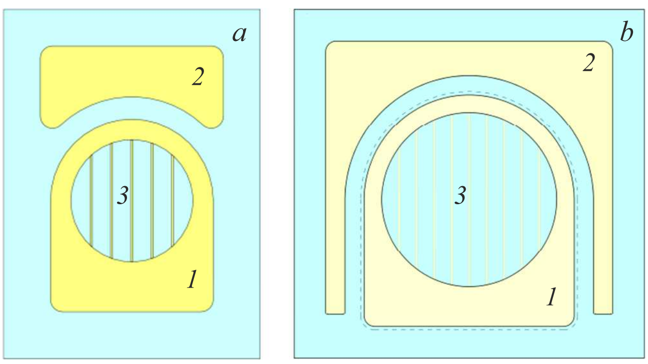

Figure 2. Schematic representation of the topology of the contact pads (*1*) to the layer of *p*-type of conductivity and (*2*) to the layer of *n*-type of conductivity formed on the front surface of InGaAs/InP PVC with the diameter of the photosensitive area (*3*) 300 (*a*) and 500 μm (*b*).

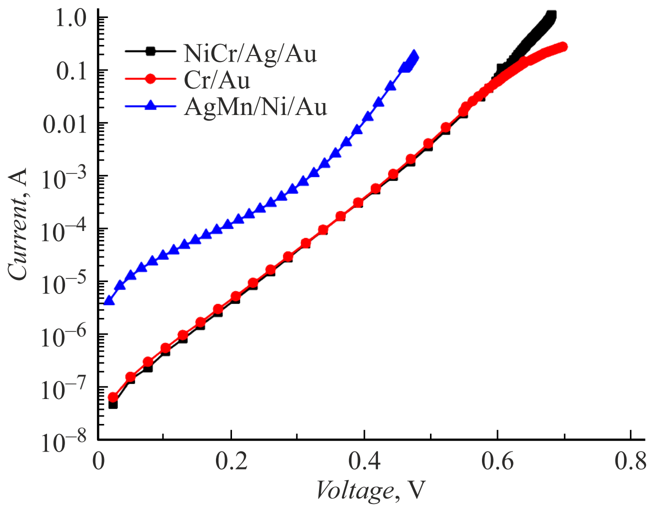

Figure 3. A direct branch of the IV characteristic of PVC with a diameter of the photosensitive region of 300 μm with contact systems to InGaAs of *p*-type of conductivity: NiCr/Ag/Au, Cr/Au and AgMn/Ni/Au.

Various contact systems were considered in the study as a frontal contact to InGaAs of *p*-type conductivity: NiCr/Ag/Au, AgMn/Ni/Au, Cr/Au. An ohmic contact is not formed when the considered contact materials are sputtered to InP of *p*-type conductivity. Fig. 3 shows the dark current-voltage (IV) characteristics of PVC with contact systems to *p*-InGaAs.

A spread of dark currents of PVCs made on the same heterostructure is observed in case of usage of the AgMn/Ni/Au contact system, as well as an increase in

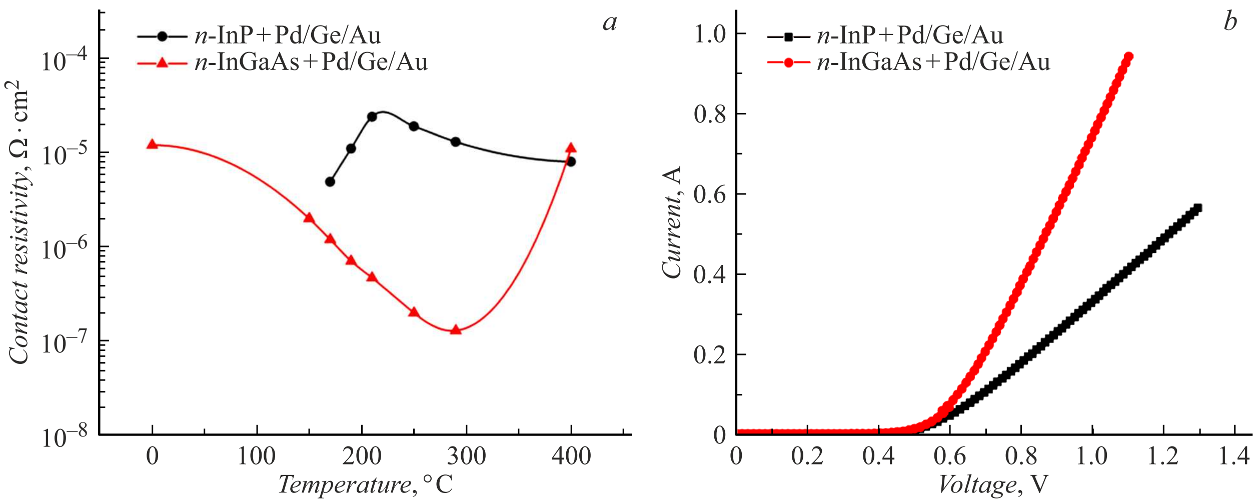

Figure 4. Dependence of the specific contact resistance of Pd/Ge/Au to InGaAs and InP layers of *n*-type of conductivity on the annealing temperature (*a*) and a direct branch of the IV characteristic of PVC with the diameter of the photosensitive region 500 μm (*b*).

leakage current due to possible shunting of the $p{-}n$-junction during diffusion of the contact material into a semiconductor during thermal annealing. The formation of a Cr/Au-based contact leads to an increase in the series resistance of the device due to the large contribution of the specific contact resistance at the metal/semiconductor interface. The minimum series resistance and leakage current are observed on samples with a contact based on NiCr/Ag/Au layers due to low values of the specific contact resistance $\sim 10^{-6}\,\Omega\cdot$cm^2 and a low degree of diffusion into the semiconductor material.

In the manufacture of PVC on a semi-insulating InP substrate, a reduction in resistive losses is achieved by forming a frontal ohmic contact based on AuGe/Ni/Au or Pd/Ge/Au layers to a heavily doped contact layer of the n^+-InGaAs or n^+-InP heterostructure. Reducing the temperature effect on the PVC during their manufacture is possible when using the Pd/Ge/Au contact system, which prevents degradation of the already formed contact of *p*-type of conductivity [18]. Fig. 4, *a* shows the dependences of the specific contact resistance on annealing in the temperature range of 150 °C–400 °C of the Pd/Ge/Au system deposited on layers of n^+-InGaAs and n^+-InP. The measurements and calculation of the contact resistivity were performed using the TLM (transmission line method) [21]. The minimum values of the specific contact resistance of $1\cdot10^{-6}{-}1\cdot10^{-7}\,\Omega\cdot$cm^2 were obtained during the formation of an ohmic Pd/Ge/Au contact to n^+-InGaAs at the annealing temperature of 170 °C–290 °C. In case of usage of n^+-InP layer, the contact resistivity values are significantly higher —$5\cdot10^{-5}{-}3\cdot10^{-4}\,\Omega\cdot$cm^2. PVCs with a diameter of 500 μm were made and their IV characteristics was measured to analyze the effect of the contact material on the series resistance of the devices (Fig. 4, *b*). A decrease in the serial resistance of the devices to $R_s = 8.8\cdot10^{-4}\,\Omega\cdot$cm^2 was recorded on structures with a layer of n^+-InGaAs, and on structures with n^+-InP, the value of R_s was $1.86\cdot10^{-3}\,\Omega\cdot$cm^2. Resistive losses can also be reduced by increasing the cross-sectional area of the contact busbars obtained by electrochemically building them using Ag/Ni/Au layers to a total thickness of 2–5 μm [22].

3. Contact systems of „bridge“ type

Studies have been carried out and a PVC design with „bridge“ type contact systems has been developed, which reduce the area of the $p{-}n$-junction and, accordingly, its capacity [23]. PVCs with a diameter of the photosensitive region of 30 and 80 μm based on InGaAs/InP heterostructure were manufactured.

The production of PVC samples includes the deposition of TiO_x/SiO_2 layers (at x, close to 2), which play the role of an anti-reflective coating for the photosensitive area of the device (the reduction in optical input losses was less than 0.5 %) and perform the function of dielectric insulation for the contact pad. For PVC on a heavily doped InP substrate of *n*-type of conductivity, a local frontal ohmic contact of *p*-type of conductivity is sprayed along the perimeter of the photosensitive region with the output of the contact pad (*2* in Fig. 5) for mounting the PVC on a dielectric coating. The „bridge“ structure was formed by etching the photosensitive region of the element, the contact mesastructure and the bridge in a single technological cycle during etching in a solution based on hydrobromic acid and potassium bichromate ($HBr:K_2Cr_2O_7$) until the active layers between the mesas are completely removed (Fig. 5). At the same time, the electrochemical thickening of the contact „bridge“ contributes not only to a reduction in resistive losses, but also to an increase in the mechanical rigidity of the PVC structure.

In the manufacture of PVC based on a structure with a semi-insulating InP substrate, a „bridge“ type contact to a

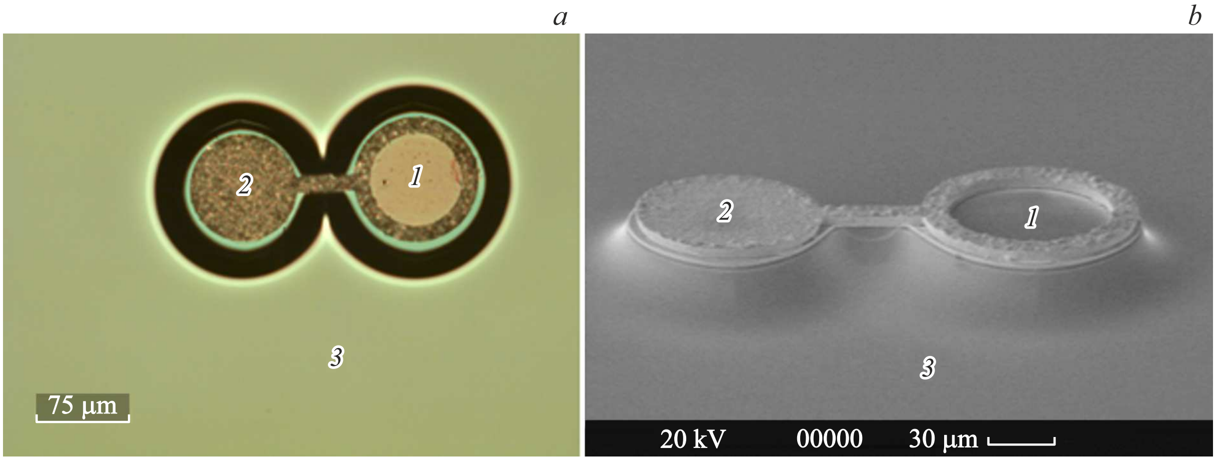

Figure 5. Photograph (*a*) and image (*b*) made on a scanning electron microscope (SEM), PVC with a photosensitive area with a diameter of 80 μm (*1*) and a frontal a NiCr/Ag/Au+Ag/Ni/Au (*2*) contact made on a heavily doped *n*-InP substrate (*3*).

layer of *n*-type conductivity is formed locally to a heavily doped contact layer of n^+-InGaAs or n^+-InP (Fig. 1, *b, c*).

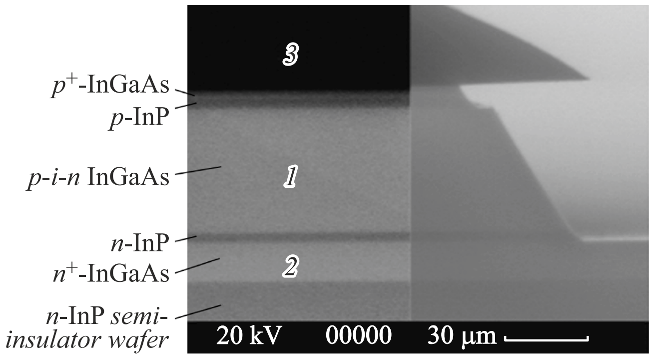

Figure 6. SEM image of the InGaAs/InP heterostructure chip (*1*) after selective etching to the n+-InGaAs contact layer (*2*) through a photoresist mask (*3*).

A working mesa is created from the front by selectively removing layers of the heterostructure sequentially in different etchants up to the contact layer. Fig. 6 shows an example of the formation of a mesa in a structure with a contact layer n^+-InGaAs:

— contact layer of p^+-InGaAs is etched in a highly diluted solution based on sulfuric acid and hydrogen peroxide ($H_2SO_4:H_2O_2$);

— wide-band window of *p*-InP and layer *n*-InP — in dilute hydrochloric acid ($HCl{:}H_2O$);

— *p–i–n*-InGaAs — in a solution based on orthophosphoric acid and hydrogen peroxide ($H_3PO_4:H_2O_2$).

A local contact to a layer of *n*-type of conductivity is formed by sputtering layers of Pd/Ge/Au, followed by its annealing at temperatures below 200 °C (*3* in Fig. 7).

The electrical properties of PVCs with a photosensitive region diameter of 30 and 80 μm, manufactured on a heavily doped *n*-InP substrate with „bridge" type contact systems, are analyzed. Measurements of the dark IV characteristic of the PVC showed the absence of leakage currents within the

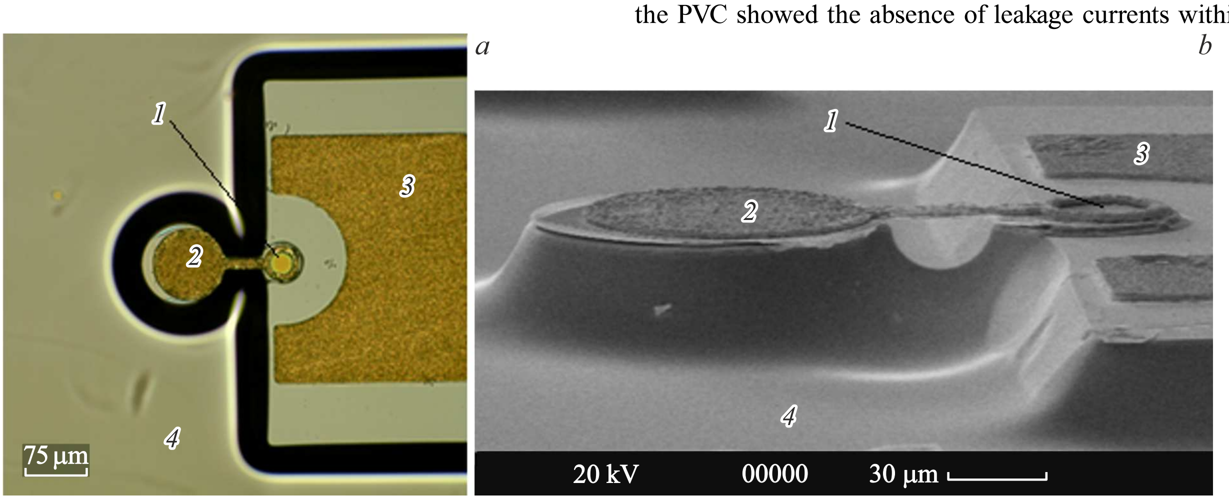

Figure 7. Photo (*a*) and SEM image (*b*) of PVC with a photosensitive area with a diameter of 30 μm (*1*) with a frontal „bridge" contact (*2*) to a layer of *p*-type of conductivity and a contact (*3*) to a layer of *n*-type of conductivity made on a InP semi-insulating substrate (*4*).

sensitivity range of the measuring equipment ($< 10^{-9}$ A at a voltage of < 0.1 V), which indicates the high quality of the mesa structure formation. The series resistance of the PVC is $R_s = (2-4) \cdot 10^{-4}\,\Omega\cdot\text{cm}^2$, which indicates a low level of resistive losses. Reducing the area of the $p-n$-junction of the element significantly increases the performance of the device, which corresponds to the main functional purpose of the PVC — reception — conversion of gigahertz level signals.

Conclusion

Various contact systems for InGaAs and InP of n- and p-types of conductivity have been studied. The minimum value of the specific contact resistance $1 \cdot 10^{-7}\,\Omega\cdot\text{cm}^2$ was achieved during the formation of an ohmic contact based on Pd/Ge/Au to the contact layer n^+-InGaAs at the annealing temperature of 290 °C and the values of $\sim 10^{-6}\,\Omega\cdot\text{cm}^2$ at an extremely low annealing temperature of 170 °C, at which degradation of devices during post-construction operations is minimized. A „bridge" type contact system has been developed with the output of the contact pad beyond the photosensitive area of the PVC, which reduces the capacity of the device by reducing the total area of the $p-n$-junction. The conducted studies of ohmic contacts made it possible to reduce the InGaAs/InP resistive losses of the PVC — the value of the serial resistance of the devices R_s is $(2-4) \cdot 10^{-4}\,\Omega\cdot\text{cm}^2$.

Conflict of interest

The authors declare that they have no conflict of interest.

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