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# Contact systems for photovoltaic converters based on InGaAsP/InP

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The investigations of the influence of the formation modes of contact systems based on Pd−Ge−Au and Au(Ge)−Ni−Au to *n*-type InGaAsP and NiCr−Ag−Au to *p*-type InGaAsP and InP on the value of specific contact resistance have been carried out. Low values of specific contact resistance of $\sim 10^{-7}\,\Omega\cdot\text{cm}^2$ were achieved when using the Au(Ge)−Ni−Au contact system (annealing temperature — 420−440°C) and $\sim 10^{-6}\,\Omega\cdot\text{cm}^2$ when deposition of Pd−Ge−Au (at low annealing temperatures $< 200$°C) for *n*-InGaAsP solid solution compositions with low phosphorus content. For *p*-InGaAsP samples with a NiCr−Ag−Au contact system, the minimum contact resistance was $\sim 10^{-6}\,\Omega\cdot\text{cm}^2$ at annealing temperatures of 460°C.

**Keywords:** Contact systems, InGaAsP/InP, thermal annealing,heterostructures, photovoltaic cells.

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Photovoltaic converters (PVCs) of monochromatic radiation based on InGaAsP/InP heterostructures are designed to be operated within the 0.8–1.75 $\mu$m wavelength range as receivers in devices for laser power transmission and optical systems [1–3].

Liquid-phase epitaxy and gas-phase diffusion, which provide high degrees of crystalline perfection of structures and an internal quantum efficiency of photoresponse close to 100%, rank among the advanced techniques of fabrication of heterostructures based on an InGaAsP quaternary solid solution on InP substrates.

Advances in technology of fabrication of high-power PVCs designed for conversion of high-density radiation necessitate refinement of techniques of production of heterostructures, ohmic contacts, and protective and antireflective coatings [4,5]. The present study is focused on the examination and design of systems of ohmic contacts to *n*- and *p*-type InGaAsP and *p*-InP that suppress resistive losses by reducing the specific contact resistivity [6,7].

InGaAsP/InP heterostructures fabricated by a combination of liquid-phase epitaxy in hydrogen and gas-phase diffusion were used in the study of contact systems. The growth of *n*-type InGaAsP layers involved doping with tin to a concentration of $(4-6)\cdot 10^{17}\,\text{cm}^{-3}$. Liquid-phase (in liquid-phase epitaxy) or gas-phase (in diffusion) doping with zinc was performed to obtain *p*-type InGaAsP and InP layers. A number of well-known contact systems based on Au(Ge)−Ni−Au, Pd−Ge−Au, Cr−Au, Ag(Mn)−Ni−Au, etc., are used widely in the production of GaAs-based optoelectronic devices [8–10]. The engineering of PVCs based on an InGaAsP/InP heterostructure requires additional studies into the formation modes of contacts and their electrical parameters.

Contacts systems based on Au(Ge)−Ni−Au and Pd−Ge−Au to *n*-type epitaxial InGaAsP layers were studied. A multilayer Au(Ge)−Ni−Au contact is a commonly used contact system that provides a specific contact resistivity of $\sim 10^{-7}\,\Omega\cdot\text{cm}^2$ [8] to *n*-type GaAs after high-temperature annealing at $T > 370$°C. However, high-temperature annealing may have a negative effect on the photovoltaic parameters of semiconductor devices with a shallow $p-n$-junction. A contact system based on Pd−Ge−Au delivers low values of specific contact resistivity ($\sim 10^{-7}\,\Omega\cdot\text{cm}^2$) to *n*-type GaAs at a thermal annealing temperature below 200°C [9,10].

Known contact systems based on Cr−Au and Ag(Mn)−Ni−Au provide a specific contact resistivity of $\sim 10^{-5}\,\Omega\cdot\text{cm}^2$ to *p*-type GaAs after annealing at $T > 370$°C. However, metals forming these contact systems diffuse into the semiconductor material to a depth down to 0.1−0.3 $\mu$m, exerting a negative influence on the characteristics of manufactured devices. A contact system based on NiCr−Ag−Au layers was examined with the object of fabricating ohmic contacts to *p*-type InGaAsP and InP. The first layer of a nickel and chromium alloy (NiCr) with a thickness of 10−20 nm ensured fine adhesion of the contact to the semiconductor surface and reduced the specific contact resistivity. The NiCr layer also served as a barrier and prevented the diffusion of silver and gold layers into the semiconductor material. This is especially important in fabrication of a shallow $p-n$-junction in PVCs based on InGaAsP/InP heterostructures (Fig. 1, *a*).

Test *n*- and *p*-type InGaAsP and InP structures with rectangular contact pads were produced for measurements of the specific contact resistivity. These contact pads corresponded in composition to the studied contact systems and were positioned at various distances from each other. The effects associated with edge surface current spreading were suppressed by forming a mesa structure along the perimeter of groups of contact pads (Fig. 1, *c*). The specific contact resistance was measured using the LTLM

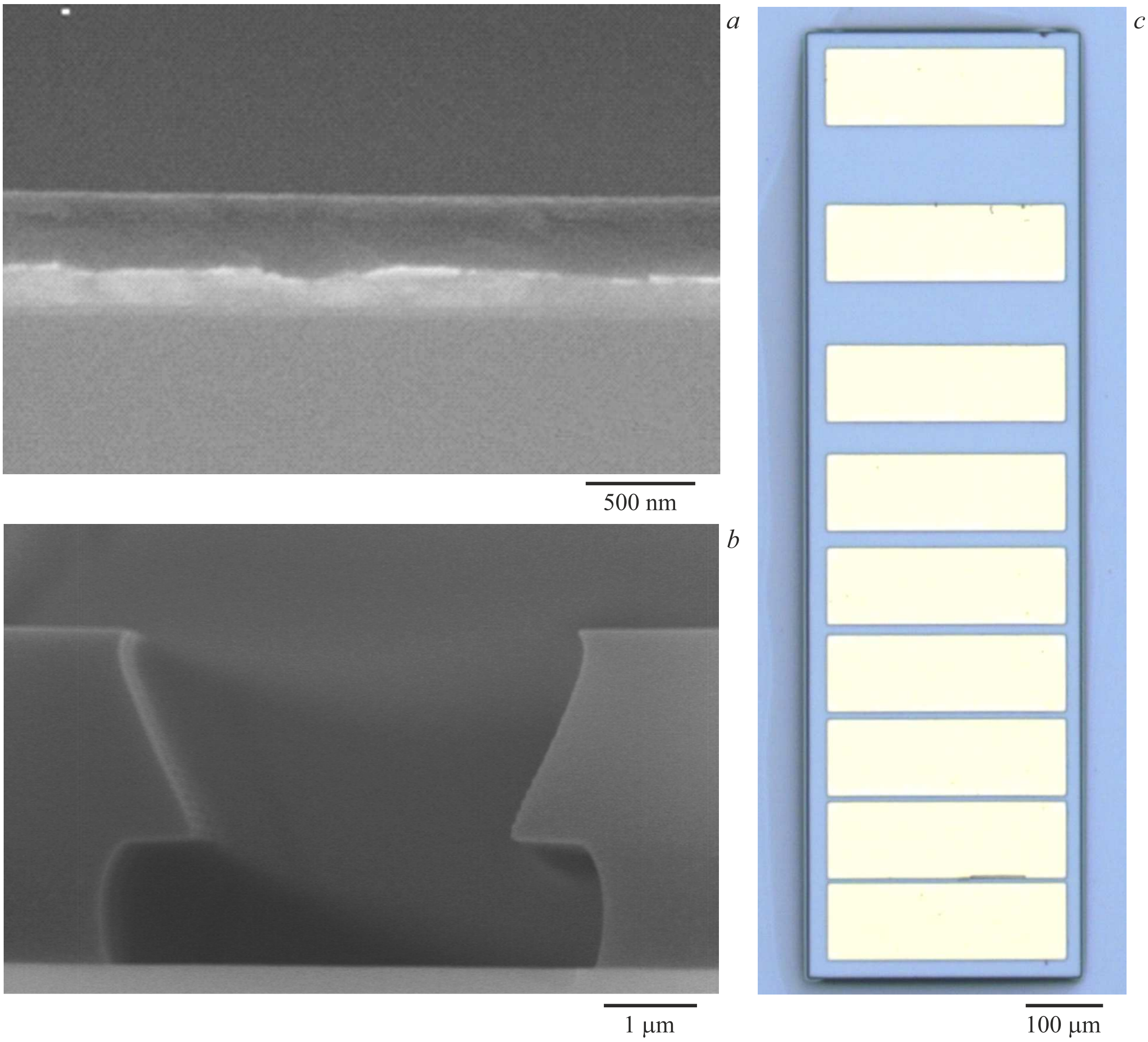


**Figure 1.** Scanning electron microscope $(a, b)$ and optical microscope $(c)$ images. $a$ — cross section images of a NiCr–Ag–Au ohmic contact, $b$ — mask based on LOR+photoresist layers, and $c$ — test sample for measurement of the specific contact resistivity.

(linear transmission line model) method with a rectangular geometry of contact pads [10].

Contact systems were formed using lift-off photolithography with a dual-layer mask with a $T$-shaped profile that contained LOR (lift-off resist) and positive photoresist layers (Fig. 1, $b$). In deposition of metals, this mask configuration preserves an accurate contact grid topology and ensures the formation of strip contacts with clean edges, which are especially important in the case of production of high-power PVCs with strip contacts narrower than $5\,\mu$m.

Contact system layers were deposited by magnetron sputtering of NiCr, Ni, and Ag and thermal resistive evaporation of an AuGe alloy, Pd, Ge, and Au in vacuum. Test samples were annealed in hydrogen $(H_2)$ atmosphere in a tube-type quartz reactor and in nitrogen $(N_2)$ atmosphere at an STE RTA100 rapid thermal annealing setup that ensured fast stabilization of the needed temperature and maintained it at a constant level for a long period of time (up to 60 min).

The measured data for a contact system based on NiCr–Ag–Au to diffusion and epitaxial $p$-InGaAsP $(E_g = 0.8\,\text{eV})$ layers, which were fabricated by liquid-phase epitaxy and a combination of epitaxy and gas-phase diffusion, and to an epitaxial $p$-type InP layer are presented in Fig. 2. As follows from Fig. 2 that the use of NiCr–Ag–Au in fabrication of a contact to an $p$-type InGaAsP quaternary solid solution, which is designed for conversion of radiation with a wavelength of $1.55\,\mu$m, with a high surface concentration of carriers obtained via zinc diffusion from the gas phase allows one to reach a specific contact resistivity of $\sim (7{-}8) \cdot 10^{-6}\,\Omega \cdot \text{cm}^2$ at an annealing temperature of 460°C. This is probably attributable to the fact that the surface concentration of carriers in diffusion samples is higher than the one in epitaxial structures [11]. However, when this contact system was used to fabricate a contact to an epitaxial $p$-InGaAsP layer doped with zinc, the specific contact resistivity could not be reduced below $5 \cdot 10^{-4}\,\Omega \cdot cm^2$; in the case of application of this multilayer contact to epitaxial $p$-InP (Zn) layers, the contact resistance was $\sim 1\,\Omega \cdot cm^2$. According to research results NiCr.Ag.Au contact system is not suitable for devices based on epitaxial $p$-InGaAsP and $p$-InP layers doped with zinc.

Contact systems based on Au(Ge)–Ni–Au and Pd–Ge–Au were examined as candidate ones for the formation of an ohmic contact to epitaxial $n$-type InGaAsP layers ($E_g = 0.8$ and 1.1 eV) doped with tin ($n = (4{-}6) \cdot 10^{17}\,cm^{-3}$) that are designed for conversion of radiation with wavelengths of 1.1 and 1.5 $\mu$m.

When a contact based on Au(Ge)–Ni–Au to an epitaxial $n$-InGaAsP layer with $E_g = 1.1$ eV was formed (curve *1* in Fig. 3, *a*), low values of the specific contact resistivity ($\sim (3{-}4) \cdot 10^{-7}\,\Omega \cdot cm^2$) were achieved at an annealing temperature range of 420–440°C. In the case of epitaxial $n$-InGaAsP layers with $E_g = 0.8$ eV (curve *2* in Fig. 3, *a*), the specific contact resistivity was $\sim (1{-}2) \cdot 10^{-7}\,\Omega \cdot cm^2$ at an annealing temperature of 420–440°C.

Lower annealing temperatures may be set for a contact system based on Pd–Ge–Au. The minimum specific contact resistivity values ($\sim (1{-}5) \cdot 10^{-6}\,\Omega \cdot cm^2$) were achieved by annealing $n$-$In_xGa_{1-x}As_{1-y}P_y$ ($E_g = 0.8$ eV) samples with the lowest phosphorus concentration $y = 0.15{-}0.1$ (Fig. 3, *b*) at temperatures of 170–200°C in $H_2$ and $N_2$ atmospheres.

The optimum modes and parameters of formation of contact systems to $n$- and $p$-type InGaAsP and $p$-InP were determined. It was found that the Pd–Ge–Au contact system provides fairly low contact resistance values $\sim (1{-}5) \cdot 10^{-6}\,\Omega \cdot cm^2$ for $n$-InGaAsP ($E_g = 0.8$ eV) quaternary solid solutions at low temperatures of annealing (170–200°C in $H_2$ and $N_2$ atmospheres). The minimum contact resistances for $n$-InGaAsP ($E_g = 0.8$ and 1.1 eV) samples with the Au(Ge)–Ni–Au contact system and $p$-InGaAsP ($E_g = 0.8$ eV) samples with the NiCr–Ag–Au contact system were $\sim (1{-}4) \cdot 10^{-7}\,\Omega \cdot cm^2$ and $\sim (7{-}8) \cdot 10^{-6}\,\Omega \cdot cm^2$, respectively, and corresponded to annealing at a temperature of 460°C in hydrogen atmosphere. The examined contact systems and annealing modes allow one to suppress ohmic losses in photovoltaic converters designed for high-power laser radiation conversion.

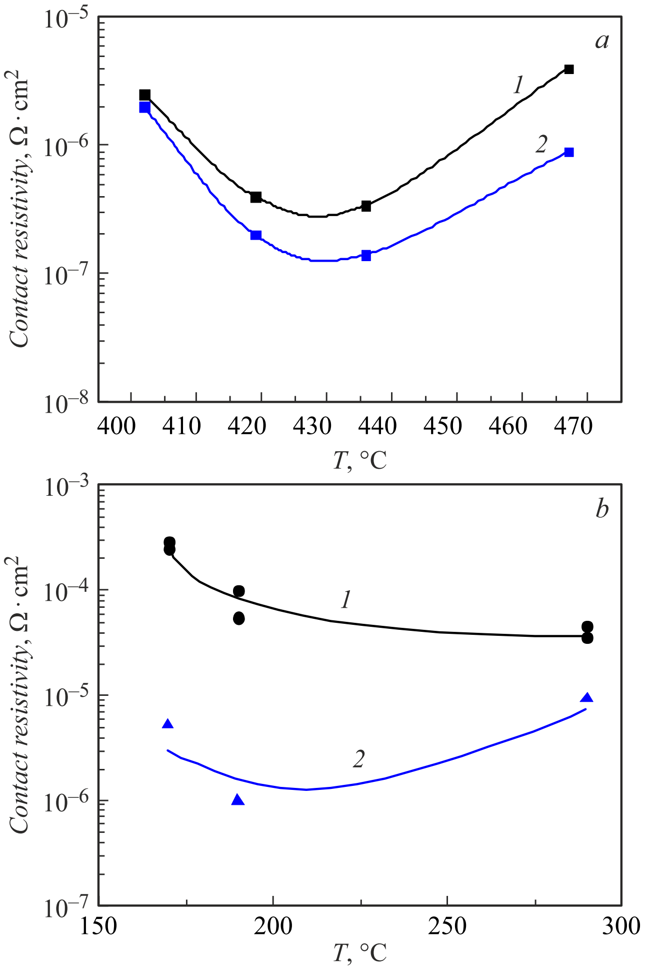


**Figure 3.** Dependence of the specific contact resistivity of AuGe–Ni–Au (*a*) and Pd–Ge–Au (*b*) ohmic contacts to epitaxial $n$-InGaAsP ($n = (4{-}6) \cdot 10^{17}\,cm^{-3}$) layers on the temperature of annealing (*a* — in $H_2$ atmosphere, *b* — in $N_2$). $E_g = 1.1$ (*1*) and 0.8 eV (*2*).

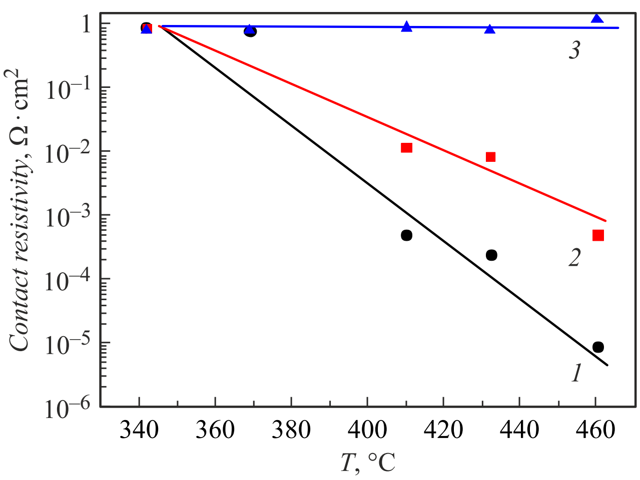


**Figure 2.** Dependence of the transition contact resistance of a NiCr–Ag–Au ohmic contact to a diffusion $p$-InGaAsP layer (*1*), an epitaxial $p$-InGaAsP layer (*2*), and an epitaxial $p$-InP layer (*3*) on the temperature of annealing (in $H_2$ atmosphere).

## Conflict of interest

The authors declare that they have no conflict of interest.

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