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# PHOTOPHYSICAL CHARACTERISTICS OF MICROLAYER PHOTODIODE *p*AlGaInAs(Zn)–*n*GaAs–Au STRUCTURES

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*The photoelectric characteristics of photodiode pAlGaInAs(Zn)–nGaAs–Au structures have been investigated. It has been established experimentally that an internal photoelectric amplification arises in these structures when the nGaAs–Au potential barrier is connected in opposition to the ($p(Al_{0.08}Ga_{0.82})_{0.9}In_{0.1}As$–nGaAs) heterojunction. The $p(Al_{0.08}Ga_{0.82})_{0.9}In_{0.1}As$–nGaAs–Au structure operates as an injection photodiode when the p–n junction operates in the forward-bias regime and as a photodiode when this junction operates in the reverse-bias regime. The influence of the depletion regions of the base zone containing deep impurity centers on the photosensitivity and the spectral range of the indicated structures has been investigated.*

**Introduction.** The interest shown in photodetectors, especially in infrared ones, is explained by the fact that these photodetectors can be used in fiber-optic communication lines and systems for recording the space and time distributions of an interference field and can serve as holographic meters of angular and linear displacements, as electronic recorders of color holographic images, and as pyroelectric transducers that can be used in different optoelectronic systems. The most frequently used types of photodetectors are photoresistors and photodiodes.

The output resistance of photoresistors is changed under the action of an optical signal. They possess photosensitivity due to the intrinsic and impurity photoeffects arising in them. However, the disadvantage of these photodetectors is their large inertia. Photodiode structures with a *p*–*n* junction and a Schottky barrier [1] also have limited application. Photodiodes based on GaAs with two planar rectifying Al [2] contacts in the form of a pin have a high photosensitivity, as high as 1.6 A/W, and possess an internal photoelectric amplification. However, their photocurrent is unstable due to the field effects and the stray capacitance between the active region and the semiinsulating substrate. High-speed, high-sensitivity multibarrier photodiodes with an *n*AlGaAs–*n*GaAs heterojunction between the surface potential barriers have the best characteristics [3]. These structures represent epitaxial *n*AlGaAs layers of thickness 1.5–2 μm grown on *p*GaAs substrates. In them, at the surfaces of the *n* and *p* regions, rectifying metal (Au)–semiconductor (Ag) junctions are formed. The indicated photodiodes have a high photosensitivity in a wide spectral range on illumination on any of their sides and at any polarity of the operating voltage. At the same time, the photosensitivity of these photodiodes to optical radiation of wavelength lower than 0.9 μm increases with increase in their operating voltage. Experiments have shown that the three-barrier Ag–*p*GaAs–*n*$Al_{0.1}Ga_{0.9}As$–Au structure has a higher photosensitivity in the wide spectral range 0.4–1.6 μm and that the photosensitivity of this structure and its spectral range can be controlled by changing the composition and parameters of corresponding regions, where the photosensitivity can reach 5 A/W. In [3], three-barrier Ag–*p*InGaAs–*n*GaAs–Ag structures with a photosensitivity of up to 20 A/W in the visible region of the spectrum were obtained, and in [4], two-barrier Ag–*n*InGaAs–*p*GaAs structures possessing a more uniform sensitivity in the spectral range 0.9–1.4 μm were obtained. The high photosensitivity of the indicated structures is due to their internal photoelectric amplification provided by the strong electric fields arising at the potential barriers. In the structures described in [3–5], the semiconductor *p*–*n* junctions were connected in opposition to the metal-semiconductor junctions. This makes it possible to realize the photodiode regime at an external voltage of any direction. From the preceding it follows that, in the structures being considered with junctions connected in opposition, an inter-

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nal photoelectric amplification can be provided and a definite spectral range can be obtained at a definite concentration of carriers in the active region and a definite composition of the heterolayers.

In one-barrier structures, internal photoelectric amplification is usually provided by the formation of a high concentration of carriers injected through the forward-biased junction as compared to the initial concentration of carriers in the active region; in this case, the thickness of the base region should be much larger than the diffusion length of the minority carriers [1]. Such photosensitive diodes form an individual class of photodetectors called injection photodiodes.

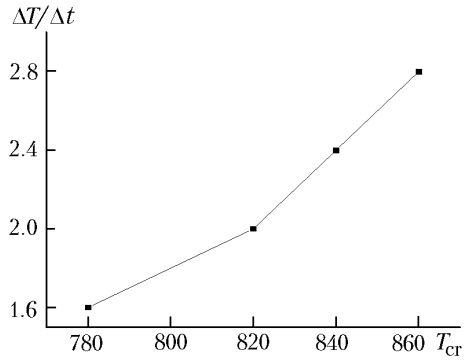
The aim of the present work is to investigate an injection photodiode based on two-barrier structures with a definite-composition heterolayer and to analyze the photoelectric characteristics of these structures. For this purpose, we will first consider certain physical-engineering problems on the obtaining of epitaxial layers on the basis of solid solutions of indium and aluminum arsenides used in photodetectors.

**Liquid-Phase Epitaxy of Solid Solutions Based on Indium and Aluminum Arsenides.** The evolution of materials used for the production of transmitters and photodetectors for fiber-optic communication systems has kept pace with the development of optical fibers. The first optical fibers most effectively transmitted a near-infrared radiation of wavelength 0.8–0.9 μm. Gallium arsenide and the three-component compound Ga–Al–As can emit and detect light in this range; therefore, the first light sources and light detectors for optical fibers were made from these materials. As optical fibers were developed, the minimum of the losses in photons was shifted to the far-infrared region: first, it was obtained at a near 1.3-μm wavelength and, quite recently, at a near 1.55-μm wavelength. Sources and detectors of radiation of this wavelength can be made on the basis of a compound consisting of three or four elements, such as the alloy In–Ga–As–P [6].

In elementary semiconductors, such as silicon or germanium, the recombination of electrons and holes leads predominantly to a heat release. At the same time, in semiconductors of the type of $A^{III}B^{V}$, such as gallium arsenide or indium phosphide, recombination energy is released predominantly in the form of infrared photons; consequently, these materials can be sources of photons. By combining, e.g., two elements of the III group of the periodic table of the elements with one element of the V group of this table it has been possible to obtain an alloy with a definite energy-gap width falling within the limits of the energy-gap widths of the component binary alloys of each of the III-group elements with the element of the V group [7].

The energy-gap width of the $A^{III}B^{V}$ semiconductor compounds can be changed by changing their composition at a constant lattice parameter (the size of an elementary cell of the crystal lattice). Triple and quadruple compounds have a definite energy-gap width. For example, when the ratio between the gallium and aluminum concentrations in the triple gallium arsenide–aluminum arsenide compound is varied, the energy-gap width of this compound changes within the range 1.4–2.2 eV corresponding to the energy-gap widths of gallium arsenide and aluminum arsenide [8]. In the case of quadruple compounds, such as In–Ga–As–P, the possibilities for control of the parameters of the material in the process of its production increase: at a definite energy-gap width, the carrier mobility, the ratio between the ionization coefficients of electrons and holes, the permittivity, and other parameters of the material can be varied.

A heteroepitaxial structure is obtained in the following way. Different-composition materials, whose lattice parameters are close to those of a substrate made from a material of the type of gallium arsenide, are built up directly on the substrate or through buffer layers that relieve stresses due to the difference in lattice parameters between their passive and active regions. It should be noted that aluminum-containing light-receiving layers having a high oxidative ability make the formation of ohmic contacts to these regions difficult. In [9], it was shown that InGaP provides a lower recombination (lower than $5 \cdot 10^3$ cm/sec) at an interface than AlGaAs ($10^4$–$10^5$ cm/sec) and, due to a smaller amount of oxygen, is a more convenient material for obtaining an ohmic contact and a Schottky barrier. Moreover, the formation of a gradient of the energy-gap width across the thickness of the generation volume of this material serves to increase the diffusion length of the minority carriers, which, in turn, makes it possible to increase the radiation resistance of a photoelectric device [9]. In this respect, of interest are AlGaInAs compounds. As was shown in [10], the composition of AlGaAs layers can be controlled in the process of their growth by changing the amount of the isovalent In impurity in a solution-melt. For example, when an AlGaInAs heterolayer was grown by forced cooling, the amount of the Al impurity decreased, beginning at the boundary between it and the substrate, with the result that a solid solution was formed with a negative energy-gap width gradient [10].



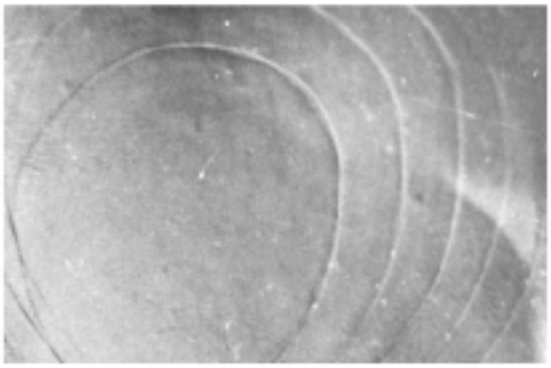



Fig. 1. Temperature regime of an epitaxy process. $\Delta T/\Delta t$, $^{o}$C/min; $T_{cr}$, $^{o}$C.

Fig. 2. Surface of the *p*AlGaInAs heterolayer grown on an *n*GaAs substrate doped with oxygen.

Thus, the photoelectric properties and the optical range of photodetectors and light sources can be varied in the process of their production by changing the composition of the heteroepitaxial layers at their *p–n* junctions.

In the present work, solid $(Al_xGa_{1-x})_yIn_{1-x}As$ solutions with different contents of Al and In were grown by the liquid-epitaxy method from the solution-melt Ga:GaAs:Al:In = 1320:150:4:41, i.e., the composition of layers was determined technologically. Our investigations have shown that the composition of the epitaxial layers obtained from the above-indicated solution-melt corresponds to the composition of the corresponding solid solution [11] determined by the x-ray phase investigations [12] and the dependence of the energy-gap width on the composition of triple solid solutions [7], i.e., $p(Al_{0.08}Ga_{0.82})_{0.9}In_{0.1}As$.

Epitaxial *p*AlGaInAs layers were grown on *n*GaAs substrates doped with oxygen with the use of a "piston" cassette [13]; this cassette differs from a "case" cassette in that the main part of the solution-melt, from which a heteroepitaxial layer is grown, is supplied to the seed-substrate by discrete portions. In this case, the solution-melt is pressed-out gradually in the process of growth of films with a definite rate (Fig. 1).

The volume of each portion is such that films are grown in the form of annular microlayers. As a result, the concentration of defects in each next layer decreases, as compared to that in the previous layer, and the quality of the layers obtained increases. Epitaxial AlGaInAs layers doped with zinc were obtained in the form of 4–8 microlayers (Fig. 2) of thickness 0.5–3 μm in the process of crystallization with an initial temperature of 830–840$^{o}$C and programmed cooling with a rate of 0.3$^{o}$C/min.

**Preparation of Experimental Samples and Investigation of Their Photophysical Characteristics.** On the basis of the heterojunctions obtained, we produced photodiode (Au +Zn)–$p(Al_{0.08}Ga_{0.82})_{0.9}In_{0.1}As$–*n*GaAs–Au structures, in which the region *n*GaAs contained oxygen impurities. The concentration of carriers in the epitaxial *p*AlGaInAs(Zn) layer of thickness ~1 μm was $4\cdot10^{17}$ cm$^{-3}$ and the carrier concentration in the substrate of thickness 350 μm was $4\cdot10^{15}$ cm$^{-3}$. Ohmic contacts of Au + Zn were applied by vacuum deposition on the side of the *p*AlGaInAs film, and a semitransparent (60–70 Å) rectifying contact of Au was formed on the back side of the substrate. Thus, the structure obtained had two counter junctions: a *p*AlGaInAs–*n*GaS heterojunction and a semiconductor-metal *n*GaAs–Au junction (Fig. 3). The area of the structure was equal to $9 \times 8$ mm$^2$.

Investigations of the dark volt-ampere characteristic of a photodiode with a *p*AlGaInAs–*n*GaAs–Au junction have shown that, in one of the directions (when the *p–n* junction operates in the forward-bias regime), the strength of the current in it increases with increase in the voltage; in this case, at a voltage of lower than 20 V the current strength is minimum (5 μA), at a voltage of higher than 30 V the current strength begins to increase and approaches the value characteristic of the breakdown regime of the blocked *n*GaAs–Au junction, and at a voltage of 80 V the current strength reaches 600 μA (Fig. 4).

In the other direction, when the *p*AlGaInAs–*n*GaAs junctions operates in the regime of blocking (the *n*GaAs–Au transition operates in the direct regime), the current increases insignificantly in a wide range of voltages; in particular, it is equal to 0.11 μA at 10 V and 0.55 μA at 90 V. The change in the current strength, detected when the voltage changed, can be explained by the fact that the strength of the current of the *p–n* junction operating

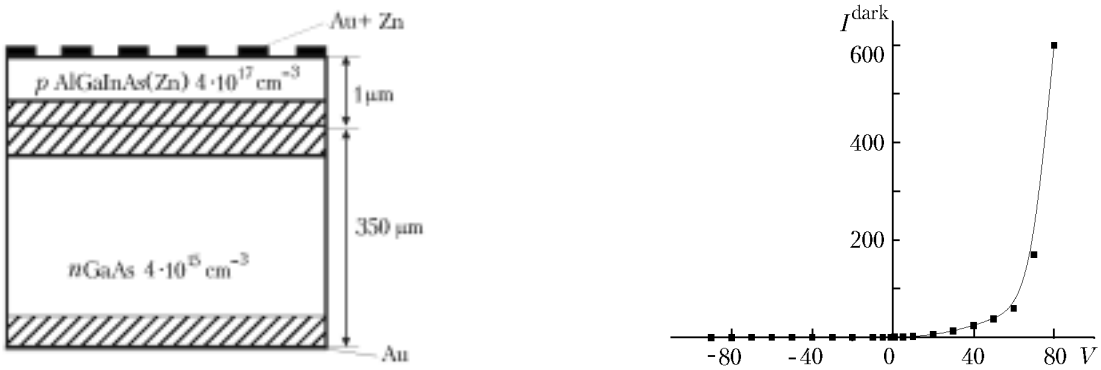



Fig. 3. Geometry of the (Au + Zn)–$p(Al_{0.08}Ga_{0.82})_{0.9}In_{0.1}As$–$n$GaAs–Au structure.

Fig. 4. Volt-ampere characteristic of the $p(Al_{0.08}Ga_{0.82})_{0.9}In_{0.1}As$–$n$GaAs–Au structure. $I^{dark}$, μA; $V$, V.

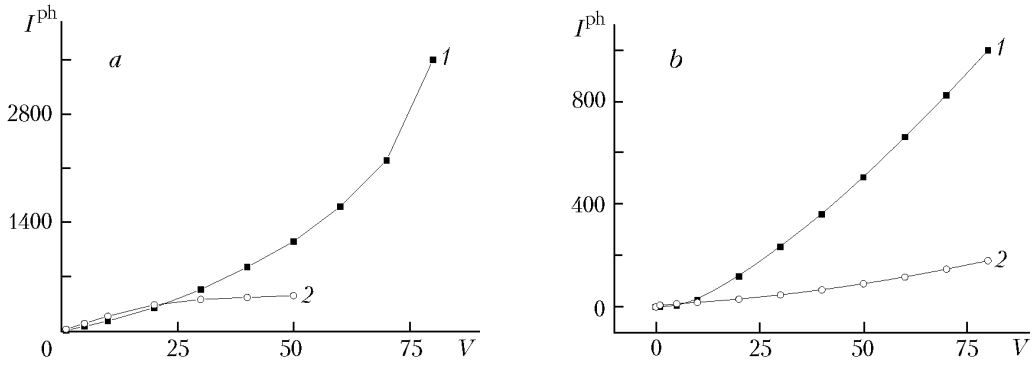



Fig. 5. Dependence of the photocurrent of the $p(Al_{0.08}Ga_{0.82})_{0.9}In_{0.1}As$–$n$GaAs–Au structure on the voltage applied on illumination on the side of the $p(Al_{0.08}Ga_{0.82})_{0.9}In_{0.1}As$ film (a) and the $n$GaAs–Au substrate (b): 1) the $p$–$n$ junction is forward-biased and the $n$GaAs–Au junction is reverse-biased; 2) the $p$–$n$ junction is reverse-biased and the $n$GaAs–Au junction is forward-biased. The luminous power is $4.68 \cdot 10^{-4}$ W. $I^{ph}$, μA; $V$, V.

in the direct-bias regime is limited by the reversely switched Schottky barrier ($n$GaAs–Au), i.e., we have the reverse branch of the volt-ampere characteristic of the Schottky barrier. When the $p$AlGaInAs–$n$GaAs heterojunction operates in the reverse-bias regime, i.e., when the Schottky barrier is forward-biased, the current experienced by the structure is determined by the reverse current of the heterojunction. In this case, the parallel-opposition connection of the two junctions is favorable for increasing their operating voltages and stabilization of the electric fields of these functions. If the field of one junction increases, the field of the other junction decreases. It should be noted that the strength of the back current of a heterojunction is smaller than that of the Schottky barrier. This means that the current generated (injected) through the forward-biased junction, especially in the case where the prebreakdown regime is approached, is not limited.

In the case where the $p(Al_{0.08}Ga_{0.82})_{0.9}In_{0.1}As$–$n$GaAs–Au structure is illuminated on the film side by an integral light source with a maximum wavelength of ~0.55 μm (Fig. 5) in the forward-bias regime, the photocurrent $I^{ph} = I^{light} - I^{dark}$ increases with increase in the voltage by a near-exponential law (Fig. 5a, curve 1), and, when the polarity of the voltage is changed, the dependence of the photocurrent on the voltage becomes saturating and sublinear in character (Fig. 5a, curve 2).

When the $p(Al_{0.08}Ga_{0.82})_{0.9}In_{0.1}As$–$n$GaAs–Au structure is illuminated on the size of the $n$GaAs–Au junction, the photocurrent increases with increase in the voltage at forward and reverse biases by an identical, near-linear law; however, in this case, the photocurrent in the forward-bias regime of operation of the $p$–$n$ junction is larger by one-

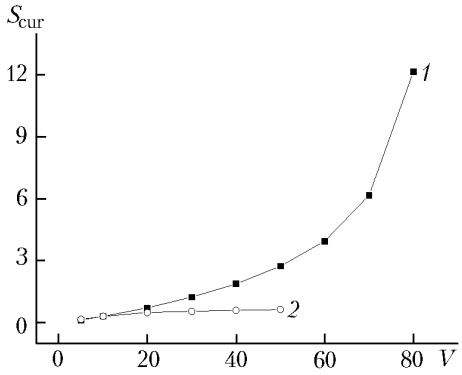



Fig. 6. Dependence of the current photosensitivity of the $p(Al_{0.08}Ga_{0.82})_{0.9}In_{0.1}As$–$n$GaAs–Au structure on the voltage applied to it in the forward-bias (1) and reverse-bias (2) regimes on illumination on the film side. The luminous power is $1.62 \cdot 10^{-4}$ W. $S_{cur}$, A/W; $V$, V.

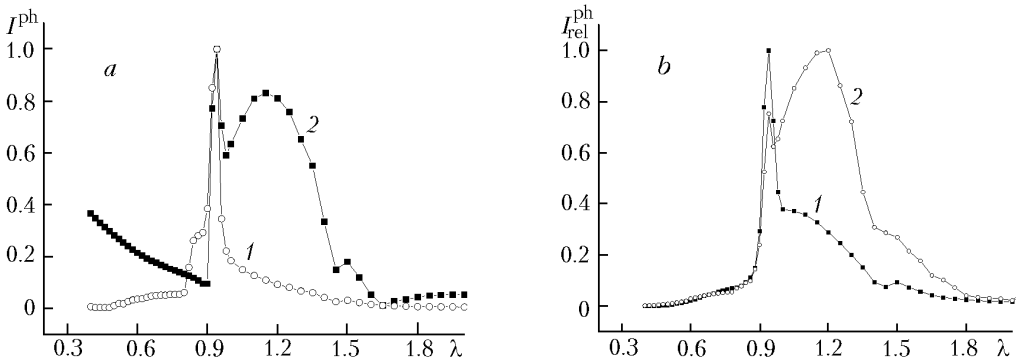



Fig. 7. Relative spectral characteristics of the $p(Al_{0.08}Ga_{0.82})_{0.9}In_{0.1}As$–$n$GaAs–Au structure measured at a voltage of 20 V (a) on excitation on the film side and the substrate side (b): the $p$–$n$ junction in the forward-bias regime (1) and in the reverse-bias regime (2). $I^{ph}$, $I^{ph}_{rel}$, μA; λ, μm.

half order of magnitude because the $n$GaAs–Au junction is blocked and the efficiency of photogeneration of carriers increases (Fig. 5b) (1000 μA as opposed to 180 μA). In the case where the $p$–$n$ junction operates in the reverse-bias regime, the $n$GaAs–Au barrier is forward-biased and the thickness of the region, where photocarriers are separated, decreases, with the result that the photocurrent and, consequently, the photosensitivity decrease, as shown in Fig. 6.

The photosensitivity detected on the film side (12.16 A/W) was higher than the photosensitivity detected on the substrate side (0.64 A/W). This can be explained by the fact that the space charge of the $p$–$n$ junction is accumulated in the active region of $n$GaAs because the concentration of carriers in $p$AlGaInAs is higher by two orders of magnitude and practically the whole depleted layer is located in the high-resistance base zone. In this case, a light current is generated as a result of the excitation of carriers from the impurity levels located in the regions where the field is strong. When an external voltage is applied, the thickness of the space-charge layer at the $p$–$n$ junction widens; in this case, changes arise also in $n$GaAs.

As is shown in Fig. 7, the spectral range of the $p(Al_{0.08}Ga_{0.82})_{0.9}In_{0.1}As$–$n$GaAs–Au structure is 0.5–1.6 μm at forward and reverse biases regardless of what surface is illuminated. Because of the existence of two barriers, in the regime of illumination of the blocked junctions, photosensitivity appears in the impurity region too at 1.2 μm (0.4 eV), and, in the case of illumination on the heterolayer side, there appears an additional peak at 1.5 μm (0.8 eV).

Gallium arsenide contains a set of impurities [14] with different level depths; these impurities can be located lower or higher than the conduction band or the valence band on either side of the $p$–$n$ junction. On excitation, they manifest themselves on the spectral characteristic as peaks [15, 16] because the structure being considered contains junctions connected in parallel opposition and these junctions, being energized, induce high-intensity electric fields ex-

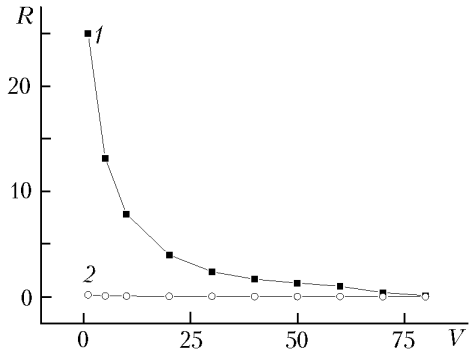



Fig. 8. Dependence of the total resistance of the $p(Al_{0.08}Ga_{0.82})_{0.9}In_{0.1}As$–$n$GaAs–Au structure on the voltage applied at dark (1) and on illumination on the film side (2) in the forward-bias regime. $R$, kΩ; $V$, V.

citing the impurity levels in the $p$ and $n$ regions on illumination. In the case where the $p$–$n$ junction is forward-biased (plus at the $p$ region), the total resistance of the structure is decreased (Fig. 8) and holes are injected into the base zone ($n$GaAs), which decreases the resistance of the structure, i.e., leads to the appearance of an internal amplification. Therefore, the $p(Al_{0.08}Ga_{0.82})_{0.9}In_{0.1}As$–$n$GaAs–Au structure operating in the forward-bias regime can be used as an injection field-effect photodiode, and this structure operating in the regime of blocking of the $p$–$n$ junction can be used as a photodetector.

In the case where the $p$–$n$ junction operates in the forward-bias regime, the heights of the potential barriers decrease when the voltage applied increases to certain values that are attained immediately on illumination beginning with the initial region of the $p(Al_{0.08}Ga_{0.82})_{0.9}In_{0.1}As$–$n$GaAs–Au structure on the heterolayer side. When the voltage further increases, the injection regime is retained due to the $n$GaAs–Au potential barrier switched reversely to the heterojunction.

**Conclusions.** Heterojunction structures $p(Al_{0.08}Ga_{0.82})_{0.9}In_{0.1}As$–$n$GaAs–Au with a rectifying contact on the substrate side have been obtained on the basis of solid $(Al_xGa_{1-x})_yIn_{1-x}As$ solutions. These structures are sensitive on both their sides and can operate at an operating voltage of both polarities. An internal photoelectric amplification arises in the indicated structures because the $n$GaAs–Au potential barrier is switched reversely to the $p(Al_{0.08}Ga_{0.82})_{0.9}In_{0.1}As$–$n$GaAs) heterojunction. When the $p(Al_{0.08}Ga_{0.82})_{0.9}In_{0.1}As$–$n$GaAs–Au structure, containing deep impurity centers, operates in the forward-bias regime, the conductivity on both its sides is modulated and these sides have a high voltage sensitivity (difference between the dark and light voltages at a definite current). Thus, the electron processes occurring in the regions of depletion in two barrier structures call for further investigations.

## NOTATION

$I^{dark}$, dark current, μA; $I^{light}$, light current arising under illumination, μA; $I^{ph}$, photocurrent, μA; $I^{ph}_{max}$, maximum photocurrent at a definite wavelength, μA; $I^{ph}_{rel}/I^{ph}_{max} = (I^{light} - I^{dark})/I^{ph}_{max}(\lambda)$, relative spectral photocurrent; $R$, resistance of the $p(Al_{0.08}Ga_{0.82})_{0.9}In_{0.1}As$–$n$GaAs and $n$GaAs–Au junctions connected in parallel, kΩ; $S_{cur}$, current photosensitivity, A/W; $T_{cr}$, crystallization temperature of the $p(Al_{0.08}Ga_{0.82})_{0.9}In_{0.1}As$ epitaxial layer, $^oC$; $\Delta T/\Delta t$, rate of cooling, $^oC$/min; $V$, voltage applied to the $p(Al_{0.08}Ga_{0.82})_{0.9}In_{0.1}As$–$n$GaAs and $n$GaAs–Au junctions connected in parallel, V; λ, wavelength of monochromatic radiation, μm. Subscripts: cr, crystallization; ph, photocurrent; light, light; dark, dark; rel, relative; max, maximum; cur, current.

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