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Characteristics and mechanism of transfer of current in multi-barrier arsenide gallium heterostructures

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Abstract
At the present stage, the development of optoelectronics and telecommunications systems involves studying the effects of the interaction between optical radiation and the electrons of a substance, and covers the problems of creating optoelectronic instruments in which these effects are used to generate, transmit, store and display information. The forthcoming tasks of optoelectronics and telecommunications systems are miniaturization of the element base, integration of elements and functions, orientation to special technologies and materials.

Keywords: the photodiode, two-barrier, three-barrier, heterojunction, base area, modulation of base

Introduction

Extremely important and promising for heterostructure optoelectronics are those in which semiconductors with different band gap widths contact within a single structure. With the use of hetero-transitions, those instruments that cannot be obtained from homo-transitions are realized. Thus, in the homo p-n transition, the thickness of the transition region is practically impossible to form less than the diffusion length or to inject carriers in a given direction, redistribute the intensity of electric fields in the p- and n-regions, and control the absorption coefficient of photons. The distribution of electric field and potential in the region of spatial charge for hetero transition is the same as in the case of p-n transition, but with different values of dielectric constants for p- and n-regions. The functional dependence of the electric field and potential in the region of the spatial charge of the hetero-transition on the coordinate will be linear and quadratic, respectively, as in the case of the p-n transition. Different values of dielectric constants and lead to a jump of the electric field in the hetero-transition at the metallurgical boundary. In this case, according to Gauss 'theorem, that is, in Indian-containing heterolayers promising for optoelectronics, by changing the parameters of the regions forming the heterotransition, it is possible to control the functional properties of semiconductor devices based on it. At the same time due to correlation of thickness of photodetector heterolayer it is possible to reach area of maximum absorption for selected spectral working range.
In this connection, the establishment of the physical nature of processes in the bulk charge regions of gallium arsenide-based hetero-transition and its compounds, as well as the study of the effect of rectifying barriers on the current and spectral characteristics of the three-barrier structure with different hetero-layer composition, is a pressing task.

Degree of study of the problem

To date, a large number of research papers have been accumulated on the electrophysical properties of hetero-transitions and heterostructures based on compounds A^3 B^5, but they do not address the electronic processes that occur when two or three potential barriers to a particular hetero-transition are connected in sequence (e.g. *AlGaInAs-GaAs*). In particular, in works [1, 2] the dependence of electric characteristics of structures with Schottky's barrier on the basis of gallium arsenide from material of formation of a barrier of contact from *Pd, Pd+Ni+W* is studied and it is shown, that any metal-semiconductor interactions are responsible for distorting the electrical characteristics of Schottky barrier instruments [2]. Shows that the creation of a guard ring to the Schottky barrier results in the formation of an additional Schottky barrier between the metal and the *p*-type region connected in series to the *p-n* transition. As a result, most of the applied voltage is placed on the additional Schottky barrier. As noted in [3], the creation of metal-semiconductor-metal rectifying contacts to the heterolayer *GaInAs* results in a strong non-uniformity of the electric field, resulting in a decrease in the speed of the photodiode MPM. On the basis of a research of photo-electric characteristics of three-barrier m_1- n-p-m_1 - structures with a heterojunction of *nAlGaAs-pGaAs* [4] is shown that in the mode of locking of a heterojunction the coverage of quasineutral areas of a heterolayer a volume charge leads to increase in photosensitivity in visible area of a range 0.5-0.9 microns. Ways to achieve the stated goal - expansion of functional capabilities of semiconductor devices in known works are carried out in various ways. Large-scale works are carried out by the school of Zh.I. Alfyrov on the creation of effective semiconductor solar cells, LEDs, lasers, photodiodes by the use of hetero-transitions [5]. By introduction of constructive changes by S.V. Averin's group, N.M. Ushakov photodiode structures on the basis of transition metal semiconductor, metal-semiconductor-metal in which effects of strengthening of photocurrent and mechanisms of a tokoperenos are studied [3] are created. On the basis of integration of semiconductor *p-n*-transition and metal-semiconductor transition of A.V. Karimov group, studies of photodiode, transistor structures are carried out to reduce their dark currents, processes of modulation of basic areas with working voltage [6, 7]. In studying the properties of metal-semiconductor barriers

based on solid solutions *SiGe* certain results have been achieved by I.G.Atabayev 's group [8].

The results of the above work indicate that in photodiode structures on the injection gain the spectral characteristics are determined by the impurity levels of the base region. However, smooth control of their spectral region in the band required for optoelectronics is practically impossible. In addition, in injection photodiodes, the desired low values of dark currents are obtained by their use at temperatures below room temperatures. In the three-barrier m_1-*p*-*n*-m_2-structure, variation of heterolayer composition from wide-zone to narrow-zone results in variation of spectral sensitivity region. However, these works do not reflect the pattern of influence on electronic processes of step-by-step formation to hetero

p-*n*-transition of photodiode structure of additional potential metal-semiconductor barriers and changes in heterolayer composition.

Thus, the works known to date do not contain information on physical and technological ways of creating special purpose structures and processes in the fields.

Scientific novelty of work

1. Three-barrier structures on the basis of a heterojunction *pAlGaInAs-nGaAs* are for the first time developed and the role of the straightening barriers in expansion of spectral range to the long-wave area is shown.
2. The principles of creation of three-barrier photodiode *Au-pAlGaInAs-nGaAs* are for the first time offered: *O-Ag* - structures, the quantities based on variation India and aluminum in a heterolayer for of different function.
3. It has been experimentally shown that when *Au-*$pAl_{0.08}Ga_{0.82}In_{0.1}As$*- nGaAs -Ag*-structure is excited, high values of photocurrent are created from the heterolayer side, due to fine location of the area of photo carriers separation and alternating compression of the quasi-linear part of heterolayer by the layer of volume charge of blocked transitions, when the photocurrent increases in proportion to thickness of the area of volume charge.
4. It has been experimentally shown that in a photodiode structure, increasing the thickness of a heterolayer to twice the diffusion length can lead to low values of the reverse current of the metal-semiconductor transition compared to the reverse current of the hetero-transition, which is due to the improvement of the metal-semiconductor boundary and the change of the thermo-electron mechanism by generation.

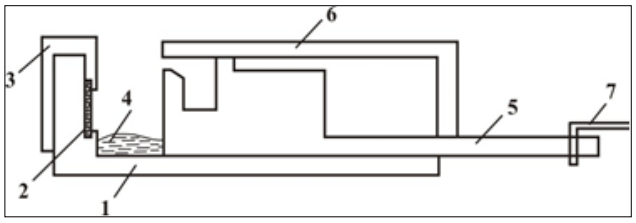
Scientific and practical significance of the study results

The results and conclusions of the thesis contribute to the expansion of physical ideas about the processes taking place in the field of volume charge of metal-and-conductive transition of one and two-phase hetero-transition structures under field and optical influences. Based on these results, it is proposed to control spectral sensitivity of photodiode structure based on hetero-transition $p\ (A\ l_y\ Ga_{1-y})_y\ In_{1-y}\ As$-*nGaAs* in visible and infrared regions of spectrum promising for reception and processing of optical signals.

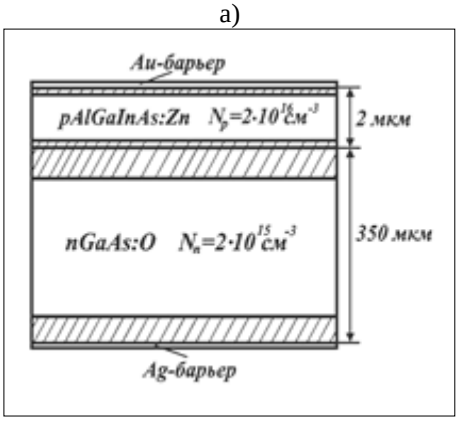
The practical significance of the obtained results is that the proposed recommendations simplify the process of matching the output parameters of the photodetector with the input parameters of the amplifier stage of photodetector devices of optoelectronics and telecommunication systems.

Implementation of results

The obtained results are the basis for development of photodetectors for optical signal reception and transmission in scientific and production associations of AS RUz and other instrument-making organizations. Based on studying physical and technological aspects of formation of indium and aluminium containing heterolayers based on gallium arsenide, a special design of the device and a method of liquid epitaxy are chosen. Growth of hetero-layers with low replacement indium content was carried out from a melt solution with a given volume in a special graphite cassette. In it the substrate was arranged vertically, and the melt solution was brought into contact with the substrate by pressing with the help of a horizontally movable piston, Fig.1, i.e. contact of the melt solution with the substrate surface is guaranteed. The advantages of this method are clear, for example, the melt solution for stopping the growth process from the vertical position is transferred to the horizontal position by moving the piston to the initial position, that is, traces of the melt solution do not remain, the presence of which leads to disruption of the morphology of the surface. At the same time, this method being an analogue of capillary liquid epitaxy, in which after the end of the growth process a solution-melt remains in the gap, in the proposed - completely leaves no traces from the surface. All this together with the suspension of the cooling process for every 1^0 C after the activation of the program cooling allowed to obtain hetero-transitions in the system $(Al_x\ Ga_{1-x})_{1-y}\ In_y\ As$- *GaAs.*



a)



b)

1- Basis; 2- substrate; Substrate 3-holder; 4-solution-fusion; 5-piston; 6- cover; 7- rod.

Fig 1: Section of shear graphite cassette with vertically mounted substrate (a) and geometric structure Au- pAl0.05 Ga0.9 In0.05 As- nGaAs: O-Ag-structure (b)

By this method, a Ga As hetero-layer pIn was also grown from a single indium containing (In0.05 Ga0.95As) melt

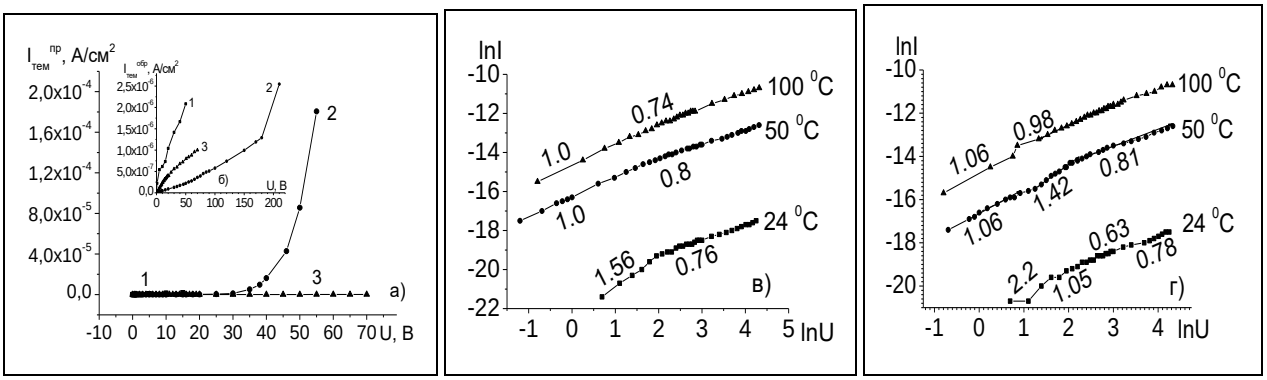
solution to determine the relationship of dielectric constants to the distribution of electric fields at the hetero-boundary. And for the purpose of comparative analysis of effect of heterolayer modulation on photovoltaic phenomena, wider-scale nAl0.2 Ga0.8 As-heterolayer based on a single aluminium-containing (Al+GaAs) solution-melt were grown by means of a combined device described in [9]. Further, three-barrier photodiode structures were specially manufactured on the basis of the obtained hetero-transitions (samples № 90; №7ФК1И; № 17FK5A).

Heterolayers of which made sample № 90 received cultivation of p (Alx Ga1-x) y In1-y As of the alloyed Zn with Np = 2•1016 cm -3 on nGaAs substrates: About with concentration of carriers Nm = 2•1015 cm-3. The thickness of the films was ~ 1-2 mkm. Evaluation of aluminium and indium in heterolayer according to the procedure given in [10] showed its compliance with the following composition of pAl0.05 Ga0. 9 In 0.05 As. Further dusting of gold to a heterolayer and silver thickness (~ 70 Å) in a vacuum on a back surface of nGaAs: O received diode m1 - p-n-m2 - structure (fig. 1. b) where for metalsemiconductor transitions Au-pAlGa 0.95In0.05As and nGaAs-Ag, respectively =0.72 eV, =0.88 eV. Heterolayer band gap width= 1.37 eV. The heights of the potential barriers (and) were determined from the dependence of the root of the square from the photo-clip calculated per photon on the energy of the photon, which is consistent with those given in [11]. The area of the structures by scribing is reduced to 5x5 mm2.

Table 1: Design and certificate data of characteristic parameters Three-barrier structures with different heterolayer composition

Harakteris-tichesky parameters	***Au-p(AlGa)$_{0.95}$In$_{0.05}$As-nGaAs:O-Ag***	***Au-pIn$_{0.05}$Ga$_{0.95}$As-nGaAs-Au***	***Au-nAl$_{0.2}$Ga$_{0.8}$As-pGaAs-Ag***
φ^{m_1-p}, *eV*	0.72	0.67	0.62
φ^{n-m_2}, *eV*	0.80	0.68	0.68
$V_k^{m_1-p}$, *V*	0.570	0.490	0.444
$V_k^{n-m_2}$, *V*	0.643	0.540	0.554
V_k^{p-n}, *V*	1.12	1.05	1.13
W^{m_1-p}, *mkm*	0.189	0.318	0.277
W^{n-m_2}, *mkm*	0.881	0.572	0.474
W^{p-n}, *mkm*	1.210	0.924	0.742
$(E_C - E_F)$, *eV*	0.157	0.139	0.126
$(E_V - E_F)$, *eV*	0.150	0.180	0.176
N_p, sm^{-3}	$2\cdot10^{16}$	$6\cdot10^{15}$	$7\cdot10^{15}$
N_n, sm^{-3}	$1\cdot10^{15}$	$2\cdot10^{15}$	$3\cdot10^{15}$
m_1	Au	Au	Au
m_2	Ag	Au	Ag
$E_g^{гетерослой}$, *eV*	1.38	1.37	1.67
E_g^{GaAs}, *eV*	1.43	1.43	1.43
ε^{GaAs}	11	11	11
$\varepsilon^{гетерослой}$	11.05	11.2	10.9

It has been experimentally established that the three-barrier photodiode structures under investigation are distinguished from known diode structures by the absence of areas due to the injection of carriers and in both directions by the occurrence of generation processes due to serially connected locking barriers. The difference in composition of hetero layers in relation to the properties of the barriers to be locked leads to different current flow in the mode of direct hetero-transition displacement, and in the mode of hetero-transition locking in a wide range of voltages (except for the area of avalanche current growth) currents change in the same character, as shown in fig.2, and b, having low values. From the analysis of these dependencies and from studies of temperature dependencies of voltampere characteristics there is a mechanism of tocoperenosis for a three-barrier structure with heterolayer *pAl$_{0.05}$Ga$_{0.9}$In$_{0.05}$As*, fig.2, c and d. In the mode of direct displacement of hetero-transition from low voltages there appear currents caused by thermoelectric emission, which are replaced by generator currents in the area of volume charge. In the hetero-transition locking mode, we first have thermoelectronic emission through metal-semiconductor transitions replaced by current growth deceleration due to electron capture by acceptor levels. Further, the increase in temperature results in thermoelectronic emission of carriers through the metal-semiconductor barrier.



Dependences of current density on forward (a) and reverse (b) voltages: *1- Au-pGa*$^{0.95}$ *In*$^{0.05}$ *As-nGaAs-Au; 2- Au-nAl*$^{0.2}$ *Ga*$^{0.8}$ *As-pGaAs-Ag; 3- Au-ppAl*$^{0.08}$ *Ga*$^{0.82}$ *In*$^{0.1}$ *As-nGaAs:O-Ag*

Voltage versus current double logarithmic scale in *Au-pAl*$^{0.08}$ *Ga*$^{0.82}$ *In*$^{0.1}$ *As-nGaAs: O-Ag-* structure for forward (c) and reverse (g) bias heterojunction.

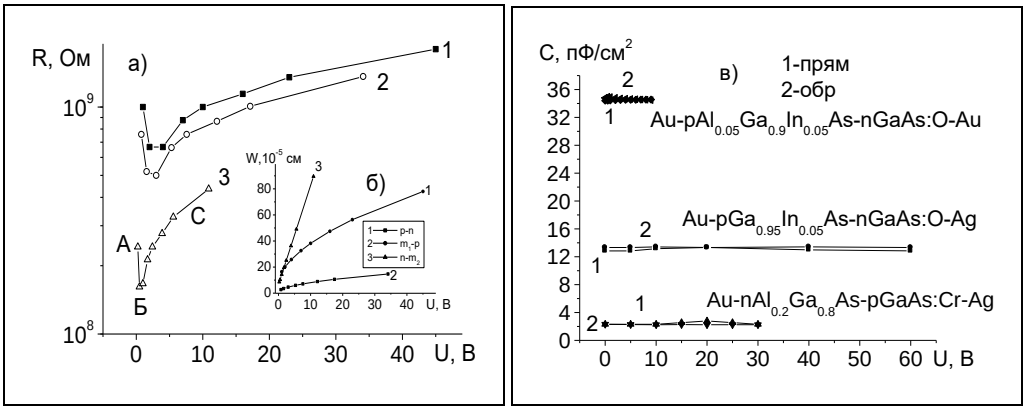
Fig 2: Voltamp characteristics of three-barrier photodiodes Based on gallium arsenide and its compounds

It has been found that the characteristic parameters of this structure estimated by the redistribution of stresses at each barrier depending on the mode of activation and analysis of the tocoperenos at a single transition are in satisfactory agreement with the conclusions made for the general *Au-pAl*$_{0.05}$*Ga*$_{0.9}$ *In*$_{0.05}$*As- nGaAs:O-Ag*-structure, as shown in Table 2. On the basis of experimental-design data, the relationships of resistances against falling voltages confirming absence of carrier injection in any of working voltage directions would otherwise have reduced resistance against voltage, Fig.3, a.

Table 2: Observed resistance versus voltage (dependence of current on tension of $I \sim U^{\gamma}$)

$U_{общ}$, В	(+) m$_1$ -p-n-m$_2$ (-)				(-) m$_1$ -p-n-m$_2$ (+)	
	$U_{обр}^{m_1-p}$, V	$\gamma_{обр}^{m_1-p}$	$U_{обр}^{n-m_2}$, V	$\gamma_{обр}^{n-m_2}$	$U_{обр}^{p-n}$, V	$\gamma_{обр}^{p-n}$
0 ÷ 2	0 ÷ 0.76	1.53	0 ÷ 0.24	1.6	0 ÷ 1	1.6
2 ÷ 5	0.76 ÷ 1.6	1.11	0.24 ÷ 0.48	0.95	1 ÷ 2	0.97
10 ÷ 70	3 ÷ 34	0.58	1 ÷ 10.89	0.6	4 ÷ 45	0.6

There is a limitation of the process of growth of the thickness of the volume charge layer of the interlocked barriers (Fig.3, b), which is explained by the invariability of the capacitance values of the three-barrier structure at any polarity of the operating voltage (Fig.3, c). Small values of capacitances are obtained due to low values of dielectric constant in three-barrier structure based on heterolayer *nAl*$_{0.1}$*Ga*$_{0.9}$ *As* compared to Indian-containing structures. The stability of the capacitances of these diode structures is related, as shown by the authors of [10], to the creation of a high field area in the locking barriers.



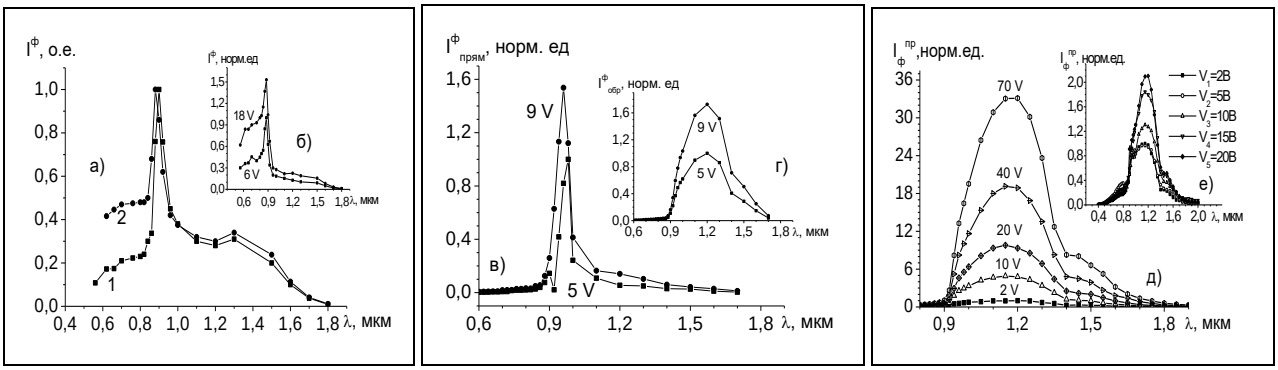
Resistance dependencies (a) and the thickness of the space charge layer, (b) each of the transitions from voltage Au-pAl$^{0.08}$Ga$^{0.82}$In$^{0.1}$As-nGaAs: O-Ag- structure. c) Specific dependencies capacities from mode inclusion in three-barrier structures.

Fig 3: Dark characteristic parameters under different inclusion modes in three-barrier structures with different heterolayer composition

Based on analysis of spectral characteristics of three-barrier photodiode structures depending on composition of heterolayer and falling voltages, possibility of controlling spectral range from ultraviolet to infrared region is shown. In the three-barrier *Au- nAl*$_{0.2}$ *Ga*$_{0.8}$ *As- pGaAs:Cr-Ag*-structure from the blocking voltage of phototos increase in the short-wave region of the spectrum when illuminated from the heterolayer, which is caused by the separation of

photovoltaic carriers from the volume charge region of the metal-heterolayer transition and the fine formation of the hetero-transition, where the efficiency of the separation of photovoltaic carriers is high. At the same time, excitation of carriers from impurity chromium levels with deeply penetrating long-wave radiation is also observed, Fig.4. a, b. In the Indian-containing three-barrier photodiode *Au-pIn$_{0.05}$ Ga$_{0.95}$ As- nGaAs:O-Au* structures, when excited by the heterolayer, the sensitivity in the short-wave region is suppressed, while in the hetero-transition locking mode the phototope acquires high values in the impurity region of the spectrum, Fig. Excitation of the photodiode *Au- pAl$_{0.05}$ Ga$_{0.9}$ In$_{0.05}$ As- nGaAs: O-Ag* -structure on the heterolayer side results in high photocurrent values compared to excitation on the substrate side, Fig. At the same time due to recombination of generated carriers by impurity centers in the area of own absorption peaks do not appear.

From the analysis of spectral characteristics studies, it was revealed that the change in composition of the heterolayer and the barriers successively connected to the hetero-transition lead to the control of the depth of modulation of the heterolayer regardless of the mode of inclusion. At the same time electron-hole pairs are generated from areas of volume charge of excited barrier and hetero-transition, as well as electrons from base area and impurity levels. In this connection, the spectral characteristic of *Au- pAl$_{0.05}$ Ga$_{0.9}$ In$_{0.05}$ As- nGaAs: O-Ag*-structure, both when changing the excited surface and the polarity of the working voltage, prevails impurity excitation over its own.



Au-nAl$^{0.2}$ *Ga*$^{0.8}$ *As-pGaAs: Cr-Ag*, when excited by: curve-1 of the substrate; Goethe curve-2 dew (a). In the locking mode of the illuminated heterojunction (b).

Au-pIn$^{0.05}$ *Ga*$^{0.95}$ *As-nGaAs:O-Au* when excited from the heterolayer in the barrier locking mode (c) and heterojunction (g)

Au-pAl$^{0.05}$ *Ga*$^{0.9}$ *In*$^{0.05}$ *As-nGaAs: O-Ag* at excited with the parties heterolayer (d) and substrate (e)

Fig 4: Spectral characteristics of the three-barrier photodiode Based on gallium arsenide with different heterolayer composition

And in the three-barrier *Au- nAl$_{0.2}$ Ga$_{0.8}$ As- pGaAs: Cr-Ag* structure, due to the low specific resistance of the substrate *(pGaAs: Cr),* effective modulation is carried out in the heterolayer, which leads to the control of photosensitivity only in the shortwave region of the spectrum.

When excited from the heterolayer side, depending on the mode of inclusion in the three-barrier *Au- pIn$_{0.05}$ Ga$_{0.95}$ As-nGaAs: O-Au*-structure, photovoltaic carriers are alternately generated from the heterolayer and the modulated substrate.

Conclusion

1. Qualitative analysis of redistribution of falling voltages between barriers in three-barrier Au-p (AlGa) 0.95.In0.05 As- nGaAs: O-Ag-structure was carried out in order to study processes of modulation of volume charge layer of potential barriers.
2. The effect of heterolayer composition, change of structure and concentration of carriers of basic areas on photoelectric characteristics of photodiode structures with hetero-transition, allowing to control characteristic parameters of photodiode structures, is revealed.
3. Physicotechnological aspects of formation of heterolayers in a system ralgainas-nGaAs are proved: About depending on structure and from quality of the replacing elements in interrelation with constructive changes.
4. Qualitative analysis of tocoperenosis mechanism in three-barrier photodiode Au-p (AlGa)0.95In0.05 AsnGaAs:O-Ag-structure determined by generation processes involving impurity levels and electron capture by impurity centers, as well as generation of minor carriers in the area of volume charge of interlocked barriers is proposed.
5. It is experimentally established that creation of the straightening barrier to a heterolayer suppress injection of carriers in a heterojunction pAlGaInAs-nGaAs resulting in prevalence of impurity photocurrent over own.
6. It is shown that modification pAlGaInAs-nGaAs a heterojunction at the expense of consistently created potential barriers allows to operate changes of spectral characteristics.
7. The principles of creation of three-barrier photodiode Au-pAlGaInAs-nGaAs- Ag - the structures based on variation of quantity India in a heterolayer depending on its functional purpose are for the first time offered.
8. Based on temperature studies, an increase in spectral photocurrent with an increase in temperature is shown, which is due to an increase in carrier collection coefficient with a decrease in band gap width and a change in Fermi quasi-levels.
9. Practical schemes of different purpose are proposed using three-barrier photodiode structures on hetero-transitions.

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