The microduty bipolar phototransistor on the base of gallium arsenic n-p-m-structure

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Abstract

In the present paper, the results of the research on light characteristics of gallium arsenic two-barrier n-p-m-structure - analogue of bipolar phototransistor are presented. Experimentally, it is shown that photoelectric characteristics vary depending on switching on conditions of nGaAs-pGaAs-Ag structure. The researched structures differ with functionability in photodiode and phototransistor modes as microduty devices.

Keywords: Microconditions; Phototransistor; Two-base; Barrier; Photo-voltaic effect

1. Introduction

In connection with the increased necessity for fast transfer of large volume of data and for their confidential coding and decoding, the development of photoelectric semiconductor devices and research on optical methods for the reception and transfer of signals by optical fibers have been carried out. It is an urgent problem. For the decision on this problem special one-junction as well as multi-junction devices on the base of elementary semiconductors and on that of semiconductor compounds were developed by technologists for effective photoelectric devices [1]. In each case, low value of working current proceeding of useful signal without distortions are achieved by constructive changes in appropriate area. Microcondition structures are of interest in this connection [2,3]. The feature of microduty transistors is that they can work not only at microconditions but also at nominal conditions. In particular, phototransistors can be used at large light signals while nominal transistors cannot be used at microconditions. Especially at work of transistor in the field of low collector currents, it is better to apply special type of transistors which are designed to work at microconditions, or to combine them with field effect transistors.

In the present paper, the results of the research on light characteristics of gallium arsenic two-barrier n-p-m-structure - analogue of bipolar phototransistor are presented.

2. Substantiation of choice of n-p-m-structure on the base of gallium arsenide

It is known that in photoreceivers, working area is formed on the base of p-n-homojunction created by diffusion of impurities [4], which is more effective for collection of photocarriers in comparison with heterojunction. Since the diffusion p-n-junction may increase the reverse currents, some authors [5] use method of liquid epitaxy for formation of p-n-junction for photoreceiver structures. This method has great opportunities to control the parameters of the grown epitaxial layer. For reduction of losses of produced energy in these structures, the current collection is realized through ohmic contacts made on surface layer of p-type. At the same time, in the photoreceivers replacing the ohmic contact by rectifying metal-semiconductor junction facilitates not only to preserve sensitivity, but also to increase the photocurrent [6].

In bipolar transistor n-p-n-structures replacing one of the semiconductor junctions by metal-semiconductor junction allows excluding the accumulation of charges and distortions in processed signal [7]. For this reason, for manufacturing bipolar phototransistor with extensive functional possibilities, we chose nGaAs-pGaAs-Ag-structures excited by a semi-transparent potential barrier.

The researched structure is made on the base of n-p-junction, formed by growing from liquid phase of epitaxial layer pGaAs on the nGaAs substrate with carrier concentration

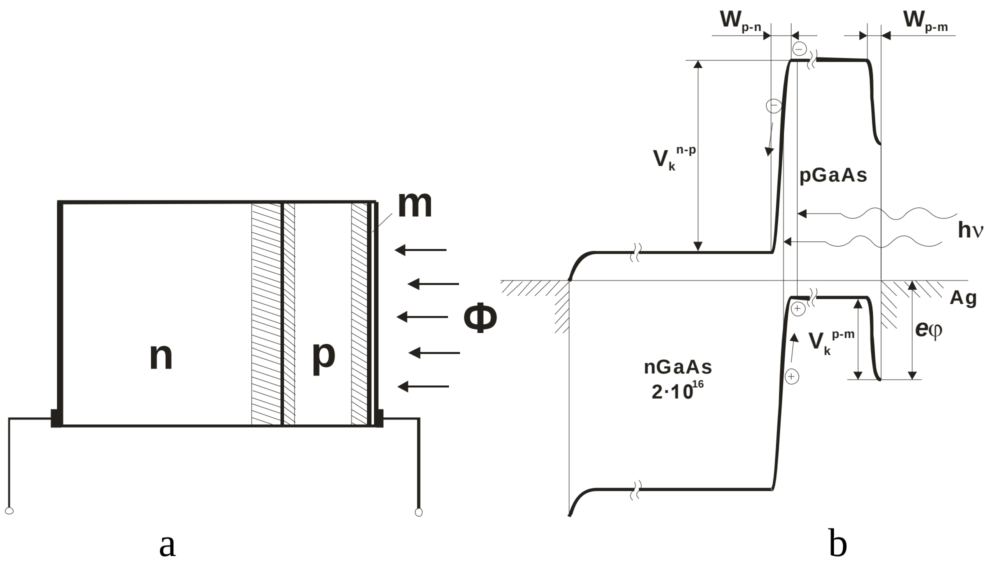

Figure 1. The geometrical design (a) and the qualitative initial gap diagram (b) of nGaAs-pGaAs-Ag-structure.

$2{\cdot}10^{16}$ cm^{-3}. Direct formation of epitaxial base layer on the bulk crystal's surface with linear distribution of the impurities along its thickness lets get graded n-p-junction. A temperature condition of pGaAs epitaxy layer's growth process is selected so that diffusion of zinc from melting into substrate is eliminated. Duration of growth process is 2-3 minutes. Concentration of carriers in pGaAs epitaxial layer with thickness 1.5 microns is $5{\cdot}10^{17}$ cm^{-3}. On the back side of nGaAs substrate with thickness 400 microns ohmic contact made from the alloy In+Sn is fixed by dusting in vacuum; on the surface of epitaxial layer pGaAs rectified potential barrier is formed from translucent Ag. The area of nGaAs-pGaAs-Ag-structure is equal to 21 mm^2. Its geometrical design is shown in Figure 1a. While in well-known transistor n-p-n and p-n-p structures due to their symmetry it is possible to modulate only base layer, specified choice of researched structure's parameters provides modulation of nGaAs-layer by n-p-junction and pGaAs-layer by metal-p-junction at various voltage bias. Besides, the formation of base pGaAs-layer from thin epitaxial layer (1÷1.5 microns) creates conditions for penetration of light radiation up to nGaAs-substrate and excitation of photocarriers on n-p-junction. It is necessary to note that researched structure is a special type of three-barrier Ag-pGaAs-nAl$_{0.1}$Ga$_{0.9}$As-Au-structure, which differs with replacing rectified contact by ohmic one. Here, it is necessary to pay attention to the fact that Ag-pGaAs-junction in both structures is photoreceiver. It is possible to expect that photoelectrical effects connected to the given junction will take place also in two-barrier nGaAs-pGaAs-Ag-structure (probably in a little bit changed form). In this plan, it is possible to observe Franz-Keldysh effect found out earlier by authors of [8]. So, research on the photoelectric characteristics of two-barrier nGaAs-pGaAs-structure is interesting for physics and practice too.

3. Photovoltaic effect in nGaAs-pGaAs-Ag-structure

By virtue of identity of nGaAs-pGaAs junction and active p-n-junction of the photoconverter, photogalvanic characteristics of nGaAs-pGaAs-Ag-structure were researched first. For this purpose, nGaAs-pGaAs-Ag-structure was illuminated from semi-transparent potential barrier by tungsten lamp with radiation's maximum ~ 800 nm [9] coinciding with the maximum band-band absorption of gallium arcenicum and photogalvanic electromotive force was fixed at positive polarity on the electrode of Ag barrier and negative polarity on the electrode of ohmic contact of nGaAs (Figure 2).

These circumstances specify that generation of photocarriers takes place in the base pGaAs-layer and is divided by electrical field of p-n-junction. Thus potential pGaAs-Ag-barrier does not render any obstacle for current transport, because it is directly biased by appearing photoelectrical motive force. At the increase of illumination intensity, open-circuit voltage (U_{xx}) increases and at 500 lux it gets saturation with maximum = 0.43 eV (Figure 3). This U remains constant up to 1500 lux. Short circuit current ($I_{s.c.}$) in illumination interval from

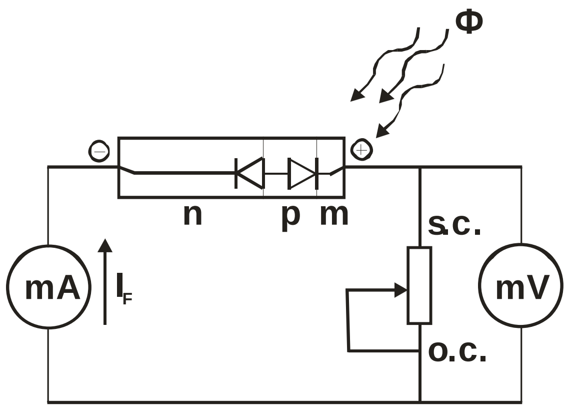

Figure 2. The scheme of switching on of nGaAs-pGaAs-Ag-structure for research of photo-electric characteristics.

0 to 2500 lux grows linearly (Figure 4). Above mentioned polarity of photoelectrical motive force allows concluding that photogenerated holes reach collector contact without any obstacle and photogenerated electrons are delivered effectively to ohmic contact. It is necessary to note that metal-semiconductor barrier also helps at working voltage preservation of photogalvanic conditions in n-p-junction as well as in two-barrier structure with metal-semiconductor junctions [10]. Besides, the presence of potential pGaAs-Ag-barrier causes essential distinction of current transport mechanisms and light characteristics at the change of voltage bias.

4. Research on current transport's mechanism in nGaAs-pGaAs-Ag-structure

The researched unbiased structure (Figure 1b) consists of two junctions – semiconductor nGaAs-pGaAs-junction and metal-semiconductor pGaAs-Ag-junction. With regard to polarity of applied voltage to n-p-junction, we have forward bias when (-)n-p-m(+) and at the change of polarity of voltage, we respectively have reverse bias (Figure 5a, curve 2). Analysis of current-voltage characteristic specifies that in both modes the dependence of the current on the voltage is described by sedate dependence. As shown in Figure 5b, three typical sections appeared on the current-voltage characteristic in transistored (-)n-p-m(+) clutching condition. On the initial section, an exponent γ_1 equals 0.34, and then changes into transient section 1.15→3.1 and over 9V, $\gamma_3 = 0.32$. On the first section, we have carrier generation in space-charge region, which then changes into thermal electron emission and lasing processes due to increasing rate of widening space charge region of pGaAs-Ag-junction. At these conditions, at zero voltage, we have in the base layer generation of minority carriers, and creating the photogalvanic electric motive force in p-n-junction. With increasing of applied voltage, p-n-junction becomes forward biased when pGaAs-Ag-junction is reverse biased. As a result of redistribution of voltage

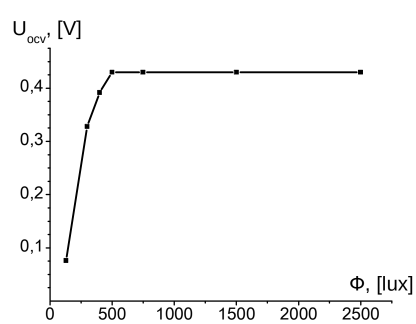

Figure 3. Dependence of photogalvanic electromotive force from illumination's intensity of nGaAs-pGaAs-Ag-structure.

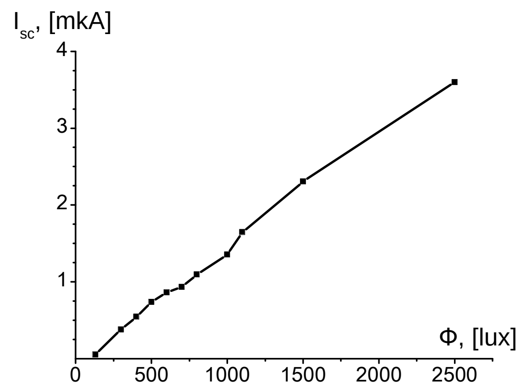

Figure 4. Lux-ampere characteristic of nGaAs-pGaAs-Ag-structure.

between n-p and p-m-junctions intensity of electrical field in reverse biased p-m-junction increases with creating conditions for realization of Franz-Keldysh's effect, that is generating photocarriers at energies less than those necessary for band-band excitation. So, photogeneration processes move from the base under potential barrier of metal-semiconductor junction.

At forward bias current-voltage characteristic is defined by electronic processes on n-p-junction at low voltages, and by p-m-junction at high voltages (Figure 5b). In other direction (+)n-p-m(-) current-voltage characteristic is determined by blocking of n-p-junction (Figure 5c). In beginning at low voltages we have generation processes (γ=0.27) right up to 5 V (γ=0.88), which are replaced at high voltages by recombination processes.

Here at low voltage light radiation, getting to the base generates electron-hole pairs, which are divided by n-p-junction's electrical field. With increasing of applied reverse voltage, photodiode conditions are realized because metal-semiconductor junction is forward biased.

Analysis of current transport's mechanisms shows that due to generation

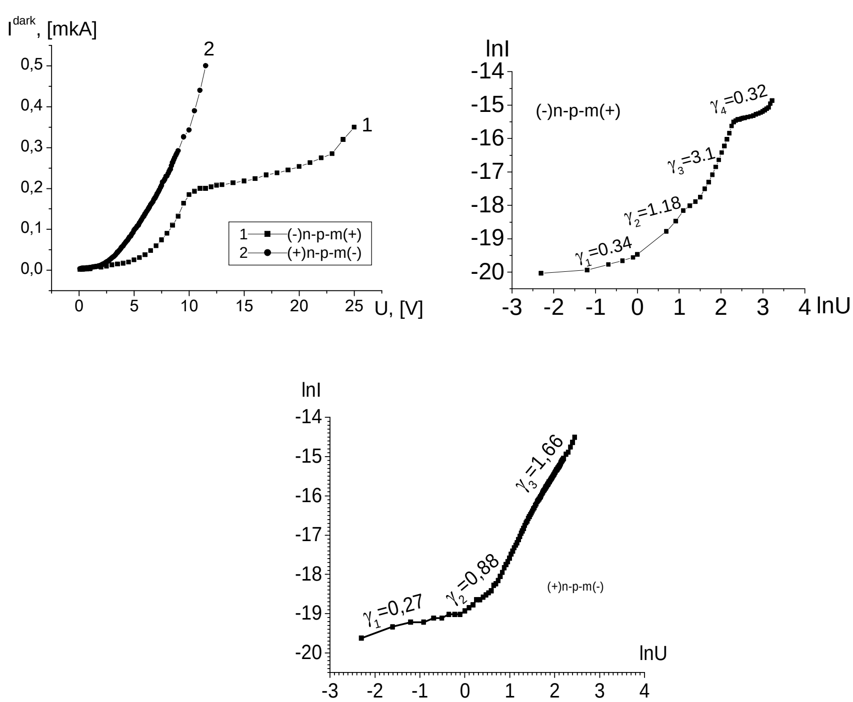

Figure 5. Current-voltage characteristics of nGaAs-pGaAs-Ag-structures at various conditions (a,b,c).

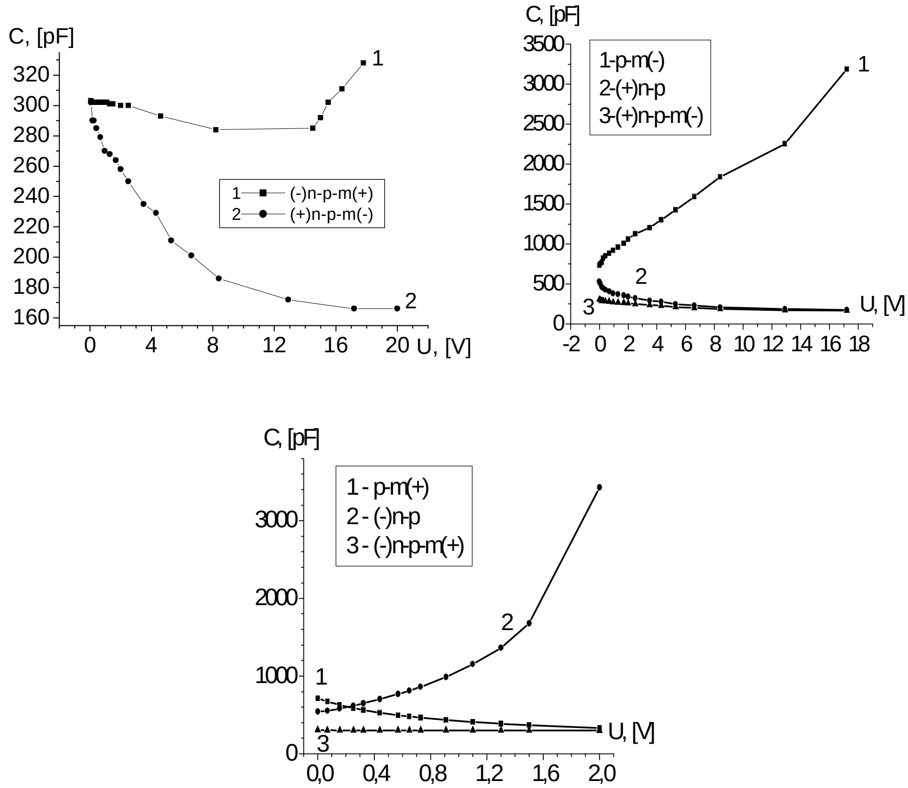

Figure 6. Volt-capacity characteristics of n-p-m-structure (a) and those of the each junction at various conditions: (b) (+) n-p-m(-) and (c) (-) n-p-m(+).

processes in space charge layer of n-p-junction we have low dark currents. In the case of forward bias on p-n-junction the injection-recombination processes conduce to getting low currents. That provides to application of this structures as microduty devices.

The current-voltage characteristics of structure correlate with volt-capacity characteristics. So, at direct bias of n-p-junction (Figure 6a, curve 1) at low voltages (at (-)n-p-m(+)) the capacitance of structure decreases with increasing of voltage which is caused by expansion of space charge layer. Further in the voltage interval from 8V to 14.5V capacitance remains constant, because the space charge layer also becomes constant. At high voltages increasing of capacitance is caused by significant narrowing of space charge layer on the other junction (n-p-junction). As a result, we have increasing of total capacitance of consistently connected n-p and p-m-junctions.

At the other direction (-)n-p-m(+), we have rather sharp decreasing of capacitance which is caused by expansion of space charge layer of p-n-junction.

The dependence of space charge layer's thickness on voltage, dynamics of its change and physical processes taking place in the space charge layer are responsible to current transport's mechanism and photoelectric characteristics of structure. Experimental rated data of index of exponent, index of degree and space charge layer's thickness depending on switching on conditions are tabulated in Table 1.

Since in nGaAs-pGaAs-Ag-structure n-p and pGaAs-Ag-junctions are consistently connected, it is possible to measure experimentally the value of effective total capacitance. On the basis of initial data and results of measurement, it is possible to determine both thickness of space charge layer and capacitance.

Space charge layer's thickness of metal-semiconductor junction is determined by the expression [11]:

$$W^{p-m} = \sqrt{\frac{2\varepsilon\varepsilon_0 (V_c \pm V)}{qN}}$$

where $V_c = \varphi - (E_c - E_f)$ - build-in potential, φ - height of the potential barrier, N - carriers' concentration in base layer. For researched nGaAs-pGaAs-Ag-structure height of the potential barrier which is determined from spectral characteristics (in coordinates:

Table 1. Experimental rated data of index of exponent, index of degree and space charge layer's thickness depending on switching on conditions.

(-)n-p-m(+)								
U, [V]	0.068	1.1	1.3	2	8.2	14.5	15	17.8
β	0.34			1.15 → 3.1		0.32		
W[micron]	6.7	6.7	6.7	6.8	7.2	7.1	6.9	6.2
E[V/cm]	$1\cdot10^2$	$1{,}6\cdot10^2$	$1{,}9\cdot10^3$	$2.9\cdot10^3$	$1.1\cdot10^4$	$2\cdot10^4$	$2.2\cdot10^4$	$2.8\cdot10^4$
(+)n-p-m(-)								
U, [V]	0.059	0.068	1.3	1.7	4.3	6.6	12.9	17.2
γ	0.27			0.88		1.66		
W,[micron]	6,7	7,3	7,6	7,7	8,9	10,1	11,8	12,3
E, [V/cm]	$0.88\cdot10^2$	$0{,}9\cdot10^2$	$1{,}7\cdot10^3$	$2.2\cdot10^3$	$4.8\cdot10^3$	$6.6\cdot10^3$	$1\cdot10^4$	$1.4\cdot10^4$

root of response from photon energy) is equal to 0.64 eV and build-in potential to 0.54 eV accordingly. Concentration of carriers in pGaAs is equal to $5\cdot10^{17}$ cm^{-3}. For these data at zero bias we have for thickness of space charge layer of p-m-junction: $W^{p-m} = 0.0286$ microns. From effective thickness of space charge layers ($W^{n-p-m} = 0.0663$ microns) of consistently connected n-p and p-m-junctions with total capacitance 308 pF, we get thickness of exclusion layer of n-p-junction: $W^{n-p} = 0.037659$ microns. From that, we can also determine the value of p-m-junction's capacitance, using the expression $c = \varepsilon\varepsilon_0 \cdot S / W$, where S - area of the junction.

Dependences of space charge layer's thickness for given working voltage are shown in Figure 7a, where curve 1 for direct biased p-m-junction and curve 2 for reverse biased n-p-junction. Curve 3 is obtained on the basis of experimental data of dependence of capacitance on voltage (Figure 6b, curve 3). From the figure, one can see that the value of total capacitance (curve 3) is even smaller than that of reverse biased junction.

At photoreception conditions of the reverse biased metal-semiconductor junction, intensity of electrical field gets high values and current-voltage dependence has exponential kind. It is possible to explain it that resistance of p-m-junction is smaller than resistance of n-p-junction and so p-m-junction does not limit current proceeding through the structure.

At the change of working voltage's polarity we have blocking of n-p-junction and current-voltage characteristics is described by power function. As a result it turns out that current transport's mechanism is determined by n-p-junction, that is direct biased p-m-junction does not interfere current transport and its current becomes equal to the current of n-p-junction.

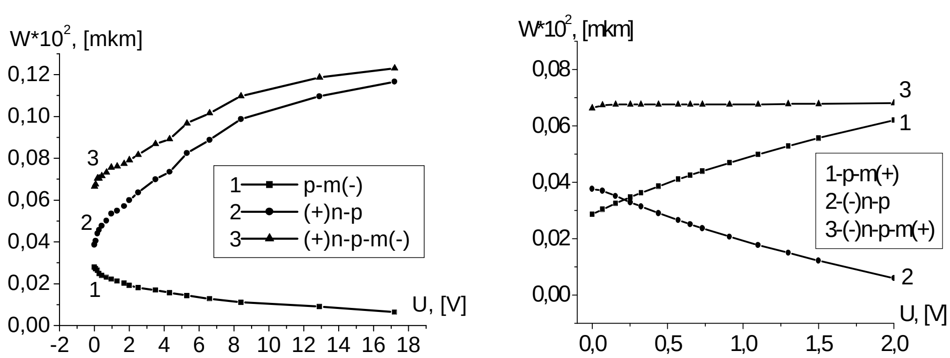

Figure 7. Dependences of space change layer's thickness of the each junction at conditions: (a) (+)n-p-m(-) and (b) (-)n-p-m(+).

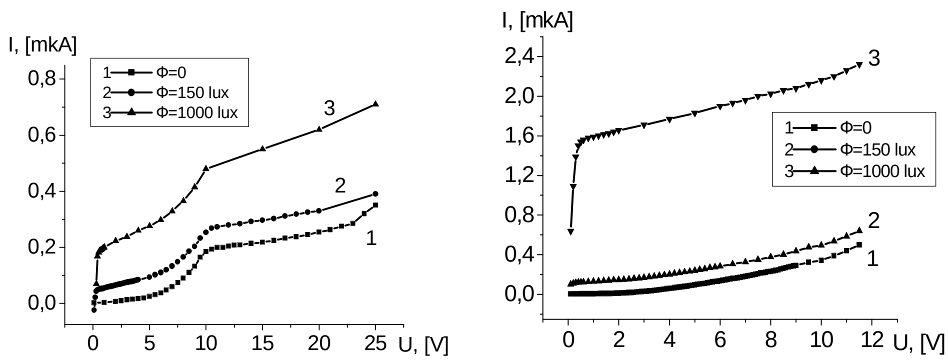

Figure 8. Light characteristics of nGaAs-pGaAsAg-structure at conditions: (a) (-)n-p-m(+) and (b)(+)n-p-m(-).

So it is possible to suppose that photoelectric characteristics will also vary depending on switching on conditions of nGaAs-pGaAs-Ag structure.

5. Photodiode effect and phototransistor one in nGaAs-pGaAs-Ag-structure

Researches of nGaAs-pGaAs-Ag-structure have shown at illumination from side of potential barrier on conditions (+)n-p-m(-) with increasing of voltage more than 10V current's growth is observed (Figure 8a), and dependence of photocurrent on voltage has growing character. Such behavior of photocurrent specifies that photodiode conditions are realized, that is with increasing of voltage the concentration of generated photocarriers also increases.

At the change of working voltage's polarity (+)n-p-m(-) for given light intensity (1000 lux) we have 8 multiple increase of photocurrent (Figure 8b). At increasing of light radiation's intensity proportional increasing of photocurrent (Figure 3) is observed. Photocurrent's dependence on voltage at all intensities of illumination remains invariable and it has saturation character as well as in bipolar phototransistors [12].

At illumination of nGaAs-pGaAs-Ag-structure from the side of potential pGaAs-Ag-barrier at conditions (+)n-p-m(-) in p-base layer electron-hole pairs appear as a result of band-band excitation (Figure 9, position 1). Holes

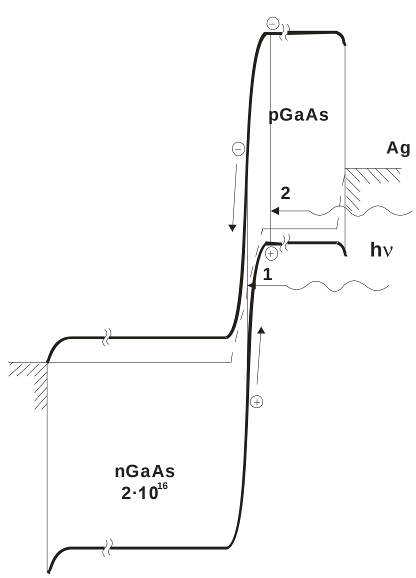

Figure 9. The energy gap diagram of nGaAs-pGaAs-Ag-structure at condition (+)n-p-m(-).

(minority carriers) are accumulated in p-base layer (Figure 9, position 2), increasing positive charge. In the result potential barrier's height decreases and holes, overcoming it, turning into a collector and reach ohmic contact of nGaAs without any obstacles. Decreasing of potential barrier's resistance causes redistribution of voltage applied to structure as well as increasing of dark current causing transistor effect.

6. Conclusions

Thus, the researched structure can be applied as microduty device which can operate in the photodiode or phototransistor modes. The comparison of light characteristics of nGaAs-pGaAs-Ag-structure in the photodiode and phototransistor modes shows that the greatest amplification takes place on phototransistor mode (Figure 8b).

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