

# The Electro-Physical and Photo-Electrical Properties of the Solid Solutions (GaAs)<sub>0.69</sub>(Ge<sub>2</sub>)<sub>0.17</sub>(ZnSe)<sub>0.14</sub> and (GaAs)<sub>0.71</sub>(Ge<sub>2</sub>)<sub>0.25</sub>(ZnSe)<sub>0.04</sub>

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**ABSTRACT:** Epitaxial layers of the solid solutions (GaAs)<sub>0.69</sub>(Ge<sub>2</sub>)<sub>0.17</sub>(ZnSe)<sub>0.14</sub> and (GaAs)<sub>0.71</sub>(Ge<sub>2</sub>)<sub>0.25</sub>(ZnSe)<sub>0.04</sub> were grown up from the limited volume of the tin solution-melt by the method of liquid phase epitaxy. It is determined that current-voltage (*I-V*) characteristics of thin structures ( $d = 10 \mu\text{m}$ ) at the small voltages (to 0.4) is described by exponential dependence  $I = I_0 \exp(qV/ckT)$ , and at the big ones ( $V > 0.5 \text{ V}$ ) - by power dependence of type  $J \sim V^\alpha$  where the exponent  $\alpha$  changes at the voltage increasing. In the thicker ( $d = 20 \mu\text{m}$ ) structures the direct branch of the current-voltage characteristics is also described exponential dependence  $I = I_0 \exp(qV/ckT)$  at small voltage (to 1 V), and at voltage ( $V > 1 \text{ V}$ ) there is a sublinear dependence of the current at voltage increasing  $V \approx V_0 \exp(Jad)$ . The sublinear part of the *I-V* characteristics is explained based on the theory of effect of injection depletion. The photosensitivity peak of structure at energy of photons 2.62 eV is detected. It is explained impurity levels of ZnSe lying in the valence zone of the solid solution.

**KEYWORDS:** heterostructure, majority and minority carriers, recombination, drift, injection depletion.

## I. INTRODUCTION

The wide band semiconductors of the type  $A^3B^5$  are perspective materials for creation on their basis the electro-optical devices, working in average and distant infrared spectrum of radiation. Intensive works on creation and research of various device structures based on InSb, InAs, GaSb, GaAs and their solid solutions are conducted [1-4]. Among these materials GaAs and its solid solutions with compound composition have special interest as mobilities of the electrons and holes in them are very considerable [5-7], and on their basis can be developed fast acting electro-optical devices. Besides solid solutions of replacement (GaAs)<sub>1-x-y</sub>(ZnSe)<sub>x</sub>(Ge<sub>2</sub>)<sub>y</sub> because of variation of values  $x$  and  $y$  give a chance to expand the spectral range of action of the structures on their basis from 1.1 eV to 2.65 eV [8]. However wide use of the instrumental structures made based on GaAs and its solid solutions is limited because of insufficient study of electro-physical and photoelectrical properties of such materials and structures on their basis.

The purpose of the given work is research of *I-V* characteristics and photo-electric properties of the heterostructure of type  $n\text{-GaAs} - p\text{-}(\text{GaAs})_{0.69}(\text{Ge}_2)_{0.17}(\text{ZnSe})_{0.14}$  and  $n\text{-GaAs} - p\text{-}(\text{GaAs})_{0.71}(\text{Ge}_2)_{0.25}(\text{ZnSe})_{0.04}$ .

## II. SAMPLES AND EXPERIMENTAL TECHNIQUE

It is known that the formation of substitutional solid solutions based on GaAs, Ge<sub>2</sub> molecules and binary compounds ZnSe is related to the conditions of formation of continuous substitutional solid solutions, founded on molecular-statistical and crystallochemical representations. These conditions are proposed in the form of [9]:

$$\Delta z = \sum_{i=1} z_i^m - \sum_{i=1} z_i^n = 0, \quad (1)$$

$$\Delta r = \left| \sum_{i=1} r_i^m - \sum_{i=1} r_i^n \right| \leq 0.1 \cdot \sum_{i=1} r_i^m \quad (2)$$

where,  $z_i^m$  and  $z_i^n$  - valences;  $r_i^m$  and  $r_i^n$  - the covalent radii of atoms solvent  $m$  and soluble  $n$  chemical element or elements forming molecules solvent  $m$  and soluble  $n$  compounds respectively  $i = 1, 2, 3, 4$ . Condition (1) provides electro-neutrality of soluble chemical elements or compounds in the dissolving semiconductor material; it is executed

when the dissolved elements are isovalence relatively solvent of semiconductor. Condition (2) provides for the closeness of the geometric parameters of solvent  $m$  and soluble  $n$  connections, precluding the occurrence of significant distortions of the crystal lattice in the solid solutions. The smaller  $\Delta r$ , the less the energy of elastic distortions of the crystal lattice: consequently, the crystalline perfection of the solid solution and the greater solubility  $n$  in  $m$ . When the difference of the sum of the covalent radii of the atoms of the components' molecules forming the solution more than 10%, the formation of substitutional solid solution of these components are negligible.

As it is known GaAs and Ge<sub>2</sub>, GaAs and ZnSe as well as Ge<sub>2</sub> and ZnSe are isovalence and for them the condition (1) of electro-neutrality is performed:

$$\begin{aligned} Z_{\text{Ga}^+} + Z_{\text{As}} &= Z_{\text{Ge}^+} + Z_{\text{Ge}}, \\ Z_{\text{Ga}^+} + Z_{\text{As}} &= Z_{\text{Zn}^+} + Z_{\text{Se}}, \\ Z_{\text{Ge}^+} + Z_{\text{Ge}} &= Z_{\text{Zn}^+} + Z_{\text{Se}}, \end{aligned} \quad (3)$$

Differences between the sum of the covalent radii of the atoms of the molecules GaAs, Ge<sub>2</sub> and ZnSe constitute respectively

$$\begin{aligned} \Delta r_1 &= |(r_{\text{Ga}} + r_{\text{As}}) - (r_{\text{Ge}} + r_{\text{Ge}})| = |2,41 \text{ \AA} - 2,41 \text{ \AA}| = 0, \\ \Delta r_2 &= |(r_{\text{Ga}} + r_{\text{As}}) - (r_{\text{Zn}} + r_{\text{Se}})| = |2,41 \text{ \AA} - 2,42 \text{ \AA}| = 0,01 \text{ \AA}, \\ \Delta r_3 &= |(r_{\text{Ge}} + r_{\text{Ge}}) - (r_{\text{Zn}} + r_{\text{Se}})| = |2,41 \text{ \AA} - 2,42 \text{ \AA}| = 0,01 \text{ \AA} \end{aligned} \quad (4)$$

that, is no larger than 1%; therefore they satisfy the condition of the formation the solid solution of substitution (2), their mutual substitution does not greatly deform the crystal lattice. The presence at the front of crystallization of the molecular formations  $C_2^{IV}$ ,  $A^{III}B^V$  and  $A^{II}B^{VI}$  helps quasi-molecular substitution in the solid phase. Respectively  $C_2^{IV} \rightarrow A^{III}B^V$ ,  $C_2^{IV} \rightarrow A^{II}B^{VI}$ ,  $A^{III}B^V \rightarrow A^{II}B^{VI}$  implies necessarily the existence of pairs of  $C^{IV} - C^{IV}$ ,  $A^{III} - B^V$ ,  $A^{II} - B^{VI}$  for any value of  $x$  and  $y$  in the form of compounds  $(\text{GaAs})_{1-x-y}(\text{Ge}_2)_x(\text{ZnSe})_y$ .

Substitutions of two atoms of the molecule GaAs for two atoms of Ge-Ge or ZnSe in the crystal lattice result in quantitative change of the interaction forces between the nearest neighbors, but covalent-tetrahedral nature of the relationship in the crystal lattice remains. Substitutional solid solution in the form of  $(\text{GaAs})_{0,69}(\text{Ge}_2)_{0,17}(\text{ZnSe})_{0,14}$  and  $(\text{GaAs})_{0,71}(\text{Ge}_2)_{0,25}(\text{ZnSe})_{0,04}$  is a stable phase, however it is possible appearance of local micro-stress growing character and no large distortion of energy's values of crystal lattice's elastic stress.

For our research solid solutions  $(\text{GaAs})_{0,69}(\text{Ge}_2)_{0,17}(\text{ZnSe})_{0,14}$  and  $(\text{GaAs})_{0,71}(\text{Ge}_2)_{0,25}(\text{ZnSe})_{0,04}$  were grown in the installation with vertical quartz reactor. Horizontally placed substrate separated from each other graphite props were fixed in the graphite cassette of the reactor. In the space between the two - the upper substrate and the lower one - liquid tin solution-melt was poured through lateral slits of the cassette. The distance between the upper substrate and lower one was varied in the limit of 0.25–2.5 mm by selection of props with different thickness. Thus, we can adjust the volume of the liquid solution-melt. Single-crystalline wafers of GaAs  $n$ -type conductivity diameter 20 mm of the marks AGCS with carrier concentration of the charge  $\sim 5 \cdot 10^{17} \text{ cm}^{-3}$ , with orientation (100) were used as substrates. Composition of the solution-melt, consisting of the components Sn, GaAs, Ge and ZnSe, were calculated based on the results of experimental research the liquid phase of system Sn–GaAs–Ge–ZnSe and literature data [10-12]. Growth of the layers was realized from tin solution-melt by compelled cooling in atmosphere of the hydrogen-purified palladium. The rate of the compelled cooling at the optimal regime was 1 - 1.5 deg/min.

Crystallization of the solid solution  $(\text{GaAs})_{0,69}(\text{Ge}_2)_{0,17}(\text{ZnSe})_{0,14}$  and  $(\text{GaAs})_{0,71}(\text{Ge}_2)_{0,25}(\text{ZnSe})_{0,04}$  layers carried out in the temperature range 730 – 640 °C and 730 – 590 °C and with rate of the growth  $\vartheta=0,15 \text{ \mu m/min}$ . Crystallization of GaAs from the solution-melt takes place at the initial moment of the growth because at the selected temperature epitaxy solution is saturated related to GaAs. At lower temperatures there are conditions for growing the solid solutions  $(\text{GaAs})_{0,69}(\text{Ge}_2)_{0,17}(\text{ZnSe})_{0,14}$  and  $(\text{GaAs})_{0,71}(\text{Ge}_2)_{0,25}(\text{ZnSe})_{0,04}$ , since at these temperatures the solution-melt becomes supersaturated elements Ge and ZnSe.

The grown epitaxial films have had different thicknesses - 10 ÷ 20  $\mu\text{m}$  and the  $n$ -type conductivity with resistivity  $0,1 \div 0,3 \text{ \Omega} \cdot \text{cm}$  and carrier concentration  $5,1 \div 5,8 \cdot 10^{17} \text{ cm}^{-3}$ .

The chemical composition of the epitaxial layer was determined from X-ray analysis. It is shown that the distribution of the components on the surface is homogeneous and along thickness of the film content ZnSe and of Ge<sub>2</sub> varies  $0 \leq x \leq 0,17$ ,  $0 \leq y \leq 0,14$ ,  $0 \leq x \leq 0,25$  and  $0 \leq y \leq 0,04$ . It reduces the elastic stresses because of the mismatch the lattice parameters of the substrate and those of the film [13]. To studies  $I$ - $V$  characteristics of the structures the metal contacts were created by vacuum deposition - solid ones on the backside and quadrangular ones, with the area 9 mm<sup>2</sup> from the silver on the side of the epitaxial layer. The dark  $I$ - $V$  characteristics were measured at temperatures of 25 - 150 °C. The spectral dependence of the photosensitivity  $n$ - $(\text{GaAs}) - p$ - $(\text{GaAs})_{1-x-y}(\text{ZnSe})_x(\text{Ge}_2)_y$  structures was measured by optical spectrometer equipped with monochromatic mirror of the firm CARL ZEIS JENA with quartz optics. That gave possibility to investigate samples at the range of photons' energies from 1 to 3 eV.



III. RESULTS AND THEIR DISCUSSION

III-a. Influence of temperature on I-V characteristics of the n-GaAs – p-(GaAs)<sub>0.69</sub>(Ge<sub>2</sub>)<sub>0.17</sub>(ZnSe)<sub>0.14</sub> heterostructures.

The first part of I-V characteristics (from zero to 0.25 V) is presented in fig.1. It is represents an ohmic dependence, i.e.  $J \sim V^1$ . At increasing applied voltage in the range from 0.25 to 0.4 V exponential dependence is observed (fig.1 a).

I-V characteristics at all temperature is described by expression:

$$I \approx I_0 \cdot e^{\frac{qV}{ckT}} \tag{5}$$

The exponent "c" in the exponential I-V characteristics is defined from experimental data as:

$$c = \frac{q}{kT} \cdot \frac{V_2 - V_1}{\ln \frac{I_2}{I_1}} \tag{6}$$

Such dependence of current from voltage has been predicted for the first time by V.I. Stafeev [14] and then specified in [15] for p-n-n<sup>+</sup> - structures with an exponent "c" which has the following appearance:

$$c = \frac{2b + ch(W / L_p) + 1}{b + 1} \tag{7}$$

where,  $b = \mu_n / \mu_p$  - the relation of electrons and holes mobilities for the solid solution (GaAs)<sub>0.69</sub>(Ge<sub>2</sub>)<sub>0.17</sub>(ZnSe)<sub>0.14</sub>, which is equal  $b \approx 3.1$ . Knowing  $b$ , we can find  $W/L_p = 4,16$ , then calculate the diffusion length of minority carriers of the current –  $L_p = 4.8 \mu m$ . It allows to define production  $\mu_p \tau_p = qL_p^2/kT$  which at the room temperature is equal  $\sim 8.9 \cdot 10^{-10} \text{ cm}^2/\text{V}$ . Mobility of the majority carriers  $\mu_p$ , defined by the Hall method, is  $\sim 360 \text{ cm}^2/\text{V}\cdot\text{s}$ . Based on this data we define values  $I_0$ ,  $c$  and  $b$  at various temperatures, they are resulted in tabl.1.

**Table1.** The values of pre-exponential factor  $I_0$ , the indicator of the exhibitor "c" in the expression (5) and the relation of the electrons and holes mobilities  $b$  for n-GaAs – p-(GaAs)<sub>0.69</sub>(Ge<sub>2</sub>)<sub>0.17</sub>(ZnSe)<sub>0.14</sub> heterostructures at various temperatures.

$t, ^\circ\text{C}$	25	50	75	100	125
$I_0, (\text{A})$	$2.6 \cdot 10^{-6}$	$3.63 \cdot 10^{-6}$	$4.43 \cdot 10^{-6}$	$6.73 \cdot 10^{-6}$	$5.54 \cdot 10^{-6}$
$c$	9.56	9.65	9.55	9.62	10.55
$b$	3.1	3.05	3.14	3.102	5.38

As we can see from the table at temperatures 25 - 100° C value  $I_0$  (A) increases but  $c$  and  $b$  - almost do not change. At 125° C the appreciable increase of their values are observed. It is probably, connected with that concentration of the centers influencing mobility of carriers of the current in the range of temperatures 25 - 100° C is not constant. At temperature 125° C formations of the various charged centers, scattering carriers of current and changing their mobility is possible. Results of these calculations are resulted in tabl.1. As it is seen from fig.1  $bI$ -V characteristics of these structures at voltage  $V > 0.5 \text{ V}$  are described by dependence of type  $J \sim V^\alpha$ , where  $\alpha$  changes from 2 to 3 and increases at voltage increasing. The first part  $J \sim V^2$  is observed at voltage from 0.5 to 1.7 V and can be explained by drifting model of ohmic relaxation [16]. At further increasing of voltage sharp current increasing of type  $J \sim V^{2.7}$  is observed. Probably, processes of an intracomplex electronic exchange causing "delay" of recombination processes begin. In this case, the rate of recombination of free carriers will not describe by statistics of Shockley-Reed, and will assume more difficult form [17, 18]:

$$u_r = N_r \frac{c_n c_p (pn - n_i^2)}{c_n (n + n_1) + c_p (p + p_1) + \alpha \tau_i pn} \tag{8}$$

where  $N_r$  - concentration of the recombination centers,  $n, p$  - concentrations of electrons and holes,  $n_i$  – intrinsic concentration of the current carriers in the semiconductor,  $c_n, c_p$  - coefficient of capture of electrons and holes accordingly,  $n_1, p_1$  - equilibrium concentration of electrons and holes, when Fermi's level coincides with recombination impurity level,  $\alpha$  - a member describing an intracomplex exchange,  $\tau_i$  - time of an intracomplex exchange. This member in denominators (8) increases at increasing of excitation. At small excitation, this member is negligibly small and the rate of recombination is described by statistics of Shockley - Reed. At this I-V characteristics is described by drift model of the current transport and has an usual square-law appearance, i.e.  $\alpha_I = 2$ , corresponding to the ohmic relaxation of the volume charge [16]:

$$V = \sqrt{\frac{8d^2J}{9q\mu_n\mu_p\tau_pN_D}} = B_0\sqrt{J}, \quad (9)$$

where,  $\mu_p = 360 \text{ cm}^2/\text{V}\cdot\text{s}$  and  $\tau_p = 2.5 \cdot 10^{-7} \text{ s}$  - mobility and life time of holes,  $\mu_n = 1113 \text{ cm}^2/\text{V}\cdot\text{s}$  - mobility of electrons,  $J$  - current density,  $d = 10 \text{ }\mu\text{m}$  - thickness of the base,  $N_D = 1.4 \cdot 10^{15} \text{ cm}^{-3}$  - concentration of shallow donor impurity centers. By the inclination of dependence  $J \sim V^2$  we can define value  $B_0 = 59.23 \text{ V}\cdot\text{cm}\cdot\text{A}^{-1/2}$ .

The following part of the  $I$ - $V$  characteristics  $J \sim V^\alpha$  where  $\alpha = 2.7$  are realized at voltage from 1.7 to 2.2 V when the recombination of nonequilibrium carriers of the current occurs with "delay", i.e. last member in the denominator (8) becomes essential. In this case,  $I$ - $V$  characteristics has following analytical expression [16].

$$V = \frac{(b+1)d^2N_R}{N_D\mu_p\tau_i} + \frac{d}{q\mu_p(b+1)C}\sqrt{J} - \frac{2(b+1)N_Rd^2c_n}{N_D\mu_p\alpha\tau_iC}\frac{1}{\sqrt{J}} = A + B\sqrt{J} - \frac{D}{\sqrt{J}} \quad (10)$$

where,  $A$ ,  $B$  and  $D$  - parameters, depending on concentration of the ionized deep impurities, relations of mobility of electrons and holes, thickness of the base. In tab.2 the values of parameters  $A$ ,  $B$  and  $D$ , depending on temperature are resulted. As it is seen from tab.2 parameters  $A$ ,  $B$  and  $D$ , defining value of  $V$  and depending on concentration of the ionized recombination centers, mobility of the current carriers and the thickness of base increase in an interval 25 - 100° C and decrease considerably at 125° C. Such dependence is probably connected with appreciable influence of the time of intracomplex exchange  $\tau_i$ .

**Table2.** The values of parameters  $A$ ,  $B$  and  $D$  in the expression (10) at various temperatures.

$t, \text{ }^\circ\text{C}$	25	50	75	100	125
$A, \text{ (V)}$	2.65	2.67	2.69	2.74	2.63
$D, \text{ (V}\cdot\text{m}\cdot\text{A}^{-1/2})$	13.25	15.9	21.67	23.97	22.7
$B, \text{ (V}\cdot\text{A}^{1/2}\cdot\text{m}^{-1})$	13.07	15.7	21.5	23.8	22.5

Later (see fig. 1.b.) at voltage from 2.2 to 3 of CVC has the form  $J = A_1V^3$ , i.e. the part of  $I$ - $V$  characteristics submits to Lampert's law [16]

$$J = \frac{125\varepsilon\tau\mu_n\mu_p}{18} \frac{V^3}{d^3} \quad (11)$$

and called the drift model of the dielectric relaxation.

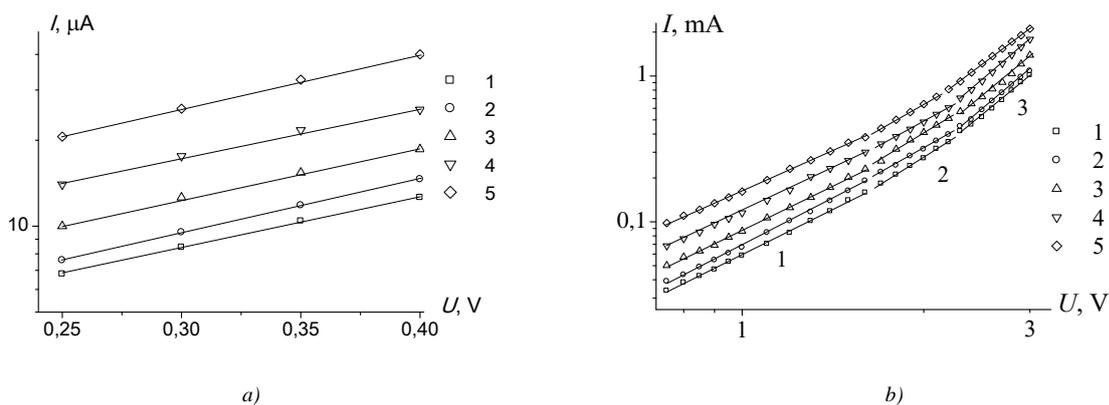


Fig.1. The dark current-voltage characteristic of  $n$ -GaAs -  $p$ - $(\text{GaAs})_{0.69}(\text{Ge}_2)_{0.17}(\text{ZnSe})_{0.14}$  structures in half-logarithmic (a) and logarithmic (b) scales at various temperatures, °C: 1 - 25, 2 - 50, 3 - 75, 4 - 100, 5-125.

**III-b. Research of current transport mechanism in  $n$ -GaAs -  $p$ - $(\text{GaAs})_{0.71}(\text{Ge}_2)_{0.25}(\text{ZnSe})_{0.04}$  heterostructures at various temperatures**

For definite the mechanism of current transport in the given structures  $I$ - $V$  characteristics have been investigated at various temperatures (fig.2). It is seen in fig.2  $I$ - $V$  characteristics of direct voltage at temperatures 25 - 150° C consist of two characteristic parts.  $I$ - $V$  characteristics of  $n$ -GaAs -  $p$ - $(\text{GaAs})_{0.71}(\text{Ge}_2)_{0.25}(\text{ZnSe})_{0.04}$  structures at direct voltage is resulted in fig.2 a in half-logarithmic scale. Initial exponential part of  $I$ - $V$  characteristics (to 0.8 V) is described well by the formula (5). For this case, the value "c" is defined under the formula (6) at various temperatures and it is resulted in the tabl.3. It is seen from the tabl. 3, that the value "c" decreases at increasing temperature from 25°

C to 150° C. Using experimental data for  $d = 17.79 \mu\text{m}$  and for  $b = 6,2$  from (7) we find value  $L_p$  diffusion lengths of the majority carriers, which is equal  $4.67 \mu\text{m}$ . Mobility of the majority carriers – holes – defined on the Hall method, amounted  $m_p = 355 \text{ cm}^2/\text{V}\cdot\text{s}$ ; for this estimation value of mobility of minority carriers  $\mu_n = b \cdot \mu_p = 2200 \text{ cm}^2/\text{V}\cdot\text{s}$  was taken. Product of mobility for the of life time of the majority carriers ( $\mu_p \cdot \tau_p$ ) can be calculated under the formula:

$$\mu_p \tau_p = \frac{qL_p^2}{kT} \tag{12}$$

At room temperature product  $\mu_p \tau_p \sim 8.4 \cdot 10^{-6} \text{ cm}^2/\text{V}$ ; it has allowed to define life time of the majority carriers  $\sim \tau_p = 2.37 \cdot 10^{-8} \text{ s}$ .

The pre-exponential factor  $I_0$  in the formula (5) looks like [15]:

$$I_0 = \frac{kT}{q} \cdot \frac{S \cdot b \cdot ch(d / L_p)}{2(b + 1) \cdot L_p \cdot \rho \cdot tg(d / 2L_p)} \tag{13}$$

where  $\rho$  - specific resistance of the interlining layer located between substrates Ge and the epitaxy layer of the solid solution  $(\text{GaAs})_{0.71}(\text{Ge}_2)_{0.25}(\text{ZnSe})_{0.04}$  (i.e. p - n junction). Value  $I_0$  defined from experimental points of curves  $I$ - $V$  characteristics at room temperature is equal  $28.7 \cdot 10^{-6} \text{ A}$ . By means of the equation (13) and the data of the tabl.3 the specific resistance  $\rho$  of the interlining layer between the substrate and the epitaxial films has been calculated, which was  $54.1 \cdot 10^6 \Omega \cdot \text{cm}$  at room temperature. From the tabl.3 it is also seen that at temperature increasing specific resistance of the layer between the substrate and the epitaxial film decreases.

**Table3.** Characteristic parameters of the solid solution  $(\text{GaAs})_{0.71}(\text{Ge}_2)_{0.25}(\text{ZnSe})_{0.04}$

$t, ^\circ\text{C}$	25	50	75	100	125	150
$I_0, \text{A}$	$28.7 \cdot 10^{-6}$	$31.8 \cdot 10^{-6}$	$36.4 \cdot 10^{-6}$	$41.4 \cdot 10^{-6}$	$45.8 \cdot 10^{-6}$	$49 \cdot 10^{-6}$
$c$	16.5	15.3	14.37	13.5	12.8	11.9
$b$	6.2	6.8	7.4	8	8.6	9.5
$\rho, \Omega \cdot \text{cm}$	$54.1 \cdot 10^6$	$52.9 \cdot 10^6$	$50.8 \cdot 10^6$	$48.3 \cdot 10^6$	$46.9 \cdot 10^6$	$46.1 \cdot 10^6$

From  $I$ - $V$  characteristics shown in fig.2  $b$  it is seen that after usual exponential dependence on all  $I$ - $V$  characteristics irrespective from temperature, an extended sublinear part (in the range from 0.85 to 2.) appears. Probably, these parts of  $I$ - $V$  characteristics can be well described by the theory so-called «effect of injection depletion», the first time predicted theoretically in the work [19]. In this case,  $I$ - $V$  characteristics has rather specific character and is described by law:

$$V \approx V_0 e^{JaW}, \tag{14}$$

where,  $J$  - current density,  $a$  - parameter. Recently the similar dependence was observed in p - n - structures made on the basis of continuous solid solutions  $(\text{Si}_2)_{1-x}(\text{CdS})_x$  [20] and  $(\text{InSb})_{1-x}(\text{Sn}_2)_x$  [21]. It is known [22] that such  $I$ - $V$  characteristics is realized in the semiconductor structures containing high concentration of deep impurity, in conditions of contrary directions of ambipolar diffusion and drift. And in this case, the parameter  $a$  is described by simple expression [19]:

$$a = \frac{1}{2qD_p N_t}, \tag{15}$$

depending only from the diffusion coefficient of the majority carriers (i.e. from their mobility -  $D_p = \frac{kT}{q} \mu_p$ ) and concentration of deep impurity  $N_t$ . For realization of this effect which has received subsequently the name of effect of injection depletion (see [15,19,23]), observance of condition  $JaW > 2$  is necessary. In our case at room temperature  $JaW \approx 8.6$ , that is this requirement is carried out. Parameter  $a$  is easy to calculate from corresponding sublinear parts of the  $I$ - $V$  characteristics in the fig.2**b**:

$$a = \frac{\ln\left(\frac{V_2}{V_1}\right) \cdot S}{(I_2 - I_1) \cdot W}, \tag{16}$$

where  $S$  - the area of cross-section section,  $(I_1, V_1), (I_2, V_2)$  - the points chosen on experimental curves of injection depletion. As it follows from the theory, appearance of such  $I$ - $V$  characteristics is possible only at contrary directions of ambipolar diffusions of nonequilibrium carriers and their ambipolar drift which in this case is defined by injection modulation of the charge of deep impurity [15,19]. So far as we have the set of various  $I$ - $V$  characteristics,

corresponding to various temperatures, we can calculate under the formula (16) value of parameter "a" at various temperatures which are resulted in the tabl.4. The quantity "a" allows define concentration of the deep impurity responsible for occurrence of the sublinear part (14) from the formula (15) which at room temperature is  $N_t = 5.3 \cdot 10^{12} \text{ cm}^{-3}$ .

**Table4.** The values of the parameter *a* and mobilities of majority carriers  $\mu_p$  and minority carriers  $\mu_n$  depending on the temperature.

<i>t</i> , °C	25	50	75	100	125	150
<i>a</i> , (cm/A)	$6.5 \cdot 10^4$	$6.1 \cdot 10^4$	$5.78 \cdot 10^4$	$5.55 \cdot 10^4$	$5.45 \cdot 10^4$	$5.26 \cdot 10^4$
$\mu_p \cdot N_b$ (V·cm·s) <sup>-1</sup>	$1.87 \cdot 10^{15}$	$1.84 \cdot 10^{15}$	$1.8 \cdot 10^{15}$	$1.75 \cdot 10^{15}$	$1.69 \cdot 10^{15}$	$1.62 \cdot 10^{15}$
$\mu_p$ , (cm <sup>2</sup> /V·s)	355	347	339	330	319	305
$\mu_n$ , (cm <sup>2</sup> /V·s)	2201	2360	2508	2640	2743	2897

Using the data of parameter *a*, *b* and  $\mu_p \cdot N_b$ , we have defined dependences of mobility of majority carriers –  $\mu_p$  and that of minority carriers -  $\mu_n$  from temperature (tabl.4). From the tabl.4 it is seen that the majority carriers mobility  $\mu_p$  in the solid solution (GaAs)<sub>0.71</sub>(Ge<sub>2</sub>)<sub>0.25</sub>(ZnSe)<sub>0.04</sub> decreases at increasing temperature, and this one of minority carriers  $\mu_n$  increases. It, apparently, allows conclude that in the given solid solution the prevailing role in the mobility mechanism plays by dispersion of carriers on the ions of deep impurity.

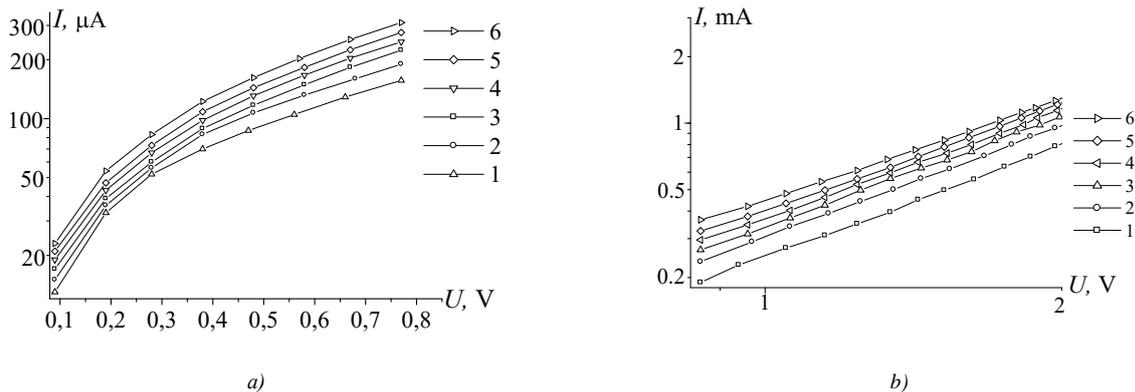
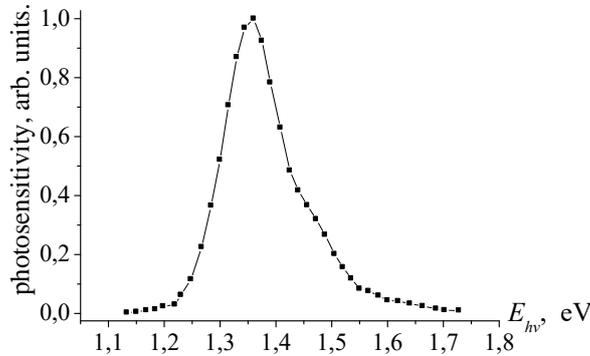


Fig.2. The exponential (a) and sublinear (b) part of current-voltage characteristic of *n*-GaAs – *p*-(GaAs)<sub>0.71</sub>(Ge<sub>2</sub>)<sub>0.25</sub>(ZnSe)<sub>0.04</sub> structures in half-logarithmic scales at various temperatures, °C: 1 - 25, 2 - 50, 3 - 75, 4 - 100, 5-125, 6 - 150

**III-c. The photosensitivity of *n*-GaAs – *p*-(GaAs)<sub>0.71</sub>(Ge<sub>2</sub>)<sub>0.25</sub>(ZnSe)<sub>0.04</sub> heterostructures**

Spectral dependence of photosensitivity of *n*-GaAs – *p*-(GaAs)<sub>0.71</sub>(Ge<sub>2</sub>)<sub>0.25</sub>(ZnSe)<sub>0.04</sub> heterostructures is presented in fig.3. It is seen that photosensitivity of the investigated structures is situated the range photons' energy from 1.13 to 1.73 eV. Photosensitivity of the investigated structure begins at photons' energy 1.13 eV. It is probably caused by narrow forbidden band component Ge<sub>2</sub> in the solid solution (GaAs)<sub>0.71</sub>(Ge<sub>2</sub>)<sub>0.25</sub>(ZnSe)<sub>0.04</sub> [5]. As the components Ge<sub>2</sub> and ZnSe replace atoms Ga and As in tetrahedral lattice of GaAs [8] connections Ga - As are weakened under the influence atoms Ge surrounding them. Since energy of connection of molecules Ge - Ge when they are in the tetrahedral lattice of germanium is defined by width of forbidden band Ge ( $E_{Ge} = 0.67 \text{ eV}$ ) and it is less than width of forbidden band GaAs ( $E_{GaAs} = 1.42 \text{ eV}$ ) energy ionization of connection Ge - Ge increases when it is in environment GaAs, and wide-band-gap component ZnSe influence not much width of forbidden band GaAs. The maximum spectral photosensitivity of the solid solution (GaAs)<sub>0.71</sub>(Ge<sub>2</sub>)<sub>0.25</sub>(ZnSe)<sub>0.04</sub> is observed at 1.34 eV, that it is less than forbidden band GaAs. However increase of spectral sensitivity is not sharp, that is probably caused by thickness of the layer of solid solutions (GaAs)<sub>0.71</sub>(Ge<sub>2</sub>)<sub>0.25</sub>(ZnSe)<sub>0.04</sub>, absorbing effectively low-energy quantum. Decrease of photosensitivity at photons' energy more than 1.34 eV by our opinion is caused by depth of the *p* - junction's barrier, which is determined by the thickness of the epitaxial layer ~ 10 μm. The diffusion length of minority carriers in the layer *n*-GaAs – *p*-(GaAs)<sub>0.71</sub>(Ge<sub>2</sub>)<sub>0.25</sub>(ZnSe)<sub>0.04</sub>, is ~ 4.67 μm, which is much smaller than the depth of the barrier, i.e. it corresponds with our proposal. Thus electron-hole pairs generated in the surface part of the structure by short-wavelength photons do not reach the separating barrier and do not participate in generation of the photocurrent. That is the main reason for the decrease of the photosensitivity of investigated structure in the short-wave range of radiation.



**Fig.3.** The spectral photosensitivity of the structure  $n\text{-GaAs} - p\text{-(GaAs)}_{0.71}\text{(Ge}_2\text{)}_{0.25}\text{(ZnSe)}_{0.04}$  at the room temperature.

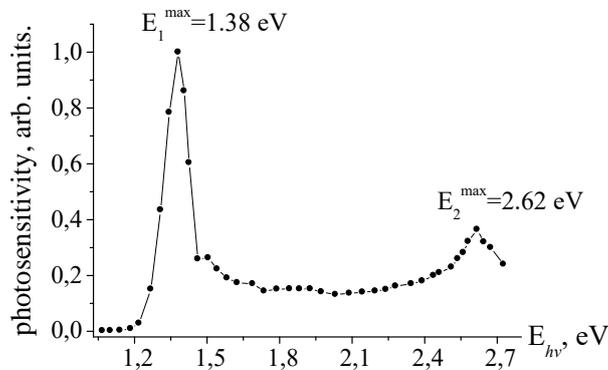
**III-e. Photo-electrical properties of  $n\text{-GaAs} - p\text{-(GaAs)}_{0.69}\text{(Ge}_2\text{)}_{0.17}\text{(ZnSe)}_{0.14}$  heterostructures**

The spectral dependence of photosensitivity  $n\text{-GaAs} - p\text{-(GaAs)}_{0.69}\text{(Ge}_2\text{)}_{0.17}\text{(ZnSe)}_{0.14}$  heterostructures at room temperature is shown in fig.4. From fig.4 it is seen that the photo-response sharply increases, beginning photons' energy 1.2 eV that testifies to active influence of narrow-band components ( $\text{Ge}_2$ ) of the solid solution on the photovoltaic effect. It is known that width of the forbidden band of germanium  $E_{g,\text{Ge}} = 0.67$  eV is less than  $E_{g,\text{GaAs}} = 1.42$  eV and  $E_{g,\text{ZnSe}} = 2.70$  eV. However absence of complete absorption Ge, probably, is caused by small thickness of the sublayer, enriched by Ge.

The maximum of photosensitivity is observed at photons' energy 1.38 eV (fig.9) that, probably, is caused by width forbidden band of solid solution  $(\text{GaAs})_{0.69}\text{(Ge}_2\text{)}_{0.17}\text{(ZnSe)}_{0.14}$ . Decrease of photosensitivity at photons' energy more than 1.38 eV, by our opinion, is caused by depth of occurrence of the dividing barrier of p - n - junction which is defined by thickness of the epitaxial layer, which in this case is  $\sim 20$   $\mu\text{m}$ .

The diffusion length of minority carriers in the layer  $p\text{-(GaAs)}_{0.69}\text{(Ge}_2\text{)}_{0.17}\text{(ZnSe)}_{0.14}$  defined by us, was  $\sim 4.8$   $\mu\text{m}$  that is less than depth of dividing barrier. That strengthens recombination of photo-induced nonequilibrium carriers of the charge. Besides, atoms of Sn partially introduced in the lattice of solid solution from stannum solution - melt, which create shallow donor level promote recombination too [24-26].

On the spectrum of photosensitivity of the investigated structure in the range of photons' energy from 2.4 eV to 2.7 eV the peak is shown obviously at 2.62 eV (fig.4). It probably is caused by wide-band component ZnSe. It is known that the covalent connection of atoms in molecules ZnSe in pure semiconductor material ZnSe with  $E_{g,\text{ZnSe}} = 2.70$  eV is more hard, than connection Ga-As and Ge-Ge. But, when molecules of ZnSe replace molecules of GaAs or  $\text{Ge}_2$  in tetrahedral lattice of solid solution, connection Zn - Se weakens under influence of atoms of Ga, As and Ge surrounding it [8].



**Fig.4.** The spectral photosensitivity of the structure  $n\text{-GaAs} - p\text{-(GaAs)}_{0.69}\text{(Ge}_2\text{)}_{0.17}\text{(ZnSe)}_{0.14}$  at the room temperature.

This, apparently, causes occurrence of impurity energy band of ZnSe located on  $\Delta E_i = E_{ph} - E_{g \text{ t.p.}}$  below the ceiling of valence band of the solid solution  $(\text{GaAs})_{0.69}(\text{Ge}_2)_{0.17}(\text{ZnSe})_{0.14}$ . As ZnSe is direct gap semiconductor, and the mole contents of ZnSe molecules in the solid solution constitutes  $\sim 10^{18} \text{ cm}^{-3}$  it also testifies active participation of connection Zn-Se in photovoltaic effect at photons' energy  $E_{ph} > 2.4 \text{ eV}$  [8].

#### IV. CONCLUSION

Thus, based on the obtained results it is possible to do following conclusions:

- Optimal technological conditions of growth structurally perfect epitaxial layers of the solid solutions  $(\text{GaAs})_{0.69}(\text{Ge}_2)_{0.17}(\text{ZnSe})_{0.14}$  and  $(\text{GaAs})_{0.71}(\text{Ge}_2)_{0.25}(\text{ZnSe})_{0.04}$  on GaAs substrates (rate of cooling- 1 – 1.5 hailstones/mines, temperature 730 - 640° C and 750 - 610° C, growth rate  $\theta = 0.15$  microns/mines) are defined;
- the current-voltage characteristic of heterostructures  $n\text{-GaAs} - p\text{-}(\text{GaAs})_{0.69}(\text{Ge}_2)_{0.17}(\text{ZnSe})_{0.14}$  has dependence ( $J \sim V^\alpha$ ) at direct direction of the current and consists of several parts in which  $\alpha$  has various values. That is probably caused by formation compound recombination complexes including nanostructures; the current voltage characteristics of  $n\text{-GaAs} - p\text{-}(\text{GaAs})_{0.71}(\text{Ge}_2)_{0.25}(\text{ZnSe})_{0.04}$  structures at small voltage (to 0.8 V) are described by exponential by dependence  $I = I_0 \exp(qV/ckT)$ , and at voltage ( $V > 0.85 \text{ V}$ ) there is part of sublinear increase of current at voltage of type  $V \approx V_0 \exp(Jad)$  which is explained by theory of effect of injection depletion;
- decrease of mobility of majority carriers and increase of mobility of minority carriers at temperature increase allows to conclude that in the given solid solution the essential role in the mobility mechanism is played by dispersion of charge carriers not only by compound complexes, but also by nanostructures.
- the photosensitivity of the heterostructures  $n\text{-GaAs} - p\text{-}(\text{GaAs})_{0.69}(\text{Ge}_2)_{0.17}(\text{ZnSe})_{0.14}$  and  $n\text{-GaAs} - p\text{-}(\text{GaAs})_{0.71}(\text{Ge}_2)_{0.25}(\text{ZnSe})_{0.04}$  has peculiarity caused by components ZnSe in GaAs with different values of energy of covalent ionization of communication of corresponding molecules;
- observable decrease of photosensitivity in short-wave range of spectrum is explained by smaller value of the diffusion lengths of majority carriers in comparison with depth of location of the dividing barrier.

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