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THE MECHANISM OF CURRENT TRANSFER IN n-GaAs – p$(ZnSe)_{1-x-y}(Ge_2)_x(GaAs_{1-\delta}Bi_\delta)_y$ HETEROSTRUCTURES

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The I-V characteristics of heterostructures n-GaAs – p-$(ZnSe)_{1-x-y}(Ge_2)_x(GaAs_{1-\delta}Bi_\delta)$ exhibit a characteristic quadratic law - $J \sim V^2$ I-V curve, followed by a sharp pre-breakdown current growth, which well explains the observed straight branch of the I-V characteristics and this regularity remains unchanged at different temperatures. The analysis of the I-V characteristics of n-GaAs-p-$(ZnSe)_{1-x-y}(Ge_2)_x(GaAs_{1-\delta}Bi_\delta)$ heterostructures with an extended intermediate solid solution layer shows that the drift mechanism of charge transport predominates under forward bias conditions.
Keywords: *Heterostructure; Substrate; Liquid phase epitaxy; Film; Solid solution; Compound; I-V characteristics; Drift mechanism; Charge transport; Temperature*
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INTRODUCTION

One of the current challenges of today is solving a range of technical problems related to expanding the capabilities of nano- and microelectronic systems and complexes, specifically the ability to simultaneously operate in a wide range of semiconductor device engineering. Although there are currently a large number of studies dedicated to this issue, many questions regarding the mechanisms of how different impurities affect the electrophysical properties of semiconductors and various physical processes occurring in non-equilibrium states are still far from being understood, due to the possibility of doping semiconductors with various impurities (atomic, molecular, isovalent). There is a scarcity of studies dedicated to the investigation of molecular dopants, the behavior of dopants in solid solutions depending on the composition of the base material, and the interaction of dopants in semiconductor materials.

The authors [1] obtained heterojunctions based on the $A^{III}B^{V}$-$A^{II}B^{VI}$ compound through isovalent substitution and investigated the characteristics of the physical properties of such structures [2, 3]. The process of obtaining heterojunctions has a diffusion character. As a result of diffusion of isovalent atoms between the substrate and the diffusion heterolayer, a solid solution of variable composition is formed, which smoothes out the lattice parameter and the coefficient of thermal expansion, as well as eliminates the lattice mismatch between the contacting materials. In such structures, effective edge luminescence is achieved due to isovalent dopants. The concentration of isovalent dopants reaches ~ 10^{19} cm^{-3}, without altering the width of the semiconductor's band gap. Isovalent substitution leads to a "cleaning" effect in the material, meaning that intrinsic defects, such as vacancies, are healed by the dopant atoms, resulting in a reduction in the concentration of non-radiative recombination centers [4].

The authors [5] have investigated monoatomic, triatomic, and cluster doping in the ZnSe - GaAs system using calculations of pseudopotential plane waves. Cluster doping $(Zn\text{-}Se_4)^{3+}$ (as a donor) and $(Se\text{-}Zn_4)^{3-}$ (as an acceptor) in GaAs, as well as $(As\text{-}Ga_4)^{3+}$ (as a donor) and $(Ga\text{-}As_4)^{3-}$ (as an acceptor) in ZnSe, will be stable at extremely extreme chemical potentials and will contribute to the introduction of a large number of free carriers. Cluster doping provides a lower level of acceptor or donor than monoatomic or triatomic doping. There is a strong tendency for Ga+As to cluster in ZnSe, compared to Zn+Se in GaAs, leading to an asymmetric dependence of the band gap on the composition of the solid solution. Specifically, the addition of a small amount of Ga+As to ZnSe results in a sharp decrease in the band gap width of the base material, whereas the addition of Zn+Se to GaAs does not significantly change the band gap width. [5].

The aim of this study is to investigate certain electrophysical properties of $(ZnSe)_{1-x-y}(Ge_2)_x(GaAs_{1-\delta}Bi_\delta)_y$ solid solutions synthesized on silicon substrates using liquid-phase epitaxy.

MATERIALS AND METHODS

Epitaxial layers of n-GaAs – p-$(ZnSe)_{1-x-y}(Ge_2)_x(GaAs_{1-\delta}Bi_\delta)_y$ were grown by liquid phase epitaxy method as described in reference [6]. Two horizontally positioned substrates – upper and lower – were secured in a vertical graphite cassette. Gallium arsenide substrates, cut from monocrystalline GaAs with a (100) orientation in the form of 20 mm diameter disks and a thickness of ~ 350 μm, had n-type conductivity with a carrier concentration of 5×10^{17} cm^{-3}. The crystallization process of the thin film was carried out by forced cooling in a hydrogen atmosphere purified with palladium

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from a tin solution melt. The composition of the melt solution was chosen based on data from [7, 8] and initial studies of the GaAs-Ge-ZnSe-Sn system. Samples were grown at various parameters of liquid-phase epitaxy. Films with predetermined physical properties were grown at a temperature range of crystallization of the bismuth-containing melt solution from 750 to 650°C and a substrate cooling rate of 1°C/min. The grown films had p-type conductivity and a thickness of 10 μm.

When investigating the current-voltage characteristics (I-V curves) of semiconductor heterostructures, special attention is given to selecting ohmic contacts. This means that carrier injection does not occur at the contact, and there is a linear relationship between current and voltage for any polarity. In practice, this implies that a contact can be considered ohmic if the voltage drop across it is much lower for any polarity compared to the voltage drop across the rest of the circuit. This is achieved in practice by creating a region of strong doping in the semiconductor between the metal and the bulk of the semiconductor. To obtain ohmic contacts to the heterostructures of n-GaAs – $p(ZnSe)_{1-x-y}(Ge_2)_x(GaAs_{1-\delta}Bi_\delta)_y$, we used Au and Ag. The ohmicity of the obtained contacts was initially assessed on a profilometer, and subsequently verified by measuring the voltage drop and determining their resistance. For the hole conductivity type of semiconductor solid solutions $(ZnSe)_{1-x-y}(Ge_2)_x(GaAs_{1-\delta}Bi_\delta)_y$, contacts with the lowest specific resistance and good linearity were achieved by vacuum deposition of Au and Ag on the surface of epitaxial layers followed by annealing at a temperature of 150°C.

RESULTS AND DISCUSSION

To investigate the I-V characteristics of structures obtained by vacuum deposition, ohmic contacts were created - continuous ones on the back side and square-shaped ones, with an area of 6 mm^2 made of silver, on the side of the epitaxial layer. Volt-ampere characteristics were measured in the forward (when "+" was applied to $p\text{-}(ZnSe)_{1-x-y}(Ge_2)_x(GaAs_{1-\delta}Bi_\delta)_y$ and reverse (when "-" was applied to n-GaAs) directions at various temperatures (Fig. 1).

Figure 1 shows the typical current-voltage characteristics (I-V curves) of multi-component heterostructures n-GaAs - $p\text{-}(ZnSe)_{1-x-y}(Ge_2)_x(GaAs_{1-\delta}Bi_\delta)$. It can be observed that the structure exhibits excellent rectifying properties with a rectification coefficient determined as the ratio of forward current (J_{dir}) to reverse current (J_{rev}). At equal applied voltage values, the rectification coefficient $k = J_{dir}/J_{rev}$ ranges from 2000 to 2500 in the voltage range from 0.1 to 3 V. Additionally, in this voltage range, both in forward and reverse directions, there is no saturation of the current in the I-V characteristics at all temperatures, indicating a low density of surface states at the p-n junction interface [9]. Analysis shows that the I-V characteristics at all temperatures, plotted on a logarithmic scale, fit well to straight lines in the forward bias direction and are described by power-law dependencies of the form – $J = A \cdot V^{\alpha}$ with different values of the exponent α.

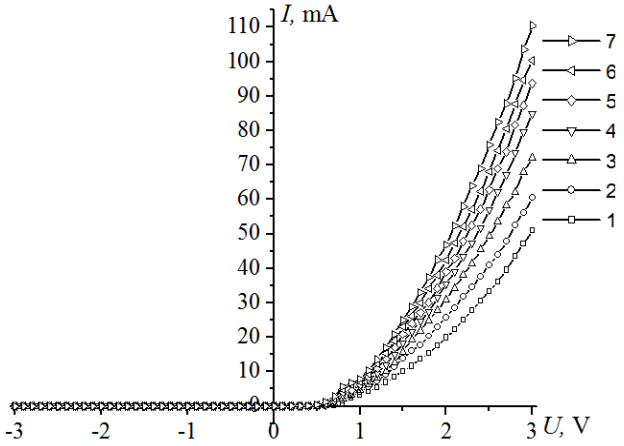

Figure 1. Typical current-voltage characteristics of n-GaAs – $p\text{-}(ZnSe)_{1-x-y}(Ge_2)_x(GaAs_{1-\delta}Bi_\delta)$ heterostructures at various temperatures: 1 – 30°C, 2 – 50°C, 3 – 70°C, 4 – 90°C, 5 – 110°C, 6 – 130°C, 7 – 150°C

On the initial segment of the I-V curve from 0.1 to 0.3 V, a region of a spike is observed: $J \sim V^{\alpha}$ ($\alpha \approx 2$) (Figure 2). The conducted analysis indicates that such a dependence follows the regularity [10].

$$V = M(J)B_0\sqrt{\frac{J}{2}}. \tag{1}$$

where $M(J)$ is calculated according to the following formula:

$$M(J) \approx 1 + 3m\left[2 + C\left(\alpha\tau_i / c_p\right)\sqrt{J}\right]^2, \tag{2}$$

$$m = 2\tau_i N_d V_p^* / 8b(b+1)n_p d\ ,$$

and

$$C = \left[bn_p / qV_p^* (b+1) \right]$$

In these relationships, V_p* is a parameter determined by the non-ideal nature of the injecting contact [11].

The current-voltage characteristic in the form of (1) is manifested when the recombination velocity in the denominator of this expression has the form [11].

$$u_r = N_r \frac{c_n c_p \left(pn - n_i^2 \right)}{c_n \left(n + n_1 \right) + c_p \left(p + p_1 \right) + \alpha \tau_i pn}, \tag{3}$$

where N_r is the concentration of recombination centers (complexes); n, p- are the concentrations of electrons and holes; n_i - is the intrinsic concentration in the semiconductor; c_n, c_p - are the capture coefficients of electrons and holes; n_1, p_1 - are the equilibrium concentrations of electrons and holes when the Fermi level coincides with the energy level of the impurity (the so-called static Shockley-Read factors); τ_i - is the time that takes into account various electron exchange processes within the recombination complex; α - is a coefficient depending on the type of defect complexes. A similar recombination mode is possible not only in the cases listed above but also in semiconductors with developed recombination-stimulated restructuring of metastable recombination complexes, such as negatively charged acceptor – positively charged dopant ion or positively charged donor - negatively charged vacancy.

At low excitation levels, i.e., $c_n \left(n + n_1 \right) + c_p \left(p + p_1 \right) \gg \alpha \tau_i pn$ when the contribution of the last term in the denominator of (3) becomes negligibly small, the recombination rate is described by the Shockley-Read statistics. In this case, the current-voltage characteristic (I-V curve) in drift carrier transport mode has a typical form corresponding to ohmic relaxation of bulk charge [12]:

$$V = \sqrt{\frac{8d^3 J}{9q\mu_p \mu_n \tau_p N_d}} = B_0 \sqrt{J}, \tag{4}$$

the definition was determined as follows.
Initially, the value of B_o is determined from the slope of the experimental straight line $J = V^{\alpha}$, which in this case was B_o = 0.001 V·A$^{(-1/2)}$ at room temperature. Then, using the expression

$$B_0 = \sqrt{\frac{8d^3}{9q\mu_p \mu_n \tau_p N_d}}, \tag{5}$$

using the experimental data for d = 5 μm and $\tau_p \approx 10^{-8}$ s, we find the value of N_d - the concentration of shallow donor impurity centers, which is equal to $1.2 \cdot 10^{15}$ cm^{-3}. The mobility of the main carriers – holes, determined by the Hall method, was μ_p = 300 cm^2/V·s, and for estimation, the value of the mobility of minority carriers was taken as $\mu_n = b \cdot \mu_p$ = 1890 cm^2/V·s, where b is the ratio of electron and hole mobilities, which according to our estimates was 6.3 [11].

The value of B_o increases from 0.001 V·A$^{(-1/2)}$ to 0.369 V·A$^{(-1/2)}$ with increasing temperature, while the mobility μp and the lifetime τp of the main carriers, and consequently, the concentration of shallow donor impurity centers N_d, decrease. This apparently suggests that in this solid solution, the predominant role in the mobility mechanism is played by carrier scattering on ions of deep impurities [13].

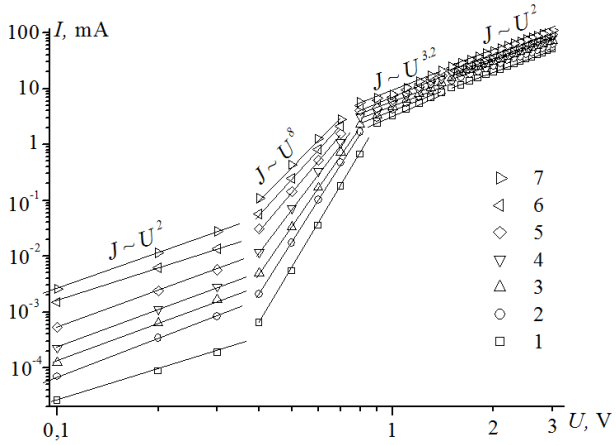

Figure 2. Volt-ampere characteristics of n-GaAs – p-(ZnSe)$_{1-x-y}$(Ge$_2$)$_x$(GaAs$_{1-\delta}$Bi$_\delta$) heterostructures in the forward direction in logarithmic scale at different temperatures: 1 – 30°C, 2 – 50°C, 3 – 70°C, 4 – 90°C, 5 – 110°C, 6 – 130°C, 7 – 150°C.

With further increase in voltage, as shown in Figure 2, starting from V = 0.4 V, there is a sharp increase in the current $J = A \cdot V^{\alpha}$ with a power exponent $\alpha \approx 8$. This region is called pre-breakdown region. In this case, the third term in

the denominator of expression (3) for the recombination rate becomes significant, and the recombination rate no longer follows the Shockley-Read statistics, but acquires a completely different form [14]:

$$u_r = \frac{N_r}{\tau_i}\left(1 - \frac{2}{\tau_i c_p p}\right), \tag{6}$$

The current-voltage characteristic (I-V curve) –

$$J = \frac{q^2 (b+1)^2 N_r d^3}{\varepsilon \tau_i^2 c_p (V_0 - V)}, \tag{7}$$

where ε is the dielectric constant and

$$V_0 = \sqrt{\frac{q(b+1)N_r d^4}{2\varepsilon \tau_i \mu_p}} = const .$$

From (7), it can be observed that the denominator of this expression decreases with increasing voltage, indicating a rapid growth in current. The sharp increase in current within the voltage range V = (0.4-0.8) V is described by this dependency [13].

According to the theory [15], the range from 0.9 to 1.5 V of the current-voltage characteristic is described by the expression $J = A \cdot V^{3,2}$ (Fig. 2) and occurs when the recombination of non-equilibrium charge carriers mainly occurs with a delay, i.e. with the participation of complexes where electronic exchange takes place inside. In this case, the inequality is realized in the denominator of expression (3)

$$c_n(n + n_1) + c_p(p + p_1) < \alpha \tau_i pn , \tag{8}$$

the analytical expression for I-V (curve) is as follows

$$V = \frac{(b+1)d^2 N_r}{N_d \mu_p \tau_i} + \frac{d}{q\mu_p (b+1)C}\sqrt{J} - \frac{2(b+1)N_r d^2 c_p}{N_d \mu_p \alpha \tau_i C}\frac{1}{\sqrt{J}} = A + B\sqrt{J} - \frac{D}{\sqrt{J}} . \tag{9}$$

Where *A*, *B*, and *D* are parameters dependent on the concentration of ionized atoms of deep impurities, the ratio of electron and hole mobilities, and the thickness of the interlayer transition, respectively, which can be determined from experimental data. To determine parameter A, two experimental points V_1, J_1 and V_2, J_2 are selected on the straight line of the $J \sim V^{3,2}$ dependence. The calculation results indicate that parameter *A* remains almost unchanged with increasing temperature (Table 1).

This indicates that in the first term of the expression (9), the ratios N_r/τ_i remain unchanged. Next, three experimental points (V_1, J_1), (V_2, J_2), (V_3, J_3) were selected to determine the parameters *B* and *D* from the section of rapid current growth. The calculation results are presented in Table 1, indicating that as the temperature increases, the parameter *D* increases while the value of *B* decreases. This could be a consequence of the increase in parameter "*C*" in equation (3), which is associated with the concentration of holes at the interface between the p-$(ZnSe)_{1-x-y}(Ge_2)_x(GaAs_{1-\delta}Bi_\delta)$ film and the n-(GaAs) substrate, as well as the hole capture coefficients c_p.

Table 1. The values of parameters A, B, and D in expression (9) calculated from experimental I-V characteristics at various temperatures

t, °C	30	50	70	90	110	130	150
A. V	0.69	0.7	0.705	0.711	0.717	0.723	0.73
D. $V \cdot mA^{-1/2}$	1.38	2.12	2.44	2.94	4.16	5.58	7
B. $V \cdot A^{1/2}$.	0.0174	0.0156	0.0146	0.0134	0.0131	0.013	0.0128

Analysis has revealed that expression (9) enables describing the slope value of the volt-ampere characteristics of the $J \sim V^{\alpha}$ type, including the segment of sharp current increase.

After the section of sharp current growth $J \sim V^{\alpha}$, where $\alpha = 2$ (Fig. 2), when the last term in the denominator of expression (3) starts to play a decisive role and the recombination rate U_r reaches full saturation $Ur = N_{r/\tau i}$, a second quadratic section appears and the I-V characteristic is described by the expression [13]:

$$V = \frac{(b+1)d^2 N_r}{2N_d \mu_p \tau_i} + \frac{d}{q\mu_p (b+1)C}\sqrt{J} . \tag{10}$$

The estimation of the value of N_r/τ_i for this segment is carried out similarly to the segment of sharp current growth. For two given experimental points, an equation of the straight line is constructed, from which the value of the constant corresponding to the value of the first term of the expression (10) is determined.

$$\frac{A}{2}=\frac{(b+1)d^2N_r}{2N_d\mu_p\tau_i}$$

Substituting the known values of d, b, and N_d into (11), we obtain the quantity $N_{r/\tau i} = 5.2\cdot10^{18}$ cm^{-3} s^{-1}

CONCLUSIONS

Thus, single-crystalline solid solutions of n-GaAs – p-$(ZnSe)_{1-x-y}(Ge_2)_x(GaAs_{1-\delta}Bi_\delta)_y$ p-type conductivity were grown on single-crystalline n-GaAs substrates with (100) orientation by liquid phase epitaxy method. The volt-ampere characteristics of heterostructures n-GaAs – p-$(ZnSe)_{1-x-y}(Ge_2)_x(GaAs_{1-\delta}Bi_\delta)$ exhibit a characteristic quadratic law - $J\sim V^2$ I-V curve, followed by a sharp pre-breakdown current growth, which well explains the observed straight branch of the I-V curve and this regularity remains unchanged at different temperatures. After the pre-test section, two characteristic sections are observed, which are described by expressions (10) and (11). The analysis of the current-voltage characteristics (I-V curve) of n-GaAs – p-$(ZnSe)_{1-x-y}(Ge_2)_x(GaAs_{1-\delta}Bi_\delta)$ heterostructures with an extended intermediate solid solution layer shows that the drift mechanism of charge transport predominates under forward bias conditions.

Based on this data, it is possible to assume the successful implementation of the discussed heterostructures in voltage multiplication schemes and in converters (rectifiers) of direct voltage, where high requirements for frequency and time parameters of signals are not imposed, as well as in electronic and thermoelectronic devices.

Conflict of Interests

The authors declare that they have no conflict of interests

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МЕХАНІЗМ ПЕРЕДАЧІ СТРУМУ В ГЕТЕРОСТРУКТУРАХ n-GaAs–p$(ZnSe)_{1-x-y}(Ge_2)_x(GaAs_{1-\delta}Bi_\delta)$

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Вольт-амперні характеристики (ВАХ) гетероструктур n-GaAs–p$(ZnSe)_{1-x-y}(Ge_2)_x(GaAs_{1-\delta}Bi_\delta)$ демонструють характерний квадратичний закон – ВАХ $J \sim V^2$ з різким зростанням передпробійного струму, що добре пояснює спостережувану пряму гілку ВАХ, і ця закономірність залишається незмінною при різних температурах. Аналіз ВАХ гетероструктур n-GaAs- p-$(ZnSe)_{1-x-y}(Ge_2)_x(GaAs_{1-\delta}Bi_\delta)$ з протяжним проміжним шаром твердого розчину показує, що при прямому зміщенні переважає дрейфовий механізм переносу заряду.

Ключові слова: *гетероструктура; підкладка; рідкофазна епітаксія; плівка; твердий розчин; з'єднання; ВАХ; дрейфовий механізм; зарядний транспорт; температура*