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EFFECT OF TEMPERATURE ON THE CURRENT-VOLTAGE CHARACTERISTICS OF n-GaAs-p-$(ZnSe)_{1-x-y}(Ge_2)_x(GaAs_{1-\delta}Bi_\delta)_y$ HETEROSTRUCTURES

Akramjon Y. Boboev[a], **Iqboljon M. Soliev**[b], **Nuritdin Y. Yunusaliyev**[a], **Murodiljon M. Xotamov**[a]
[a]*Andijan State University named after Z.M. Babur, Andijan, Uzbekistan*
[b]*Andijan State pedagogical institute, Andijan, Uzbekistan*
**Corresponding Author E-mail: aboboevscp@gmail.com*
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This paper investigates the electrophysical properties of *n*-GaAs-*p*-$(ZnSe)_{1-x-y}(Ge_2)_x(GaAs_{1-\delta}Bi_\delta)_y$ heterostructures at different temperatures. The epitaxial *n*-GaAs-*p*-$(ZnSe)_{1-x-y}(Ge_2)_x(GaAs_{1-\delta}Bi_\delta)_y$ grown on GaAs substrates showed p-type conductivity, their resistivity (5 Ω·cm), charge carrier concentration ($\rho = 1.5\cdot10^{16}$ cm^{-3}) and carrier mobility ($\mu = 300$ cm²/V·s) were determined by Hall method. Experimental values of the mobility of the main charge carriers allowed us to determine the mobility of the non-main charge carriers, which amounted to ($\mu = 1890$ cm²/V·s) by means of theoretical calculations. In the current-voltage (I–V) characteristics of the *n*-GaAs-*p*-$(ZnSe)_{1-x-y}(Ge_2)_x(GaAs_{1-\delta}Bi_\delta)_y$ heterostructure, a quadratic dependence of $J \sim V^2$ was revealed, and this dependence does not change with increasing temperature in the transition to regions with a sharp increase in current. Analysis of these regions of the volt-ampere characteristic showed that the mechanism of current flow is determined by the direct drift of charge carriers. It was proposed to use *n*-GaAs-*p*-$(ZnSe)_{1-x-y}(Ge_2)_x(GaAs_{1-\delta}Bi_\delta)_y$ heterostructures in voltage amplifiers, constant voltage converters, as well as in electronic and thermoelectronic devices.
Keywords: *Heterostructure; Epitaxy; Current-voltage characteristic; Temperature; Donor doping; Charge carriers; Mobility*
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INTRODUCTION

A3B5 wide bandgap semiconductor compounds are considered as potential materials for the production of optoelectronic devices operating in the mid- and far-infrared (IR) spectral regions. Currently, extensive research is being conducted to develop and study various electronic device structures based on InSb, InAs, GaSb, GaAs and their solid-state alloys [1-3]. Among these materials, GaAs compounds and their complex solid alloys $(GaAs)_{1-x-y}(Ge_2)_x(ZnSe)_y$ are of particular interest, in particular due to the high mobility of electrons and holes [4-6]. These characteristics make such materials suitable for the fabrication of high-speed optoelectronic devices. Additionally, the $(GaAs)_{1-x-y}(Ge_2)_x(ZnSe)_y$ solid solutions allow for the spectral range of device structures to be extended from 1.1 eV to 2.65 eV due to the wide tunability of *x* and *y* composition parameters [7]. However, the widespread practical application of devices fabricated from GaAs-based compounds and their solid solutions is limited by the insufficient understanding of the electro-physical properties of these materials and the structures based on them. Therefore, the present study aims to investigate the electro-physical properties of *n*-GaAs-*p*-$(ZnSe)_{1-x-y}(Ge_2)_x(GaAs_{1-\delta}Bi_\delta)_y$ heterostructures at various temperatures.

MATERIALS AND METHODS

$(ZnSe)_{1-x-y}(Ge_2)_x(GaAs_{1-\delta}Bi_\delta)_y$ solid solutions were grown on (100)-oriented, 400 µm thick GaAs substrates with electron-type conductivity using the liquid-phase epitaxy (LPE) method under forced cooling conditions from a Bi-containing multicomponent melt solution. The composition of the melt and the crystallization onset temperature were selected based on preliminary experimental results and the phase diagram of the GaAs–Ge–ZnSe–Bi multicomponent system. The resulting epitaxial films exhibited *p*-type conductivity, a specific resistivity of 5 Ω·cm, a charge carrier concentration of $1.5\cdot10^{16}$ cm^{-3}, carrier mobility $\mu = 300$ cm²/V·s and a thickness of 8 µm. To investigate the current-voltage characteristics (I-V curve) of the structures fabricated on the basis of $(ZnSe)_{1-x-y}(Ge_2)_x(GaAs_{1-\delta}Bi_\delta)_y$ solid solutions, ohmic contacts were formed by vacuum sputtering. Silver contacts were deposited on the back side of the sample (entire surface) and on the solid-solution side as square-shaped contacts with a surface area of 6 mm². Additionally, the temperature dependence of the current-voltage (I–V) characteristics of the *n*-GaAs-*p*-$(GaAs_{1-\delta}Bi_\delta)_{1-x-y}(Ge_2)_x(ZnSe)_y$ heterostructures was studied in both forward and reverse bias modes. The experimental data were processed using the OriginPro 2022 software package.

RESULTS AND DISCUSSION

Figure 1 presents current-voltage characteristics (I-V) of multicomponent *n*-GaAs-*p*-$(ZnSe)_{1-x-y}(Ge_2)_x(GaAs_{1-\delta}Bi_\delta)_y$ heterostructures in logarithmic scale at different (1 – 30 °C, 2 – 50 °C, 3 – 70 °C, 4 – 90 °C, 5 – 110 °C, 6 – 130 °C, 7 – 150 °C) temperatures.

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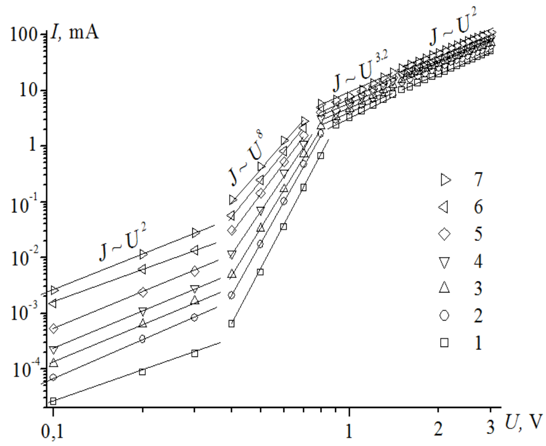

Figure 1. Current-voltage characteristics of *n*-GaAs-*p*-$(ZnSe)_{1-x-y}(Ge_2)_x(GaAs_{1-\delta}Bi_\delta)_y$ heterostructures in logarithmic scale at different temperatures: 1 – 30 °C, 2 – 50 °C, 3 – 70 °C, 4 – 90 °C, 5 – 110 °C, 6 – 130 °C, 7 – 150 °C

Analysis of the obtained results in logarithmic scale showed that in the forward bias region, at all measured temperatures, the current demonstrates a linear dependence on the applied voltage according to the expression: $J = A\cdot V^\alpha$, where α is a power-law exponent that varies depending on the voltage range [8].

In the initial region of the current-voltage characteristic, from 0.1 V to 0.3 V, a “jump” or transition region is observed, where the current follows a quadratic dependence: $J \sim V^\alpha$ ($\alpha \approx 2$). This behavior suggests that the charge transport in this voltage range obeys the following relation [9].

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

Here, the quantity *M(J)* is expressed by the following formula:

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

here, $m = 2\tau_i N_d V_p^*/8b(b+1)n_p d$; and $C = [bn_p/qV_p^*(b+1)]$. In these ratios, V_p^* - represents the imperfection value of the injection contact [10].

Thus, this particular region of the current-voltage characteristic (I-V) manifests when the denominator in the recombination rate expression reaches extremely small values. This behavior is typically observed in cases where the recombination process dominates the carrier transport mechanism, and the contact imperfection contributes significantly to the overall voltage drop across the structure [11].

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

Here, the terms are defined as follows: N_r – concentration of recombination centers (complexes), n, p – concentrations of electrons and holes, respectively, n_i – intrinsic carrier concentration in the semiconductor, c_n, c_p – capture coefficients for electrons and holes, n_1, p_1 – equilibrium concentrations of electrons and holes corresponding to the impurity energy level aligned with the Fermi level (known as Shockley–Read static factors), τ_i – time constant associated with electron exchange processes within the recombination complex, α – coefficient dependent on the type of defect complex.

This type of recombination mechanism may arise not only under the above-mentioned conditions but also in the presence of metastable recombination complexes, such as negatively charged acceptor–positively charged impurity ion pairs, or positively charged donors paired with negatively charged vacancies, which can form in various configurations within semiconductors.

At low excitation levels, i.e., when the final term in the denominator of expression (3) becomes negligible, the recombination rate can be described by the Shockley–Read statistics. In such a case, the current transport mechanism across the heterojunction based on the current-voltage characteristics (I-V) assumes a conventional form corresponding to the ohmic relaxation of the volumetric space charge under drift conditions. This behavior is described as follows [12]:

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

Firstly, the value of B_0 is determined from the slope of the experimentally obtained straight line corresponding to the relation $J=V^\alpha$, using the following expression:

$$B_0 = \sqrt{\frac{8d^3}{9q\mu_p\mu_n\tau_p N_d}}. \quad (5)$$

In our case, the value of B_0 at room temperature is found to be: B_0=0.001 V·A$^{-1/2}$ Considering the film thickness d = 5 μm and using experimental data, it is also possible to estimate the concentration of shallow-level donor impurity centers. For our structure at room temperature, this concentration is: N_d=1.2·10^{15} cm^{-3}. According to the Hall effect measurements, the mobility of the majority charge carriers (holes) is: μ_r=300 cm^2/V·s. Based on theoretical calculations, the mobility of minority carriers (electrons) can be determined using the relationship: μ_n=b·μ_r=1890 cm^2/V·s, where b is the ratio of minority to majority carrier mobilities, and in our case, at room temperature, b = 6.3 [13].

As the temperature increases, the B_0 value rises from 0.001 V·A$^{-1/2}$ to 0.369 V·A$^{-1/2}$, while the mobilities of both majority (μ_n) and minority charge carriers and their lifetimes (τ_r), as well as the concentration of shallow donor levels (N_d), decrease. This behavior indicates that in the investigated solid solutions, the diffusion of charge carriers into deeper impurity regions plays a significant role in the current transport mechanism of the heterostructures [14]. Moreover, starting from an applied voltage of V = 0.4, a sharp increase in current is observed in the current-voltage characteristics (I-V), which follows a power-law relationship of the form: J = V$^\alpha$ = 8. This region is known as the pre-breakdown region (see Figure 1). In this regime, the last term in the denominator of expression (3) begins to play a significant role in the recombination rate. Consequently, the recombination rate deviates from the Shockley–Read statistics and takes on a fundamentally different form [15].

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

The dependence of the current on the applied voltage in this regime takes the following form:

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

Here: ε – the dielectric permittivity (dielectric constant) of the grown epitaxial films. This parameter characterizes the film's ability to polarize in response to an electric field and plays a crucial role in determining the electric field distribution, capacitance, and overall electrostatic behavior of the heterostructure. It directly influences charge carrier dynamics, recombination rates, and space-charge region properties in semiconductor devices. $V_0 = \sqrt{\frac{q(b+1)N_r d^4}{2\varepsilon\tau_i\mu_p}} = const.$

From equation (7), it follows that the current increases as the denominator decreases with increasing applied voltage-that is, the current rises rapidly. This behavior indicates the onset of a highly nonlinear transport mechanism. In particular, within the voltage range V = 0.4-0.8 V, a sharp increase in current is observed, marking the transition from ohmic or quadratic behavior to a pre-breakdown or injection-enhanced regime.

This phenomenon has been thoroughly discussed in the study by [16]. In that work, the authors analyze the mechanisms responsible for such nonlinear current growth, including enhanced injection, formation of space-charge regions, and recombination through complex defect states. In the studied heterostructures, this sharp rise in current in the V = (0.4–0.8) V range is indicative of the increasing role of injected charge carriers and their recombination via complex deep-level centers. This behavior also signals the transition into a regime where classical drift-diffusion models are no longer sufficient, and recombination-limited or space-charge-limited current mechanisms begin to dominate. When the applied voltage to the studied samples is increased from 0.9 V to 1.5 V, the current-voltage relationship assumes the form: $J = A\cdot V^{3,2}$ (as shown in Figure 1). According to the theoretical analysis provided by [17], this region of the current-voltage characteristic may arise due to electron exchange through complex recombination centers during the recombination of nonequilibrium charge carriers. In this case, the final term in the denominator of equation (3) satisfies the following condition:

$$c_n(n + n_1) + c_p(p + p_1) < \alpha\tau_i pn. \quad (8)$$

The I-V curve also takes the following analytical expression:

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

where A, V, and D are quantities that depend on the concentration of ionized atoms in deep pores, the ratio of electron and hole mobilities, and the thickness of the interlayer junction base, and can be determined based on the results of experimental studies. To determine the quantity A, two experimental points V_1, J_1 and V_2, J_2 are selected from the dependence of current on voltage in the form J ~ V$^{3.2}$. The results obtained by calculation are presented in Table 1. It can also be seen from the table that the value of A does not change much with increasing temperature, which in turn indicates that the N_r/τ_i ratio does not change. In addition, it is possible to determine the values of B and D by selecting three experimental points V_1, J_1), (V_2, J_2), (V_3, J_3) in the region of a sharp increase in current flow. According to the data presented in Table 1 and the calculation results, it was found that the value of D increases with increasing temperature and the value of B decreases. This, in turn, indicates that the n-GaAs substrate and p-$(ZnSe)_{1-x-y}(Ge_2)_x(GaAs_{1-\delta}Bi_\delta)_y$ epitaxial film increase the value of "c" in the relationship (3) at the boundary of the separation and that the concentration of hole-holding centers is related to c_p. The results obtained and the results obtained using calculations show that expression (9) can be used to characterize the slope of the volt-ampere characteristic in the form $J \sim V^\alpha$.

Table 1. The values of the quantities A, B and D given in relation (9) are calculated from the experimental results of I-V curve at different temperatures

t, ºC	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·mA$^{-1/2}$	1.38	2.12	2.44	2.94	4.16	5.58	7
B. V·A$^{1/2}$.	0.0174	0.0156	0.0146	0.0134	0.0131	0.013	0.0128

After a sharp increase in the applied voltage of the current to the samples, a repeating quadratic field with $J \sim V^\alpha$, where $\alpha = 2$, was observed (Fig. 2). In this case, the last part in the denominator of relation (3) begins to play a decisive role and the recombination rate u_r $u_r = N_r/\tau_i$ is completely saturated [18]:

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

The determination of the value of Nr/τi for this region is carried out in the same way as for the region of sharp increase in the dependence of the current strength on the applied voltage. First, a straight line equation is constructed for two selected experimental points, from which the values of various quantities corresponding to the value of the first part of expression (10) are determined:

$$\frac{A}{2} = \frac{(b+1)d^2 N_r}{2N_d \mu_p \tau_i}, \tag{11}$$

Using several mathematical substitutions, based on the quantities d, b, and N_d in the relation (11), $N_r/\tau_i = 5.2\cdot 10^{18}$ cm$^{-3}\cdot$s^{-1} was obtained.

CONCLUSION

Thus, in the n-GaAs-p-$(ZnSe)_{1-x-y}(Ge_2)_x(GaAs_{1-\delta}Bi_\delta)_y$ heterostructure, the forward-biased current-voltage characteristics exhibit a transition from a quadratic relationship ($J \sim V^2$) to regions of steep current increase. It was found and theoretically supported that this behavior does not change significantly with increasing temperature.

Beyond the pre-breakdown region, the dependence of current on voltage reveals two distinct characteristic regions. The analysis of these regions in the I-V characteristics of n-GaAs-p-$(ZnSe)_{1-x-y}(Ge_2)_x(GaAs_{1-\delta}Bi_\delta)_y$ heterostructures confirms the dominance of the direct drift-based charge transport mechanism. Based on these findings, the investigated heterostructures are promising for use in voltage-multiplying devices, constant-voltage converters where high-frequency or time-domain response is not critical, and in various electronic and thermoelectronic applications.

Conflict of Interests

The authors declare that they have no conflict of interests

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ORCID

A.Y. Boboev, https://orcid.org/0000-0002-3963-708X; **N.Y. Yunusaliyev**, https://orcid.org/0000-0003-3766-5420
I.M. Soliev, https://orcid.org/0009-0003-6623-2218

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ВПЛИВ ТЕМПЕРАТУРИ НА ВОЛЬТ-АМПЕРНІ ХАРАКТЕРИСТИКИ ГЕТЕРОСТРУКТУР n-GaAs-p-$(ZnSe)_{1-x-y}(Ge_2)_x(GaAs_{1-\delta}Bi_\delta)_y$

Акрамжон Ю. Бобоєв[a], Ікболжон М. Солієв[b], Нурітдін Ю. Юнусалієв[a], Муродилжон М. Хотамов[a]
[a]*Андижанський державний університет імені З.М. Бабур, Андижан, Узбекистан*
[b]*Андижанський державний педагогічний інститут, Андижан, Узбекистан*

У цій статті досліджуються електрофізичні властивості гетероструктур n-GaAs-p-$(ZnSe)_{1-x-y}(Ge_2)_x(GaAs_{1-\delta}Bi_\delta)_y$ за різних температур. Епітаксійні n-GaAs-p-$(ZnSe)_{1-x-y}(Ge_2)_x(GaAs_{1-\delta}Bi_\delta)_y$, вирощені на підкладках GaAs, показали p-тип провідності, їх питомий опір (5 Ом·см), концентрація носіїв заряду (ρ = 1,5·10^{16} см$^{-3}$) та рухливість носіїв (μ = 300 см²/В·с) були визначені методом Холла. Експериментальні значення рухливості основних носіїв заряду дозволили нам визначити рухливість неосновних носіїв заряду, яка становила (μ = 1890 см²/В·с) за допомогою теоретичних розрахунків. У вольт-амперних (ВАХ) характеристиках гетероструктури n-GaAs-p-$(ZnSe)_{1-x-y}(Ge_2)_x(GaAs_{1-\delta}Bi_\delta)_y$ виявлено квадратичну залежність $J \sim V^2$, і ця залежність не змінюється зі збільшенням температури при переході до областей з різким збільшенням струму. Аналіз цих областей вольт-амперної характеристики показав, що механізм протікання струму визначається прямим дрейфом носіїв заряду. Було запропоновано використовувати гетероструктури n-GaAs-p-$(ZnSe)_{1-x-y}(Ge_2)_x(GaAs_{1-\delta}Bi_\delta)_y$ в підсилювачах напруги, перетворювачах постійної напруги, а також в електронних та термоелектронних пристроях.

Ключові слова: *гетероструктура; епітаксія; вольт-амперна характеристика; температура; донорне легування; носії заряду; рухливість*