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Influence of Temperature on Current-Voltage characteristics of *n*-GaAs – *p*-$(GaAs)_{1-x-y}(ZnSe)_x(Ge_2)_y$ heterostructures

Akramjon Boboev [1,*], Makhmud Kalano [2] and Sirojiddin Zainabidinov [2]

[1]Institute of Nuclear Physics, Academy of Sciences of the Republic of Uzbekistan, Tashkent, 100214, Uzbekistan

[2]Andijan State University named after Z.M. Babur, Andijan, 170100, Uzbekistan

Abstract: It is established that the I – V characteristic of such structures is described by the exponential dependence $I = I_0 \cdot exp(qV/ckT)$ at low voltages (no higher than 0.4 V) and by the power dependence $J \sim V^{\alpha}$, where the exponent α varies with increasing voltage at high voltages ($V > 0.5$ V). The results are treated within the framework of the theory of the drift mechanism of current transfer taking into account the possibility of the exchange of free carriers within the recombination complex.

Key words: *I* – *V* characteristic, voltage, current transfer, exponential, drift, recombination, electrons and holes, diffusion length, ionized atoms, deep impurities, acceptor, ion, donor, vacancy.

Introduction

Among the wide band semiconductors of the type A^3B^5 the compound GaAs and its solid solutions with compound composition have special interest as mobilities of the electrons and holes in them are very considerable [1-3], and on their basis can be developed fast acting electro-optical devices. Besides solid solutions of replacement $(GaAs)_{1-x-y}(ZnSe)_x(Ge_2)_y$ 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 [4]. However wide use of the instrumental structures made on the basis of 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 influence of temperature on current-voltage (*I* – *V*) characteristics of *n*-GaAs – *p*-$(GaAs)_{1-x-y}(ZnSe)_x(Ge_2)_y$ heterostructures.

Samples and experimental technique

The epitaxial films of $(GaAs)_{1-x-y}(ZnSe)_x(Ge_2)_y$ have been obtained by the method of liquid-phase epitaxy. As substrates, we used GaAs washers 20 mm in diameter and ~ 350 μm thick, which were cut from single-crystal *n*-GaAs with the (100) orientation and doped with tin with a concentration of $(3\div5)\cdot10^{17}cm^{-3}$ with the resistivity $\rho = 250\ \Omega\cdot cm$. Crystallization of the solid solution $(GaAs)_{1-x-y}(ZnSe)_x(Ge_2)_y$ layers carried out in the temperature range 730 – 640 °C and with rate of the growth ϑ = 0,15 μm/min. The grown epitaxial films have had thicknesses - 10 μm and the *n*-type conductivity with resistivity 0,1 Ω·cm and carrier concentration $5{,}1\cdot10^{17}$ cm^{-3}.

To study the *I* – *V* characteristics of the structures, we used the method of vacuum deposition for the fabrication of ohmic contacts to the structures continuous contacts on the rear side and silver contacts in the form of a quadrilateral 9 mm^2 in area on the epitaxial-layer side. The "dark" *I* – *V* characteristics were measured at temperatures of 300-380 K.

Results and their discussion

The initial portion of the *I* – *V* characteristics from zero to 0.25 V is ohmic, i.e. the dependence $I \sim V^1$ takes place. With increasing applied voltage in the range from 0.25 to 0.4 V, an exponential dependence (Fig.1) is observed.

**Corresponding author: Akramjon Boboev*

E-mail address: aboboevsp@umail.uz

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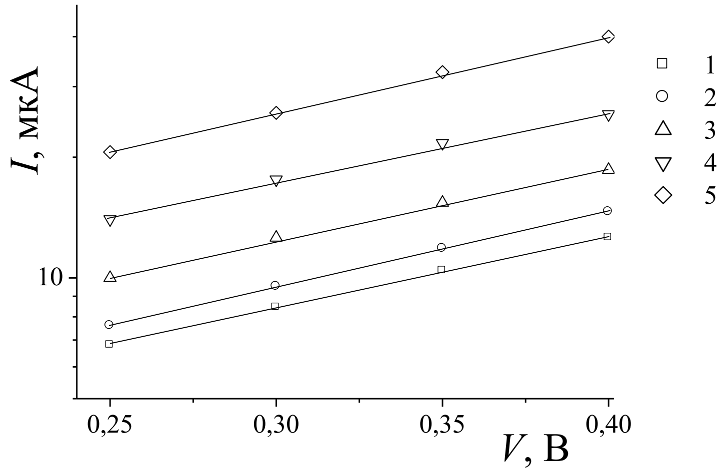

Figure 1. The "dark" $I-V$ characteristic of the n-GaAs – p-$(GaAs)_{1-x-y}(ZnSe)_x(Ge_2)_y$ structures on the semi-logarithmic scale at the temperatures T = (1) 300, (2) 320, (3) 340, (4) 360 and (5) 380 K

The $I-V$ characteristic is described irrespective of the temperature by the expression:

$$I \approx I_0 \cdot e^{\frac{qV}{ckT}} \quad (1)$$

The factor "c" in the exponent of the $I-V$ characteristic is determined from the experimental data as

$$c = \frac{q}{kT} \cdot \frac{V_2 - V_1}{\ln \frac{I_2}{I_1}} \quad (2)$$

The exponential dependence of the current on the voltage for the first time was predicted by Stafeev [5] and, then, was refined in [6] for $p-i-n$ structures with c in the exponent, which has the following form:

$$c = \frac{2b + ch(W/L_n) + 1}{b+1} \quad (3)$$

Where $b = \mu_n/\mu_p$ is the ratio of the mobilities of electrons and holes for the $(GaAs)_{1-x-y}(ZnSe)_x(Ge_2)_y$ alloy and is equal to $b \approx 3.1$. Knowing b, we can find W/L_n= 4.16; then, it is possible to calculate the diffusion length of minority charge carriers L_n = 4.8 μm. This enables us to determine the product $\mu_n\tau_n = qL^2_n/kT$, which at room temperature is equal to ~ $8.9\cdot10^{-10}$ cm^2/V. The mobility of majority charge carriers μ_p determined by the Hall method amounted to ~ 360 $cm^2/(V\cdot s)$. On the basis of these data, we determined the values of I_0, c, and b at various temperatures, which are listed in tabl.1. As can be seen from tabl.1, the values of I_0 (A) gradually increase and barely depend on c and b. At 380 K, an appreciable increase in their value is observed. This is probably associated with the varying concentration of centers affecting the mobility of charge carriers at 300–360 K. At a temperature of 380 K, the formation of various charged centers which scatter charge carriers and change their mobility is possible.

Table 1. Values of the preexponential multiplier I_0, the parameter c in the exponent of expression (1), and the ratio of the mobilities of electrons and holes for n-GaAs – p-$(GaAs)_{1-x-y}(ZnSe)_x(Ge_2)_y$ heterostructures at various temperatures

***T*, K**	**300**	**320**	**340**	**360**	**380**
***I*₀, (A)**	$2,6\cdot10^{-6}$	$3,63\cdot10^{-6}$	$4,43\cdot10^{-6}$	$6,73\cdot10^{-6}$	$5,54\cdot10^{-6}$
c	9,56	9,65	9,55	9,62	10,55
b	3,1	3,05	3,14	3,102	5,38

The results of the calculations are listed in tabl.1. As can be seen from fig.2, the $I-V$ characteristics of these structures at a voltage of $V > 0.5$ V are described by the power dependence $J \sim V^{\alpha}$, where α varies from two to three and increases with voltage. The first portion $J \sim V^2$ is observed in the voltage range from 0.5 to 1.7 V and can be accounted for within the framework of the concept of the drift mode of ohmic relaxation of the space charge [7]. With a further increase in voltage, we observed a sharp increase in the current in the form of $J \sim V^{2.7}$.

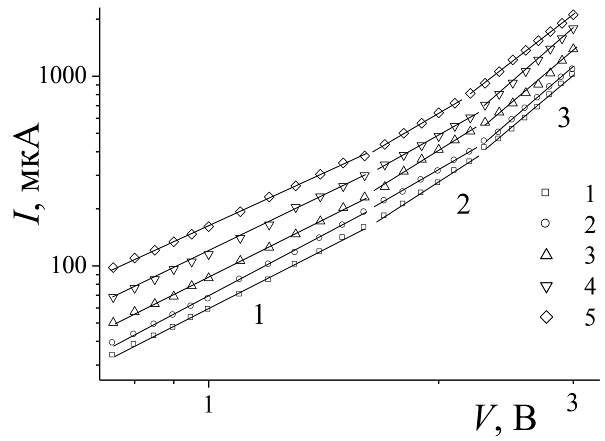

Figure 2. Typical I – V characteristic of the n-GaAs – p-$(GaAs)_{1-x-y}(ZnSe)_x(Ge_2)_y$ structures on the logarithmic scale at different temperatures T = (1) 300, (2) 320,(3) 340, (4) 360, and (5) 380 K.

Apparently, the processes of intracomplex electron exchange resulting in a "delay" in the onset of recombination processes to play the role here. In other words, the recombination rate of free carriers is no longer subjected to Shockley-Read statistics, and further takes a complex form [8, 9]:

$$u_r = N_r \frac{c_n c_p (pn - n_i^{\,2})}{c_n(n+n_1) + c_p(p+p_1) + \alpha \tau_i pn} \qquad (4)$$

Where N_r is the concentration of recombination centers; n and p are the electron and hole concentrations; n_i is the intrinsic concentration of charge carriers in the semiconductor; c_n and c_p are the capture cross sections for electrons and holes, respectively; $n_1$and p_1 are the equilibrium electron and hole concentration in the case where the Fermi level coincides with the impurity level; $\alpha\tau_i pn$ is the term describing intracomplex exchange; and τ_i is the intracomplex-exchange time. This term in the denominator of expression (4) increases with excitation level. At a low excitation level, this term is negligibly small, and the recombination rate is described by Shockley-Read statistics. In this case, the I – V characteristic in the drift mode of the current transfer has the usual quadratic form; i.e. α_1= 2 corresponding to ohmic relaxation of the space charge [7]:

$$V = \sqrt{\frac{8d^2 J}{9q\mu_n \mu_p \tau_p N_D}} = B_0 \sqrt{J} \qquad (5)$$

Where μ_p = 360 $cm^2/(V\cdot s)$ and τ_p= $2.5\cdot 10^{-7}$ s are the mobility and the lifetime of holes; μ_n = 1113 $cm^2/(V\cdot s)$ is the mobility of electrons; J is the current density; d = 10 μm is the base thickness; and N_D= $1.4\cdot 10^{15}$ cm^{-3} is the concentration of shallow donor impurity centers. From the slope of the dependence $J \sim V^2$, we determined the value of B_0, which amounted to B_0= 59.23 V·cm A^{-1}. The next portion of the I – V characteristics, $J \sim V^{\alpha}$, where α = 2.7 is observed at voltages from 1.7 to 2.2 V, when the recombination of nonequilibrium charge carriers occurs mainly with a delay; i.e. the last term in the denominator of Eq. (4) becomes substantial. In this case, the I – V characteristic has the following analytical expression [7]:

$$V = \frac{(b+1)d^2 N_R}{N_D \mu_p \tau_i} + \frac{d}{q\mu_p (b+1)C}\sqrt{J} - \frac{2(b+1)N_R d^2 c_n}{N_D \mu_p \alpha \tau_i C}\frac{1}{\sqrt{J}} = A + B\sqrt{J} - \frac{D}{\sqrt{J}} \qquad (6)$$

Where A, B, and D are parameters dependent on the concentration of ionized atoms of deep impurities, the ratio of the electron and hole mobilities, and the thickness of the interlayer-junction base, respectively. In tabl.2, we list the values of the parameters A, B, and D depending on temperature. As can be seen from tabl.2, the parameters A, B, and D determining the value of V and dependent on the concentration of ionized atoms, i.e. on the concentration of recombination centers N_R, the mobilities of charge carriers, and the thickness of the interlayer-junction base gradually increase in the range 300-360 K and appreciably decrease at 380 K.

Table 2. Values of parameters *A*, *B*, and *D* in expression (6) at various temperatures

***T*, K**	**300**	**320**	**36740**	**360**	**380**
B	3,1	3,05	3,14	3,1	5,38
***A*, (В)**	2,65	2,67	2,69	2,74	2,63
***D*, (В·м·А$^{-1/2}$)**	13,25	15,9	21,67	23,97	22,7
***B*, (В·А$^{1/2}$·м$^{-1}$)**	13,07	15,7	21,5	23,8	22,5

Such behavior is probably related to the significant effect of the intracomplex-exchange time τ on these processes. Beyond this portion (see fig.2), the *I* – *V* characteristic has the form $J = A_1V^3$ at voltages from 2.2 to 3 V. This is the portion of the *I* – *V* characteristic subjected to the Lampert law

$$J = \frac{125\varepsilon\tau\mu_n\mu_p}{18}\frac{V^3}{d^3} \qquad (8)$$

and referred to as the drift mode of dielectric relaxation.

Conclusions

Thus, on the basis of the performed investigations' results, it is possible to make the following conclusions:

1. The current-voltage characteristic $J \sim V^{\alpha}$ of the *n*-GaAs – *p*-$(GaAs)_{1-x-y}(ZnSe)_x(Ge_2)_y$ heterostructures in the forward-current direction consists of several portions in which α has various values. This is probably related to the formation of composite recombination complexes of the type of negatively-charged acceptor – positively-charged interstitial ion or positively-charged donor – negatively-charged vacancy, which results in a "delay" in the recombination processes.
2. In such alloys, the recombination rate is determined also by the local centers of nanoformations or the simultaneous participation of complexes and local centers instead of only by the nature of the complexes and simple charged centers.

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