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Research Article

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Current Transfer Mechanism in Heterostructures *n*-Si-*p*-$(SiGe)_{1-x-y}(GaAs)_x(ZnSe)_y$

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Abstract The possibility of producing single crystal substitutional solid solution $SiGe)_{1-x-y}(GaAs)_x(ZnSe)_y$ on the Si substrates by liquid phase epitaxy bismuth molten solution are shown. It is detected that the direct branch of the *I-V* characteristics of these structures at low voltages (up to 0.8 V) is described by an exponential dependence $I=I_0exp(qV/ckT)$, and portion of the sublinear growth with voltage $V\approx V_0exp(Jad)$ at $V>1V$. The experimental results are explained on the basis of the theory of the injection depletion. It is shown that the mobility of majority carriers decreases and the minority carriers increases with increasing temperature.

Keywords substrate, film, liquid phase epitaxy, *I-V* characteristics sublinear growth, injection depletion

Introduction

Liquid-phase epitaxy in slide cartridge with successive growth of the layers of $Si_{1-x}Ge_x$ solid solution from restricted volume of tin melt solution of $Si_{1-x}Ge_x$-GaAs heterostructure was described in [1]. Silicon plates with *n*-type conductivity possessing resistivity of 10–2–102 Ω cm, with the (111) crystallographic orientation were chosen as substrates. Photosensitivity of fabricated pSi-n$(Si_2)_{1-x}(GaAs)_x$ structures involves the spectral range of 0.427−1.1 μm, which is rationalized by the generation of nonequilibrium charge carriers in Si substrate and $(Si_2)_{1-x}(GaAs)_x$ film [2]. Growth of multicomponent Si-$Si_{1-x}Ge_x$-$(Ge_2)_{1-y}(GaAs)_y$ structures was carried out from tin melt solution in the temperature range of 700−1050°C at the gap thickness of h = 0.5 mm between substrates and the cooling rate of 0.6–1.0 deg/min [1]. An analysis of raster images of the surface and chip of epitaxial layer of $(Ge_2)_{1-x}(GaAs)_x$ showed that there are no macroscopic defects and metallic inclusions, while distribution of components along the film surface is uniform. Photoluminescence spectrum of epitaxial layers of $(Ge_2)_{1-x}(GaAs)_x$ was studied in [1]. At 77 K, emission bands corresponding to the band-gap energy of GaAs are observed and there is also a long wave length band with the emission maximum at 1.18 eV. A comparative analysis of electrophysical and photoelectrical properties of n/Si-p/Ge-p/GaAs, n/Si-p/Si1 – *x*Ge*x*-p/GaAs, n/Ge-p/GaAs structures was also carried out and it was shown that the n/Sip/$Si_{1-x}Ge_x$-p/GaAs structure possesses highest electrophysical characteristics.

Materials and Methods

We have studied the solid solutions $(SiGe)_{1-x-y}(GaAs)_x(ZnSe)_y$ grown by liquid phase epitaxy from a limited volume bismuth molten solution in an atmosphere of purified hydrogen palladium. The substrate was Si washer with diameter 20 mm and thickness 350 microns, with the crystallographic orientation (111) n - type conductivity and with resistivity 1 Ω·cm. Epitaxial layers were p - type conductivity and thickness of the layers was 10 microns.

To study electrophysical characteristics of the fabricated heterostructures, ohmic contacts were formed through vacuum deposition, which are continuous from the backside and tetragonal with the area of 4 mm2 made from silver from the epitaxial layer side.

Results & Discussion

To determine the mechanism of current transport were measured *I-V* characteristics of these structures at different temperatures (fig. 1.). One can see from fig. 1 *I-V* characteristics forward at temperatures of 298 - 398 *K* consists of two distinctive sections. Initial exponential section of the *I-V* characteristics up to *1 V* is well approximated by the well-known theory of V.I. Stafeev [3] and elaborated in [4] for p-i-n-structures:

$$I = I_o e^{\frac{qV}{ckT}} \tag{1}$$

where *q*- elementary charge, *k* - Boltzmann constant, *V* - the bias voltage, *T* is the absolute temperature. The value of *"c"* in the exponent can be directly calculated from the experimental points of the exponential section curves *I-V* characteristics using the relation

$$c = \frac{q}{kT} \cdot \frac{V_2 - V_1}{\ln \frac{I_2}{I_1}}, \tag{2}$$

where in I_1, I_2 - current values of two voltages V_1, V_2. Values *"c"* which calculated according to this formula, at different temperatures are shown in table 1. As it seen from table 1 the *"c"* decreases with increasing temperature from 298 *K* to 398 *K*.

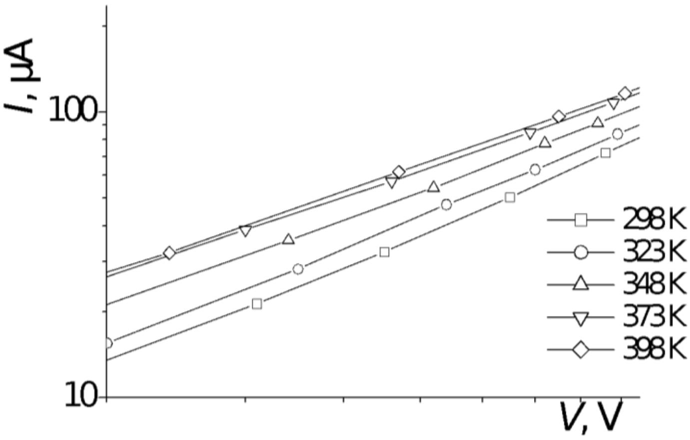

Figure.1. Current-voltage characteristics of n-Si-p-$(SiGe)_{1-x-y}(GaAs)_x(ZnSe)_y$ structures in the forward direction in a logarithmic scale at different temperatures

On the other hand, as it shown in [3] *"c"* given by the following expression:

$$c = \frac{2b + ch\left(\frac{d}{L_p}\right) + 1}{b+1}, \tag{3}$$

where *d* - thickness of the base, in our case *d* = 20 m, L_p-diffusion length of the major carriers - holes defined by the formula:

$$L_p = \sqrt{\frac{\varepsilon\varepsilon_0 kT}{q^2 p}} \tag{4}$$

where ε - dielectric constant determined from experimental data using the formula $C = \varepsilon\varepsilon 0S / d$, where ε_0 - dielectric constant, *q* and *p* - charge and majority carrier concentration: $b = \mu_n/\mu_p$ ratio of electron and hole mobilities.

Table 1: Characteristic parameters of the solid solution $(SiGe)_{1-x-y}(GaAs)_x(ZnSe)_y$

T (K)	298	323	348	373	398
I_0 (A)	$11.96 \cdot 10^{-6}$	$12.26 \cdot 10^{-6}$	$14.5 \cdot 10^{-6}$	$19 \cdot 10^{-6}$	$16 \cdot 10^{-6}$
C	17.75	15	12.53	12.8	10.23
B	12.7	15.4	19.25	18.74	24.9
ρ (Ohm·cm)	$46.35 \cdot 10^{6}$	$49.47 \cdot 10^{6}$	$45.63 \cdot 10^{6}$	$46.27 \cdot 10^{6}$	$47 \cdot 10^{6}$
τ, s	$1.1 \cdot 10^{-8}$	$1.08 \cdot 10^{-8}$	$1.05 \cdot 10^{-8}$	$9.9 \cdot 10^{-9}$	$8.5 \cdot 10^{-9}$

Using d = 20, and b = 12.7, from (4) one can find the value of the diffusion length L_p of major carriers, which is equal to $3.3\cdot10^{-6}$ m.

Mobility major carriers - holes, determined by the method of Hall, was μ_p = 378 $cm^2/V\cdot s$, the value of the mobility of the minority carriers (electrons) of the current defined from $\mu_n = b\cdot\mu_p$ = 4800 $cm^2/V\cdot s$. Then calculates the product of the mobility on the lifetime of the majority carriers ($\mu_p\cdot\tau_p$) by the formula

$$\mu_p \tau_p = \frac{qL_p^2}{kT}. \tag{5}$$

At room temperature the product $\mu_p\tau_p$ is ~ $4,16\cdot10^{-6}$ cm^2/V; in turn, it is possible to determine the lifetime of the majority carriers ~ $\tau_p = 1,1\cdot10^{-8}$ s. Exponential factor I_0 in the formula (1) has the form [3]:

$$I_o = \frac{kT}{q}\cdot\frac{S\cdot b\cdot ch(d/L_p)}{2(b+1)\cdot L_p\cdot\rho\cdot tg(d/2L_p)} \tag{6}$$

where S - the sample area, ρ - resistivity layer between the Ge substrate and the solid solution $(Ge_2)_{1-x-y}(GaAs)_x(ZnSe)_y$ (i.e, the p-n junction). Value I_0, determined from the experimental points of the curves *I-V* characteristics data table 1 and using equation (6) at room temperature was equal to $12\cdot10^{-6}$ A. Also calculated resistivity ρ of transition layer of the substrate and the film, which was $4,6\cdot10^{7}$ Ohm·cm at room temperature. It is shown in the table 1 that with increasing temperature resistivity layer between the substrate and the epitaxial film is almost unchanged.

In fig. 2 in a semi-logarithmic scale, were recorded at different temperatures. The initial section of the *I-V* characteristics (fig.1a) for all temperatures can be described by an exponential dependence:

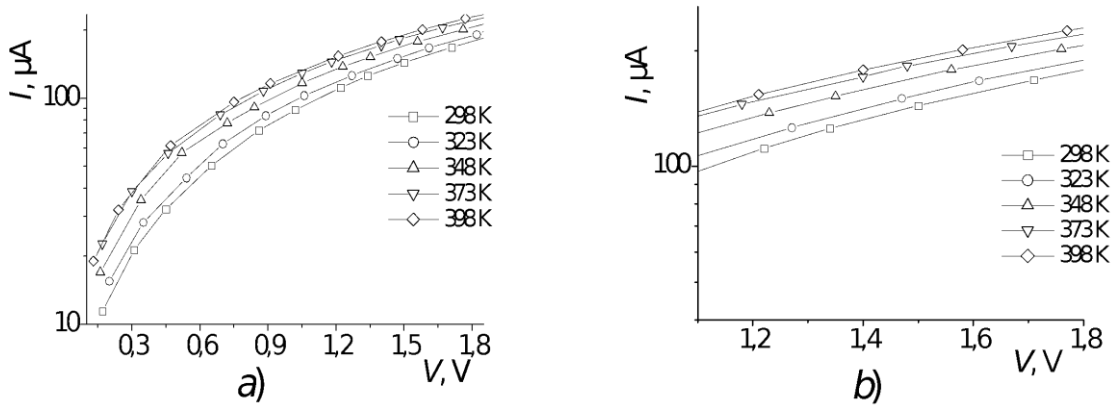

Figure 2: Voltage characteristics of n-Si-p-$(SiGe)_{1-x-y}(GaAs)_x(ZnSe)_y$ structures in the forward direction in the semi-logarithmic scale at different temperatures (a) and sublinear plots (b)

$$J = J_0 \exp\left(\frac{qV}{ckT}\right), \tag{7}$$

with exponent $c \approx 17{,}75$. This clearly shows that the structures have a sufficiently long base [4], i.e. $d/L_p > 1$, where d - length of the base, L_p - the diffusion length of minority carriers. At the same time on all *I-V* characteristics traced sublinear areas. These plots are shown separately for the investigated temperatures in fig.2, b. Clearly, these areas *I-V* characteristics can be well described by the theory of the effect of the injection depletion, first theoretically predicted in [5]. According to the theory, this effect can be observed in opposite directions of ambipolar diffusion and drift of nonequilibrium carriers in not long diode structures under the condition $Jad > 2$, the *I-V* characteristics is described by:

$$V \approx V_0 \cdot e^{Jad}, \tag{8}$$

where J - the current density, a - parameter. It is known that this type of *I-V* characteristics implemented in semiconductor structures containing high concentration of deep impurities in opposite directions conditions of ambipolar diffusion and drift, in which case the parameter *"a"* is described by the simple expression [4]:

$$a = \frac{1}{2qD_p N_t}, \quad (9)$$

depends only on the diffusion coefficient of the major carriers (i.e. their mobility - $D_p = \frac{kT}{q}\mu_p$) and the concentration of deep impurities N_t. For implementation of this regime, which was later called the effect of the injection depletion, must be met in terms of $Jad > 2$. In our case, at room temperature $Jad \approx 9.26$, that is, this requirement is satisfied [4].

Parameter *"a"* can easily be calculated from the relevant sections of sublinear *I-V* characteristics (fig. 1(b):

$$a = \frac{\ln\left(\frac{V_2}{V_1}\right)\cdot S}{(I_2 - I_1)\cdot d}, \quad (10)$$

where S - the cross sectional area, (I_1, V_1), (I_2, V_2) – points, selected sites on the experimental curves of the injection depletion. As follows from the theory, the emergence of such *I-V* characteristics is possible only if the opposite directions of the ambipolar diffusion of nonequilibrium carriers and ambipolar drift, which in this case is determined by the modulation of the charge injection of deep impurities [4].

Since we have a set of different *I-V* characteristics corresponding to different temperatures, according to the formula (4) we can calculate the value of the parameters *"a"* at different temperatures, which are listed in tabl.2.

Table 2: Values of parameter *(a)* and the diffusion coefficient of the majority carriers *(D_p)* depending on the temperature.

T, K	298	323	348	373	398
***a*, (cm/A)**	$10.4\cdot10^5$	$10.16\cdot10^5$	$9.87\cdot10^5$	$9.34\cdot10^5$	$8.8\cdot10^5$
D, (cm^2/s)	9.9	10.1	10.37	11	12.8
$\mu_p\cdot$(cm^2/V·s)	378	360	343,6	339	333
$\mu_n\cdot$(cm^2/V·s)	4800	5544	6614	6852	8391

A value of *"a"* allows from the formula (3) determine the concentration of deep impurities, responsible for the appearance of a sublinear section (2), which at room temperature is $N = 3\cdot10^{11}$ cm^{-3}. From table 2, it is seen that μ_p of main carrier in the solid solution n-Si-p-$(SiGe)_{1-x-y}(GaAs)_x(ZnSe)_y$ decreases and minority carrier μ_n increases with increasing the temperature. This apparently leads to the conclusion that in this solid solution the prevailing role-played the scattering mechanism of the mobility of carriers on deep impurity ions.

Conclusion

First time, grown single-crystal solid solutions of $(SiGe)_{1-x-y}(GaAs)_x(ZnSe)_y$ with p-type conductivity on n-Si substrates with orientation (100) by the method of liquid phase epitaxy from tin solution-melt.

It is shown that the direct branch of the current-voltage characteristics of $J \sim V^{\alpha}$ *n*-GaAs-*p*-$(GaAs)_{0.69}(Ge_2)_{0.17}(ZnSe)_{0.14}$ heterostructures in the forward direction of the current consists of several sections that differ in angles of inclination and they are caused by the formation of Ge, GaAs and ZnSe nanocrystals.

It is detected that the direct branch of the *I-V* characteristics of these structures at low voltages (up to 0.8 V) is described by an exponential dependence $I=I_0 exp(qV/ckT)$, and portion of the sublinear growth with voltage $V \approx V_0 exp(Jad)$ at $V>1V$. The experimental results are explained on the basis of the theory of the injection depletion. It is shown that the mobility of majority carriers decreases and the minority carriers increases with increasing temperature.

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