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Research Article

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The Effect of Recombination through Vacancies on the Type of Current-Voltage Characteristics of *p*Si-*n*$Si_{1-x}Sn_x$ - Structures

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Abstract The article presents the results of the study of the mechanisms of the current passage of the pSi-n$Si_{1-x}Sn_x$ ($0 \le x \le 0.04$)-structure, based on the study of current-voltage characteristics. It is determined that, pSi-n$Si_{1-x}Sn_x$ ($0 \le x \le 0.04$)-structure has very unique properties for the passage of current with temperature dependences, which is explained in the framework of the "model of the formation of defects and defect-impurity complexes".

Keywords injection, recombination center, vacancy, nonequilibrium carriers, recombination rate

1. Introduction

As is known, the current-voltage characteristics (CVC) of p-n-junctions are an important indicator of the mechanisms of current passage of such structures. The type of curves of the current-voltage characteristics makes it possible to argue about those or other properties of the mechanisms of the current passage of the p-n-junction. Usually, the creation of p-n junctions is hampered by the formation of various kinds of surface states, which drastically reduce the electrical parameters of devices made on their basis. The p-n transition obtained in a single technological cycle causes a decrease in the density of surface states due to various kinds of defects. Taking this circumstance into account, we were tasked to obtain and investigate the mechanism of the current passage of p-n structures, obtained by liquid phase epitaxy, in a single technological cycle.

2. Preparation of samples and experiments

For the studies, we fabricated pSi-n$Si_{1-x}Sn_x$ ($0 \le x \le 0.04$)-structures by growing an $Si_{1-x}Sn_x$ solid solution of n-type conductivity with a specific resistance $\rho \approx 0.8$ Ω·cm on silicon substrates of p-type conductivity $\rho \approx 1.0$ Ω·cm. When measuring the current – voltage characteristics, samples with thicknesses of 10–40 μm of the epitaxial solid solution were used. Ohmic collector contacts, solid on the back side and quadrangular with an area of 9 mm^2 on the side of the epitaxial layer, were created by vacuum deposition of silver, at a pressure of ~ 10^{-5} Torr.

Volt-ampere characteristics of pSi-n$Si_{1-x}Sn_x$ ($0 \le x \le 0.04$) heterostructures were measured in the dark at different values of the thickness of the $Si_{1-x}Sn_x$ epitaxial layer in the forward and reverse directions of current, at bias voltages from -2.6 to +2.6 V. For this, the samples are mechanically tightly mounted on a metal cryostat, which was pumped to a residual pressure of ~ 10^{-3} Torr.

To apply the voltage to the sample used power supply B5-45A and it was measured with a voltmeter B7-9. For fixing the current passing through the structure, the combined device U-300 was used.

3. The experimental part.

Studies of the current-voltage characteristics showed that with increasing temperature, the current density (J) increases, but the laws $J = f(U)$ persist for all temperatures. In the forward direction of the CVC, in the voltage range from zero to 2.6 V, no current saturation is observed, which indicates a low density of surface states [1].

From fig. 1, it can be assumed that with the growth of the applied voltage, the rectifying properties are more pronounced in this structure. To confirm the validity of this, the rectification coefficients of the pn-junction were determined. The calculated coefficients of rectification according to the formula $K_r = J_p / J_b$, where J_p and J_b current density at a fixed voltage in the forward and reverse directions gave K_r values = 28, 39 and 50, respectively, with applied voltages U= 0.5 V, 1.0 V and 2.5 V, which are in favor of this assumption.

Analysis of the CVC of pSi–nSi$_{1-x}$Sn$_x$ ($0 \le x \le 0.04$)-structures at different temperatures showed that the current transfer in such structures strongly depends on temperature. Moreover, the behavior of the CVC at different temperatures, at low and at high injection levels is different. In this connection, we investigated the temperature dependence of the CVC of the structures considered.

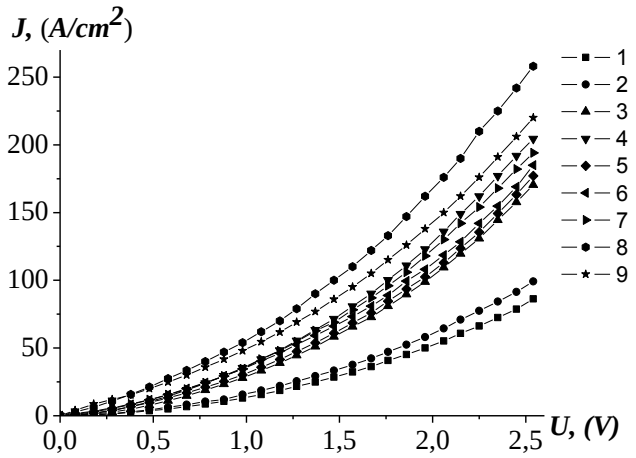

Figure 1: Voltage-current characteristics of pSi–nSi$_{1-x}$Sn$_x$ ($0 \le x \le 0.04$)- structures at temperatures: 1 - 293 K; 2 - 313 K; 3 333 K; 4 - 353 K; 5 - 373 K; 6 - 393 K; 7 - 413 K; 8 - 433 K; 9 - 453 K

On the basis of the CVC data, the dependences of the current density on temperature were plotted at fixed applied voltages, which are shown in Fig. 2.

Analysis of the straight branch of the CVC curves shows that at low levels of injection of non-equilibrium carriers, when the applied voltage U <0.38 V, the current density increases with temperature (Fig. 2a), and at voltages U> 0.5 V, the current is anomalously dependent on temperature.

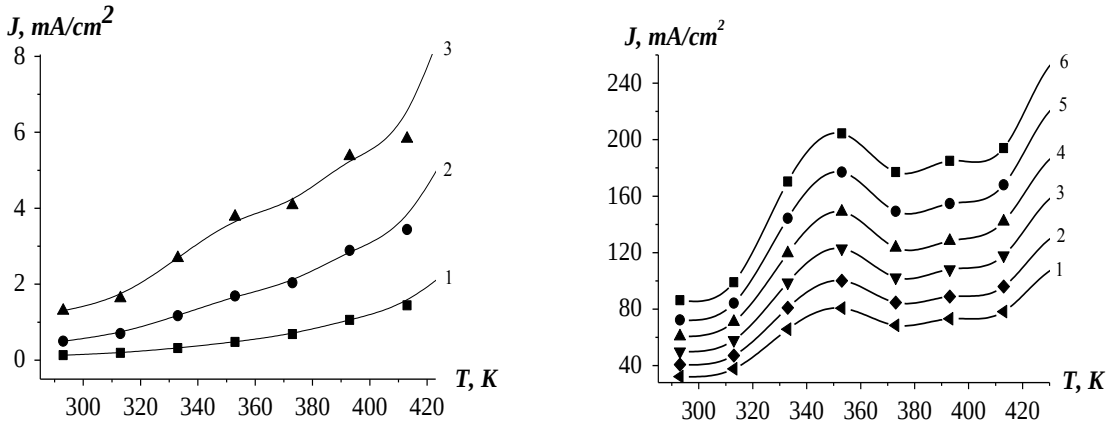

Figure 2: Dependence of current density pSi–n-Si$_{1-x}$Sn$_x$ ($0 \le x \le 0.04$)- structures on temperature at voltages: a) 1 – 0.08 V; 2 – 0.18 V; 3 – 0.28 V б) 1 – 1.57 V; 2 – 1.76 V; 3 – 1.96 V; 4 – 2.15 V; 5 – 2.35 V; 6 – 2.54 V.

As can be seen from fig. 2b with increasing temperature starting from 293 K, the current increases, reaching a maximum value at 353 K, and then decreases to temperatures of 373 K. Further, up to 413 K, a region of weak

dependence of current on temperature is observed. Starting from 413 K to 433 K, the specimen follows a rapidly growing portion of the current, which is replaced by a second falling portion of current from temperature.

4. The theoretical part

To explain these features, it is possible to involve the "model of the formation of defects and defect-impurity complexes" as a result of recombination-stimulated processes with increasing temperature [2]. The absence of an anomaly in the temperature dependence of the current at voltages U <0.38 V indicates that at these voltages the level of injection of nonequilibrium carriers is rather weak and the concentration of nonequilibrium carriers is not enough for the effect of recombination-stimulated processes on the current transfer mechanism to manifest.

According to the model, the recombination will have three channels:

$$U=U_R+U_{RV}+U_V \tag{1}$$

where U_R is the recombination through simple recombination centers N_R, U_{RV} is the recombination through defect-impurity complexes arising during the excitation process, U_V is the recombination directly through vacancies associated with the birth of new vacancies.

It is known that temperature strongly influences the formation of a vacancy in a semiconductor. The dependence of the concentration of vacancies NV on temperature is described by the exponential law [2]:

$$N_V = A \cdot \exp(-\frac{\Delta E_{Vac}}{kT}), \tag{2}$$

where ΔE_{Vac} is the activation energy of the birth of a vacancy. The birth of vacancies and defect-impurity complexes of the "vacancy + recombination impurity center" type can be described by equations [2]:

$$\frac{dN_V}{dt} = A \cdot \exp(-\frac{\Delta E_{Vac}}{kT}) \cdot p - \frac{N_V - N_{V_0}}{\tau_V}, \tag{3}$$

$$\frac{dN_{RV}}{dt} = \beta \cdot N_R \cdot V - \frac{N_{RV} - N_{RV_0}}{\tau_{RV}}, \tag{4}$$

where N_{RV} is the concentration of defect-impurity complexes; τ_V and τ_{RV} - the lifetime of vacancies and defect-impurity complexes, respectively; β - coefficient describing the probability of birth of defect-impurity complexes; NV_0 and N_{RV_0} - the initial concentration of vacancies and defect-impurity complexes. Under stationary conditions ($\frac{dN_V}{dt} = 0$, $\frac{dN_{RV}}{dt} = 0$) from (3) and (4), it is possible to determine the concentration of vacancies N_V and defect-impurity complexes [2]:

$$N_V = N_{V_0} + A \cdot \tau \cdot N_V \cdot \exp(-\frac{\Delta E_{Vac}}{kT}) \cdot p, \tag{5}$$

$$N_{RV} = A \cdot \beta \cdot N_R \cdot \tau_V \cdot \tau_{RV} \cdot \exp(-\frac{\Delta E_{Vac}}{kT}) \cdot p. \tag{6}$$

As is known, the recombination rate of free carriers, which is determined by the relation (1) under quasineutrality conditions $n \approx p$, at a sufficiently high level (and when direct recombination through vacancy levels becomes insignificant) of injection takes the form:

$$U = (N_R - N_{RV}) \cdot c_{eff} \cdot p, \tag{7}$$

where $c_{eff} = \frac{c_n \cdot c_p}{c_n + c_p}$ is the effective capture coefficient of free carriers at recombination centers N_R; c_n and c_p - the capture coefficients of electrons and holes, respectively.

From (6), taking into account (7), it can be seen that, unlike classical statistics, the recombination rate has a decrease with an increase in the level of excitation. The critical carrier concentration (p_{cr}), in which the decline of U begins, can be determined from the condition $\frac{dU}{dp} = 0$:

$$N_R - 2\chi \cdot p_{cr} = 0, \tag{8}$$

Where $\chi = A \cdot N_R \cdot \tau_V \cdot \tau_{RV} \cdot \exp(-\frac{\Delta E_{Vac}}{kT})$,

$$p_{cr} = \frac{N_R}{2\chi}, \tag{9}$$

moreover, this concentration depends only on the material properties and temperature, in particular $\exp(-\frac{\Delta E_{Vac}}{kT})$, which explains well the current drop at a certain temperature. Thus, at this concentration, the recombination rate increases linearly with temperature and, accordingly, the lifetime $\tau = \frac{p}{U}$ of non-equilibrium carriers $\tau = \frac{p}{U}$ will not be more constant (as in the usual Shockley-Reed statistics), but will increase with the level of excitation.

Accordingly, the diffusion length of nonequilibrium carriers $L = \sqrt{D\tau}$ will also increase with increasing excitation level.

Therefore, even in the simplest case, when the current passing through the pn-junction is determined by the expression [3]:

$$I = 2q\frac{Dp}{L}p(0), \tag{10}$$

It may decrease with increasing temperature due to an increase in magnitude. This well describes the decay of the J (U) curves at temperatures of 353 and 433 K.

However, with increasing temperature, direct recombination through vacancy levels becomes essential. Since the process of recombination-stimulated vacancy production is underway, the number of vacancies directly depends on the level of excitation and the number of recombination events. Following the fact that the largest portions of energy are released during recombination directly through simple N_R recombination centers, and also that the number of free vacancies is much larger than the number of related N_{RV} vacancies, so you can determine

$$U_V = (N_V - N_{RV})R_V \approx N_V(U_R)R_V. \tag{11}$$

According to the latter, *U(p)* will again increase with the level of excitation, which satisfactorily explains the increase in current on the CVC in the temperature range 413–433 K.

5. Conclusions

We want to note that we have obtained and investigated the electrical properties of p-n structures, obtained in a single technological cycle, by the method of liquid phase epitaxy. By analyzing the CVC, it was determined that

the pSi-n$Si_{1-x}Sn_x$ ($0 \leq x \leq 0.04$)-heterostructure has rather anomalous properties of current flow with temperature dependences, which are explained in terms of the intensive production of vacancies and defect-impurity complexes with increasing temperature, which is decisive for the rate of recombination of nonequilibrium carriers.

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