THE ANNEALING OF HIGH - LEVEL DOPED MATERIALS ON THE BASE OF THE n – AND p – $Si_{0.7}Ge_{0.3}$ SOLID SOLUTION UNDER REACTOR IRRADIATION

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N- and p-type samples of Si-Ge solid solution with the resistivity of $(4...7)\cdot 10^{-3}$ Ohm·cm, unannealed after high-temperature baking have been investigated. Samples were irradiated up to the fluence ~10^{20} n°·cm^{-2} in reactor active zone at the temperature ~500 ºC in mixed neutron field. It has been observed that in the process of reactor irradiation not only phosphorus or boron precipitation, but the annealing of samples occurs resulting in the increase of doped substituting impurities solubility and hence in the reduction of resistivity. It is shown that the radiated redistribution can be described by diffusion and relaxation processes. The dose dependence on resistivity as a function of fast-pile neutron fluence was calculated and interpreted in terms of the effective medium theory. Activation energies of the doping impurities annealing process and characteristic dimensions of defect clusters have been defined.

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INTRODUCTION

Silicon-germanium alloys have been used in practical thermoelectric energy conversion applications for a relatively great number of years [1]. Study of the high-temperature properties of Si-Ge solid solution under nuclear irradiation is of great importance.

The directed search is possible at thorough study of material properties under nuclear irradiation, that induces the intense temperature spikes (Θ-spikes). Mathematical study of this process was carried out in [2]. It was shown that the sample shape and boundary conditions determine only the average temperature of the sample volume and don't influence the probability density of spikes. The local heating gives rise to melting of small volume region, properties of which are changed after recrystallization. The melt regions and dimensions of the created defect clusters are determined by the energy of primary knock-on atoms, which was spent on elastic collisions.

The volume of cascades has nearly 100 impurity atoms, and the number of the primary displaced atoms exceeds the thousand. The whole process of displacement of atoms in cascades is completed for ~10^{-13} s. For the period of ~10^{-12} s received kinetic energy is transmitted to the lattice and only chaotic, similar to liquid, distribution of atoms has time to be realized [3].

In order to study the influence of irradiation on the material properties the measurements of conductivity, diffusion coefficients and others are usually carried out. Time of measurements considerably exceeds the duration of Θ-spike. Thus, the changes of measured macroscopic parameters will be observed only under the conditions of the overlapping of the local melting regions and the plastic deformation regions [4].

The diffusion processes both within thermal peak and out of its limits have no time to occur [5], as the diffusion of atoms of overheated liquid for such period does not exceed 0.1...1.0 nm.

EXPERIMENT

The samples of n- and p-type conductivity of silicon-germanium alloys with the resistivity $\sim(4...7)\cdot 10^{-3}$ Ohm·cm, obtained by the method of high-temperature baking after the doping by natural mixed isotopes of phosphorus and boron are investigated, but long-lasting annealing at ~900 ºC has not been carried out. The irradiation was executed by total spectrum of neutrons in active zone of the WWR-M reactor at temperature ~500°C. The measurement of resistivity was executed in the process of irradiation and received information was processed using the computer programs. In Fig. 1, 2 the experimental data of resistivity of n- and p-$Si_{0.7}Ge_{0.3}$ samples after various doses of irradiation by fast neutrons are shown as points. The solid lines show the theoretical curves of resistivity as a function of fast neutron fluence in frameworks of the effective medium theory.

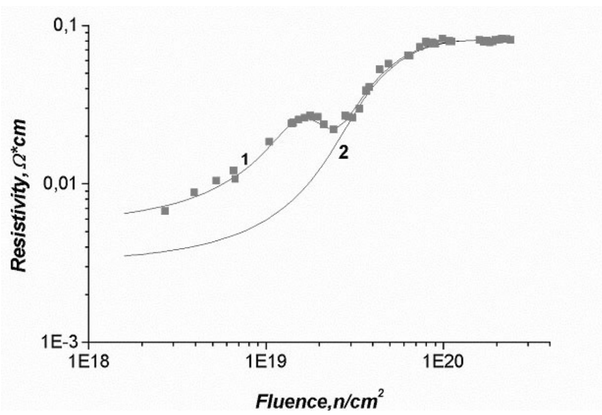

Fig. 1. Resistivity of n- $Si_{0.7}Ge_{0.3}$ as a function of fast-pile neutron fluence:
. - experimental values;— - theoretical dependence: 1 -unannealed sample; 2 - annealed sample

defect clusters (N_c) created by neutrons in the unit of time and volume, according to the expression:

$$N_c = \Sigma \cdot I , \tag{1}$$

where I is the flux of fast-pile neutrons with energy $E_n > 100$ keV ($I = 3.1 \cdot 10^{13}$ $\mathrm{n^o \cdot cm^{-2} \cdot s^{-1}}$).

The volume fraction, occupied by defect clusters of the average radius r_o, in dependence on the irradiation time (t), is equal ([3], p. 252):

$$f = 1 - \exp\left(- \frac{4}{3} \cdot \pi \cdot r_o^3 \cdot \Sigma \cdot I \cdot t \right) . \tag{2}$$

In the cascade of knocked-out atoms the intensive redistribution of lattice atoms and the doped impurities occur. These discrete stochastic events are connected with instantaneous local increase of temperature during the creation of defect clusters. The temperature in these local regions increase for a short time to the melting temperature. But only high temperatures (about the temperature of $Si_{0.7}Ge_{0.3}$ melting) make the main contribution into the frequency of the impurity jumps. Therefore, it can be supposed that all changes, which take place in the local regions of melting due to Θ-spike, began to appear under condition that their fraction of sample volume tends to the unit. Then the radiated redistribution can be described by diffusion and relaxation processes in the whole of volume.

At such approach the "front" of temperature within sample in dependence on irradiation dose (Φ) will be changed proportional to the fraction of recrystallization volume and can be presented as:

$$T(\Phi) = T_{ir} + T_o \cdot \left[1 - \exp(- \Sigma \cdot V \cdot \Phi) \right] ;$$

$$T_o = T_m - T_{ir} ; \quad V = \frac{4}{3} \cdot \pi \cdot r_2^3 , \tag{3}$$

where $\Phi = I \cdot t$ is the fluence of fast-pile neutrons; V is the volume of intensive redistribution of atoms with the radius r_2; T_{ir}, T_m are the sample irradiation and melting temperatures.

Then characteristic time of relaxation in the annealing of doped impurity (τ_1) becomes the function of the irradiation dose:

$$\tau_1(\Phi) = \tau_o \cdot \exp\left(\frac{E_a}{kT(\Phi)} \right) , \tag{4}$$

where τ_o is a constant, which by order of value is inversely proportional to the frequency factor of defect clusters annealing; E_a is energy of activation of doped impurity annealing.

It was noticed [1], that samples of n- and p-$Si_{0.7}Ge_{0.3}$ exposed to the long annealing after high-temperature baking at the beginning of irradiation increase the resistivity due to phosphorus or boron precipitation. This loss of electrical activity of doped impurity occurs in conducting matrix of samples and can be determined by the removal constant time (τ_2) of doped impurity on

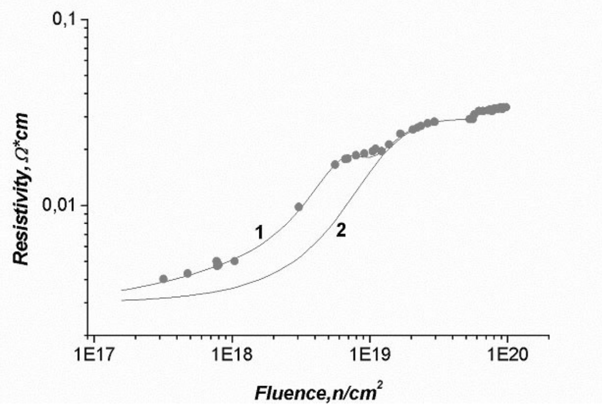

Fig. 2. Resistivity of p-$Si_{0.7}Ge_{0.3}$ as a function of fast-pile neutron fluence:
• - experimental values; —— - theoretical dependence: 1 - unannealed sample; 2 - annealed sample

THEORY

At high temperatures the continuous redistribution of atoms of the solid, stipulated by thermal movement, occurs. Atoms in diamond-like lattices can migrate both by vacancies and by interstitials, and in the most common case - simultaneously. Thus, the atoms from a lattice site can go to tetrahedral and octahedral interstitials and back to sites, annihilating with the vacancies located therein. The appropriate transitions of impurity atoms can be characterized by the relaxation time (τ). If relaxation time reaches values 10^{-2} s and more, it is possible to neglect the diffusion, but one can not neglect the relaxation. Due to statistical nature of this process the time of presence of atom in lattice in one of the balance position varies with temperature according to the exponential law. Under the radiation the redistribution of atoms occurs, depending upon the exposure dose. So it is known [6], that the neutrons with energy higher than 36 keV transmit to lattice atom the energy, sufficient for formation of the whole cascade of knocked-out atoms, after reorganization of which the damage regions with high density of defects in local volume are created. The probability of their formations in n-$Si_{0.7}Ge_{0.3}$ samples will be determined by the macroscopic cross-section ($\Sigma = 0.15$ $\mathrm{cm^{-1}}$) of fast-pile neutron scattering in assumption, that each scattered neutron creates cluster irrespective of the irradiation temperature. Such assumption is based on the fact that if the increased irradiation temperature causes the annealing of small size clusters, high doping level of Si-Ge samples can result in space division of formed subcascades. The authors of the work [7] have calculated by Monte-Carlo method cascade sizes, created by primary knocked-out atoms (PKA) from bismuth to nitrogen in Si. It is shown, that with reduction of PKA weight the size of average cascade grows and the formation of isolated subcascades is possible. In the case of p-$Si_{0.7}Ge_{0.3}$ it is necessary to take into account the clusters, created by the reaction $^{10}B(n,\alpha)^7Li$ [1]. It is possible to calculate the number of sinks. Nature defects, dislocations and crystal boundaries of thermoelectric materials, and as well as defect clusters, created by irradiation can act as for doped impurity sinks. The theory of effective medium , containing defect clusters with the conductivity σ_1 in the conducting matrix with conductivity σ_o is presented by the following expressions [8]:

$$\sigma_{ef} = f \cdot \sigma_o\,; \; f = a + \left(a^2 + x/2\right)^{0.5};$$

$$a = 0.5 \cdot \left[(1.5 \cdot C - 0.5) \cdot (1 - x) + x/2\right]; x = \sigma_1/\sigma_o, \quad (5)$$

where σ_{ef} is the sample conductivity with introduced defect clusters; C is the fraction of conducting volume.

Taking into account the known expression (2) for the fraction of non-conducting volume occupied by defect clusters, C is equal to:

$$C = \exp\left(-\Sigma \cdot V_k \cdot \Phi\right); \quad V_k = 4/3 \cdot \pi \cdot r_1^3, \quad (6)$$

where V_k is the average volume of defect clusters, including space charge region of a radius r_1.

As one can see from fig. 1, 2 the resistivity of samples increases with irradiation dose. But when the volume fraction of thermal peaks during formation of defect clusters comes nearer to 70 %, the resistivity of conducting matrix $\rho_m(\Phi)$ decreases, according to the expression:

$$\rho_m(\Phi) = \left[\rho_o^{-1} + \rho_a^{-1} \cdot \exp\left(\frac{-\Phi}{I\tau_2}\right) - \rho_a^{-1} \cdot \exp\left(\frac{-\Phi}{I\tau_1(\Phi)}\right)\right]^{-1}, \quad (7)$$

where ρ_o is the resistivity of sample before irradiation; ρ_a is the change of resistivity of sample, if the annealing was performed after thermal baking.

Therefore effective conductivity (σ_{ef}) of such sample without preliminary annealing changes with irradiation dose according to (5), if the resistivity of its conducting matrix equals $\rho_m(\Phi)$, according to the expression (7).The joint solution of equations (5) at condition (1) and (6) has allowed to calculate the average radius of defect clusters, created by irradiation in reactor of n- and p-$Si_{0.7}Ge_{0.3}$ at temperature ~810°C and to describe the change of the effective resistivity of samples after $(1.5...3) \cdot 10^{19}\ n^o \cdot cm^{-2}$ doses of irradiation (see fig. 1, 2; curves 2). Then it was assumed, that the samples have been annealed after high-temperature baking before irradiation. For detailed description of experimental data at any irradiation dose in given work (calculation of effective conductivity, according to (5)) the change of resistivity in the conducting matrix of samples, according to expressions (4, 7) was taken into account. Then the process of the precipitation of doping impurity with characteristic time (τ_2), occurring during irradiation and is distributed to its fraction, which was caused due to the lack of annealing of samples after high-temperature clinkering. The results of the calculations are given in table.

Parameters of defect clusters: the radius of the disordered (r_1) and liquid (r_2) regions and also the activation energy (E_a) of phosphorus and boron under radiation annealing with the relaxation characteristic times (τ_2, τ_0) for high-doped n- and p-$Si_{0.7}Ge_{0.3}$ were calculated

Parameters	Type of $Si_{0.7}Ge_{0.3}$	
	n	p
Σ , cm^{-1}	0.15	0.39
ρ_o , $Ohm \cdot cm$	$3.2 \cdot 10^{-3}$	$3.0 \cdot 10^{-3}$
ρ_1 , $Ohm \cdot cm$	$8.1 \cdot 10^{-2}$	$2.9 \cdot 10^{-2}$
ρ_a , $Ohm \cdot cm$	$7.5 \cdot 10^{-3}$	$1.4 \cdot 10^{-2}$
r_1 , cm	$40 \cdot 10^{-8}$	$44 \cdot 10^{-8}$
r_2 ,cm	$50 \cdot 10^{-8}$	$50 \cdot 10^{-8}$
τ_o , s	$1.5 \cdot 10^{-5}$	$3.5 \cdot 10^{-6}$
τ_2 , s	$7 \cdot 10^3$	$7 \cdot 10^3$
E_a , eV	3.3	3.45

DISCUSSION

One can see from the table, that the fast-pile neutrons in n- and p-$Si_{0.7}Ge_{0.3}$ create defect clusters with approximately equal average radius. The rate of their introduction differs more than two times. The defined activation energy for boron and phosphorus migration during irradiation process has appeared to be less, than in silicon [9].Characteristically, that the phosphorus and boron diffusivities in Ge are equal only at the temperature, close to its melting. It is known, that it can be explained by the dependence of diffusivity of these impurity on vacancies charge in Ge. And nearly the same diffusivities of phosphorus and boron in Si in wide temperature region are connected with the neutrality of vacancies. Let us evaluate the diffusion coefficients of phosphorus and boron of n- and p-$Si_{0.7}Ge_{0.3}$ at irradiation process in active zone of reactor. One can consider, that in solid solutions Si-Ge, with increase of Ge content the diffusivity of phosphorus will increase and the boron diffusivity will decrease. Such diffusivity change of these doping impurities would be symmetric in comparison with their diffusion in Si, if the introduction of Ge in Si is only the result of the increase of fraction of charged vacancies. The authors [10] have shown, that the diffusion of phosphorus in $Si_{0.7}Ge_{0.3}$ is subject to the Arrhenius law:

$$D^P = D_o \cdot \exp\left(-\frac{E_a}{kT}\right), \quad (8)$$

where D^P is the P diffusivity in $Si_{0.7}Ge_{0.3}$ at temperature (800...1050) °C; $D_o = 3.7 \cdot 10^{-7}$ cm^2/s is the pre-exponential factor; $E_a = 1.62$ eV is the activation energy for phosphorus migration.

The similar dependence was received for the B diffusivity in Si [11] in the range of (700...1150) °C at $D_o = 6 \cdot 10^{-7}$ cm^2/s and $E_a = 1.68$ eV and at more high temperature with $D_o = 17.1$ cm^2/s and $E_a = 3.66$ eV [9]. The calculation shows, that at temperature

~1330 K these both dependencies give close values of B diffusivity in Si. This temperature, according to [12], is the point of transition from vacancy mechanism of the Ge-diffusion in Si to self-interstitials mechanism at more high temperature.

The theory [13] predicts, that this temperature in Si is equal 1220 K. The authors [10] consider, that the diffusion of phosphorus in $Si_{0.7}Ge_{0.3}$ is caused by the same defects, as in Si, i.e. at temperature below 1250 K it is caused by monovacancy mechanism. According to data (table 1), the recovery of electrical activity of phosphorus in n-$Si_{0.7}Ge_{0.3}$ at irradiation by fast-pile neutrons at temperature 810 K one can describe as the relaxation process (4) with characteristic time $\tau_o = 1.5 \cdot 10^{-5}$ s and $E_a = 3.3$ eV. Therefore, the diffusion coefficient of phosphorus in $Si_{0.7}Ge_{0.3}$ can be usually described by Arrhenius equation: $D^P = D_o^P \cdot \exp(-3.3/kT)$. Comparing the expression (8) with the latter at temperature 1250 K one can receive, that the pre-exponential factor D_o^P is equal 2.1 cm^2/s. At such comparison the observed process of radiationally accelerated diffusion of the doped impurity is caused only by higher temperature of their diffusion in thermal peaks. So, the diffusion coefficient of phosphorus in $Si_{0.7}Ge_{0.3}$ is ~ 5.6 times higher, than in Si at 1250 K. In $Si_{0.8}Ge_{0.2}$ the values of B diffusion coefficient are one order less, than in Si, because of the Ge and B atoms interaction [14, 15].

The formation of B complexes with Ge can happen probably due to the elastic deformation of lattice, the minimum condition of which requires, that the atoms, causing this deformations, were joined in complexes. In our case one can assume, that at such fast melting of cascade regions in p-$Si_{0.7}Ge_{0.3}$ boron will not participate in the creation of the complexes with Ge atoms. Then at temperature 1250 K B diffusivity in $Si_{0.7}Ge_{0.3}$ will only be in 5.6 times less, than in Si. According to data (table 1) the recovery of boron electrical activity in p-$Si_{0.7}Ge_{0.3}$ during reactor irradiation by neutrons at temperature 810 K is also possible to describe by the relaxation process (4) with parameters $\tau_o = 3.5 \cdot 10^{-6}$ s, $E_a = 3.45$ eV. After the comparison at temperature 1250 K, as in case of phosphorus, we receive the pre-exponential factor of B diffusion in p-$Si_{0.7}Ge_{0.3}$ $D_o^B = 0.44$ cm^2/s. Irradiation temperature of samples n- and p-$Si_{0.7}Ge_{0.3}$, equal 810 K, is not enough, to observe directly the diffusion of boron or phosphorus even at such irradiation times. But one can study at this temperature the relaxation of electrical properties of solids, connected with the transition of doped atoms from one site to other. Then it is possible to determine the appropriate relaxation times and corresponding diffusivity. Therefore, one can think, that in research samples studied at irradistion in the active zone of reactor the increase of electrical activity of doped impurity is caused by radiation-accelerated diffusion. It can be connected with the melting, though extraordinary fast, of sample regions due to PKA thermal peaks formation. In the process of the cooling such regions become homogeneous, causing the effect of radiation acceleration of diffusion. The PKA on average spends on elastic collisions ~28 keV. The other energy is spent on ionization and is scattered by lattice electrons during period of $\sim 5 \cdot 10^{-16}$ s. In our experiment small-sized clusters are annihilated at irradiation temperature without creating the melting regions and the average cluster is disintegrated on 2...3 subclusters. Therefore the mean energy for the formation of thermal peak is equal ~10 keV, which is spent on elastic collisions with atoms of lattice by PKA. Authors [16] has shown, that the size of cascade, created by 10 keV PKA, is equal L ~100 Å in Si. Brinkman [17] has argued, that regions of size approximately ~ 10^4 atoms are extraordinary fast melted with significant redistribution of particles because of turbulent flows. The strict mathematical description of the radiation-induced diffusion (RID) have given by Dienes and Vineyard [18] :

$$D_{RID} = (N_o/12) \cdot L^5 , \tag{9}$$

where $N_o = I \cdot \Sigma$ is the number of thermal spikes, formed in volume of 1 cm^3 by 1 second, and Σ is the cross-section of formation of thermal spikes.

Then $D_{RID}^P = 1.2 \cdot 10^{-18}$ cm^2/s is the radiation-induced diffusion coefficient of phosphorus in n-$Si_{0.7}Ge_{0.3}$ presented at condition, that the radius of melting region $r = 62.5$ Å. The process of recovery of electrical activity of phosphorus is completed at the dose of fast neutrons $\sim 2.0 \cdot 10^{19}$ cm^{-2} and boron dose ~ $7 \cdot 10^{18}$ cm^{-2}, that corresponds to radiuses of melted zone ~62.5 Å and 58.6 Å, and melted volume fraction is equal 90...95 %, accordingly.

From expression $\chi = c \cdot \rho \cdot D_T$, where χ is the thermal conductivity of n- and p-$Si_{0.7}Ge_{0.3}$ samples ($\chi = 2.85 \cdot 10^{-2}$ W K^{-1}cm^{-1}), c is the specific heat ($c = 31.2$ W $\cdot$ s$^{-1} \cdot$ K$^{-1} \cdot$ moth^{-1}), ρ is density ($\rho = 3.38$ gr/cm^3) one can find the temperature conductivity coefficient (D_T) ($D_T = 1.1 \cdot 10^{-2}$ cm^2/s) at temperature of 1500 K close to that of crystal melting [19].The influence of thermal spikes, created by PKA on radiation-induced diffusion of impurities have been considered by the authors [20]:

$$D_{RID} = \left(\pi^{1.5}/3\right) \cdot \Gamma(2/3) \cdot D_o \cdot (N_o/D_T) \cdot$$
$$\cdot (k \cdot Q/(c \cdot \rho \cdot Q_m))^{5/3} , \tag{10}$$

where $\Gamma(2/3) = 1.354$; k is Boltzmann constant; $Q_m = 3.3$ eV is the activation energy for phosphorus migrations; $Q = 10$ keV is PKA energy, spent on elastic collisions.

Then, according to (10) $D_{RID}^P = 2.4 \cdot 10^{-18}$ cm^2/s for phosphorus. According to Brinkman the radiation-accelerated diffusivity of boron $D_{RID}^B = 2.2 \cdot 10^{-18}$

cm^2/s, and according to (10) this value is equal $1.2 \cdot 10^{-18}$ cm^2/s. At the beginning of irradiation (see fig. 1, 2) the growth of the resistivity of n- and p-$Si_{0.7}Ge_{0.3}$ samples is observed, that is connected with the reduction of concentration of electrically active impurities of phosphorus and boron and is characterized by time constant $\tau = 7 \cdot 10^3$ s. The irradiation, creating vacancy-interstitial pairs, transfers the doped impurities from sites to the interstitial positions. Therefore the kinetics of formation of defect complexes, steady at irradiation temperature 810 K, can be calculated and the migration of doping impurity of boron and phosphorus is described through self-interstitial mechanism. Usually the diffusion is considered as the process of random movement of diffusion particles, which jump in succession along axes X on the distance Δx. In the Fick differential equation the value $D = (\Delta x)^2 / 2\tau$ is given, representing a diffusivity during random movement of particles in the given direction. In case of crystal lattice: $D = a \cdot d^2 / \tau$ ($d = 5.5 \cdot 10^{-8}$ cm, $a = 1/12$, $\tau = 7 \cdot 10^3$ s), so at irradiation in reactor of n- and p- $Si_{0.7}Ge_{0.3}$ at temperature 810 K the diffusivities of phosphorus and boron are equal $D = 3.6 \cdot 10^{-20}$ cm^2/s. Received expressions for the diffusivity of phosphorus and boron:

$$D^P = 2.1 \cdot \exp(-3.3/kT),$$

$D^B = 0.44 \cdot \exp(-3.45/kT)$, which are correct at high temperature (T>1250 K), can be used correctly at 810 K during the irradiation process (the monovacancy diffusion mechanism should not result in electrical activity loss of doped impurity). Then the diffusion coefficient of boron and phosphorus ($D = 3.6 \cdot 10^{-20}$ cm^2/s) received above can be realized at 840 K - local temperature for the P interstitial diffusion and at 910 K - local temperature for the B interstitial diffusion, that testifies to radiation-accelerated diffusion of these impurities. Atom Ge, receiving the energy of 41 keV creates in Ge lattice overheated to 1060 K region of radius 95 Å and the duration of existence of thermal spike is equal $3 \cdot 10^{-12}$ s ([3], p. 248). The mentioned calculations had shown that in the alloy of n- and p-$Si_{0.7}Ge_{0.3}$ on the average the region of 60 Å, existence of which was $9 \cdot 10^{-12}$ s, was melted. The P and B diffusivities being equal $\sim 3 \cdot 10^{-4}$ cm^2/s at the melting point are quite sufficient for atoms to overcome one internuclear distance during melting time existence.

The processes of doped impurity annealing is completed at quite definite dose of the irradiation of n- and p-$Si_{0.7}Ge_{0.3}$ by fast-pile neutrons (see fig. 1, 2). One can characterize them according to (4), by constant times of restoration of electrical activity of phosphorus $\tau^P = 1.25 \cdot 10^6$ s and boron $\tau^B = 1.29 \cdot 10^6$ s. Such process of restoration take place in each region, which is equal to the size of thermal spike. Then one can assume that the coefficient of radiation-induced diffusion can be determined according to the expression:

$$D_{RID} = 4\pi \cdot r^2 / 2\tau, \qquad (11)$$

where r is radius of thermal spike, τ is constant time of restoration of electrical activity of dopant.

Then the coefficient of radiation-induced diffusion for phosphorus in $Si_{0.7}Ge_{0.3}$ is equal $D^P_{RID} = 2.0 \cdot 10^{-18}$ cm^2/s and for boron $D^B_{RID} = 1.7 \cdot 10^{-18}$ cm^2/s at 810 K, according to (11).

CONCLUSION

Dose dependence of the n- and p-$Si_{0.7}Ge_{0.3}$ resistivity after high-temperature baking without annealing is described in frameworks of effective medium theory and theory of radiation - induced diffusion of doped impurities. The observable features of the dose dependence of resistivity of n- and p-type SiGe solid solutions are connected with doped impurities annealing in the process of irradiation in reactor and are explained by the defect clusters formation. Coefficients of interstitial diffusion of phosphorus and boron in n- and p-$Si_{0.7}Ge_{0.3}$ are determined.

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ОТЖИГ ВЫСОКОЛЕГИРОВАННЫХ МАТЕРИАЛОВ НА ОСНОВЕ ТВЕРДОГО РАСТВОРА n- и p-$Si_{0.7}Ge_{0.3}$ В ПРОЦЕССЕ РЕАКТОРНОГО ОБЛУЧЕНИЯ

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Исследованы образцы n- и p-типа проводимости твердого раствора кремний-германий с удельным сопротивлением $(4...7)\cdot 10^{-3}$ Ом/см, не прошедшие отжига после высокотемпературного спекания. Образцы облучались до флюенса $\sim 10^{20}$ $n^o\cdot см^{-2}$ в активной зоне реактора ВВР-М при температуре ~500 ºС в смешанном нейтронном поле. В процессе облучения наблюдались не только преципитация легирующей примеси бора и фосфора, но и увеличение их растворимости, обусловленное кластерами дефектов. Показано, что радиационное перемешивание можно описать на языке диффузионных и релаксационных процессов. Изменение удельного сопротивления в зависимости от флюенса быстрых нейтронов описано в рамках теории эффективной среды. Определены энергии активации процесса отжига легирующих примесей и характерные размеры кластеров дефектов.

ВІДПАЛ ВИСОКОЛЕГОВАНИХ МАТЕРІАЛІВ НА ОСНОВІ ТВЕРДОГО РОЗЧИНУ n- ТА p-$Si_{0.7}Ge_{0.3}$ В ПРОЦЕСІ РЕАКТОРНОГО ОПРОМІНЮВАННЯ

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Досліджені зразки n- та p-типу провідності твердого розчину кремній-германій з питомим опором $(4...7)\cdot 10^{-3}$ Ом/см, що не пройшли відпал після високотемпературного спікання. Зразки опромінювались до флюєнсу $\sim 10^{20}$ $n^o\cdot см^{-2}$ в активній зоні реактора ВВР-М при температурі ~500 ºС в змішаному нейтронному полі. В процесі опромінювання спостерігались не тільки преципітація легуючої домішки бору та фосфору, але й збільшення їх розчинності, що обумовлено кластерами дефектів. Показано, що радіаційне перемішування можна описати в термінах дифузійних та релаксаційних процесів. Зміна питомого опору в залежності від флюєнсу швидких нейтронів описана в рамках теорії ефективного середовища. Визначені енергії активації процесу відпалу легуючих домішок та характерні розміри кластерів дефектів.