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Influence of growing and doping methods on radiation hardness of *n*-Si irradiated by fast-pile neutrons

A.P. Dolgolenko[1], P.G. Litovchenko[1], A.P. Litovchenko[2], M.D. Varentsov[1], V.F. Lastovetsky[1], G.P. Gaidar[1]

[1]*Institute for Nuclear Research NASU, 47, prospect Nauky, 03028 Kyiv, Ukraine,*
Fax: 380 (44) 2654463, E-mail: gaydar@kinr.kiev.ua
[2]*Istituto Nazionzle di Fisica Nucleare and Dipartamento di Fisica Universita di Padova, via Marzolo 8, I-35131, Padova, Italy.*

Abstract. Silicon *n*-type samples with resistivity ~$2.5\cdot10^3$ Ohm·cm grown by the method of a floating-zone in vacuum (FZ), in argon atmosphere (Ar) and received by the method of transmutation doping (NTD) are investigated before and after irradiation by various doses of fast-pile neutrons at room temperature. The radiation hardness of *n*-type silicon is shown to be determined first of all by the introduction rate of defect clusters and their parameters and then by the introduction rate of defects into the conducting *n*-Si matrix. The presence of oxygen, argon atoms and *A*-type defects (dislocation loops of the interstitial type) mainly increases the radiation hardness of *n*-Si. The effective concentration of carriers in irradiated silicon was calculated in the framework of Gossick's model taking into account the recharges of defects both in the conducting matrix of *n*-Si and in the space-charge regions of defect clusters. Grown by the method of the floating-zone melting in argon atmosphere the neutron-transmutation-doped silicon (NTD) has elevated radiation hardness. The introduction rate of divacancies in the conducting matrix of n-Si (NTD) is about five times less than in *n*-Si (FZ) and ~2 times less than in *n*-Si (Ar). The availability of the deformation strain field surrounding the argon-type impurities as well as *A*-type defects is supposed to promote the annihilation of divacancies with interstitial atoms of silicon.

Keywords: silicon, neutron irradiation, radiation hardness, radiation defects, clusters.

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1. Introduction

The increase of radiation hardness of high-resistance *n*-Si, used for creation of semiconductor detectors of nuclear irradiation, have always been under specific attention. Detectors have to work at room temperature for a long time in nuclear radiation fields. Therefore, the problem of obtaining the material with the improved radiation hardness is always actual. The study and the search for new kinds of silicon detectors with high radiation hardness became very actual for a wide use in experiments on particle colliders like the Large Hadron Collider (LHC) at CERN. The presence of the oxygen, carbon as well as isovalent impurities such as Sn, Ge is shown to have an influence on the radiation hardness of silicon and devices based on it [1, 2]. The increased radiation hardness of neutron-doped silicon was observed in [3].

If speaking about radiation hardness of materials, it is understood their ability to preserve their properties under the effect of nuclear radiation. The quantitative characteristics of radiation hardness are assigned in accordance with the investigated value. Parameters and a type of radiation as well as conditions of irradiation are indicated. So, the radiation hardness of nuclear radiation detectors is a dose of radiation, at which the users can no longer be reconciled with deterioration of the properties of detectors. Usually this is the dose, at which $n \rightarrow p$ inversion of detector depleted region occurs. Photodetectors possess little radiation hardness, since their properties are determined by the lifetime of current carriers. Doping of lead telluride-based alloys with indium results in the Fermi level stabilization leading to high radiation hardness that exceeds the respective parameter of analogs at least by 4 orders of magnitude [4].

Gold doping of silicon reduces to some extent the damaging effects of neutron irradiation, as the silicon vacancies are occupied by gold atoms [5]. Thus, gold doping improves the radiation hardness of silicon detectors, and it means that detector lifetime in the Large Hadron Collider (LHC) would be increased. The availability of *A*-, *B*-, or *D*-type microdefects in *n*-Si (FZ) grown by the method of a floating-zone in vacuum with variable speed from 1 to 6 mm/min. at irradiation by ^{60}Co gamma rays reduces the degree of radiation change of charge carrier lifetime [6].

The study and search of new silicon detectors of improved radiation hardness is also very urgent in prospect of their wide use in LHC experiments. Preliminary results on various float-zone and epitaxial-grown detectors (*n*-type) after irradiation at room temperature by 1 MeV neutrons and 24 GeV protons have been presented in [7]. This study proves that there are epitaxial materials from which detectors can be manufactured.

Radiation hardness for fast neutrons (1 MeV), high energy protons (24 GeV) and ^{60}Co gamma rays of planar detectors processed from highly oxygenated silicon are compared with standard silicon detectors [8, 9]. Oxygen-enriched detectors have better radiation hardness to proton irradiation (by a factor of two) than normal detectors, but no noticeable difference was observed with neutron irradiation. The effect of high radiation hardness of silicon is maximum for gamma irradiation.

It is interesting to note that the thermal donor doped silicon shows the best radiation hardness to proton irradiation as both factors are responsible for detector degradation: donor removal effect and compensation by double vacancies are reduced [9]. After introduction of oxygen into Si at 1100°C during 6 hours, the time for cooling from 550 to 350°C was about three hours. This time was long enough to create a significant concentration of thermal donors in Si [9].

The radiation-induced damage in silicon $p^+/n/n^+$-junctions was widely studied earlier in order to understand the changes in the operational characteristics of particle detectors in high energy physics experiments [10, 11]. Review [12] adduces the data of numerous researches on radiation damage in silicon used for creation of detectors.

In order to predict radiation hardness of irradiated semiconductor detectors, the identification of radiation defect models in silicon [13] are conducted, as the developed earlier models have so far the semiempirical nature.

The aim of this work was: (i) to investigate radiation hardness of *n*-type silicon grown by various methods; (ii) to state the reason of the radiation hardness increase in case of the neutron-transmutation-doped *n*-Si (by the theoretical description of the change of *n*-Si electrophysical properties under the irradiation by fast neutrons) and (iii) to outline methods of the increase of radiation hardness of *n*-Si and devices based on it .

2. Experiment

N-type silicon samples with resistivity ~$2.5\cdot10^3$ Ohm·cm grown by the method of the floating-zone in vacuum (FZ), in argon atmosphere (Ar) and received by the method of neutron-transmutation doping (NTD) are investigated before and after irradiation by various doses of fast-pile neutrons. The irradiation by fast neutrons was carried out on the horizontal channel of the research reactor WWR-M at room temperature. The flux of fast-pile neutrons was determined by the threshold indicator ^{32}S with the accuracy 10% and led to the neutron energy ~100 keV. Measurements of the conductivity and Hall constant were performed using the Van der Pauw method on *n*-Si square samples of $10\times10\times1$mm^3 in sizes by the compensatory method with the accuracy of 3%. The contacts were created by Al rubbing into polished silicon surface.

3. Theory

It is known that the irradiation of monocrystalline Si by fast-pile neutrons results in the formation not only clusters but also simple defects of *A*-, *E*- type centers and divacancies both in the conducting matrix and in the space charge regions of defect clusters. Fast neutrons of the reactor during scattering on silicon atoms spend on the average the energy on elastic collisions equal to 26 keV and create defect clusters (30–1000)Å in size. The clusters are surrounded by the region of space charge in high-resistance *n*-Si ~10^4 Å in radius. The region of congestion of defects remains crystalline in spite of high concentration of defects because of the high mobility of vacancies and interstitial atoms of silicon. The large factors of short-term nonthermal annealing (up to 50 in *p*-Si) is observed. The defect clusters are enriched by divacancies (~ 10^{20} cm^{-3}) and their structure is still crystalline silicon [14], as IR absorption and properties of divacancies annealing are not changed. High resolution TEM-investigations [15] is shown that agglomeration of interstitial atoms was not observed and the optical diffractogram taken from the defected area clearly shows the amorphous structure. In our opinion, it is possible a diffusion of interstitial atoms to the surface of silicon because of the small thickness of the region investigated (~10 nm) is a reason of amorphous regions forming. The authors [16] using electron diffraction patterns of silicon irradiated by $5\cdot10^{20}$ n°·cm^{-2} fast neutrons ascertained the amorphous phase is not observed.

For determination of radiation hardness of Si, the dose dependence of electrical coefficients of semiconductor is usually calculated, namely, the concentration and mobility of charge carriers are obtained from the Hall and conductivity *emf* measured at room temperature. The criterion of radiation hardness may be the carrier removal rates by various defects including clusters from the conduction band of *n*-Si. In our studies, we calculated the radiation hardness (R_h) of *n*-Si as $R_h = n_0/v_0$ $(\Phi \to 0)$, where n_0 is the concentration of carriers in n-Si sample before irradiation, v_0 is the carrier removal rate at little radiation doses. But for the theoretical description of the dose dependence of the effective carrier concentration the temperature dependence of the defect recharges both in conducting matrix of n-Si and in the space-charge regions of defect clusters is required to know. According to [17], the effective concentration of carriers (n_{eff}) depending upon irradiation dose (Φ) and temperature (T) is equal to:

$$n_{eff}(T,\Phi) = n(T,\Phi)\cdot(1-f(T,\Phi)), \tag{1}$$

with $f(T,\Phi) = 1-\exp(-\Sigma V(T)\Phi)$,
where $n(T, \Phi)$ is the carrier concentration in the conducting matrix of n-Si; $f(T, \Phi)$ is the volume fraction occupied by clusters; $V(T)$ is the volume of an average defect cluster. Assuming that each scattered fast neutron creates a cluster of defects, the macroscopic cross-section for the cluster introduction (Σ) under irradiation of n-Si in WWR-M reactor is $\Sigma = 0.15\ \mathrm{cm}^{-1}$.

The average statistical cluster in n-Si irradiated by fast neutrons has a concentration of defects (divacancies) $>10^{19}\ \mathrm{cm}^{-3}$ [18]. Therefore, from Gossick's model [19] that requires the conditions $L_1 \leftrightarrow R_1 \leftrightarrow R_2$ to be satisfied, applies with n-type silicon samples having resistivity greater that 40 Ohm·cm, for the volume $V(T)$ is derived

$$V(T) = \frac{4\pi\varepsilon\varepsilon_0 R_1}{qN_d}\Psi_p(T), \tag{2}$$

where R_1 and R_2 are average radii of defect congestions and the space charge region of defect clusters, respectively; ε, ε_0 are the dielectric constants of material and vacuum, respectively; q is the electron charge; L_1 is the Debye-Huckel length in the disordered region of clusters; N_d is the net donor density in the n-type matrix and $\Psi_p(T)$ is the total difference in electrostatic potential between the matrix and the center of the disordered region (assumed to be spherical).

Proceeding from Gossick's model for the volume (2) and according to (1) we obtain:

$$n_{eff}(T,\Phi) = n(T,\Phi)\times$$
$$\times\exp\left[-\frac{4\pi\varepsilon\varepsilon_0\,\Sigma R_1\Phi}{N_2(T,\Phi)\cdot q^2}\cdot\left(\mu - kT\ln\frac{N_c(T)}{N_2(T,\Phi)}\right)\right], \tag{3}$$

where $N_2(T, \Phi)$ is the concentration of screening centers in the space-charge regions of defect clusters; μ is the Fermi level position in the center of the cluster relative to the bottom of the conduction band; $N_c(T)$ is an effective state density in the conduction band.

We know that the Fermi level is connected to thermodynamic character of a system. Therefore, we can define μ and $kT\ln\dfrac{N_c(T)}{N_2(T,\Phi)}$ as an increment of a free energy of a system (cluster and conducting matrix) when adding to it one electron under the condition of a constancy of volume and temperature. Then, we can define $\dfrac{q^2 N_2(T,\Phi)}{4\pi\varepsilon\varepsilon_0 R_1\Sigma\Phi}$ as a diminution of a free energy of all system at formation of $\Sigma\Phi$ clusters in unit of silicon specimen volume. The divacancy, as known, is a multicharge center. In intrinsic silicon, the Fermi level will be placed at a neutral level of the divacancy (Ev + 0.52 eV) on our evaluations. When capturing a free electron (supplied by ionization of dopants), the energy of the center will increase on 0.16 eV. Therefore, with increase of dopant concentration, the Fermi level in a cluster (μ) will be displaced to the conduction band (E_c). At a high injection of holes through p-n-transition, the cluster core has been depicted as p-type because of the acceptor-like behaviour of the TSC peak [20]. In our opinion, after capture of holes divacancies pass in to a neutral charge state, and therefore, the Fermi level in clusters becomes equal E_v + 0.52 eV.

According to Gossick's model of the defect clusters, the positively charged donors screen the negatively charged congestion of acceptor type defects. If neutrons transfer to silicon atoms energy less than 4.7 keV, the defect clusters are not formed, but vacancies and interstitial atoms are generated statistically equally probably in the volume of the sample. Thus, stable radiation defects are evenly introduced both into the conducting matrix of the sample and into the region of the space charge of clusters. With a decrease of sample temperature, acceptor defects in the region of the space charge of clusters are partially recharged, which reduces the screening effect of the positively charged donors.

In the work [21], shown theoretically and experimentally is the necessity take into account the recharges of defects in the region of the space charge of defect cluster. Thus, we deviate from the pure Gossick model, namely: by showing that the position of the Fermi level in the cluster (μ) relatively to the conduction band depends on the dopant concentration in silicon; the screening center concentration (the donors) in the space-charge region is defined by the recharges of acceptor defects.

Let us consider semiconductor (n-Si) phosphorus-doped with the net concentration N_d and average degree of compensation by acceptors (boron) in the range of temperatures from the room one up to those of liquid nitrogen. Let neutrons create uniform point defects of the acceptor type (except for disorder regions) with a concentration $N_a < N_d$. Let us consider n-Si as nondegenerated ($N_d < 10^{14}\ \mathrm{cm}^{-3}$). Then, with increasing the temperature of n-Si sample from 77 K, we shall have some electron concentration in the conduction band because of the thermal energy of ionization (E_a) of defect-acceptor levels in the conducting matrix $n(T, \Phi)$, and in the region of the space charge of defect clusters $N_2(T, \Phi)$:

$$n(T,\Phi,E_a)=\frac{1}{2}\cdot\left(N_d-\frac{N_a(\Phi)}{\lambda}-n_{11}\right)\times$$
$$\times\left(\sqrt{1+\frac{4\cdot N_d\cdot n_{11}}{\left(N_d-\frac{N_a(\Phi)}{\lambda}-n_{11}\right)^2}}+1\right), \tag{4}$$

$$n_{11}=gN_c(T)\exp\left(-\frac{E_a}{\lambda kT}\right),$$

where $g = 2$ is the factor of acceptor level degeneration; $N_a(\Phi)$ is the concentration of radiation-induced acceptor defects after radiation dose Φ; n_{11} is equal to the concentration of electrons in the conduction band of n-Si, when the Fermi level coincide with the level E_a and E_a/λ one-level defect that may be in the matrix and in the space-charge region of defect clusters, respectively.

Usually, at the room temperature, the electrons are seized from the conduction band to the deep acceptor defect levels of E–centers type (E_c–0.47 eV). Then, the net donor concentration will depend on the radiation dose: $N_d(\Phi) = N_d - n\Phi$, where ν is the carrier removal rate, for example, by E-centers. The position of the acceptor level of defects in the upper area of the forbidden band is defined as $(E_c - E_a)$. Then, when $\Phi = 0$, $n_{11} = 0$ ($E_a \to \infty$), $N_a(\Phi) = 0$, $N_d(\Phi) = N_d$ and hence $n(T,0) = n_0$ (n_0 is the carrier concentration before irradiation).

The bend of energy bands in the cluster at the distance of Debye screening with a temperature decrease leads to the space heterogeneous recharge of the acceptor type defects according to (3). If the acceptor defect is located in the conducting matrix $\lambda = 1$ and in case of its presence in the space-charge region of clusters $\lambda = 1.5$. As it is shown in [21], the value $\lambda = 1.5$ remains in the whole range of investigated radiation doses of n-Si. It is assumed that the value $\lambda = 1.5$ remains the same in high-resistance n-Si irradiated by fast neutrons. The determined λ value, in our opinion, is conditioned by the presence of potential barriers surrounding clusters of defects.

In the absence of statistical interaction between the levels of radiation defects, i.e., when in the forbidden band they are away from each other on the value of the order of several kT, the concentration of carriers in the conducting n-Si matrix can be determined with account of the total concentration of carriers $n_1(T, \Phi, E_1)$, $n_2(T, \Phi, E_2)$, $n_3(T, \Phi, E_3)$, that will be injected to the conduction band due to the ionization of acceptor levels, i.e. A-centers as well as levels of divacancies at the change of temperature (T) under irradiation dose (Φ) (Fig. 1):

$$n(T,\Phi)=n_1(T,\Phi,E_1)+n_2(T,\Phi,E_2)+$$
$$+n_3(T,\Phi,E_3)-2N_d(\Phi)+N_a(\Phi), \tag{5}$$

where $n_i(T, \Phi, E_i)$ is defined by equation (4) under $\lambda = 1$ ($i = 1,2,3$).

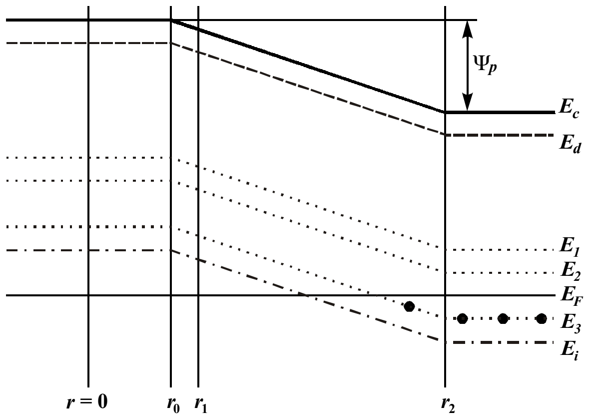

Fig. 1. Electron energy band scheme for transition between a damage region of cluster ($r < r_1$) and conduction matrix ($r > r_2$) of n-Si with a net concentration N_d donors ($E_c - E_d$) and radiation-induced acceptor energy levels ($E_c - E_i$) (i = 1, 2, 3).

The concentration of screening centers in the space-charge regions of defect clusters is similarly equal to:

$$N_2(T,\Phi)=N_{21}(T,\Phi)+N_{22}(T,\Phi)+$$
$$+N_{23}(T,\Phi)-2N_d(\Phi)+\frac{N_a(\Phi)}{\lambda}, \tag{6}$$

where $N_{2i}(T, \Phi, E_i)$ is defined by equation (4) under $\lambda = 1.5$ (i = 1,2,3). Here N_a is a concentration of the second acceptor level. If $\Phi = 0$, then $n_i(T, 0) = N_d(0)$ according to (4).

4. Dose dependence of *n*-Si electrophysical coefficients

Measured at room temperature the dose dependence of the mobility of the charge carriers is presented in Fig. 2a. It is seen that the mobility of charge carriers changes in all n-Si samples with the increase of the dose of irradiation by fast neutrons irrespective of the growing methods, but after the fluence ~10^{13} n°·cm^{-2} it begins to decrease sharply. So, in the range of radiation doses (1…2)·10^{13} n°·cm^{-2} in n-Si (NTD), the volume fraction occupied by the defect clusters (f) approaches to the unity (strong overlap of the regions of the space charge of clusters), the Hall mobility is equal to $\mu_h = \mu\cdot N_p/N_{eff}$. Here N_{eff} is averaged by the volume of the crystal concentration of carriers inversely proportional to the Hall constant, and the value of conductivity is determined by the electron concentration at the level of the flow (N_p). Such a behavior of electron mobility testifies that n-Si radiation hardness is first of all determined by the introduction rate of the defect clusters and only then by the introduction rate of defects in the conducting matrix of samples. The sharp change of charge carrier mobility, in our opinion, is connected with defect cluster recharges, when newly created divacancies reject holes, that are captured into clusters. After the radiation dose equal to $2\cdot10^{13}$ n°·cm^{-2} the Fermi level position in clusters and in the conducting matrix is leveled relative to the bottom of the conduction band reaching the value (E_c – 0.528 eV) in *n*-Si (FZ), (E_c – 0.523 eV) in *n*-Si (Ar) and (E_c – 0.511 eV) in *n*-Si (NTD). At the radiation dose of more than $3\cdot10^{13}$ n°·cm^{-2} N_{eff} growth is observed, but there is no reliable expression for calculation of the Hall constant (R). Such a behavior, in our opinion, is conditioned by the beginning of $n \rightarrow p$ inversion and by the recharge of the defect clusters.

According to equations (3–6), the effective carrier concentration in *n*-Si samples grown and doped by various methods was calculated depending on the radiation dose by fast-pile neutrons at the room temperature (Fig. 2b). Then the temperature dependence of the carrier concentration in the conducting matrix of n-Si (for the calculation) was modeled only by two radiation defect levels (E_c – 0.43 eV) and (E_c – 0.315 eV) with introduction rates ν_i and ν_j, respectively.

Less effect on the coordination of the dose dependence theoretical description of the effective carrier concentration with the experimental values is rendered by the selection of the second deep acceptor level of defect (E_c – 0.315 eV), than by the carrier concentration in the samples before irradiation.

The used levels of radiation defects do not explain the temperature dependence of the concentration of carriers in the conducting matrix that is clear from Fig. 3. Nevertheless, the concentration of carriers calculated on the basis of experimental data (curve 2) does not differ much from the modeled temperature dependence of the carrier concentration in the conducting matrix (curve 1) at the room temperature.

At this temperature, it is the level of divacancy (E_c – 0.43 eV) that is responsible for removal of carriers from the conduction band and for the compensation of donors. Therefore, the calculation is much simplified, if to assume in the equation (4):

$$N_a(\Phi) = \nu_j \Phi\,,\;\; N_d(\Phi) = n_0 - \nu_i \Phi\,, \tag{7}$$

and then according to equations (1-4) the effective carrier concentration can be calculated.

The main calculation parameters are presented in Table 1. Fig. 2b and Table 1 demonstrate that the neutron-transmutation-doped *n*-Si (NTD) grown by the method of the floating-zone in argon atmosphere has the elevated radiation hardness.

Nevertheless all the investigated samples, grown by different methods, contained oxygen (~10^{16} cm^{-3}). The reason of the decrease in the rate of divacancies introduction into the conducting *n*-Si matrix grown in the at-

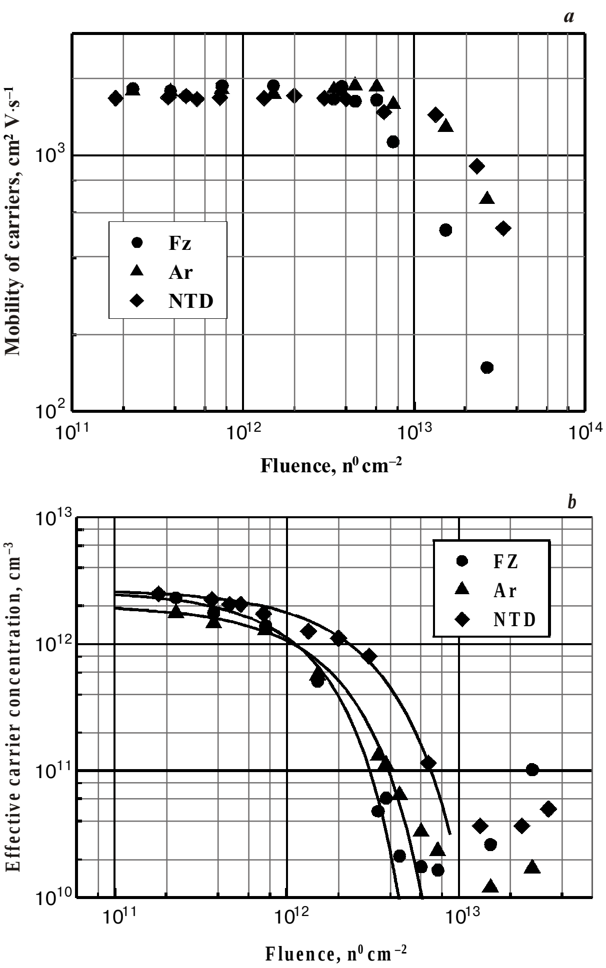

Fig. 2. The dependence of effective electron mobility (a) and effective concentration of electrons (b) at room temperature on the fluence of fast-pile neutrons for ● – *n*-Si (FZ), ▲ – *n*-Si (FZ), ◆ – *n*-Si (FZ).
The average concentration of carriers ($\bar{n}_0$) in *n*-Si for: (FZ) – $2.65\cdot10^{12}$; (Ar) – $2.04\cdot10^{12}$; (NTD) – $2.69\cdot10^{12}$ cm^{-3}.

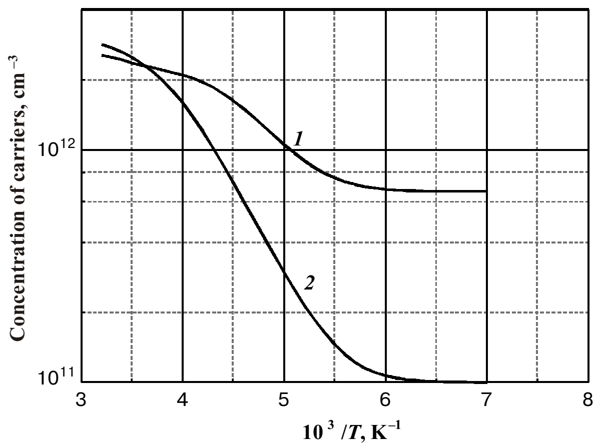

Fig. 3. The concentration of carriers in the conducting matrix of *n*-Si (NTD) irradiated by the fluence of fast-pile neutrons $2\cdot10^{12}$ n°·cm^{-2}: *1* – the model calculation; *2* – the calculation of experimental data according to equations (5, 6).

Table 1. The introduction rates of radiation defects ν_i (E_c – 0.43 eV) and ν_j (E_c – 0.315 eV) and parameters of defect clusters: R_1 and μ used for description (in grown by various methods (FZ, Ar, NTD) n-Si with average concentration of carriers ($\bar{n}_0$) before the irradiation) the dependence of effective concentration of carriers on the fluence of fast-pile neutrons (3).

Si sample	$\bar{T}$, K	$\bar{n}_0$, cm^{-3}	ν_i, cm^{-1} (Ec – 0.43 eV)	ν_j, cm^{-1} (Ec – 0.315 eV)	μ, eV	R_1, Å
FZ	294.4	$2.65\cdot10^{12}$	1.16	0.66	0.528	92
Ar	294.4	$2.04\cdot10^{12}$	0.46	0.66	0.523	76
NTD	298.5	$2.69\cdot10^{12}$	0.26	0.79	0.511	76

mosphere of argon, apparently, lies in the method of growing itself.

5. Temperature dependence of carrier concentration

The effective concentration of carriers (n_{eff}) after radiation fluence Φ may be calculated according to the Eqs 3–6.

The technique of calculation and expressions for calculating the average cluster radius are described in detail in [22]. The carrier concentration in the conducting matrix of n-Si samples after various radiation doses by fast-pile neutrons was determined according to the equations (4, 5). According to Eqs 3–6, the results of calculation of effective electron concentration temperature dependences in n-Si (NTD) after various radiation doses by fast-pile neutrons are shown in Figs 4–6 as solid lines and experimental data as dots.

The parameters of defect clusters, point defects in the conducting matrix of n-Si (NTD) samples and corresponding carrier removal rates are given in Table 2 and Table 3, respectively. From Table 2, it is seen that the average radius (R_1) of defect clusters grows with the increase of irradiation dose changing from 36 to 92 Å.

After the fluence above ~10^{13} n°cm^{-2}, the Fermi level position relatively to the bottom of the conduction band in clusters and in the conducting matrix of n-Si (NTD) is leveled, reaching the value (E_c – 0.51 eV) at room temperature. When the temperature decreases, Fermi level moves to the middle of the forbidden band similar to the case of intrinsic silicon. Therefore, it might be supposed that clusters of defects have lost the external region of space charge. The temperature dependence of carrier concentration is described by (E_c–0.62 eV) slope after the radiation dose $1,33\cdot10^{13}$n°·cm^{-2} (Fig. 6). The concentration of defects in clusters is known to be of the same order with the state density in the conduction band. Therefore, it is assumed that under the decrease of temperature the conduction electrons recombine with the holes on defects of the cluster. Since the divacancies are the main defects in a cluster the observed slope (E_c – 0.62 eV), probably, belongs to the acceptor level (E_v + 0.51 eV) of the divacancy that has been predicted by Vinetskii [23].

The carbon and oxygen concentrations in the samples of n-Si (NTD) don't exceed the value 10^{16} cm^{-3}. At

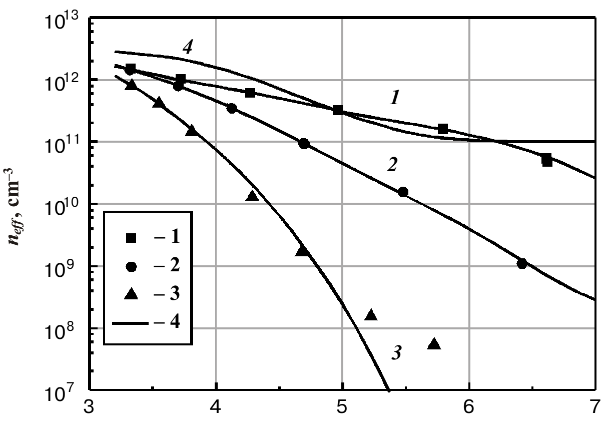

Fig. 4. The dependence of effective concentration of electrons on reciprocal temperature for n-Si (NTD) after irradiation by the fluence of fast-pile neutrons: *1* – $3.67\cdot10^{11}$; *2* – $4.67\cdot10^{11}$; *3* – $5.40\cdot10^{11}$; *4* – $7.33\cdot10^{11}$ n°·cm^{-2}.

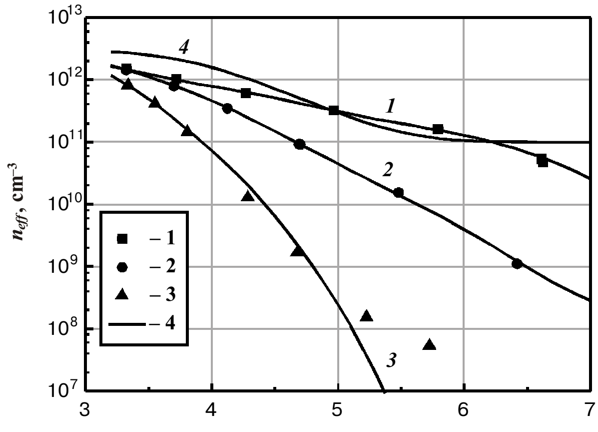

Fig. 5. The dependence of effective concentration of electrons on reciprocal temperature for n-Si (NTD) after irradiation by the fluence of fast-pile neutrons: *1* – $1.33\cdot10^{12}$; *2* – $2.0\cdot10^{12}$; *3* – 3.0×10^{12} n°·cm^{-2}; *4* – the concentration of electrons in the n-Si conducting matrix with the fluence $2\cdot10^{12}$ n°·cm^{-2}.

Table 2. Calculated concentration (N_a) and energy of levels (E_a) for radiation defects in the conducting matrix *n*-Si (NTD) irradiated by various doses of fast-pile neutrons (Φ); N_b is a concentration of screening centers outside the damaged region of defect clusters with an average radius R_1.

($n^\circ \cdot$ cm^{-2})	n_0 (cm^{-3})	N_b (cm^{-3})	N_a (cm^{-3})	$E_c - E_a$ (eV)	R_1(Å)
$3.67 \cdot 10^{11}$	$2.67 \cdot 10^{12}$	$2.52 \cdot 10^{12}$	$6.0 \cdot 10^{11}$	0.18	36
$4.67 \cdot 10^{11}$	$2.68 \cdot 10^{12}$	$2.52 \cdot 10^{12}$	$7.0 \cdot 10^{11}$	0.18	57
$5.4 \cdot 10^{11}$	$2.64 \cdot 10^{12}$	$2.51 \cdot 10^{12}$	$7.95 \cdot 10^{11}$	0.18	58
$7.33 \cdot 10^{11}$	$2.51 \cdot 10^{12}$	$2.33 \cdot 10^{12}$	$1.08 \cdot 10^{12}$	0.19	64
$1.33 \cdot 10^{12}$	$2.35 \cdot 10^{12}$	$2.05 \cdot 10^{12}$ $1.05 \cdot 10^{12}$ $7.5 \cdot 10^{11}$	$1.0 \cdot 10^{12}$ $3.0 \cdot 10^{11}$ $1.9 \cdot 10^{12}$	0.315 0.261 0.204	60
$2.0 \cdot 10^{12}$	$3.07 \cdot 10^{12}$	$2.57 \cdot 10^{12}$	$2.47 \cdot 10^{12}$	0.36	76
$3.0 \cdot 10^{12}$	$3.07 \cdot 10^{12}$	$2.32 \cdot 10^{12}$ $5.2 \cdot 10^{11}$	$1.8 \cdot 10^{12}$ $0.9 \cdot 10^{12}$	0.405 0.39	86
$4.0 \cdot 10^{12}$	$2.38 \cdot 10^{12}$	$1.48 \cdot 10^{12}$	$1.2 \cdot 10^{12}$	0.39	92
$6.67 \cdot 10^{12}$	$2.51 \cdot 10^{12}$	$2.44 \cdot 10^{12}$	$1.75 \cdot 10^{12}$	0.43	92
$1.33 \cdot 10^{13}$	$2.79 \cdot 10^{12}$	$2.79 \cdot 10^{12}$	$2.78 \cdot 10^{12}$	0.62	–

the same time the introduction rate of divacancies by fast-pile neutrons in the conducting matrix of *n*-Si (NTD) is five times slower than that of *n*-Si (FZ). The introduction rate of level (E_c – 0.39 eV) attributed to a four-vacancy defect (V_4) is the same as in *n*-Si (Cz) [22]. But the introduction rate of A-centers (VO) is about 1.5 times higher than in *n*-Si (FZ).

It is known that the higher is the temperature or the dose of irradiation the deeper are the levels of radiation defects in the sample. Many defects, as can be seen from Table 3 have been already identified. The accuracy of determination is not worse than in the DLTS measurements, where already at little radiation doses the entire spectrum of the radiation defects is displayed. The study of neutron-doped *n*-Si with the concentration of phosphorus ~10^{14} cm^{-3} under reirradiation by fast-pile neutrons showed that the introduction rate of divacancies in the conducting matrix of silicon has decreased ~ 2 times more.

6. Discussion

Thus, the neutron-transmutation-doped *n*-Si grown in argon atmosphere is shown to have increased radiation hardness. The main feature of the increased radiation hardness of *n*-Si (NTD) is: the fast-pile neutrons create in this material defect clusters with smaller sizes of defect congestions and with nearly 2 times slower introduction rate of

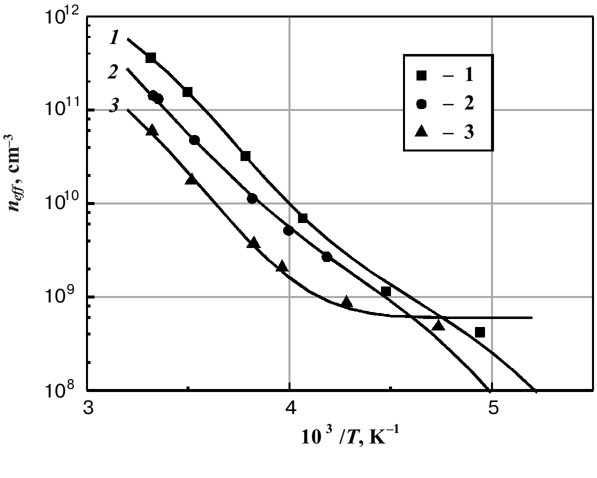

Fig. 6. The dependence of effective concentration of electrons on reciprocal temperature for n-Si (NTD) after irradiation by the fluence of fast-pile neutrons: 1 – $4.0 \cdot 10^{12}$; 2 – $6.67 \cdot 10^{12}$; 3 – $1.33 \cdot 10^{13}$ n°·cm^{-2}.

Table 3. The removal rate of carriers (ν) by radiation defects in the conducting matrix of *n*-Si (NTD) irradiated by fast-pile neutrons

$E_c - E_a$, (eV)	ν, (cm^{-1})	Reference data
0.18	1.54	VO_i (A-centre); C_iC_s
0.19	1.47	
0.315	0.75	
0.261	0.23	$V_2^{=}$
0.204	1.42	
0.36	1.23	V_2O
0.39	0.3	E170 (V_4)
0.405	0.6	
0.43	0.26	V_2^-
0.47	$5.1 \cdot 10^{-3}$	PV (E-centre)
0.62	0.15	

divacancies into the conducting matrix of samples in comparison with silicon grown in argon atmosphere. It is known that if silicon is grown in argon atmosphere atoms of argon can enter into the silicon lattice, and the recovery annealing of neutron-doped *n*-Si results in the formation of dislocation loops. So, the presence of argon atoms and dislocation loops in silicon lattice creates the deformation strain fields, which seem to promote the recombination of divacancies and self-interstitials of silicon.

7. Conclusions

In our opinion, one of the ways to increase the radiation hardness of silicon is to create the recombination centers of vacancies and interstitial atoms according to the type of dislocation loops.

References

1. RD48 Status Report (R&D On Silicon for future Experiments), CERN / LHCC-39, June 1997.
2. B.G. Svensson and J.L. Lindström, Generation of divacancies in silicon by Mev electrons:Dose rate dependence and influence of Sn and P // *J. Appl. Phys.*, **72**(12), pp. 5616-5621 (1992).
3. I.I. Kolkovskii, L.F. Lugakov, V.V. Shusha, Recombination properties of irradiation defects in Si (NTD) // *Fiz. Techn. Polupr.*, **20**(5), pp. 964-967 (1986) (in Russian).
4. B.A. Akimov, N.B. Brandt, L.I. Ryabova, D.R. Khokhlov, Promising Alternative to the Modern High - Performance Infrared Photodetectors // *Proceedings of International Conference* "*Physics of electronic materials*", Kaluga, Russia, October 1-4, 2002, p.15.
5. M. McPherson, T. Sloan and B.K. Jones, Suppression of irradiation effects in gold-doped silicon detectors // *J. Phys. D: Appl.Phys.*, **30**, pp. 3028-3035 (1997).
6. P.F. Lugakov, L.A. Kazakevich, Recombination of charge carriers in irradiated silicon containing as-grown microdefects // *IRS-2001. Proceeding of the Fourth International Conference* "*Interaction of Radiation with Solids*", Minsk, Belarus, October 3-5, 2001, pp. 176-177 (in Russian).
7. B. Dezillie, S. Bates, M. Glaser, F.Lemeilleur, C. Leroy, Radiation hardness of silicon detectors manufactured on wafers from various sources // *Nucl. Instr. and Meth. in Phys. Research A.*, **388**, pp.314-317 (1997), International Conference on Radiation Effects on Semiconductor Materials, Detectors and Devices, Florence, Italy, 6-8 March 1996.
8. X.B. Xie, H.S. Cho, C.Y. Chien, G.W. Liang, W. Huang, W. Huang and Z. Li, New Designs of Silicon Pixel Detectors Fabricated from Normal and Oxygen-Enriched Silicon Substates // IEEE *Trans. Nucl. Sci.*, **47**(6), IETNAE part 1, pp. 1807-1811 (2000).
9. B. Dezillie, Z. Li, V. Eremin, W. Chen, and L.J. Zhao, The Effect of Oxygen Impurities on Radiation Hardness of FZ Silicon Detectors for HEP after Neutron, Proton and Gamma Irradiation // *IEEE Trans. Nucl. Sci.*, **47**(6), pp.1892-1897 (2000).
10. E. Borchi, M. Bruzzi, Z. Li, S. Pirollo, Shallow Level Analysis in Irradiated Silicon // *IEEE Trans. Nucl. Sci.*, **47**(4), pp. 1474-1477 (2000).
11. B. Dezillie, Z. Li, V. Eremin, M. Bruzzi, S. Pirollo, S.U. Pandey, C.J. Li, Improved neutron radiation hardness for Si detectors: application on low resistivity starting material and / or manipulation of N_{eff} by selective filling of radiation-induced traps at low temperatures // *IEEE Trans. Nucl. Sci.*, **46(**3), pp. 221-227 (1999).
12. G. Lindström, M. Moll, E. Fretwurst, Radiation hardness of Silicon detectors-a challenge from high-energy physics // *Nucl. Instr. and Meth. in Phys. Research A.* **426**, pp.1-15 (1999).
13. L.F. Makarenko, V.Yu. Yavid, Ya.I. Latushko, N.I. Zamiatin. IRS-2001. Identification of radiation defect models to predict radiation hardness of silicon detectors for ionizing radiation // *Proceeding of the Fourth International Conference* "*Interaction of Radiation with Solids*", Minsk, Belarus, October 3–5, 2001, pp. 178-180 (in Russian).
14. L.J. Cheng and J.Lori, Characteristics of Neutron Damage in Silicon // *Phys. Rev.*, **171(**3), pp. 856-862 (1968).
15. T. Gessner, M. Pasemann, and B. Schmidt, Calculation of Neutron-Induced Defect Clusters in Silicon and Comparison with TEM Investigations // *Phys. Stat. Sol. (a).* **77**, pp.133-138 (1983).
16. M.L. Swanson, J.R. Parsons, C.W. Hoelke, The disordered regions in neutron-irradiated and ion-bombarded Ge and Si // *Radiation Effects in Semiconductors.* Gordon and Breach, N. Y., 1971, pp. 359-366.
17. A.P. Dolgolenko and I.I. Fishchuk, Defect Clusters and Simple Defect Build-up Kinetics in Fast-Neutron Irradiated n-Si // *Phys. Stat. Sol.(a)*, **50**, pp.751-755 (1978).
18. B.C. MacEvoy and S.J. Watts, Defect Engineering Radiation Tolerant Silicon Detectors // in: *Proc. of 7th Internat. Autumn Meeting Gettering and Defect Engineering in Semiconductor Technology GADEST'97*, Spa (Belgium), October 5 to 10, 1997, pp, 221-232.
19. B.R. Gossick, Disordered Region in Semiconductors // *J. Appl. Phys.* **30***,* pp.1214-1218 (1959).
20. M. Bruzzi, E. Borchi and A. Baldini, Using thermally stimulated currents to visualize defect clusters in neutron-irradiated silicon // *J. Appl. Phys.* **72**(9), pp.4007-4013 (1992).
21. A.P. Dolgolenko and I.I. Fishchuk, A-Centres Build-up Kinetics in the Conductive Matrix of Pulled n-Type Silicon with Calculation of Their Recharges at Defect Clusters // *Phys. Stat. Sol.(a)*, **67,** pp.407-411 (1981).
22. A.P. Dolgolenko, Variation of Carrier Removal Rate with Irradiation Dose in Fast-Pile Neutron Irradiated *n*-Si // *Phys. Stat. Sol.(a)*, **179**, pp.179-188 (2000).
23. V.L. Vinetskii, On Statistics of Conductivity in Si Containing Divacancies // *Phys. Stat. Sol.*, **41**, pp. k93-k97 (1970).