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

in frame of - CERN-RD50 project-

Development of Radiation Hard Sensors for

Very High Luminosity Colliders

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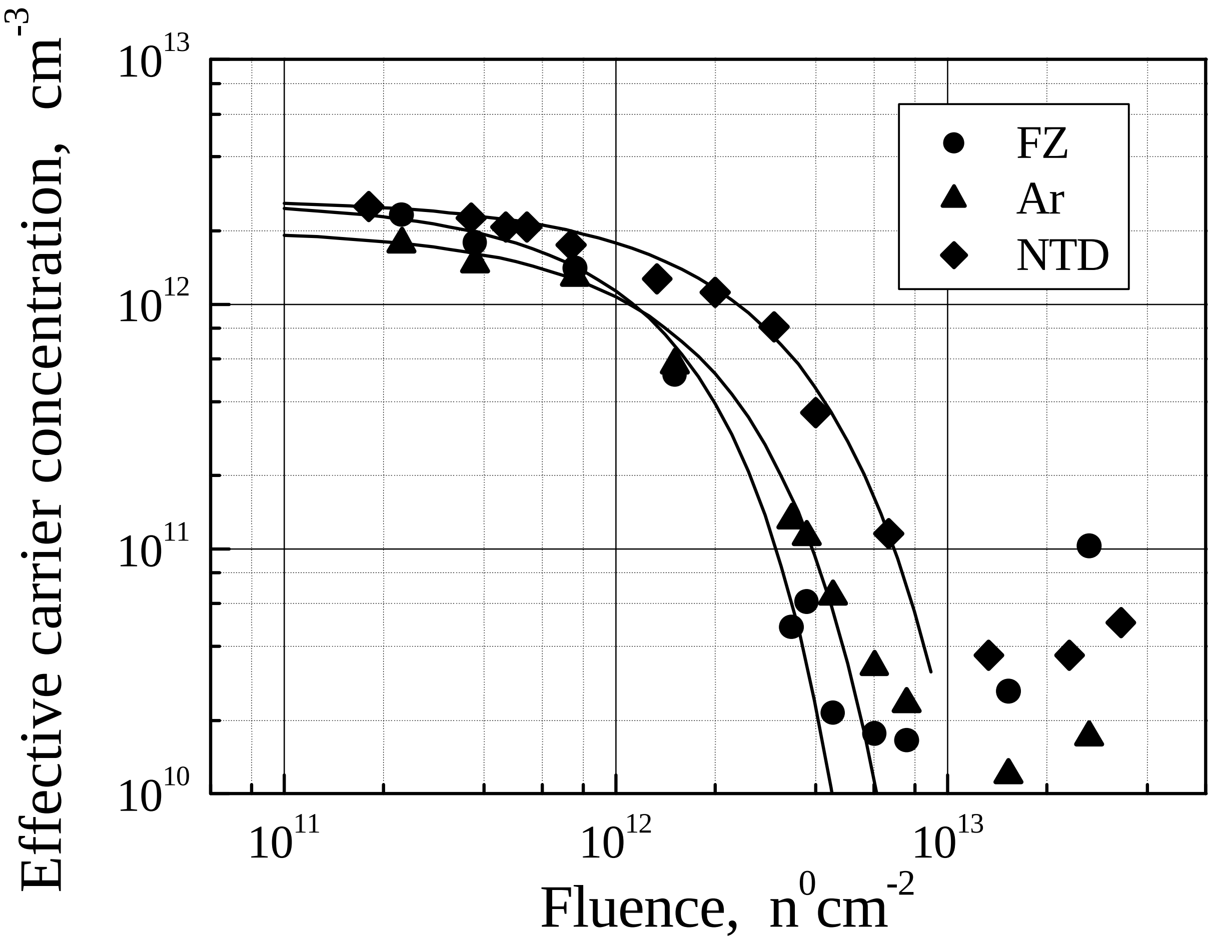
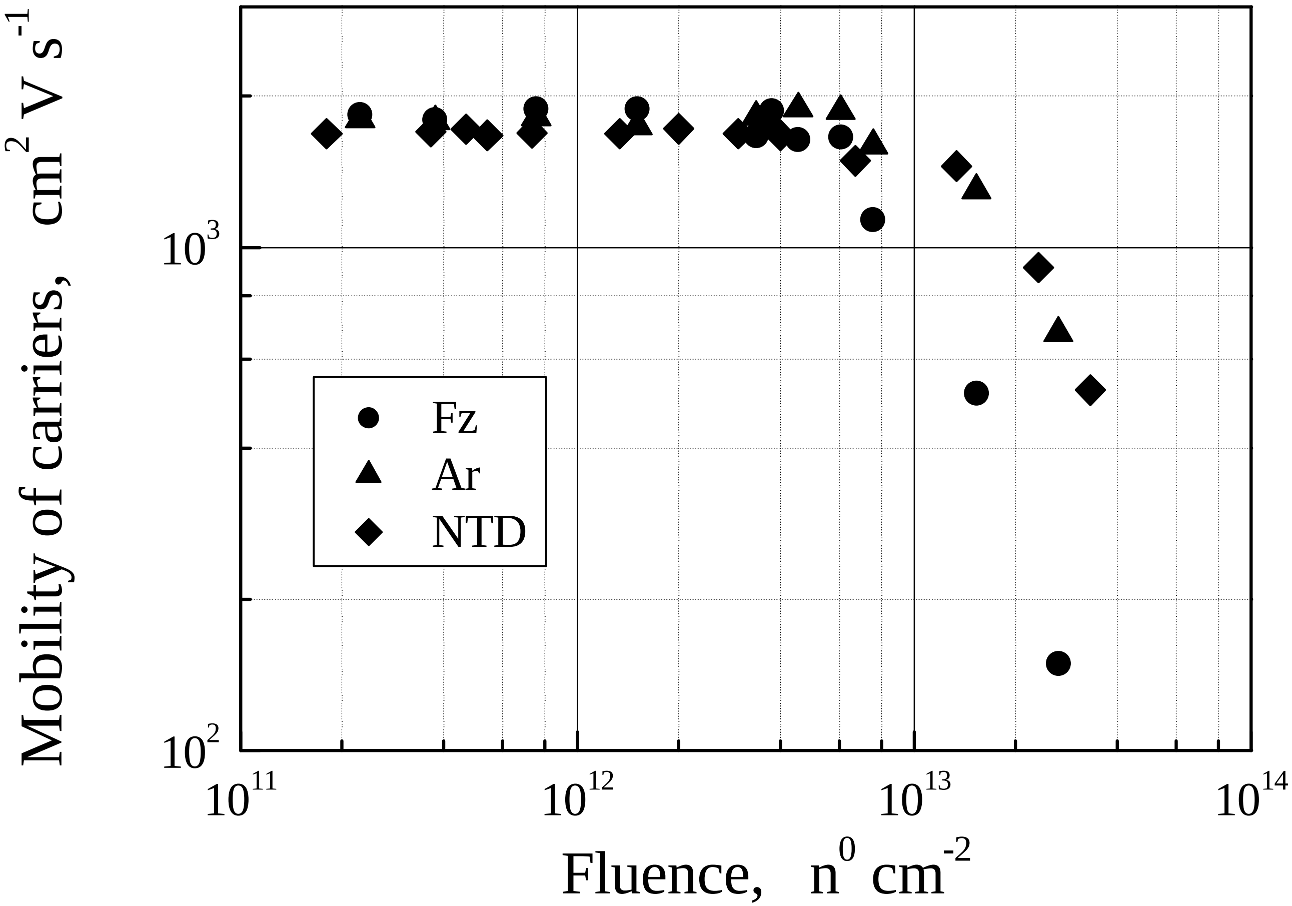
The effective concentration dependence



The effective concentration dependence of electrons at room temperature vs. the fluence of fast neutrons for ●-n Si(FZ), ▲-n-Si(Ar), ♦-n-Si(NTD).

The average concentration of carriers (n_0) in n-Si for: (FZ) — $2.65 \cdot 10^{12}$; (Ar) — $2.04 \cdot 10^{12}$; (NTD) — $2.69 \cdot 10^{12} cm^{-3}$

The effective electron mobility



The effective electron mobility dependence vs. fluence of fast neutrons at room temperature for ●-n Si(FZ), ▲-n-Si(Ar), ♦-n-Si(NTD)

The carriers average concentration (n_0) in n-Si for:
(FZ) — $2.65\cdot10^{12}$; (Ar) — $2.04\cdot10^{12}$; (NTD) — $2.69\cdot10^{12}$ cm^{-3}.

The effective concentration dependence explanation

The effective carrier concentration in n-Si samples grown and doped by various techniques calculated vs. the fast neutrons fluence at room temperature. The carrier concentration vs. temperature in conducting matrix of n-Si (for the calculation) was modelled only by two radiation defect levels (E_c-0.43 eV) and (E_c-0.315 eV) with introduction rates n_i and n_j, respectively.

At the fluence $2 \cdot 10^{13}$ n·cm^{-2} the Fermi level position in clusters and in the conducting matrix is situated relative to the bottom of the conduction band has a 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 fluence higher $3 \cdot 10^{13}$ n·cm^{-2} the holes concentration increase is observed. Unfortunately, for the Hall constant (R) calculation is no reliable expression for this case.

In our opinion, this fact is conditioned by the beginning of n®p inversion and the defect clusters recharge.

Theoretical explanations

The crystal volume part occupied by defect clusters $f(T,\Phi)$ is determined by the expression

$$f(T,\Phi) = 1 - \exp(-\Sigma V(T)\Phi) \ , \qquad (1)$$

V(T) is a average defect cluster volume. Φ is a fluence. If 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 Σ=0.15 cm^{-1}.

The effective carriers concentration (n_{eff}) vs. fluence and temperature (T) is:

$$n_{eff}(T,F) = n(T,F)\cdot(1 - f(T,F)), \qquad (1a)$$

where $n(T,\Phi)$ is a carrier concentration in the conducting matrix of n-Si;

Gossick's model for the cluster defect volume state that:

$$V(T) = \frac{4pee_o R_1}{qN_d}\Psi_p(T) \qquad (2)$$

where R_1 is average radius of defect;

e, e_o are the dielectric constants of material and vacuum, respectively; q is the electron charge;

N_d is the total donor density in the n-type matrix;

$\Psi_p(T)$ is the total difference in electrostatic potential between the matrix and the center of the disordered region (assumed to be spherical).

The Gossick`s model for the volume (2) and according to (1,1a) we obtain:

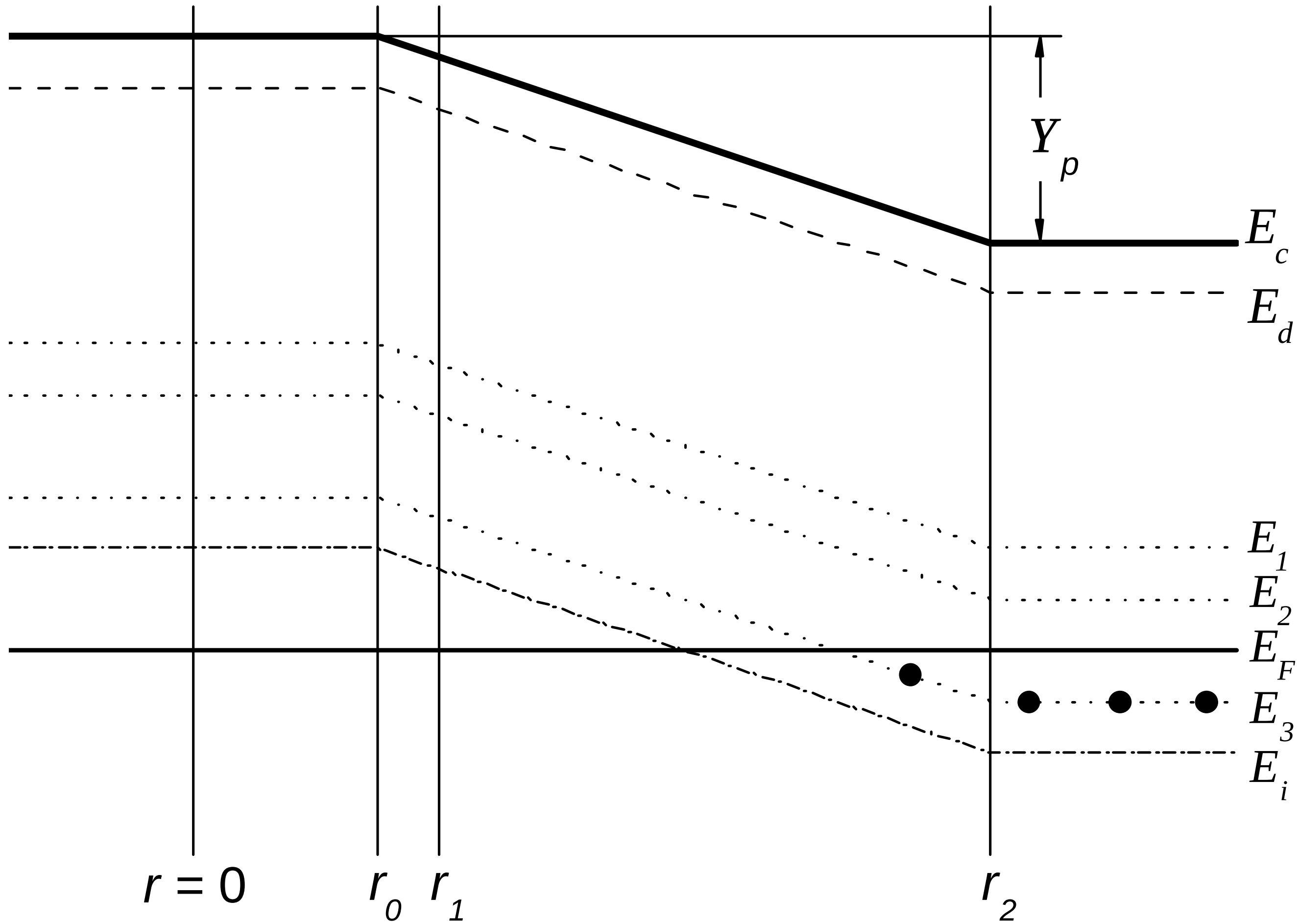
$$n_{eff}(T,\Phi) = n(T,\Phi)\cdot\exp\left[-\frac{4pee_o \Sigma R_1\Phi}{N_2(T,\Phi)\cdot q^2}\cdot\left(m - kT\ln\frac{N_c(T)}{N_2(T,\Phi)}\right)\right] \qquad (3)$$

where $N_2(T,?)$ is a screening centers concentration 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.

Theoretical explanations



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)

Theoretical explanations

In neutrons irradiated n-Si the electrons concentration in the conductive band determined by:

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

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

where g = 2 is a factor of degeneration of the acceptor level;

$N_a(F)$ is the concentration radiation-induced acceptor defects after fluece ? ;

n_{11} is equal to concentration of electrons in conductive band of n-Si,

when the Fermi level coincide with a level E_a and E_a/l one-level defect,

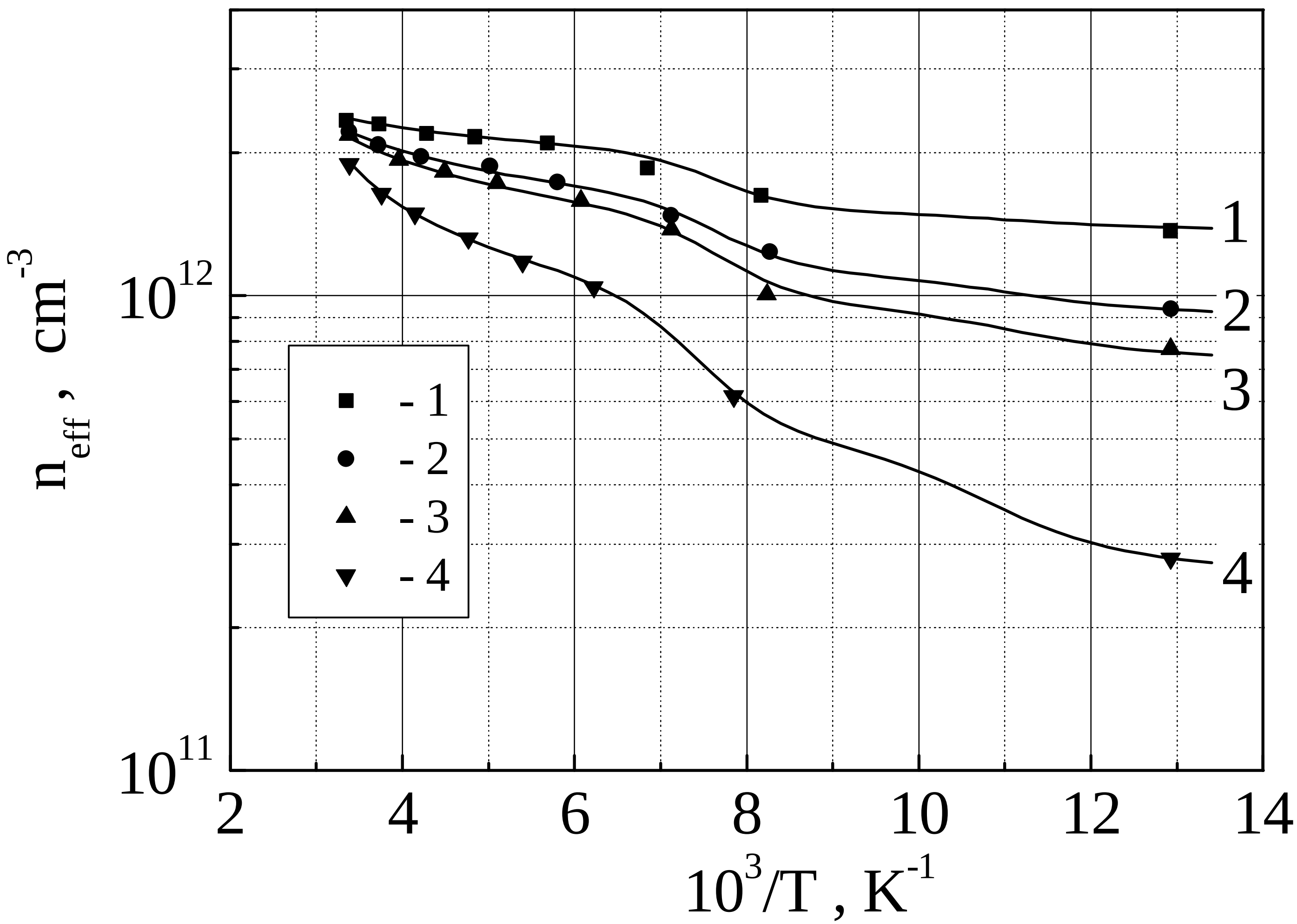
which may be in matrix and in space-charge region of defect cluster respectively.

$N_2(T,F)$ is the electrons concentration in the space charge region of cluster defect.

If the acceptor defect is located in the conducting matrix λ =1

and in case of its presence in the space-charge region of clusters λ =1.5.

The effective concentration dependence



The effective electrons concentration dependence vs. temperature for n-Si (NTD) after irradiation by the fast neutrons to fluence: 1 - $3.67\cdot10^{11}$; 2 - $4.67\cdot10^{11}$; 3 - $5.40\cdot10^{11}$; 4 - $7.33\cdot10^{11}$ $n\cdot cm^{-2}$

The effective concentration dependence

The carriers effective concentration at fluence can be calculated according to equations (3-6).

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

where $n_i(T,F,E_1)$ is determined by equation (4) at l=1 (i=1,2,3). (5)

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

$$N_2(T,F)=N_{21}(T,F)+N_{22}(T,F)+N_{23}(T,F)-2N_d(F)+\frac{N_a(F)}{l} \quad (6)$$

where $N_{2i}(T,F,E_i)$ is defined by equation (4) at l=1.5 (i=1, 2, 3).

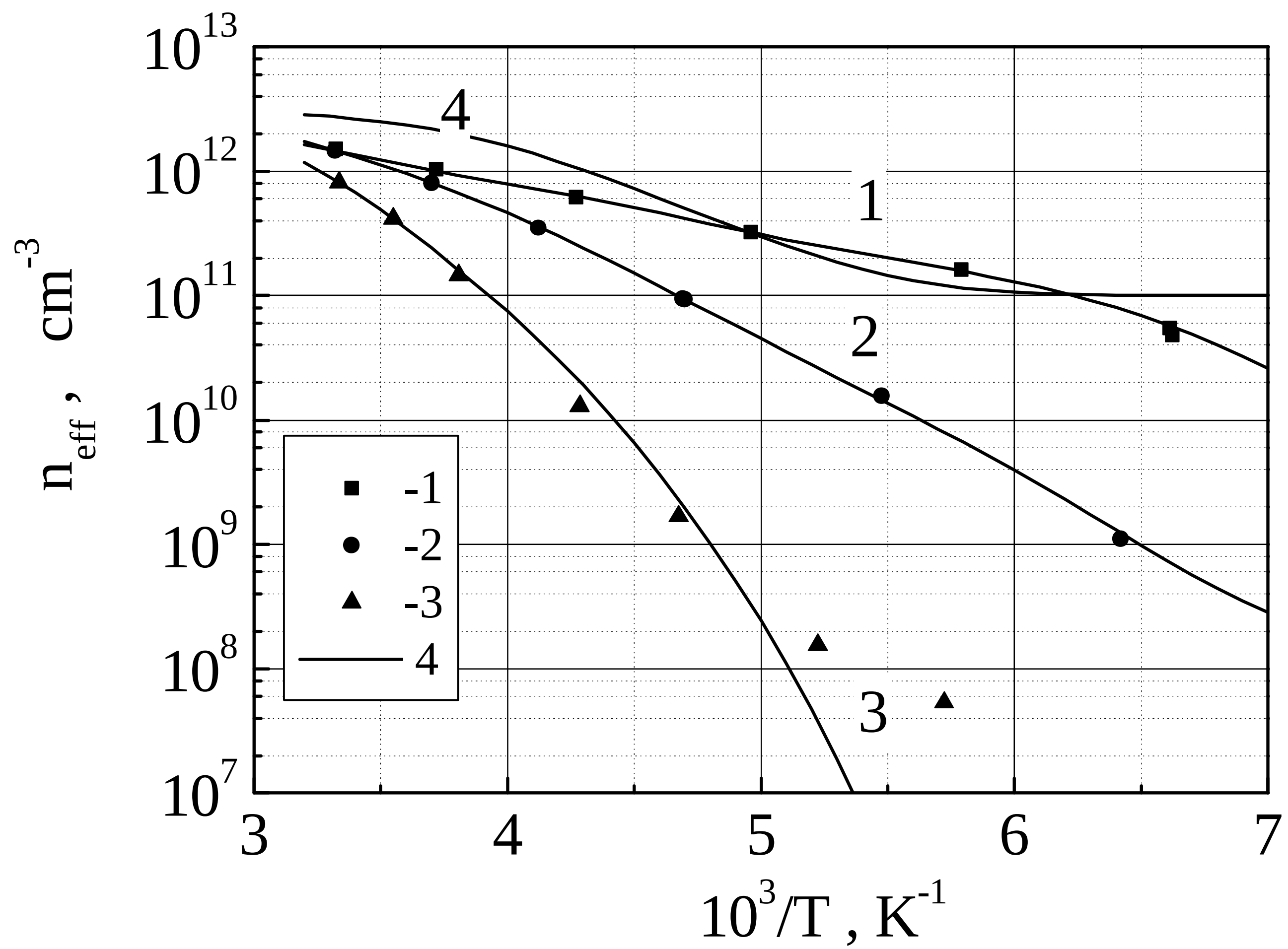
N_a is a second acceptors level concentration. If $F=0$, then $n_i(T,0)=N_d(0)$ according to (4). The average radius of defect clusters is one of most important its parameters. From equations (1), (1a) and (2) for n-Si(ρ≥40 Ω·cm) at low fluence with follows:

$$\ln n(T)=\ln n_{eff}(T)+\frac{4pee_0R_1\Sigma\Phi}{q\cdot N_2(T)}\left(m-kT\ \ln\frac{N_c(T)}{N_2(T)}\right) \quad (7)$$

Considering (7) at two temperatures T_1 and T_2 where n(T), N_2(T) remains constant (for the case n-Si T_1≈300 K and T_2≈200 K) one obtains for the calculation of the average radius of cluster:

$$\overline{R}_1=\frac{q^2N_2\ln\frac{n_{eff}(T_1)}{n_{eff}(T_2)}}{4pee_0\Sigma\Phi k\ln\frac{\left[N_c(T_1)/N_2\right]^{T_1}}{\left[N_c(T_2)/N_2\right]^{T_2}}} \quad (8)$$

The effective concentration dependence



The electrons effective concentration dependence vs. temperature for n-Si (NTD) after irradiation by the fast neutrons to fluence: 1 - $1.33 \cdot 10^{12}$; 2 - $2.0 \cdot 10^{12}$; 3 - $3.0 \cdot 10^{12}$ $n \cdot cm^{-2}$; 4 — the concentration of electrons in the n-Si conducting matrix with the fluence $2 \cdot 10^{12}$ $n \cdot cm^{-2}$

Calculated concentration

F (n·cm^{-2})	n_o (cm^{-3})	N_b (cm^{-3})	N_a (cm^{-3})	E_c-E_a (eV)	R_1(Å)
$3.67\cdot10^{11}$	$2.67\cdot10^{12}$	$2.52\cdot10^{12}$	$6.0\cdot10^{11}$	0.18	36
$4.67\cdot10^{11}$	$2.68\cdot10^{12}$	$2.52\cdot10^{12}$	$7.0\cdot10^{11}$	0.18	57
$5.4\cdot10^{11}$	$2.64\cdot10^{12}$	$2.51\cdot10^{12}$	$7.95\cdot10^{11}$	0.18	58
$7.33\cdot10^{11}$	$2.51\cdot10^{12}$	$2.33\cdot10^{12}$	$1.08\cdot10^{12}$	0.19	64
$1.33\cdot10^{12}$	$2.35\cdot10^{12}$	$2.05\cdot10^{12}$ $1.05\cdot10^{12}$ $7.5\cdot10^{11}$	$1.0\cdot10^{12}$ $3.0\cdot10^{11}$ $1.9\cdot10^{12}$	0.315 0.261 0.204	60
$2.0\cdot10^{12}$	$3.07\cdot10^{12}$	$2.57\cdot10^{12}$	$2.47\cdot10^{12}$	0.36	76
$3.0\cdot10^{12}$	$3.07\cdot10^{12}$	$2.32\cdot10^{12}$ $5.2\cdot10^{11}$	$1.8\cdot10^{12}$ $0.9\cdot10^{12}$	0.405 0.39	86
$4.0\cdot10^{12}$	$2.38\cdot10^{12}$	$1.48\cdot10^{12}$	$1.2\cdot10^{12}$	0.39	92
$6.67\cdot10^{12}$	$2.51\cdot10^{12}$	$2.44\cdot10^{12}$	$1.75\cdot10^{12}$	0.43	92
$1.33\cdot10^{13}$	$2.79\cdot10^{12}$	$2.79\cdot10^{12}$	$2.78\cdot10^{12}$	0.62	-

Calculated concentration (N_a) and energy levels (E_a) for radiation defects in the conducting matrix n-Si (NTD) irradiated by various fluencies of fast neutrons (Φ);

N_b is a concentration of screening centers outside the damage region of defect clusters with an average radius R_1

Carrier removal rate

E_c-E_a (eV)	n (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	

The carrier removal rate of (ν) by radiation defects in the conducting matrix of n-Si (NTD) irradiated by fast neutrons

The introduction rates

Si sample	**T, K**	**n_0, cm^{-3}**	**n_i, cm^{-1} (E_c – 0.43 eV)**	**n_j, cm^{-1} (E_c – 0.315 eV)**	m, 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

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 m used for definition dose dependence of the carriers concentration in grown by various technique (FZ, Ar, NTD) n-Si with average concentration of carriers (n_0) before irradiation.

CONCLUSION

✓ N-Si grown in argon ambient is more radiation hard, compare to silicon (FZ) grown in vacuum.

✓ The neutron transmutation doped n-Si is more radiation hardness relative FZ silicon grown in vacuum and argon ambient.

✓ The argon atoms presence and dislocation loops in silicon lattice cases the deformation strain fields that seem to be stimulate of divacancies recombination and self-interstitials of silicon.

✓ Thus, mentioned effect could be useful for improving of the silicon radiation tolerance.

Present status activity of pre-irradiation project

5 high purity 4 inch FZ silicon pre-irradiated wafers and **2** reference ones have been processed by **ITC-IRST**.

2 high resistivity 4 inch pre-irradiated MCZ wafers and **1** reference one have been processed by **ITC-IRST**.

Diodes have been tested by 10 kHz C-V and I-V measurements

The main part of diodes is sufficient for electrical characterization.

The problem: Non optimal polishing of wafers have been done.

The obtained structures have been irradiated in CERN by 24 GeV protons and will be irradiated in October at Kiev reactor by fast neutrons.

The irradiation in Lubljana Research Reactor is also planed.

Improved method of wafer polishing.

7 NTD n-Si(Topsil) have been sent to ITC-IRST for processing**.**

3 high resistivity 4 inch n- Si and have been pre-irradiated and now are in polishing process

7 high resistivity 4 inch p- Si and have been pre-irradiated now are in polishing process