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RADIATION HARDNESS STUDIES ON SILICON DETECTORS IN FAST NEUTRON FIELDS

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Abstract

Electrical and spectrometric damage tests in two fast neutron environments for ELMA and SGS detectors are presented. Results on depletion voltage, α damage constants and self-annealing are discussed. Supplementary damage effects due to nuclear reactions are evaluated. The large spread of the data in the self-annealing corrected α damage constant versus hardness parameter plot shows the difficulty in comparing the results obtained at different neutron facilities.

1 Introduction

Extensive radiation hardness studies for Si detectors to be used at new colliders (LHC, HERA) have been made worldwide to characterize their behaviour in the intense radiation fields expected in the respective interaction regions. In spite of a more or less clear picture already accepted in the high-energy physics community regarding the possibilities of using Si in the detector systems in future experiments, there are still a lot of questionable aspects of the problem, due to the very many factors influencing the detector behaviour.

2 Neutron Spectra

Radiation damage studies on silicon detectors have been performed with fast neutrons at two irradiation facilities: the ITN- $\Sigma\Sigma$ facility at the VVR-S reactor at the Institute of Physics and Nuclear Engineering (IPNE), at the Institute of Atomic Physics (IAP) Bucharest and the fast pulsed reactor IBR-2 at the JINR Laboratory for Neutron Physics in Dubna. The neutron spectra obtained can be characterized for radiation hardness test purposes by the following parameters [1]:

- the average energy $\langle E \rangle$
- the spectral index (SI)
- the hardness parameter (HP)
- the gamma dose-neutron fluence ratio (A)

The $\Sigma\Sigma$ facility is a spherical fission source and has been described in a previous paper [1]. The flux density at nominal reactor power (2MW) is $3.385 \times 10^9 n/cm^2 s$, with a non-uniformity of 2.5% in a vertical section, and of 6% along the thermal axis, from the center to the edges.

The JINR Dubna facility is situated in the fast neutron beam of the IBR-2 pulsed reactor, belonging to the Activation Analysis Group of the Laboratory for Neutron Physics [2]. The flux density is about $3 \times 10^8 n/cm^2 s$ in the plane of the cross-section used for detector irradiations at 720cm from the center of the core. Beam uniformity is assured on an area of about $(15 \times 20)cm^2$. Flux is monitored by activation technique (Ni) with an accuracy of 5%.

The spectra of the two facilities are presented in fig. 1 and the main parameters describing the fields are given in Table 1.

For a comparison with other spectra used in radiation hardness tests on Si, we give some further data from literature, on similar facilities. Estimates were made by us from references where the parameters characterizing the spectra have not been published. (Table 2)

Facility	SI	$\Phi[n/cm^2 s]$	$\langle E \rangle [MeV]$	HP	$A[Gy/n/cm^2]$
$\Sigma\Sigma$	17.2 ± 0.7	$3.385 \cdot 10^9$	0.827	0.704 ± 0.07	$1.9 \cdot 10^{-12}$
IBR-2	11.69^+	$3 \cdot 10^8$	1.601^+	1.062^+	$5.6 \cdot 10^{-11}$

⁺ The data for this spectrum have an energy cut at 0.5 MeV, so our calculations have been limited to the energies above this value; the parameters SI, $\langle E \rangle$, HP would be modified: SI increased, and $\langle E \rangle$ and HP decreased, if extrapolating the spectrum into the keV region.

Table 1: Parametric characterization of the $\Sigma\Sigma$ and IBR-2 neutron irradiation facilities

Neutron source	SI	$\langle E \rangle [MeV]$	HP	Remarks [ref.]
T(p,n) ³ He	–	1.2	0.88	[3]
D(d,n) ³ He	–	5.0	1.6	"
T(d,n) ⁴ He	–	14.1	1.88	"
Be(d,n)B	–	6.2	1.53	"
²⁵² Cf	–	2.1	1.06	"
Am-Be	–	4.8	1.42	"
reactor	–	2.1	1.06	"
PSAIF	0.79	1.09	1.08	[4]
ISIS-RAL	4.1	2.44	1.6	[5, 15]
⁷ Li(p,n) ⁷ Be	–	1.109	0.912	[6]
$\Sigma\Sigma$	17.2	0.827	0.704	[1]
IBR-2	11.69	1.601	1.062	[2]

Table 2: Data on neutron irradiation spectra for radiation hardness testing

Comparing the spectra to those expected at future colliders, the $Z\bar{Z}$ and $IBR\text{-}2$ spectra seem to be adequate for the neutron radiation tests, being close to the “1 MeV” spectrum expected [7].

Depletion voltage

Standard I-V, C-V measurements have been performed, similar to those described by several authors [12, 13], with special care taken for the correct measurement of the bias voltage, which is affected by the changes in the highly irradiated detectors (resistivity is modified). Direct measurements of voltage have been performed on

Electrical measurements — C-V, I-V characteristics — have been performed in the Laboratory for Particle Physics at JINR Dubna for the detectors manufactured by ELMa (a complete characterization of the detectors is given in [9, 10]) and at Microelectronica S.A., Bucharest for the SGS-Thomson detectors.

4 Electrical measurements

Detector thickness for both types of detectors is approximately $400\mu\text{m}$. resistivities of 5–7k Ωcm (described in [11]). ST (SGS-Thomson), obtained from INFN Milano and Florence, Italy, with initial $-(0.5 \times 0.5) \times 10^4 \text{ cm}^2$ detectors, with p^+n^+ structure, manufactured by of 2–4 k Ωcm (described in [8, 9, 10]). Dubna-ELMA Zelenograd Russia collaboration, with initial resistivities of the bulk –large area ($2 \times 2 \text{ cm}^2$ detectors, with steep p^+n junction, manufactured in the

The Si pad detectors used are diode structures on n-type Wacker Chemitronics FZ (float zone) $< 111 >$ silicon, manufactured in standard planar technology:

3 The detectors

We should remark that the parameters given in Table 2 depend very much on the cuts applied to the spectrum at low energies. Especially HP depends very much on the spectrum in the 0.1–0.5 MeV region where the damage cross-section has very steep variations. This parameter should be used with care for comparing the damage in the detectors irradiated at different facilities.

the detectors, and corrections due to the increase of the leakage current have been calculated. The quantity extracted is the full depletion voltage from the C-V characteristics.

In the usual “plane condenser” model, equations (1)–(3)

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For the non-irradiated detector, the relations above are valid, and the dependence $C = f(1/\sqrt{V})$ is linear, but this is not true anymore for increasingly damaged detectors. (In log-log C-V scale, the slopes for non-irradiated and small-fluence irradiated detectors are 0.5 within the experimental errors). This way, the

$$\begin{aligned} |N_{eff}| &= \frac{2\epsilon_0\epsilon_r}{ed^2}V_{dpl} \\ \rho &= \frac{2\epsilon_0\epsilon_r\mu V_{dpl}}{d^2} \end{aligned} \quad (5)$$

For full depletion $x = d$, $V = V_{dpl}$, and

At bias voltages applied, the effect of the built-in voltage is negligible, so one can make a straight line fit in C-V log-log scale, in the bias region below the full depletion capacity saturation, and above the flat-band voltage step. The slope obtained should be 0.5, assuming the plane condenser model works.

$$C(V) \approx \sqrt{\frac{2}{\epsilon_0\epsilon_r} \frac{1}{|N_{eff}|} \frac{e}{1} \sqrt{V}} \quad (4)$$

are supposed to be valid, so

C =capacity
 x =depleted thickness
 $|N_{eff}|$ =relative impurity concentration
 ρ =resistivity
 ϵ_0 =permittivity of free space
 μ =mobility of the maj. charge carriers
 ϵ_r =relative permittivity
 V_b =built-in voltage
 e =electron charge
 A =detector area

with

$$\rho = \frac{e\mu |N_{eff}|}{1} \quad (3)$$

$$x = \sqrt{\frac{2\epsilon_0\epsilon_r}{e |N_{eff}|} (V + V_b)} \quad (2)$$

$$C(x) = \frac{x}{\epsilon_0\epsilon_r A} \quad (1)$$

whole discussion referring to parameters like $|N_{eff}|$ or ρ , assuming the simple plane condenser model, is qualitative, or provides at most an average description. We consider that the direct calculation of $|N_{eff}|$ from eq. 5 is more precise in the context presented above, in comparison with the other variants of the method of calculation of $|N_{eff}|$ [3] (from the slope of the $\ln C = f(V)$, $C = f(1/\sqrt{V})$ or $C^2 = f(V)$ dependences).

Inverse current in the junction

The current in the junction is dominated by the volumic generation current, highly dependent on temperature

$$I_{vol} \propto T^2 \exp\left(-\frac{\epsilon_g}{2kT}\right) \quad (\epsilon_g = \text{energy gap in Si}), \quad (6)$$

proportional to the active volume of the detector

$$I_{vol} = \frac{en_i x A}{2\tau}, \quad (7)$$

with τ the average minority carrier lifetime and

$$n_i^2 = 1.5 \times 10^{13} \text{ cm}^{-6} \left(\frac{T}{k}\right)^3 \exp\left(-\frac{\epsilon_g}{kT}\right).$$

In the frame of the model, the I-V dependence is $I \propto \sqrt{V}$ type (from eqs. (7), (4)), reaching a plateau for $V = V_{depl}$. In the real case, due to further lateral extension of the electric field, I increases above V_{depl} . The inflexion point at full depletion is less clear than in the C-V case, these measurements are not used for the determination of V_{depl} .

5 Spectrometric measurements

Alpha spectrometry provides an alternative and, at the same time, complementary method of study of the radiation hardness properties of the Si pad detectors. Our measurements have been performed at Bucharest University, on a standard spectrometric chain, consisting mainly of ORTEC modules: charge -sensitive preamplifier (ORTEC 121), amplifier (ORTEC 485), multichannel analyser (Canberra 4096 channels). Two HV sources (ORTEC 428A: 1–1000V, ORTEC 456: 0–3kV) have been used, to cover the range of bias, for the detectors of different resistivities (due to radiation damage), and bias voltage applied on the detector has been measured with an electrostatic voltmeter.

The α sources used were ^{241}Am ($E_\alpha = 5.5 \text{ MeV}$) and ^{233}U ($E_\alpha = 4.8 \text{ MeV}$), in a fixed geometry.

The information which can be extracted from this type of measurements is mainly related to the depletion voltage and charge collection efficiency.

The range of $\sim 5 \text{ MeV}$ α particles in Si is about $25 \mu\text{m}$, so, one can use the dependence of the rear side α signal versus bias voltage, to extract the voltage corresponding to full depletion. The pulse height is [14]:

$$V_s = \frac{eE_\alpha}{wC} \quad (8)$$

with w = the average energy necessary to produce an electron-hole pair

One might expect again, in the model of a steep junction a $V_s \propto \sqrt{V}$ dependence, but, as the α particles are absorbed outside the sensitive volume, the dependence is different, due to charge losses outside the depleted volume.

The quantity we used was the ratio

$$\frac{E_r}{E_f} = \frac{V_{s,r}}{V_{s,f}} = \frac{Q(n^+)}{Q(p^+)} \quad (9)$$

with indices r, f for rear- and front-side α incidence respectively, and Q the collected charges for α incidence on the p^+ , n^+ side of the detector respectively.

For a few volts, the front signal is saturating, so the effect corresponding to the dependence is describing the increase of the depleted region, and the ratio becomes equal to 1 at $V = V_{depl}$.

The accuracy of the method is much affected by the lack of a clear criterion for the determination of the value of the depletion voltage. But anyhow, the spectrometric method gives the same values within the errors as the electrical C-V measurements, presenting a more visual picture of the type conversion.

6 Radiation damage considerations

At present, it is generally accepted that the following conclusions regarding the radiation hardness at neutrons are valid [3, 12, 13]:

1. The leakage current increases with neutron fluence following a linear dependence

$$\frac{\Delta I_{vol}}{V} = \alpha \Phi \quad (10)$$

Some parametrisation for the self-annealing behaviour has been tried for the leakage current [3, 13], but there is no theoretical basis for using the same parameter values for different detectors and irradiation experiments.

2. From the behaviour of the depletion voltage with fluence, usually a $|N_{eff}|$ versus fluence dependence is calculated. As we already mentioned, as far as the model is so approximate, we consider this description not very conclusive.

3. Though there have been some attempts of unifying the results from different groups[3], working with different radiation spectra, by normalization to 1 MeV equivalent neutrons, it is still difficult to compare these results. It is not really clear yet which of the very many influences (variables) are essential in the study, and how close real spectra at colliders will produce the same effects as our damage-simulation tests and estimates.

7 Results

The results presented here are based on a set of pad detectors, irradiated with fast neutron fluences in the ranges of 10^{11} – 2×10^{13} at IBR-2, and 5×10^{10} – 10^{15} n/cm^2 at $\Sigma\Sigma$. Measurements have been performed in a time range of 3–722 days after the irradiation.

1. Fig.2 and 3 give the dependences versus bias voltage of C and Q(p^+)/Q(n^+). Results on V_{depi} are presented in Table 3. Some comments are to be made on the results:

- With our data we cannot see a clear self-annealing behaviour of V_{depi} (N_{eff}) in time, within the errors of our estimates.
- The determination of V_{depi} for the sample irradiated at 8×10^{12} n/cm^2 is to a great degree arbitrary, as we cannot find a more or less linear dependence in log scale C–V, approaching the saturation region. The dependence seems to be more complicated than a power law, so it is clear that for that sample no plane-condenser model can be applied. Though, from the alpha measurements, we see that the detector is still working, and resolution is not very much affected by the neutron damage. This case is very similar to the one discussed in [11].
- The two methods of computing V_{depi} (C–V, PHA) give comparable results taking into account the high imprecision of the PHA method.
- V_{depi} (N_{eff}) is decreasing for fluences up to inversion. Data above inversion show a discontinuity for the detectors irradiated in two different facilities. Unfortunately we have no data for detectors irradiated at the same facility all over the fluence range.

$$\alpha = a_1 \exp(-t/a_3) + a_2 \exp(-t/a_4) \quad (11)$$

which works with only two exponentials in the range of annealing time of our experiment (3–722 days). Two sets of data have been fitted separately for different facilities because the hardness parameter is different.

- Due to the uncontrolled conditions in measuring the reverse current on SGS detectors, the fitted values for $\alpha(0)$ are affected by large systematic errors. The $\alpha(0)$ value estimated for all the detectors irradiated at the $\Sigma\Sigma$ facility is:

$$\alpha(0) = (8.9 \pm 1.0) 10^{-17} A/cm$$

- The fit for the ELMMA detectors irradiated at IBR-2 is more reliable. Results are shown in fig.5. The curve is the fit for the ELMMA detectors irradiated at IBR-2 which gives

$$\alpha(0) = (7.1 \pm 1.4) 10^{-17} A/cm$$

$$a_1 = (5.02 \pm 1.37) 10^{-17} A/cm$$

$$a_2 = (2.07 \pm 0.02) 10^{-17} A/cm$$

$$a_3 = (5.39 \pm 1.62) d$$

$$a_4 = (2020 \pm 910) d$$

Facility	Fluence [n/cm ²]	V _{depl} [V]		N _{eff} [10 ¹¹ cm ⁻³]	ρ [kΩcm]
		from C-V	from PHA		
	0	52.4±0.5	51±3	4.2	10.4
IBR	6 10 ¹¹	46.3±0.5	40±3	3.7	11.8
IBR	2 10 ¹²	32.6±0.4	32±3	2.6	16.8
IBR	8 10 ¹²	~14	~17	1.1	39.8(p:11.3) ⁺
IBR	1.6 10 ¹³	163.8±0.7	–	13	(p:9.6)
ΣΣ	5.2 10 ¹³	107.2±1.4	–	8.6	(p:6.9)
ΣΣ	8.2 10 ¹³	179.6±1.4	–	14	(p:8.9)

⁺p: means that ρ is computed for p-type silicon after type inversion

Table 3: Results on depletion voltage measurements

Detector type	time [days]	α ± Δα [10 ⁻¹⁷ A/cm]	α _{FIT} [10 ⁻¹⁷ A/cm]	
			IBR-2	ΣΣ
ELMA	3	4.76	0.47	4.74
"	7	4.17	0.41	3.43
"	10	2.60	0.26	2.89
"	83	1.99	0.20	1.99
"	451	1.73	0.17	1.66
"	722	1.37	0.15	1.43
ELMA	3	5.56	0.83	6.40
"	14	3.43	0.51	2.92
SGS(Milano)	22	2.29	0.45	2.37
(Florence)	33	3.07	0.70	2.17
SGS(Milano)	35	2.16	0.43	2.16
"	163	1.92	0.38	1.98
"	224	1.99	0.40	1.91

Table 4: α values for detectors irradiated at the IBR-2 and ΣΣ facilities

On the same figure we plotted the α values for all the detectors irradiated at the ΣΣ facility.

The values of α(0) are affected by two systematic errors which work in opposite sense:

- one is decreasing the α(0) value with about 26% due to the fact that we neglected in the fit the short cooling time exponentials (the evaluation of this contribution is taken from [13]).
- the other is increasing α(0) with about 25% due to the fact that all the measurements have been performed at 23–24°C and we did not apply a temperature correction, because it has not been measured in all cases.

We conclude that the two errors compensate their contribution to α(0).

- Figure 6 shows the α(0) values versus the hardness parameter for different experiments on neutron damage in silicon detectors. All the data are corrected for self-annealing and temperature. The plot shows a large spread of the data which is an indication of the systematic errors which affect such experiments.

To check whether there are supplementary sources of damage in the ΣΣ facility, suggested by the higher value of α(0) obtained, we estimated the contribution of nuclear reactions in boron and aluminium as presented in the next section.

8 Damage due to supplementary irradiation effects in ΣΣ

Results on the detectors irradiated at the ΣΣ facility seem to indicate a larger hardness parameter (HP) than that computed on the neutron spectrum, using the KERMA factor for dislocations.

Therefore we tried to evaluate the contribution to damage of other possible reactions during the irradiation:

- neutrons of low and intermediate energy can induce in the p⁺ layer of the detector the nuclear reaction

in which the final nuclei contribute with a part of their kinetic energy (2.8 MeV) to the dislocations in the silicon layer.

For the evaluation of the part of the energy of the He and Li nuclei causing displacement, we used the Lindhard theory with the approximations given in [16]. A complete description of the computational model is given in [17]. Figure 7 gives the dislocation energy calculated for helium and lithium nuclei in silicon. An overestimation of 10–15% of this energy is possible for alpha particles with energies above 600keV, due to the approximations used.

2. The detectors have been covered during the irradiation with a 0.3mm thick aluminum foil. Intermediate energy neutrons produce the activation of this foil. The maximum energy of the electrons is 2.865 MeV and they may contribute to the dislocations in silicon. With the energy dependence of the cross section from [18] we evaluated the energy deposited by the electrons in dislocations in silicon.

3. Finally, in the $\Sigma\Sigma$ facility, there is high energy gamma radiation background from prompt fissions, which also can, in principle, contribute to dislocation creation. This contribution is negligible (less than 4×10^{-6} of the neutron effect in the same energy region), due to the low number of photons with energies above the dislocation threshold (15%) and the smaller displacement cross-section of photons relative to neutrons (10^{-4} – 10^{-5}).

Figure 8 gives a comparison between the dislocation energies deposited in silicon by fast neutrons, helium and lithium nuclei, resulting from boron reactions, and electrons from aluminium activation, versus neutron energy.

We can see that the fast neutrons are the principal source of dislocations for neutron energies higher than 20 keV. The contribution of the electrons from aluminium activation is negligible. For epithermal neutrons, helium and lithium can produce a significant number of displacements, result in agreement with that expected from [19].

Summing up the whole energy deposited in displacements in silicon, from effects other than fast neutrons, already taken into account in the HP calculation, we can find a supplementary damage of about 1% in the 0.4 eV–20 keV energy range. Thus the larger value of the α damage constant at $\Sigma\Sigma$, significant in the context of the comparison of the data for different neutron sources should be explained by other effects.

9 Conclusions

High resistivity silicon pad detectors have been irradiated in neutron environment up to fluences of 10^{14} n/cm², using two fast neutron facilities (IBR-2 at JINR Dubna and $\Sigma\Sigma$ at IAP Bucharest).

Results on full depletion bias voltage have been obtained from C–V characteristics and pulse height analysis at front and back alpha particle irradiation. Both methods give similar values. Type inversion is seen at about 8×10^{12} n/cm².

After inversion V_{dep} increases monotonically as obtained in other experiments. Leakage current has been measured at full depletion voltage for different cooling time. The damage constant α versus self-annealing time dependence has been fitted with a two-exponential law. A plot of $\alpha(0)$ versus the hardness parameter shows a large spread of the $\alpha(0)$ values for different irradiation facilities, fact due perhaps to the many uncontrolled parameters in the initial samples, irradiation spectra and measurement conditions.

Supplementary effects due to nuclear reactions in boron and aluminium have been evaluated and their contribution has been found negligible compared with fast neutron damage.

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References

[1] T. Angelescu *et al.*, NIM A345(1994)303

[2] V.M. Nazarov, private communication

[3] R. Wunstorf, DESY FHIK-92-01 (1992), Hamburg, Int. Rep. —Systematische Untersuchungen zur Strahlenresistenz von Silizium Detektoren für die Verwendung in Hochenergiephysik Experimenten

[4] E. Fretwurst *et al.*, NIM A342 (1994)119

[5] M. Edwards, D.R. Rein, *in* CERN 90-10, ECFA 90-133, vol. 3, (1990),(*eds.* G. Jarlskog, D. Rein), p. 584

[6]

G. Kegel—Radiation damage studies with accelerator generated neutrons (presented at the 1st Int. Conf. on Large Sc. Appl. Rad. Hardn. Semic. Det., Florence 1993)

[7]

D.E. Groom, (*ed.*), Tech. Rep. SSC–SR–1033, SSC Lawrence Berkeley Laboratory (1988)
G.R. Stevenson, the same as [5], p.566

[8]

CMS—Letter of Intent, CERN–LHCC 92–3, LHCC/I1 (1992)

[9]

A.E. Cheremukhin *et al.*—Investigation of silicon planar detectors for the LHC project, Dubna 1994 (to be published)

[10]

A.E. Cheremukhin *et al.*— Radiation hardness of silicon detectors for collider experiments, Dubna 1994 (to be published)

[11]

M. Bosetti *et al.* NIM A343 (1994)435

[12]

F. Lemeilleur *et al.* CERN/ECP 91–21 (1991)
Nucl. Phys. B (Proc. Suppl.) 32 (1993)415
CERN/ECP 93–8 (1993)

[13]

E. Fretwurst *et al.*, NIM A326 (1993)357

[14]

D.N. Poenaru, N. Vâlcov—Measurement of Nuclear Radiation with Semiconductor Devices, Ed. Academiei, Bucharest (1967)

[15]

K. Gill *et al.*, NIM A322(1992)177

[16]

J. Lindhard *et al.*, Danske Videnskab. Selskb. Mat.-Fys. Medd. 33 (1963)10

[17]

A. Radu—Irradiation defects in silicon detectors, Diploma Thesis, Bucharest University 1994

[18]

J.R. Stehn *et al.*—Neutron Cross–Sections, BNL 325, No.2 (1964)

[19]

I. Arimura, C. Rosenberg, IEEE Trans. Nucl. Sci. NS-20 (1973)274

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Time dependence of the α damage constant for ELMA and SG S detectors

Fig.6.

Energy spectrum dependence of the $\alpha(0)$ damage constant

Fig.7.

Energy deposited in silicon due to α and Li nuclei

Fig.8.

Energy deposited in defect creation in 300 μ m silicon

Fig.1 Fast neutron spectra for the $\Sigma\Sigma$ and IBR-2 facilities

Fig.2 C-V characteristics for ELMA detectors

Fig.3 Collected charge versus bias voltage for ELMA detectors

Fig. 4 Fluence dependence of reverse current density for ELMA detectors

Fig.5 Time dependence of the α damage constant for ELMA and SGS detectors

Fig.6 Energy spectrum dependence of the $\alpha(0)$ damage constant

Fig.7 Energy deposited in silicon due to α and Li nuclei

Fig.8 Energy deposited in defect creation in 300μm silicon