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CERN/ECP 91-21
5 November 1991

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ABSTRACT

Ion-implanted silicon pad detectors fabricated on different n-type and p-type silicon wafers with initial resistivities between 2.6 and 12.9 k Ω cm have been irradiated with neutrons of ~ 1 MeV energy, up to a fluence of $5 \cdot 10^{13}$ n cm $^{-2}$. The evolution of diode leakage current and capacitance characteristics is presented as a function of the neutron fluence. The reverse diode current increases proportionally to the neutron fluence. There is evidence that the doping of the initial n-type material evolves towards intrinsic and inverts to an apparent p-type at fluences between $1 \cdot 10^{13}$ and $3 \cdot 10^{13}$ n cm $^{-2}$, depending on the initial silicon resistivity. There is also evidence that p-type material remains of the same conduction type with a slight increase of the acceptor doping with fluence. The signal shape and the charge collection efficiency for incident β particles have also been measured. Results from this work may contribute to show the feasibility of silicon detectors in the supercolliders, in particular, for a silicon tracker and preshower under study for the LHC.

Presented at the 1991 IEEE Nuclear Science Symposium and Medical Imaging Conference,
5-9 November 1991, Santa Fe, USA

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Abstract

Ion-implanted silicon pad detectors fabricated on different n-type and p-type silicon wafers with initial resistivities between 2.6 and 12.9 kΩcm have been irradiated with neutrons of ~1 MeV energy, up to a fluence of $5 \cdot 10^{13} \text{ n cm}^{-2}$. The evolution of diode leakage current and capacitance characteristics is presented as a function of the neutron fluence. The reverse diode current increases proportionally to the neutron fluence. There is evidence that the doping of the initial n-type material evolves towards intrinsic and inverts to an apparent p-type at fluences between $1 \cdot 10^{13}$ and $3 \cdot 10^{13} \text{ n cm}^{-2}$, depending on the initial silicon resistivity. There is also evidence that p-type material remains of the same conduction type with a slight increase of the acceptor doping with fluence. The signal shape and the charge collection efficiency for incident β particles have also been measured. Results from this work may contribute to show the feasibility of silicon detectors in the supercolliders, in particular, for a silicon tracker and preshower under study for the LHC.

1. INTRODUCTION

Silicon particle detectors of various types for use in experiments at future high-luminosity hadron colliders will have to sustain a high flux of high-energy particles from the proton-proton interactions and low energy neutrons (in the megaelectronvolts range) from cascades and showers in the surrounding absorbers. Calculations [1] indicate fluences up to $10^{14} \text{ n cm}^{-2}$ per year in the central cavity.

This article presents experimental results about the evolution of diode-reverse currents, effective doping concentration and the speed of charge collection as a function of neutron fluence up to $5 \cdot 10^{13} \text{ n cm}^{-2}$.

Ion-implanted planar silicon single diodes with various geometrical sizes and initial resistivities from 2.6 to 12.9 kΩcm have been provided by several manufacturers: Canberra Semiconductor N.V., Inter technique S.A. and Micron Semiconductor Ltd. Their characteristics are summarized in tables 1 and 2. Most of them have been made on initial n-type conduction material and a few samples are on p-type.

Several samples of each series have been irradiated in the test facility of ISIS at the Rutherford Appleton Laboratory (RAL) [2] or at the ACOI irradiation facility of the PS at CERN [3]. The neutron energy spectrum of each facility presents a peak ~1 MeV. Such a spectrum is representative for the neutron spectrum to be expected in the

future hadron-collider environment [1]. The absolute neutron fluence is estimated to be known at $\pm 20\%$, while the relative calibration does not exceed $\pm 2\%$.

The crystal defects and the charge carriers generated by the radiation influence the electrical characteristics at the surface as well as in the volume of a silicon device. In a single diode detector in a fully depleted mode, mainly the bulk is affected by atomic displacements due to non-ionizing energy loss. Neutrons create defect states acting as generation/recombination centres: the consequence is an increase in the diode reverse current proportional to the decrease of the minority carrier life time. This increase of the reverse current as a function of the neutron fluence is found to be linear and sect. 2 is dealing with this.

The neutron induced defects in the bulk create charge centres acting as acceptors modifying the initial doping concentration and consequently the resistivity. The effective impurity concentration as a function of the neutron fluence is calculated from C-V curves and its evolution for n-type and p-type detectors is reported in sect. 3.

Collection time and collection efficiency of the charges generated by relativistic electrons in a non-irradiated detector and in an irradiated one have been measured and the results are presented in sect. 4.

Table 1
The n-type and p-type diodes characteristics.

Manufacturer	Ref.	Type	Shape	Size	Nominal		Initial	Nominal		Max.	Volume	α	
					area	Thickness		area	Thickness				
										cm ²	cm	cm ²	cm
Inter technique	143 B	n	Square	D=1	0.15	0.023	310	9.03	0.0007	PSAIF	36.0	1.798	3.70
Inter technique	142 C	n	Square	D=1	0.15	0.023	310	8.82	0.0007	PSAIF	18.5	1.798	3.64
Canberra S.	41	p	Round	D=0.65	0.332	500	15.62	0.0166	PSAIF	18.5	1.200	3.77	
Canberra S.	42	p	Round	D=0.65	0.332	500	14.42	0.0166	PSAIF	18.5	1.200	3.66	

Table 2
The n-type diodes with various initial resistivities.

Manufacturer	Ref.	Type	Shape	Size	Nominal		Initial	Nominal		Irradiation facility	Max. fluence	Volume corr. factor	α factor
					area	Thickness		area	Thickness				
					cm ²	cm	cm ²	cm	cm ²	cm	10 ¹² n cm ⁻²	10 ⁻¹⁷ A cm ⁻¹	
Canberra S.	C12	n	Round	D=1	0.785	304	3.00	0.0239	ISIS	4.5	1.120	3.41	
Canberra S.	C21	n	Round	D=1	0.785	300	7.15	0.0236	PSAIF	43.5	1.075	2.51	
Canberra S.	C22	n	Round	D=1	0.785	300	7.15	0.0236	PSAIF	43.5	1.064	2.46	
Inter technique	I31	n	Round	D=1	0.855	298	2.58	0.0255	ISIS	4.5	1.129	3.40	
Inter technique	I32	n	Round	D=1	0.855	298	2.58	0.0255	ISIS	4.5	1.141	3.73	
Inter technique	I5	n	Square	0.5	0.250	319	4.85	0.0080	ISIS	4.5	1.185	3.70	
Inter technique	I6	n	Square	0.5	0.250	308	4.85	0.0077	PSAIF	43.5	1.131	4.07	
Inter technique	I7	n	Round	0.8	0.503	296	7.12	0.0149	ISIS	4.5	1.149	3.50	
Inter technique	I9	n	Square	0.5	0.250	508	12.94	0.0127	ISIS	4.5	1.333	3.28	
Inter technique	I10	n	Square	0.5	0.250	509	11.58	0.0127	PSAIF	43.5	1.321	3.59	
Micron S.	M1	n	Square	1	1.000	317	10.05	0.0317	ISIS	2.9	1.094	2.66	
Micron S.	M2	n	Square	1	1.000	317	10.05	0.0317	ISIS	4.5	1.128	3.08	
Micron S.	M3	n	Square	1	1.000	317	10.05	0.0317	ISIS	50.0	1.093	3.68	
Micron S.	M5	n	Square	1	1.000	317	10.05	0.0317	PSAIF	43.5	1.084	3.66	

(*) From Associazione per lo Sviluppo Scientifico e Tecnologico del Piemonte (ASP).

2. DIODE REVERSE CURRENT

The increase of the diode reverse current is a consequence of defects induced by neutrons at the surface and in the bulk of the detector. The volume component due to generation current is preponderant after irradiation as shown by the fact that the current is proportional to the square root of the bias voltage.

The generation current is exponentially dependent on the temperature at which the measurement is performed [4] and our data are normalized at 20°C using the equation

$$I_{20}/I_T = (293.2/T)^2 \times \exp[(1.21/2k)(1/T - 1/293.2)], \quad (1)$$

k being the Boltzmann constant and T the temperature in Kelvin degrees.

This current component is generated in the active volume of the detector which is determined by the depletion thickness and the lateral extension. To be independent of the depletion thickness the reverse current has to be measured at full depletion voltage. The effective volume S_{eff} due to the lateral field extension is calculated from the value of the capacitance C_m measured at full depletion

$$S_{eff} = C_m / C_g A_g x_d, \quad (2)$$

with the geometrical capacitance $C_g = \epsilon_0 \epsilon_{si} (A_g / x_d)$, A_g being the junction implanted side area and x_d the detector thickness. The volume correction factor due to the lateral field extension for each detector is given in tables 1 and 2.

The volume leakage current I/V is then defined as the measured current at full depletion voltage divided by the effective volume S_{eff} and normalized at 20°C. The volume current increase can be expressed as

$$\Delta I/V = \alpha \Phi, \quad (3)$$

where α is the reverse current damage coefficient and Φ is the fluence in neutron cm^{-2} .

Figure 1 shows the reverse current increase in small steps of fluence for the n-type detector 143 B, each data point being measured about half an hour after irradiation. The current jumps at fluences of 6 and 17 $10^{12} \text{ n cm}^{-2}$ correspond to annealings due to respectively 19 h and 65 h of irradiation interruptions. For each step in fluence we have calculated the α value. These can be regarded to be constant at $5 \cdot 10^{-17} \text{ A cm}^{-1}$ above $\sim 20 \cdot 10^{12} \text{ n cm}^{-2}$ within the random fluctuations indicated by the error bars in fig. 1.

Figure 2 shows the leakage current increase measured a few days after each irradiation step for the n-type detectors listed in table 2. The α coefficients as shown in the same table extend from 2.5 to $4.1 \cdot 10^{-17} \text{ A cm}^{-1}$. The discrepancies observed from one detector to another are uncorrelated with their initial characteristics, although C21 and C22 present lower values of α . The average value of α ($3.3 \pm 0.8 \cdot 10^{-17} \text{ A cm}^{-1}$) is lower than those given by other experimenters (4.8 to 8) [5] and this can only in part be explained by our volume correction and by the absence of an annealing correction.

Figure 3 shows the current increases for the n-type diode 142 C and for the p-type diode 42 irradiated at the same time.

Each measurement was performed within half an hour after irradiation. The α values 3.6 ± 0.2 for n-type and 3.9 ± 0.2 for p-type diodes are close. It might be concluded that the reverse current increase for n-type and p-type diodes is rather similar at least up to a fluence of $1.85 \cdot 10^{13} \text{ n cm}^{-2}$.

Fig. 1 Leakage current versus fluence for detector 143B (table 1) measured about half an hour after each irradiation step.

Fig. 2 Leakage current versus fluence for the n-type detectors listed in table 2, measured a few days after each irradiation step.

Fig. 3 Leakage current versus fluence for an n-type diode and for a p-type diode.

The influence of the room temperature annealing effect is shown by measuring the reverse current at various times after irradiation. As shown in fig. 4 for detectors irradiated at three

fluence levels, we observed a reduction of ~25% after 12 days. Even after 5 months this effect is not more than to 30 – 40%. Continuous monitoring of the leakage current of a biased detector during irradiation up to 10^{14} n cm⁻² and during the subsequent annealing shows only a limited short-term annealing, even immediately after the irradiation has been stopped (fig. 5). This result, closely resembling detector operation in a real experiment, indicates that a permanent electric field prevents annealing of reverse current. However, the bias voltages can be switched-off during accelerator shut-downs and in this way one may still introduce some annealing [6].

Fig. 4 Leakage current room temperature annealing versus time after irradiation.

Fig. 5 Leakage current annealing for a biased detector. The current has been continuously recorded during and after irradiation.

3. EFFECTIVE DOPING CONCENTRATION

The defects generated by neutrons in a silicon device change both donor and acceptor concentrations which are originally present in the bulk. Also conversion of electrically inactive defects into donors or acceptors may occur [7]. However, the resulting net effect is the creation of acceptor-like centres. As a consequence the doping concentration is seen to evolve with the neutron fluence and an initial n-type material may change its conduction type above a certain fluence level. Z. Li and H.W. Kraner [8] have developed a two-trap level model which predicts both the effects of C-V frequency dependence and dopant compensation. Several groups [9, 10] have introduced a parametrization to describe the removal of the initial impurities N_0 and the creation of acceptor-like centres. The effective impurity concentration N_{eff} can be expressed as a function of the neutron fluence ϕ

$$N_{eff} = N_0 \exp(-c\phi) - \beta\phi \quad (4)$$

From Poisson's equation, assuming an abrupt junction and a constant charge density, the effective impurity concentration of a diode bulk is related to the depletion depth x_d for the full depletion voltage V_d , V_0 being the built-in voltage

$$N_{eff} = (2\epsilon / q)(V_d + V_0) / x_d^2 \quad (5)$$

From C-V curves, knowing the diode thickness, it is possible to measure the full depletion voltage and to calculate the effective impurity concentration as a function of the neutron fluence.

The V_d is obtained as the extrapolation of the C-V curve to the minimum value of the capacitance. The C-V curve for irradiated diodes are frequency-dependent [8], however, the extrapolated values remain the same. Before irradiation, the capacitance is inversely proportional to the square root of the voltage; this is no more true after irradiation suggesting a non-uniform doping concentration evolution. Consequently, our estimation of N_{eff} can be considered as an average value of the bulk doping concentration.

Figure 6 shows such measurements performed at 1.6 KHz for an initial n-type detector with 11.8 kΩcm resistivity irradiated up to 5.10^{13} n cm⁻². For successive irradiation the full depletion voltage is initially decreasing to reach a minimum value and is progressively increasing again. This can be interpreted first as a decrease of donor concentration and then as an inversion of the material towards an apparent p-type.

Fig. 6 The C-V curves for a single detector irradiated at increasing fluences.

Figure 7 shows the effective impurity concentration versus neutron fluence for the various initial n-type detectors listed in table 2. For high initial resistivity diodes there is a lower impurity concentration to be compensated and the type inversion takes place at $\sim 10^{13}$ n cm⁻²; for low initial resistivity diodes the doping type inversion happens above $\sim 2.10^{13}$ n cm⁻².

The evolution in smaller steps of fluence of the effective number of impurities versus fluence is shown in fig. 8 for an n-type detector 143 B, with an initial resistivity of 9 kΩcm. There is a clear evolution of the initial n-type towards an apparent p-type bulk.

Figure 9 shows the effective doping concentration versus neutron fluence for the initial n-type diode 142 C and for the

p-type diode 42 irradiated at the same time. Although the fluence is limited, there is evidence that the donor concentration of the initial n-type diode reaches a minimum at $\sim 10^{13} \text{ n cm}^{-2}$ and would have had an evolution towards an apparent p-type like the one of fig. 8. The p-type diode in comparison remains with the original conduction type and is increasing slightly its acceptor concentration with fluence.

Fig. 7 Effective impurity concentration deduced from C-V measurements, versus neutron fluence, for detectors with various initial resistivities (table 2).

Fig. 8 Effective impurity concentration versus neutron fluence for a detector with $9 \text{ k}\Omega\text{cm}$ initial resistivity. This is the same sample as the one shown in fig. 1 with the same remark about the jumps at 6 and $17 \cdot 10^{12} \text{ n cm}^{-2}$.

Simple fits of N_{eff} versus fluence, using eq. (4) with $C = 0$, give $\beta = 0.026 \pm 0.002$ for the n-type diode of fig. 8 and $\beta = 0.029 \pm 0.003 \text{ cm}^{-1}$ for the n-type diode of fig. 9. For the p-type diode shown in fig. 9, N_{eff} remains rather constant up to $8 \cdot 10^{12} \text{ n cm}^{-2}$ probably due to the removal of initial acceptors that compensates the creation of acceptor-like defects. A fit of the experimental points beyond this fluence gives $\beta = -0.027 \pm 0.003 \text{ cm}^{-1}$. As β represents the probability to create an acceptor state by a neutron per unit length in silicon, it can be deduced that this probability is the same for n-type and p-type material.

The n-type bulk material has been p^+ implanted on the junction front side and n^+ implanted on the ohmic rear side. For an apparent p-type inverted diode after high neutron

irradiation, a junction should be present on the back side. For low voltages at which the diode is partially depleted, the high-field region develops from the junction side, which can be identified by comparing the signal responses to an alpha source positioned successively on each side.

Fig. 9 Effective impurity concentration versus neutron fluence for an n-type diode and for a p-type diode.

Figure 10(a) for a non-irradiated n-type detector and fig. 10(b) for an initial n-type one irradiated at $5 \cdot 10^{13} \text{ n cm}^{-2}$ show the energy spectra of alpha particles (^{241}Am) for successive voltages. The full depletion voltages are respectively $\sim 30 \text{ V}$ before irradiation and $\sim 110 \text{ V}$ after irradiation. For low voltages full energy peaks are observed for incidence on the front side for the non-irradiated detector and on the rear side for the irradiated one. For high voltages the full energy peaks are similar for both detectors and for both sides.

Figure 11 shows the measured ratio of peak amplitude response versus bias voltage for the alpha source placed on the front side and on the rear side of the non-irradiated detector (a) and of the irradiated one (b). Although there is evidence for the appearance of a main junction on the rear side for the irradiated detector, confirming the bulk inversion hypothesis, it seems that even at rather low voltages some events with high amplitudes are detected with the alpha source on the front side. That suggests the presence of local junctions remaining on the front side after high fluence irradiation. The question is still open whether it is due to local n-type areas remaining in the inverted material, to deep-level centres generated by the neutron damage and acting as donors or to conversion of initial electrically inactive defects, as oxygen atoms for instance, into donor centres as suggested in ref. [7].

In order to confirm the evolution of initial n-type material towards apparent p-type, MOS capacitors have been irradiated with neutrons. The C-V curve of such a structure is strongly dependent on the material conduction type. For n-type material accumulation occurs at positive voltage while for p-type it occurs at negative voltages.

The C-V plots of an irradiated n-type MOS capacitor as a function of the fluence are presented in fig. 12(a) at a frequency of 10 kHz and in fig. 12(b) in a quasi-static mode.

These measurements show different effects with successive irradiations:

- decrease of the capacitance at positive voltages below $\sim 10^{13} \text{ n cm}^{-2}$ (attributed to an increase of the bulk series resistance);
- constant capacitance at a fluence of $\sim 10^{13} \text{ n cm}^{-2}$ (the same value at which a diode implanted on the same wafer becomes intrinsic);
- increase of the capacitance at negative voltages above $\sim 10^{13} \text{ n cm}^{-2}$;
- regular decrease of the flat-band voltage.

These results are in accordance with bulk evolution from n-type to apparent p-type.

Fig. 10 Energy spectra for alpha particles at various bias voltages: (a) for a non-irradiated detector and (b) for an irradiated one ($5.10^{13} \text{ n cm}^{-2}$).

Fig. 11 Alpha source front/rear peak amplitude ratio: (a) for a non-irradiated diode and (b) for an irradiated one ($5.10^{13} \text{ n cm}^{-2}$).

Fig. 12 The C-V curve evolution for a MOS capacitor irradiated at successive fluence: (a) at 10 kHz frequency (b) in a quasi-static mode.

4. SIGNAL CURRENT RESPONSE FOR RELATIVISTIC ELECTRONS

The detectors for future high-luminosity hadron colliders will have to detect particles at high rate and must have a fast response in order to be able to identify events coming from the successive bunches separated by 16 ns for LHC. Silicon detectors are good candidates for this purpose and we have investigated if the current signal shape is degraded after neutron irradiation.

We have compared the signal current response for relativistic electrons from 1 cm^2 identical detectors, one non-irradiated and the other irradiated at $5.10^{13} \text{ n cm}^{-2}$. The signal is detected on the diode rear side, towards which the electrons from the e-h created pairs are drifting, and a fast amplifier (HP 8447 F) is used.

The typical shape of the current signal pulse as a function of time is shown in fig. 13(a) for a non-irradiated diode ($V_d \sim 30 \text{ V}$) and in fig. 13(b) an irradiated one ($\phi = 5.10^{13}$, $V_d \sim 110 \text{ V}$), both diodes being biased at 140 V. The pulse responses have similar duration and the main difference is the lower amplitude for the irradiated detector. We suppose that part of the deposited charge is trapped at defects in the irradiated detector.

The timing parameters — the peaking time, the FWHM and the fall time — are all little dependent on the bias voltage beyond 100 V; even after $5.10^{13} \text{ n cm}^{-2}$ they remain in the

range of a few nanoseconds. The identical timing shapes could be explained by the fact that the current signal is induced by the charge displacement with a drift velocity which is itself not affected by the neutron irradiation.

Fig. 13 Typical time development of the signal current response to relativistic electrons: (a) for a non-irradiated diode, (b) for an irradiated one ($5.10^{13} \text{ n cm}^{-2}$).

The integral of the current pulse is calculated using the digital oscilloscope integration function. It represents the total charge detected at the input of a fast amplifier. The ratio of the charge collection for the irradiated detector to the non-irradiated one versus the bias voltage is presented in fig. 14, showing a deficit of $\sim 12\%$ above 160 V. If Q_0 and Q_{irr} are the charge collection respectively for the non-irradiated and for the irradiated detector, and assuming the charge deficit for the irradiated detector to be linear with the neutron fluence ϕ , the charge collection deficiency is

$$(Q_0 - Q_{\text{irr}}) / Q_0 = \gamma \phi . \quad (6)$$

From our measurement we get $\gamma = 0.024 \pm 0.004$ $10^{-13} \text{ n cm}^{-2}$.

5. CONCLUSION

Neutron irradiation of unbiased initial n-type silicon diodes leads to a rather linear increase of their reverse current showing a 30 – 40% room temperature annealing after several months. Their initial-effective impurity concentration is evolving progressively with fluence from an n-type towards an intrinsic conduction type and then to an apparent p-type. This is deduced from full-depletion voltage measurements and from the evolution of MOS capacitor characteristics.

Fig. 14 Signal charge collection ratio between an irradiated diode ($5.10^{13} \text{ n cm}^{-2}$) and a non-irradiated one, versus voltage.

Initial p-type diodes conserve their conduction type but increase equally in current.

The shape of the current pulse induced by the charge generated by incident β particles in an irradiated detector is not affected although the charge collection shows $\sim 2.5\%$ deficit per $10^{13} \text{ n cm}^{-2}$ for measurements up to $5.10^{13} \text{ n cm}^{-2}$. This is a very encouraging result in view of fast silicon detector applications.

Acknowledgements

The authors like to thank M. Edwards and D. Munday for their help with the irradiations at RAL, M. Tavlet for the irradiation at CERN and the SITP Collaboration for ample discussions.

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