Neutron, Proton, and Gamma Irradiations of Silicon Detectors

CERN Detector R&D Collaboration RD-2

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Abstract

Future high-energy hadron colliders (LHC, SSC) will generate a high flux of hadronic and electromagnetic particles in the experimental areas which has to be sustained by the detectors. The performance and electrical characteristics of silicon detectors evolve with time, during and after irradiations with 1 MeV neutrons up to $1.1 \times 10^{14} \text{ n cm}^{-2}$, with 24 GeV protons up to $9.5 \times 10^{13} \text{ p cm}^{-2}$, and with ^{60}Co gammas up to 10 Mrad. Ion-implanted single-diode silicon detectors with an area of 1 cm^2 have been used for these studies.

I. INTRODUCTION

Future high-energy hadron colliders will generate in their interaction regions high fluxes of hadrons in the energy range of 1 GeV, albedo neutrons of $\sim 1 \text{ MeV}$, and electromagnetic particles below 400 MeV [1]. Because of their potential for high-accuracy particle track location, their small thickness, and their low bias voltage, silicon detectors are attractive for the planned experiments. However, they have to resist fluxes of the order of $10^{13} \text{ particles cm}^{-2} \text{ year}^{-1}$. Extensive studies are in progress in order to understand silicon detector characteristics exposed in severe radiation environment, generally using neutrons [2,3] or protons [4] as the radiation source. This work extends our previous results obtained with $\sim 1 \text{ MeV}$ neutrons [5] to 24 GeV protons, and ^{60}Co gammas, in order to compare the evolution of the reverse current, the effective impurity concentration, and the charge collection efficiency of silicon detectors irradiated with different particles.

The irradiation facilities, the measurement methods, and the annealing corrections are presented in Section II, and the experimental results in Section III.

II. EXPERIMENTAL CONDITIONS

A. Irradiation facilities

Neutron irradiations were performed at the CERN/PSAIF facility which produces several bursts per minute providing an

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average flux of $\sim 5 \times 10^8 \text{ n cm}^{-2} \text{ s}^{-1}$ [6]. The absolute neutron fluence calibration is estimated to be $\pm 15\%$. The broad neutron energy spectrum which shows a peak slightly below 1 MeV represents approximately the energy of the albedo neutrons expected to be present in the collider experiments. Taking into account the time needed for measurements at intermediate fluences ~ 3 days were necessary to reach $10^{14} \text{ n cm}^{-2}$.

The T7 defocused primary extracted beam from the CERN PS was used for proton irradiations at 24 GeV/c. The protons are delivered in 4-8 bursts per minute providing an average flux of $\sim 5 \times 10^9 \text{ p cm}^{-2} \text{ s}^{-1}$, and the absolute proton fluence calibration, obtained from Al foil activations, is $\pm 6\%$. About one day was necessary to reach $10^{14} \text{ p cm}^{-2}$ including the intermediate measurement time.

The ^{60}Co source of the PAGURE facility at Saclay was used for the gamma irradiations with dose rates of 125 and 250 krad/h and dose calibration errors of $\pm 5\%$.

The temperature of the exposition areas was $\sim 26^\circ\text{C}$ for neutron and proton irradiations, and $\sim 21^\circ\text{C}$ for gamma irradiations.

B. Measurement methods

The silicon diode electrical characteristics were obtained from the current-voltage (I-V), and capacitance-voltage (C-V) measurements performed with a Keithley 237 High-Voltage Source Measure Unit (1100 V maximum voltage), and an HP 4194A Impedance Analyser used at 10 kHz excitation frequency.

The full depletion voltage for a detector with a thickness x_d is deduced from the C-V curve, and the effective impurity concentration N_{eff} is calculated from the equation

$$N_{\text{eff}} = 2 \epsilon V_d / q x_d^2 \quad (1)$$

with ϵ the silicon permittivity, and q the electron charge.

The diode reverse current I_r is obtained from the I-V curve. I_r is mainly due to the generation current produced in the depletion volume V of the detector which depends on the applied voltage, on the lateral electric field extension [5], and on the temperature. The radiation-induced increase of the volume current $\Delta I_r / V$ is measured at full depletion voltage and normalized at 20°C .

Table I
Initial characteristics of silicon detectors and maximum irradiation fluence

Detector	Type	Thickness (μm)	Area (cm ²)	N ₀ (10 ¹¹ cm ⁻³)	Particles	Energy (MeV)	Maximum fluence (cm ⁻²)
M4	n	317	1	3.4	n	~ 1	11.2 × 10 ¹³
M18	n	309	1	4.1	p	2.4 × 10 ⁴	7.5 × 10 ¹³
M25	n	308	1	2.1	p	2.4 × 10 ⁴	7.5 × 10 ¹³
M29 (biased)	n	303	1	2.7	p	2.4 × 10 ⁴	7.5 × 10 ¹³
M48	n	300	1	4.5	p	2.4 × 10 ⁴	9.5 × 10 ¹³
M16 M30 (biased)	n	299	1	2.0	γ	~ 1.25	1.9 × 10 ¹⁶ 10 Mrad

Electrons from a ¹⁰⁶Ru source with an energy > 2 MeV, selected by an external trigger, were used for charge collection efficiency measurements.

The current pulse induced by a particle in a silicon diode is detected via a fast current amplifier (Phillips Scientific 6954 model, wideband amplifier) with 50 Ω input impedance. Although the response time of this amplifier is better than 1 ns, the RC time constant of the system is ~ 1.7 ns due to the 1 cm² detector capacitance (35 pF). The pulse is recorded on a LeCroy digital oscilloscope used in averaging mode to improve the signal-to-noise ratio.

The single diode silicon detectors used for these studies were manufactured by Micron Semiconductor Ltd from n-type silicon bulk p+ implanted on one side to form the junction, and n+ implanted on the other side to form the ohmic contact. Table I presents, for each detector, the initial characteristics and the maximum fluence at which it has been irradiated for a given type of particle. The detectors were exposed in successive steps of fluence. After each step they were removed for 1 to 2 hours to make the I-V and C-V measurements, and to record the current signal response to relativistic electrons.

C. Short-term annealing and annealing corrections

Figure 1 shows for detectors irradiated with neutrons, protons, and gammas, the time evolution of the relative reverse current intended as the measured current normalized to the current value just at the end of irradiation. For gammas the annealing (21°C) is very fast, and the initial current has mainly recovered after approximately one day. For neutrons and protons the behaviour of the reverse current annealing (~ 26°C) is very similar. This has already been reported by the Hamburg group [7] for 14 MeV neutrons and 25 MeV protons.

This group has extended the annealing measurements to the reverse current and the effective impurity concentration for neutrons, and has fitted the annealing time constants (τ_i, τ'_i)

with the relative amplitudes (A_i, A'_i) for annealing of the bulk generation current I_T and the N_{eff} [2]. The reverse current I₀ and the effective impurity concentration N₀ at a time t = 0 can be calculated from the reverse current I_T(t), normalized at 20°C, and N_{eff}(t) measured at a time t from the equations

$$I_T(t) = I_0 \sum_i A_i \exp(-t/\tau_i) \quad (2)$$

and

$$N_{eff}(t) = N_0 \sum_i A'_i \exp(-t/\tau'_i) \quad (3)$$

Fig. 1 Evolution with time of the relative reverse current of detectors after the end of irradiations with neutrons (~ 26°C), protons (~ 26°C), and gammas (~ 21°C).

In order to compare the neutron and proton radiation-induced effects for different irradiation times and for different measurement delays, and in view of the results shown in Fig. 1, the coefficients calculated in ref. [2] have been applied for I_T and N_{eff} annealing corrections for neutron as well as for proton results.

III. EXPERIMENTAL RESULTS

A. Diode reverse current as a function of the fluence

Figures 2 and 3 present the diode reverse current increase versus neutron and proton fluence, respectively. The lower points show the data measured 0.5 to 2 hours after the end of each irradiation, with a total irradiation period of ~ 3 days for neutrons and ~ 1 day for protons. The upper points are the data corrected for annealing (Section II.C). For both irradiations, the reverse current increases linearly with the fluence. The reverse current damage constant values, obtained by fits of the data as a function of the fluence ϕ , using the equation

$$I_r / V = \alpha \phi, \quad (4)$$

are shown in Table II for the measured data and for the annealing corrected data. The measured coefficient is higher for protons than for neutrons, due to a shorter proton annealing time. After correction for annealing, however, the coefficients are approximately equal for both types of particles, taking into account uncertainties on the absolute fluence and on the annealing coefficients. The result does not differ significantly for the M29 detector biased during and after proton irradiation.

Bates exposed silicon diodes of smaller dimensions in the same proton beam (24 GeV), but he measured a smaller value $\alpha = 5.3 \times 10^{-17} \text{ A cm}^{-1}$ corrected for annealing [8]. The calculations of Van Ginneken for the non-ionizing energy loss indicate nearly identical values for 1 MeV neutrons and GeV protons [9], supporting our results.

Figure 4 shows the reverse current as a function of the gamma dose for detectors unbiased during irradiations. The values obtained just after the irradiations and 8 months later do not differ very much, supporting the assumption that for unbiased detectors the rather small increase of the reverse current is permanent.

For the M30 detector, which was biased during irradiation, the reverse current measured approximately one hour after irradiation is a factor of 4 higher than the value obtained for the unbiased detector at the same dose.

Fig. 2 Reverse current at full depletion plotted against neutron fluence

Fig. 3 Reverse current at full depletion plotted against proton fluence

Table II

Measured and annealing corrected coefficients for reverse current increase (α), acceptor creation (β), donor removal (c) and charge collection deficit (γ) with corresponding statistic errors.

Detector	Particles	Measured coefficients				Annealing corrected coefficients			
		α ($10^{-17} \text{ A cm}^{-1}$)	β (cm^{-1})	c (10^{-13} cm^2)	γ (10^{-14} cm^2)	α ($10^{-17} \text{ A cm}^{-1}$)	β (cm^{-1})	c (10^{-13} cm^2)	
M4	n	$3.1 \pm .2$	$.014 \pm .001$	$1.3 \pm .02$	$.125 \pm .015$	$6.7 \pm .4$	$.073 \pm .001$	$1.87 \pm .04$	
M18	p	$4.8 \pm .2$	$.028 \pm .001$	$1.17 \pm .1$	–	$7.2 \pm .4$	$.091 \pm .002$	$4.05 \pm .2$	
M25	p	$5.3 \pm .2$	$.025 \pm .002$	$1.86 \pm .1$	–	$8.9 \pm .4$	$.077 \pm .004$	$3.85 \pm .6$	
M29 biased	p	$4.7 \pm .2$	$.023 \pm .002$	$3.67 \pm .2$	–	$7.7 \pm .4$	$.079 \pm .002$	8.3 ± 1.2	
M48	p	–	–	–	$.117 \pm .015$	–	–	–	–
M16	γ	$\sim 5 \times 10^{-6}$	–	–	0	–	–	–	–

Fig. 4 Reverse current at full depletion plotted against γ dose

However, the reverse current measured 8 months later is similar and, taking into account Fig. 1, the non-permanent defects induced in the biased detector should have recovered after ~ 1 day.

The low-energy gamma-induced reverse current damages in a biased detector are attributed to a conductive interface layer induced by a positive charge accumulated in the SiO_2 . From the permanent gamma-induced reverse current the coefficient obtained (Table II) is six orders of magnitude lower than for neutrons and protons.

B. Effective impurity concentration as a function of the fluence

The effective impurity concentration plotted against fluence is shown in Figs 5 and 6 for neutron and proton irradiations. The lower points are the measured data obtained with the same conditions as for the reverse current, and the upper points are the annealing corrected data. Conduction-type inversion from n-type to p-type is observed for both neutron and proton irradiations at about the same fluence level, supported by the assumption of acceptor-like defects induced in the silicon bulk by particle non-ionizing energy losses. N_{eff} as a function of the fluence is parametrized using

$$N_{\text{eff}} = -N_0 \exp(-c \phi) + \beta \phi \quad (5)$$

where the exponential term expresses the removal of the initial donors N_0 and the linear term the creation of acceptors. The coefficients of the fits for the measured and the annealing corrected data are listed in Table II. The higher value of the measured coefficient β obtained for protons than for neutrons is due to the shorter irradiation time for protons, leading to a smaller annealing. The values of the coefficient β corrected for annealing are slightly higher for protons than for neutrons, but the difference is not really significant when taking into account the value ($\beta = 0.079 \pm 0.006 \text{ cm}^{-1}$) obtained for neutrons by Fretwurst et al. [2]. The coefficients c differ substantially, but the limited number of experimental points before type

inversion, uncertainties on annealing coefficients, and possible inaccuracy in the simple model described by Eq. (5) have limited the fit adequacy.

Fig. 5 N_{eff} plotted against neutron fluence

Fig. 6 N_{eff} plotted against proton fluence

Figure 7 shows the effective impurity concentration for several detectors before (squares) and after (triangles) gamma irradiations up to 10 Mrad. The changes of N_{eff} are insignificant even for the M30 detector biased during irradiation, and it can be concluded that the initial doping concentration is not affected by ~ 1 MeV gammas.

Fig. 7 N_{eff} plotted against gamma dose

C. Charge collection efficiency as a function of the fluence

The charge collection efficiencies have been obtained from the integration of the current pulse response induced by relativistic electrons in silicon detectors biased above their depletion voltages at 160 V, even for the maximum fluences achieved.

Figure 8 shows the pulses for a non-irradiated detector (a), and for a detector irradiated with neutrons at a fluence of $1.1 \times 10^{14} \text{ n cm}^{-2}$ (b). In this latter case the peak amplitude has decreased and a tail extends up to 30 ns. However, 90% of the charge is collected in less than 15 ns.

Fig. 8 Current pulse response from the β source: a) for M6 not irradiated, and b) for M4 irradiated at $1.12 \times 10^{14} \text{ n cm}^{-2}$. Both detectors are biased at 160 V.

Figures 9, 10, and 11 show the charge collection efficiency over 20 ns (less than the 25 ns interbunch crossing time expected at the LHC) as a function, respectively, of the neutron and proton fluences, and of the gamma dose. The charge collection deficit is expressed by

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

The values of γ are listed in Table II for two detectors irradiated with neutrons and protons. A similar deficit of $\sim 12\%$ is obtained for neutron and proton irradiations up to $\sim 10^{14}$ particles cm^{-2} , for a collection time of 20 ns in agreement with the results of Chilingarov [10].

For gamma irradiations no deficit has been measured up to 10 Mrad.

Fig. 9 Charge collection efficiency plotted against neutron fluence

Fig. 10 Charge collection efficiency plotted against proton fluence

Fig. 11 Charge collection efficiency plotted against gamma dose

These measurements were made ~ 1 hour after the irradiations and no appreciable modification of the charge collection deficit were observed in measurements performed several months later at bias voltages, larger than 160 V, needed by the full depletion voltage increase with long-term annealing at room temperature (Fig. 13). At these voltages the time needed for collection of the induced charge is always less than 20 ns [10].

D. Long-term room temperature annealing

As already reported by various groups for neutron [5,11,12] and proton [4] irradiations, there is a long-term evolution of the reverse current and of the full depletion voltage after the end of the irradiation. Figure 12 shows the reverse current at full depletion voltage, as a function of time, for two detectors irradiated respectively with neutrons ($1.1 \times 10^{14} \text{ n cm}^{-2}$), and protons ($7.5 \times 10^{13} \text{ p cm}^{-2}$). In both cases, there is a fast annealing during the first days, after which the reverse currents remain rather stable. The slight increases after several months could be attributed to the full depletion voltage increases.

Fig. 12 Reverse current at full depletion and at room temperature plotted against time after irradiation with neutrons and protons.

Figure 13 shows the long-term evolution of the full depletion voltage for the same detectors as above that have experienced a conduction-type inversion and have a similar behaviour. There is an annealing during the first week, corresponding to a decrease of N_{eff} which can be explained by the recombination of the irradiation-induced acceptor defects. Then, a reverse annealing takes place over several months, corresponding to an increase of N_{eff} . This process has recently been investigated [12]. An explanation, based on experimental data, assumes the existence of interactions between radiation-induced electrically inactive defects which generate electrically active acceptor-like centres.

Fig. 13 Full depletion voltage at room temperature plotted against time after irradiation with neutrons and protons.

Taking into account that the reverse annealing is temperature-dependent [10, 11], i.e. no reverse annealing has been observed at 10°C and below, further irradiations at lower temperature are underway within the RD-2 Collaboration to find optimum conditions for long-term operation of irradiated detectors at reasonable full-depletion bias voltages.

IV. CONCLUSIONS

For equivalent fluences up to 10^{14} particles cm^{-2} , the silicon diode reverse current increase, the effective impurity concentration evolution, and the charge collection efficiency are similar for ~ 1 MeV neutron and 24 GeV proton irradiations.

This supports the assumption that the ionization energy losses do not contribute to the silicon bulk damages. This is in agreement with the calculations of Van Ginneken [9]. For irradiation with ~ 1 MeV gammas up to 10 Mrad the radiation-induced effects are negligible.

However, it may not be the case for gammas with an energy above 20 MeV [9] which will be produced in the LHC with a flux ~ 1 order of magnitude greater than the fluxes of neutrons and protons [1].

For neutron and proton irradiations the charge collection deficit is $\sim 12\%$ for a collection time of 20 ns and for fluences up to 10^{14} particles cm^{-2} . The long-term behaviour at room temperature of heavily-irradiated detectors shows an annealing of the reverse current. Their full depletion voltage, after an initial annealing, experiences a reverse annealing which could however be avoided by operating the detectors at a lower temperature. The silicon detectors are operational over the full irradiation range, even around the region of conduction-type inversion, and remain fast devices with an acceptable charge collection deficit.

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