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Electrical properties and charge collection efficiency for neutron-irradiated p-type and n-type silicon detectors

CERN detector R&D Collaboration RD-2

F. Lemeilleur, M. Glaser, E.H.M. Heijne, P. Jarron, E. Occelli* and J. Rioux**

CERN, Geneva, Switzerland

Ion-implanted n-type and p-type detectors have been irradiated with neutrons of ~ 1 MeV up to a fluence of 10^{14} cm^{-2} . From I-V and C-V measurements the reverse current and the full depletion voltage have been determined at successive levels of neutron fluence. The effective doping concentration versus fluence and the reverse current damage coefficient are presented. Room temperature annealing after the irradiation is discussed. At successive levels of neutron fluence, the shape of the current pulse induced by relativistic electrons and α particles has been studied using a fast current amplifier. For a detector irradiated up to $1.1 \cdot 10^{14} \text{ n cm}^{-2}$ and biased at $\sim 20\%$ above the depletion voltage, the charge collection deficit for ~ 2 MeV electrons is $< 20\%$ for an integration time of 15 ns. For α particles the current pulse is different for front and rear side incidence and its shape changes with neutron fluence. This shape is related to the electric field inside the detector and therefore provides another way to determine the neutron-induced effective impurity concentration.

1. INTRODUCTION

In view of the use of silicon detectors in the future large hadron collider (LHC) experiments, extensive studies have been performed to measure the evolution of silicon detector properties when irradiated with ionizing and non-ionizing particles [1], with neutrons [2-5] and with protons [6]. In 1991 the Oak Ridge, Firenze and Minsk Workshops have been dedicated to the study of radiation hardness of silicon detectors in a variety of applications.

In this article we extend our previous measurements [4] to a higher neutron fluence with

emphasis on measurements of effective impurity concentration and charge collection efficiency, derived from particle-induced current pulse shape. Two n-type and p-type single-pad detectors, with parameters shown in table 1, have been irradiated in December 1991 at the CERN-PSAIF facility with ~ 1 MeV neutrons up to a fluence of $1.12 \cdot 10^{14} \text{ n cm}^{-2}$ at a flux of $\sim 5 \cdot 10^8 \text{ n cm}^{-2}\text{s}^{-1}$. The unbiased detectors were exposed in successive steps. After each step they were removed during 1 to 2 h to perform the I-V and C-V measurements, and to record the current pulse responses to β and α particles from radioactive sources.

Table 1

Det.	Manuf.	Type	Thickness [μm]	Area [cm^2]	Initial resistivity [$\text{k}\Omega \text{ cm}$]	Maximum irradiation [$10^{12} \text{ n cm}^{-2}$]	α meas. [$10^{-17} \text{ A cm}^{-1}$]	α ann. corr. [$10^{-17} \text{ A cm}^{-1}$]
M6	Micron S	n	300	1	12.2	0	—	—
M4	Micron S	n	317	1	12.2	112	3.1 ± 0.2	6.7 ± 0.4
45	Canberra S	p	500	0.332	13.6	90	4.0 ± 0.3	7.4 ± 0.4

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

** University of Montreal, Montreal, Canada.

Section 2 presents the results of the reverse diode current measurements and the effective impurity concentration as a function of the neutron fluence. Section 3 is dealing with the current pulse shape and the charge collection efficiency.

2. ELECTRICAL PROPERTIES

The non-ionizing energy loss of protons and neutrons in the bulk of silicon diodes goes in part into atomic displacements leading to defects in the crystal. They are acting as generation-recombination centres which decrease the minority carrier life time. As a consequence, the diode reverse current increases. The initial doping concentration is modified proportionally with the particle fluence because the defects are charged and "acceptor-like".

2.1 Diode reverse current

For a good diode the reverse current is mainly due to the generation-current produced in the depleted volume V of the detector which depends on the applied bias voltage, on the lateral field extension (calculated from the measured value of the diode capacitance [4]) and on the temperature. The increase of the volume current $\Delta I/V$, normalized at 20°C and at full depletion measured as a function of the neutron fluence ϕ gives a linear relationship

$$\Delta I/V = \alpha \phi, \quad (1)$$

where α is the reverse current damage coefficient.

During the exposure periods and before the measurement can be performed (30–60 min in our case), room temperature annealing is taking place. As a consequence, the value of the measured current depends on the delay after which the measurement is performed. Lindström has calculated [7], from experimental results, the coefficients for time dependence of the n-type diode current annealing

$$I(t) = I(0) \sum_{i=1}^5 A_i e^{-\frac{t}{\tau_i}} \quad (2)$$

with τ_i the characteristic time constants. By applying this annealing correction the reverse current

damage coefficient α should become more independent of both the exposure and the measurement time.

Figure 1 shows the measured reverse current as a function of the neutron fluence for the n-type (M4) and the p-type (45) detectors. The values of the measured coefficients α are listed in Table 1 and compared with those obtained by applying the self-annealing correction. It should be noted that the correction factors are not necessarily identical for n-type and the p-type diodes. Contrary to earlier data [8], but in agreement with ref. [4], the reverse current is larger for the detector manufactured on the p-type wafer than for the one from the n-type wafer. Further measurements with p-type detectors with a different thickness and obtained with a modified process are in progress.

Fig. 1 Reverse current without annealing correction vs neutron fluence for M4 (initial n-type) and 45 (p-type) detectors.

2.2 Effective impurity concentration from C-V measurements

For a homogeneous charge density in the bulk and an abrupt junction, the effective impurity

concentration N_{eff} is related to the applied voltage V and the corresponding depletion depth x by the equation

$$N_{\text{eff}} = (2\epsilon_{\text{si}}/q)(V + V_0)/x^2 \quad (3)$$

with V_0 the built-in voltage, which is ~ 0.6 V.

For an irradiated detector the measured capacitance ($C = \epsilon_{\text{si}} \times \text{surface}/x_d$) is no longer inversely proportional to the square root of the bias voltage [1, 4 and 6] and is frequency-dependent [9]. This suggests a non-uniform impurity concentration inside the bulk. However, from the C-V curve measured at 10 kHz and extrapolated to the minimum capacitance, the full depletion voltage can be determined and for a detector of known thickness a homogeneous apparent N_{eff} has been calculated at each step of fluence. The induced charged defects in the crystal are not stable and a room temperature annealing is taking place. As for the case of the reverse current, the annealing-corrected effective impurity concentration has been calculated [7]. Figure 2 shows N_{eff} at the time of measurement for the initial n-type and p-type diodes as a function of fluences. The initial n-type diode has inverted to an apparent p-type as already reported for neutron irradiation [1, 4 and 5] and for proton irradiation [6]. The p-type diode has remained of the same conduction type over the full irradiation range. At first, there is a slight decrease of the acceptor concentration but at higher fluence the apparent doping increases linearly with fluence.

Assuming a partial removal of the initial doping concentration and a creation of acceptor-like impurities, the experimental data for both conduction-type diodes have been fitted to the following equation

$$N_{\text{eff}} = N_0(1 - f) + f N_0 \exp(-c \phi) + \beta \phi, \quad (4)$$

Table 2

Det.	Type	N_0 [10^{11} cm^{-3}]	Measured coefficients			Annealing corrected coefficients		
			β [cm^{-1}]	c [10^{-13} cm^2]	f	β [cm^{-1}]	c [10^{-13} cm^2]	f
M4	n	-3.4	$.0159 \pm .003$	2.8 ± 0.2	$0.69 \pm .02$	$.0732 \pm .0008$	1.87 ± 0.04	1
45	p	9.2	$.0151 \pm .008$	3.6 ± 1.3	$0.15 \pm .02$	$.0632 \pm .0009$	1.38 ± 0.07	1

where f is the removed fraction of the initial impurity concentration N_0 , c is the parameter for removal and β is the parameter for creation.

The parameters of the fit through the experimental points of fig. 2 are listed in table 2. The values of β are similar for both diodes and from these data we can conclude that the probability to create an acceptor centre by a neutron per unit length in silicon is the same for the p-type and for the initial n-type diode. It can also be remarked that the best fits of the data are obtained for an initial dopant removal of $\sim 70\%$ for the n-type and of only $\sim 15\%$ for the p-type diode. Also in table 2 are indicated the annealing-corrected coefficients with the same reserve as above concerning the p-type detector.

Fig. 2 Effective impurity concentration without annealing correction versus fluence for M4 (initial n-type) and 45 (p-type) detectors. The parameters of the fitted lines are listed in table 2.

2.3 Effective impurity concentration from an α particle response

The range of an α particle from a ^{241}Am source (5.4 MeV) in the silicon is $\sim 20 \mu\text{m}$. Therefore, α particles have been used [1, 3 and 4] for probing the active volume of a silicon diode. At low voltage, the diode is partly depleted and the active volume extends from the junction side. For an α particle incident, either on the junction side or on the ohmic side, a response can or cannot be detected respectively. Using this method, it has been found that for an initial n-type diode inverted to a p-type diode after neutron irradiation the main junction has moved to the n^+ implanted side. Kraner et al. [10] have pointed out that, in this case, the gradient of the electric field $E(x)$ inside the diode has changed its sign. The current pulse is induced on the electrodes after the separation of the electrons and holes which move at the drift velocity

$$v^{e,h}(x) = \mu_{e,h} E(x) . \quad (5)$$

Obviously, the shape of the current depends on the electric field $E(x)$ at the position of the carriers.

Using the Ramo theorem [11, 12] the time dependence of the pulse $i(t)$ can be expressed as a function of the effective impurity concentration. For a unit charge q crossing a distance dx , the induced charge is $dq = q(dx/w)$, w being the thickness of the detector [13]. Using eq. (5), the current $i(x)$ is

$$i(x) = \frac{dq}{dt} = \frac{q}{w} \mu E(x) . \quad (6)$$

For a detector of physical thickness w the total depletion voltage is

$$V_d = \frac{q N_{\text{eff}}}{2\epsilon_{\text{si}}} w^2 , \quad (7)$$

with N_{eff} the doping concentration and ϵ_{si} the silicon permittivity.

For an applied voltage V , the electric field is

$$E(x) = 2V_d \frac{x-w}{w^2} - \frac{V + V_0 - V_d}{w} . \quad (8)$$

$$E(x) = (x - a) b \text{ with}$$

$$a = \frac{w}{2} + \frac{\epsilon_{\text{si}}}{N_{\text{eff}} q} \frac{V + V_0}{w} \text{ and } b = \frac{N_{\text{eff}} q}{\epsilon_{\text{si}}} . \quad (9)$$

The current $i(x)$ is obtained as a function of time by a change of variable, using $dx = \mu E(x) dt$. For a deposited charge at the position x_0 and by integration between x_0 and x , we obtain

$$x = a + (x_0 - a) e^{\mu b t} . \quad (10)$$

Then the current is

$$i(t) = \frac{q}{w} \mu b (x_0 - a) e^{\mu b t} . \quad (11)$$

Figure 3 shows, for successive steps of neutron fluence, the current pulse response for a ^{241}Am source positioned either on the p^+ (front) or on the n^+ (back) implanted side of the initial n-type M4 detector biased at $V = 160 \text{ V}$ (well above the depletion voltage: $\sim 30 \text{ V}$ at $\phi = 0$ and $\sim 110 \text{ V}$ at $\phi_{\text{max}} = 7.5 \cdot 10^{13} \text{ n cm}^{-2}$). The shorter pulses correspond to α particles incident on the front side and the longer ones to particles on the back side. The pulse edges are slightly slowed down by the time constant of 1.7 ns of the measurement set-up. In the electric field the electrons are moving towards the positive electrode (back side) and the holes towards the negative electrode (front side).

When the α source is placed on the detector front side the range of holes is short, and the induced current is mainly due to the electrons having to cross the entire detector. For the source placed on the detector back side the induced current is mainly due to the holes. As the mobility ratio is $\sim 1/3$ the current pulse is longer for holes than for electrons. Furthermore, the drift velocity of the moving charge depends on the electric field shape and the induced current is increasing or decreasing with time. This is not visible in fig. 3 for the electrons as a consequence of the limited time resolution of the system but it is clearly seen for the holes. In this case, and for increasing fluence, the slope of the hole-induced current is first decreasing, then constant and after a change of sign is increasing again.

Fig. 3 Current pulse response for the α source placed on the front side and on the back side of the M4 diode at successive levels of fluence.

This is interpreted as a change of the strength of the electric field and to its inversion when the detector inverts from an n-type to a p-type at a fluence between 0.5 and $0.8 \cdot 10^{13} \text{ n cm}^{-2}$. To measure the neutron-induced effective impurity concentration the induced current pulses can be fitted using eq. (11) including the e-h creation positions and the detection system time response. However, a simplified method can be introduced. Using the

current pulses of fig. 3 for the α source positioned on the back side of the detector, assuming that the moving holes give the main contribution to the current and measuring the current amplitudes at the same times t_2 and t_1 on the plateaus of the pulses for each step of fluence, N_{eff} can be calculated from eq. (11)

$$N_{\text{eff}} = \frac{\epsilon_{\text{si}}}{q\mu_{\text{h}}(t_2 - t_1)} \ln \frac{i(t_2)}{i(t_1)} \quad (12)$$

The values of N_{eff} obtained by this method, normalized to the initial doping concentration N_0 , are presented in fig. 4 as a function of the neutron fluence. The values of N_{eff} measured by the C-V method are given for comparison. The agreement is satisfactory and confirms the validity of the method.

Fig. 4 Effective impurity concentration deduced from the α source pulse current response and from the C-V methods vs neutron fluence.

2.4 Long-term annealing

Figure 5(a) shows the evolution of the bias voltage needed for full depletion of the n-type M4 detector after irradiation at $1.12 \cdot 10^{14} \text{ n cm}^{-2}$. The annealing time at room temperature is given in hours and the detector was not biased during the annealing.

After an initial increase of the apparent resistivity a decrease sets in after about three weeks. This behaviour has already been reported by Pitzl et al. [6] and more recently by K. Gill et al. [14]. For comparison the diode reverse current is shown in fig. 5(b). After an initial decrease the current is virtually stable at 2.7 mA cm^{-3} .

Fig. 5 (a) bias voltage and (b) reverse current, at full depletion for the M4 detector after irradiation at $1.12 \cdot 10^{14} \text{ n cm}^{-2}$ versus annealing time at room temperature.

3. CURRENT PULSE RESPONSE AND CHARGE COLLECTION EFFICIENCY

Electrons from a ^{106}Ru source with an energy $> 2 \text{ MeV}$ selected by an external trigger and α particles from a ^{241}Am source have been used for this study. The induced current pulse by a particle in a silicon diode is detected via a fast current amplifier (Phillips Scientific, wideband amplifier model 6954) with 50Ω input impedance. Although the response time of this amplifier is better than 1 ns , the RC time constant of the system is $\sim 1.7 \text{ ns}$ due to the 1 cm^2 detector capacitance ($\sim 35 \text{ pF}$). The pulse is recorded on a digital oscilloscope (Le Croy 9450) used in averaging mode to improve the signal-to-noise ratio.

The current pulse shapes for relativistic electrons are shown in fig. 6. Figure 6(a-b) compares the electron pulse responses for two similar detectors, M6 non-irradiated and M4 irradiated at $1.12 \cdot 10^{14} \text{ n cm}^{-2}$, both biased at 160 V . The main difference is a smaller amplitude and a longer tail for the irradiated diode. Also presented in fig. 6 is the integration of the current pulse performed by the oscilloscope and used for the charge collection measurements.

Fig. 6 Current pulse response from the β source: (a) for M6 not irradiated and (b) for M4 irradiated at $1.12 \cdot 10^{14} \text{ n cm}^{-2}$. Both detectors are biased at 160 V .

The pulse length induced by electrons is presented in fig. 7 as a function of the bias voltage for the same detectors as above and for either 90% or 100% of charge collection measured with the integrating oscilloscope. The full depletion voltages are respectively $\sim 30 \text{ V}$ and $\sim 130 \text{ V}$ for the

non-irradiated and the irradiated detectors. For both detectors biased at 160 V the pulse length difference is ~ 5 ns for 90% of charge collection.

Fig. 7 Electron-induced current pulse length as a function of the bias voltage before and after irradiation ($1.12 \cdot 10^{14} \text{ n cm}^{-2}$).

Figure 8 shows for the detector M4, biased at 160 V, the pulse length as a function of the neutron fluence for 90% and 100% of charge collection. The lines are the fits through the experimental points. For both cases, the pulse length increases by $\sim 40\%$ at maximum fluence. It should be noted that even after this rather high irradiation fluence 90% of the charge is collected in < 15 ns.

For the M4 diode biased at 160 V the charge collection efficiency for relativistic electrons (mip), normalized for full charge collection before irradiation, is presented versus neutron fluence in figs 9(a) and 9(b) for 20 ns and 15 ns charge integration time. The linear fits using

$$(Q_0 - Q_{irr})/Q_0 = \gamma_{\Delta t}^{mip} \phi \quad (13)$$

give the charge collection deficit coefficients

$$\gamma_{20 \text{ ns}}^{mip} = (0.0125 \pm 0.0008) \cdot 10^{-13} \text{ n}^{-1} \text{ cm}^2$$

and

$$\gamma_{15 \text{ ns}}^{mip} = (0.0190 \pm 0.0009) \cdot 10^{-13} \text{ n}^{-1} \text{ cm}^2,$$

which can be compared with our earlier measurement [4] (0.024 ± 0.004 for $\Delta t \sim 15$ ns) and with the value deduced by E. Fretwurst et al. [15] from trapping time constants measured for α particles (0.012 for maximum charge collection time).

Fig. 8 Electron-induced current pulse length vs neutron fluence for 90% and 100% charge collection.

Fig. 10 shows the charge collection efficiency for a charge integration time of 10 ns. The slope of the fitting lines are identical for $\Delta t = 10$ ns (0.0118 ± 0.0011) and for $\Delta t = 20$ ns.

These measurements show that the pulse response to relativistic electrons is not much degraded neither in time nor in charge collection for the whole range of neutron irradiation up to $\sim 10^{14} \text{ n cm}^{-2}$.

The charge collection efficiency for α particles incident on the front side or on the back side of the same detector biased at 160 V is presented in figs 11(a) and 11(b) as a function of the fluence. The result of linear fits gives

$$\gamma_{\text{front}}^{\alpha} = (0.0337 \pm 0.0007) 10^{-13} \text{ n}^{-1} \text{ cm}^2$$

and

$$\gamma_{\text{back}}^{\alpha} = (0.0273 \pm 0.0007) 10^{-13} \text{ n}^{-1} \text{ cm}^2.$$

Fig. 9 Electron-induced charge collection efficiency vs neutron fluence for: (a) 20 ns and (b) 15 ns charge integration time.

Fig. 10 Electron-induced charge collection efficiency vs neutron fluence for 10 ns integration time.

In these cases, either the electrons or the holes have to cross the entire detector thickness and contribute to the current pulse response. It can be deduced from the fact that $\gamma_{\text{front}}^{\alpha} > \gamma_{\text{back}}^{\alpha}$ that the trapping of the electrons is larger than the trapping of the holes in an irradiated detector.

It should also be remarked that for a fluence around which the apparent resistivity is very high ($5 - 12 \cdot 10^{12} \text{ n cm}^{-2}$), the charge collection efficiencies for both α and β particles are degraded somewhat more than indicated by their linear dependence behaviours.

In a simple approach, the charge collection deficit for electrons can be related to that of α particles. For relativistic particles (mip), the electrons and the holes have to cross in average half the thickness of the detector and the total charge collection deficit can be evaluated from the electron and hole charge collection deficits obtained with the α particles

$$\gamma^{\text{mip}} = 1/2 (\gamma^e/2 + \gamma^h/2) \quad (14)$$

$$\text{with } \gamma^e = \gamma_{\text{front}}^{\alpha} \text{ and } \gamma^h = \gamma_{\text{back}}^{\alpha}.$$

From the above experimental values we get

$$\gamma^{\text{mip}} = (0.0152 \pm 0.001) 10^{-13} \text{ n}^{-1} \text{ cm}^2,$$

which is close to the measured value $\gamma_{20 \text{ ns}}^{\text{mip}}$.

Fig. 11 Alpha particle charge collection efficiency vs neutron fluence: (a) for the source incident on the front side and (b) for the source incident on the back side of the detector.

4. CONCLUSION

The results of our investigations show that after neutron irradiation of a first set of a few unbiased n-type and p-type diodes, the increase of the reverse current is $\sim 30\%$ higher for p-type than for n-type, and the probability to create acceptor-like damage centres is similar for both conduction types. Given the variations between detectors from various manufacturers [4] the difference is at this stage only indicative.

The study of the current pulses from short range α particles allows to probe the internal electric field and to measure the evolution of the effective impurity concentration.

The result concerning the pulse responses to α and β particles proves that the irradiated n-type detector is operating over the full range of irradiation. For relativistic electrons and for the detector irradiated at $10^{14} \text{ n cm}^{-2}$ and biased 20% above full depletion voltage, the charge collection deficit is $\sim 12\%$ for an integration time of 20 ns and $\sim 20\%$ for 15 ns. Furthermore, there is a slight increase of the charge collection time which is quite acceptable when considering the use of these detectors in experiments at the LHC.

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