THE EFFECT OF RADIATION ON ION - IMPLANTED SILICON DETECTORS

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Abstract

Investigations on changes of characteristics of ion - implanted silicon - junction detectors when exposed to various doses of radiation ($< 10^5$ and $> 10^6$ rad) were performed. It was found that the increase of leakage current depends not only on the dose but also on the gradient of irradiation.

For doses higher than 10^6 rad, the fully depleted layer thickness of the detector before irradiation decreases and becomes dependent on temperature. Also the most probable energy loss decreases and the width of the noise distribution broadens.

Submitted to
Nuclear Instruments and Methods A

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1. Introduction

The new generation of accelerators, colliding beam machines, such as the e^+e^- LEP and SLC, and the ep HERA which are in different stages of development and construction as well as the proposed high-energy $p\bar{p}$ collider SSC, yield high intensities and rates and lower interbunch crossing times, and thus, require counters with resolving times of the order or faster than 20 ns. In calorimetric applications silicon detectors can replace currently used active samplers such as liquid argon.

Calorimeters employing uranium have additional problems such as neutrons and photons from fission processes accompanying hadronic showers and the natural radioactivity. Thus, a detailed study of the behaviour of the active material of detectors to radiation is important for the design of experiments.

In this paper, passivated ion-implanted silicon-junction detectors were exposed to various doses of radiation and investigated. The two sections of chapter 2 describe the detectors and the irradiation. The subsequent sections of chapter 3 deal with the observations on two detectors (before and after irradiation) of: (1) the depletion layer thickness, (2) the resistivity, (3) the leakage current, (4) the noise distribution and (5) the most probable energy loss produced by relativistic charged particles passing through the detector.

The results show that for a slow gradient of irradiation and a low dose ($\approx 10^5$ rad) there was a relatively low jump (compared with a fast gradient of irradiation [1]) of leakage current and almost no change in the depletion layer width. There was also a small variation of resistivity and the most probable energy loss.

For a high dose ($> 10^6$ rad) and for a detector with a resistivity of about 9 k Ω cm, the jump of the leakage current was more than one order of magnitude and the depletion layer width decreased by about 20%. The most probable energy loss decreased by about 23%. However, at 2°C the depletion layer width decreased only by 9%. In a previous investigation [1] and for a similar dose, it was found that a detector with a resistivity of about 3.5 k Ω cm did not show the decrease of the depletion layer width. Thus it seems that the lower the detector resistivity the smaller the degradation of its performance at high dose.

2. Detectors and irradiation

2.1 The detectors

Two Micron Semiconductor passivated ion – implanted silicon – junction detectors N14 and N9, with nominal area $10 \times 10 \text{ mm}^2$ were used. In fig.1 the corresponding depletion layer capacitance per unit area, C_T , as a function of bias voltage at 20°C is presented.

By fitting (fig.1)

$$C_T \approx 1.958 \cdot 10^4 / \sqrt{\rho(V + V_b)} \quad [\text{pF/cm}^2]$$

the resistivity ρ and the internal voltage V_b were obtained; and from

$$C_T \approx 1.0359 \cdot 10^4 / X_d \quad [\text{pF/cm}^2] \quad (1)$$

the depletion layer width X_d in μm , (for full depletion it is the detector thickness).

For N14 $\rho = (3.72 \pm 0.03) \text{ k}\Omega \text{ cm}$ and $V_b = (0.4 \pm 0.1) \text{ V}$ the leakage current $I = 15 \text{ nA}$ and the detector thickness $X_{dt} \approx (273 \pm 8) \mu\text{m}$.

For N9 $\rho = (9.00 \pm 0.22) \text{ k}\Omega \text{ cm}$, $V_b = (1.7 \pm 1.0) \text{ V}$, $I = 600 \text{ nA}$ and $X_{dt} \approx (370 \pm 11) \mu\text{m}$.

2.2 The irradiation

Detector N14 was exposed to an irradiation dose of $0.7 \cdot 10^5 \text{ rad}$, which is equivalent to that provided by the energy loss given by a fluence of $3.4 \cdot 10^{12}$ noninteracting relativistic particles/ cm^2 . Detector N9 was exposed to $1.4 \cdot 10^6 \text{ rad}$ or $6.8 \cdot 10^{13}$ particles/ cm^2 .

The detectors were positioned next to the beam pipe of the SPS accelerator at CERN and exposed during several weeks. Thus, the irradiation consisted mainly of high energy neutrons, high and low energy charged particles and photons [2].

3. Characteristics of irradiated detectors

3.1 Depletion layer capacitance as a function of bias voltage

Detector N14, after irradiation ($0.7 \cdot 10^5$ rad), exhibited a relatively low jump of leakage current from 15 to 136 nA at 20°C , for $V_b = 100$ V. If compared with a detector of similar resistivity, ρ , and irradiation dose [1] but irradiated during 30 s (instead of several weeks in this experiment) current I jumped from 16 nA to $12 \mu\text{A}$. It can, therefore, be concluded that the leakage current increase is sensitive to the gradient of irradiation.

At 2°C , after the same irradiation, the leakage current is about 28 nA.

The depletion layer capacitance of N14 as a function of bias voltage (fig.2) before and after irradiation showed the following:

a. The value of C_T on the plateau was 38 pF, equal for both the irradiated and the nonirradiated N14, at 20°C and 2°C . This lead to variation ΔX_d (the difference between the nonirradiated X_d and the irradiated one X_{di}) and $(\Delta X_d/X_d) 100 = (0.0 \pm 3.6)\%$

b. The resistivity after irradiation at 20°C

$$\rho = (3.55 \pm 0.03) \text{ k}\Omega \text{ cm and } V_b = (0.5 \pm 0.1) \text{ V}$$

and at 2°C

$$\rho = (3.65 \pm 0.03) \text{ k}\Omega \text{ cm and } V_b = (0.7 \pm 0.1) \text{ V}.$$

A slight reduction of ρ with irradiation is observed at 20°C but it recovers with the decrease of temperature.

For detector N9, after irradiation ($1.4 \cdot 10^6$ rad), the jump in leakage current is higher, from 0.6 to $15 \mu\text{A}$ at 20°C and bias voltage of 100V. At 2°C the jump is up to $2.5 \mu\text{A}$.

The depletion layer capacitance of N9 after irradiation, as a function of bias voltage (fig.3) is neither a square root nor a cubic root relation.

The value of C_T on the plateau (34.5 pF) is by 23% higher for the irradiated than for the nonirradiated detector (28 pF) at 20°C and by only 9% higher (30.5 pF) at 2°C .

The variation $(\Delta X_d/X_d) 100 = (19 \pm 4)\%$.

Since from function $C_T = f(V)$ it follows that the junction is neither linear-graded nor a step function, the resistivity and thus the internal voltage cannot be meaningfully evaluated.

3.2 Response to relativistic charged particles

3.2.1 Experimental set-up

A ^{106}Ru β^- source of 4 mm diameter was located 3.5 cm from the silicon device Si, namely N14 or N9 under measurement (fig.4). Downstream, another silicon detector Si_B (300 μm thick), an Al absorber (200 μm thick) and a scintillator Sc (3 mm thick) were positioned. The active areas of these devices were 1 cm^2 . The signal pulses from the silicon detectors were sent to standard Ortec-125 charge amplifiers. The preamplified signals went to Ortec-472 spectroscopy amplifiers. The output pulse from the amplifier associated to Si_B had a rise-time of about 0.4 μs and a base-line of about 1.2 μs . The threshold of the associated discriminator was set to a value slightly lower than the corresponding signal of a minimum ionizing particle traversing Si_B . Two photomultipliers were coupled to the Sc device.

The trigger was defined by the coincidence of the Si_B detector and the scintillator Sc (the latter generating a jitter of only a few ns). The trigger signal provided a gate for a peak sensing LeCroy 2259ADC, where the pulse, coming from the upstream detector, was recorded and subsequently read out by an HP2100 computer. The gate width was set to 0.7 μs for a corresponding shaping time of 0.125 μs of the amplifier associated to Si. The counting rate was about 30 triggers per second.

Before irradiation, detectors N14 and N9, together with the associated electronics, had a Gaussian noise distribution, σ_{noise} , whose values were (6.0 ± 0.4) and (4.9 ± 0.3) keV respectively. After irradiation the values became (7.1 ± 0.4) and (15.3 ± 0.9) keV.

The above described arrangement selected electrons emitted in a forward cone of $\pm 4^\circ$, with an initial kinetic energy greater than 0.8 MeV ($\beta > 0.92$). Thus, the overall energy-loss spectra are described, to a first approximation, by a Landau distribution convoluted by a Gaussian function. The standard deviation of the convoluting normal function takes into account both the noise contribution and the effect of atomic electron binding energies [3].

The most probable energy loss ϵ_{mp} is, in this case, related to traversed thickness x (in cm):

$$\epsilon_{mp} \approx 0.199 x [17.451 + \ln(x)] \quad [\text{MeV}] \quad (2)$$

This formula is eq(8) of [4] and is valid within 7%.

3.2.2 Energy – loss analysis

Data samples of about 30000 events were taken for both nonirradiated and irradiated fully depleted detectors at 20°C.

The experimental energy – loss distributions were fitted to the Landau probability density convoluted with a Gaussian. The fitting procedure in which ϵ_{mp} is one of the free parameters is described in [3].

In figs.5 and 6, the energy – loss spectra sensed by detectors N14 and N9, before and after irradiation, are presented. The full lines are the fitted functions.

It can be seen that for detector N14 (fig.5a and b) the spectra are similar and the most probable energy loss ϵ_{mp} is (75.2 ± 5.0) keV for the nonirradiated detector, corresponding to its full thickness, 273 μm , and (73.8 ± 4.4) keV for the irradiated one. From eq(2) and the measured ϵ_{mp} , the depletion layer thickness of the irradiated detector N14 was calculated and found to be (268 ± 16) μm . Thus, the variation of the fully depleted layer, $(\Delta X_d/X_d)100$, is $(1.8 \pm 5.6)\%$, which is compatible with the one measured employing the capacitance measurement.

From a comparison of the nonirradiated and irradiated detector N9 (fig.6a and b), two main differences can be observed: for the irradiated detector (1) the most probable energy – loss is lower and (2) the width of the distribution is broader.

The fitted value of the most probable energy loss is (104.2 ± 6.3) keV for the nonirradiated N9 which corresponds to the full thickness, 370 μm , and is (80.1 ± 4.8) keV for the irradiated N9. From eq(2) and the measurement of ϵ_{mp} , the thickness of the irradiated N9 was calculated and found to be (285 ± 17) μm . Thus, the variation of the fully depleted layer, $(\Delta X_d/X_d)100$, was $(22.7 \pm 5.0)\%$, which is compatible with the one found, by measuring the capacitance.

The two measurements are compatible and prove that for higher doses, above 10^6 rad, the fully depleted thickness is being reduced and becomes dependent on the temperature. For doses below 10^5 rad, no temperature dependence was observed and the fully depleted thickness is compatible with the nonirradiated one.

The broadening of the distribution of the irradiated N9 is caused by the large increase of the leakage current which leads to σ_{noise} of about 15 keV.

4. Conclusions

One general conclusion from the present and previous investigations [1] is that the leakage current of an ion-implanted silicon detector after irradiation is sensitive to the gradient of the irradiation. When two detectors of similar resistivity were irradiated by a similar dose, the one irradiated during 30s (as compared to that irradiated during several weeks), exhibited an about 80 times higher leakage current.

For doses below 10^5 rad, no temperature dependence and no change in the layer width of the fully depleted detector was observed.

In a previous investigation [1] it was found that for a device with $\rho = 3.5 \text{ k}\Omega \text{ cm}$ there was no decrease of the depletion layer width of the fully depleted detector after high irradiation ($> 10^6$ rad). In this experiment, for a similar irradiation of a detector with $\rho = 9 \text{ k}\Omega \text{ cm}$, it was found that the layer width of the fully depleted detector (which is equal to the physical thickness of the detector) before the irradiation, became smaller and dependent on temperature after irradiation. It seems, therefore, that the degradation of performance with irradiation is smaller for detectors with lower resistivity. Thus, for a highly irradiated ($> 10^6$ rad) detector the most probable energy loss decreases and the width of the noise distribution broadens, depending on the value of resistivity.

Acknowledgment

Two of the authors (PGR and AS) would like to thank Dr.Daniel Treille for his support and encouragement.

References

- [1] P.Borgeaud, J.G.McEwen, P.G.Rancoita and A.Seidman, Nucl.Instr.and Meth. 211(1983)363.
- [2] M.H.Van de Voorde, CERN 69—12, 21 May 1969.
- [3] S.Hancock, F.James, J.Movchet, P.G.Rancoita and L.vanRossum, Phys. Rev.A28 (1983) 615, and Nucl. Instr. and Meth.A235 (1985), 55.
- [4] N.Croitoru, P.G.Rancoita and A.Seidman, Nucl.Instr.and Meth.A234 (1985)444.

Figure captions

Fig.1 : Depletion layer capacitance per unit area, C_T , as a function of bias voltage for detector N14 before irradiation ($\bigcirc$) and for detector N9 before irradiation ($\blacksquare$).

Fig.2 : Depletion layer capacitance per unit area, C_T , as a function of bias voltage for detector N14, before irradiation at 20°C ($\bigcirc$), after irradiation at 20°C ($\bullet$) and at 2°C ($\blacksquare$).

Fig.3 : Depletion layer capacitance per unit area, C_T , as a function of bias voltage for detector N9, before irradiation at 20°C ($\bigcirc$), after irradiation at 20°C ($\bullet$) and at 2°C ($\blacksquare$).

Fig.4 : Experimental layout. The detector under measurement, i.e., N14 or N9, is indicated by Si.

Fig.5 : Energy-loss distribution of β^- from ^{106}Ru source sensed by detector N14: a.before irradiation, $\epsilon_{\text{mp}} = (75.2 \pm 5.0)$ keV and b.after irradiation, $\epsilon_{\text{mp}} = (73.8 \pm 4.4)$ keV.

Fig 6 : Energy-loss distribution of β^- from ^{106}Ru source sensed by detector N9: a.before irradiation, $\epsilon_{\text{mp}} = (104.2 \pm 6.3)$ keV and b.after irradiation, $\epsilon_{\text{mp}} = (80.1 \pm 4.8)$ keV.

FIG. 1

FIG. 2

FIG. 3

FIG. 4

FIG. 5 (a)

FIG. 5 (b)

FIG. 6 (a)

FIG. 6 (b)