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Silicon detectors irradiated "in situ" at cryogenic temperatures

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RD39 Collaboration

Abstract

Though several studies have proved the radiation tolerance of silicon detectors at cryogenic temperatures, following room temperature irradiation, no previous investigation has studied the behaviour of detectors irradiated "in situ" at low temperatures. In this work, effects of irradiation of 450 GeV protons at 83 K will be presented, showing that after a dose of $1.2 \times 10^{15}\,\mathrm{p\,cm^{-2}}$ a charge collection efficiency (CCE) of 55% is reached at 200 V before the annealing. The same results were found at the end of the irradiation, after the sample has spent more then one year at room temperature. This shows that the CCE recovery by low temperature operation is not affected by the temperature of irradiation and by the reverse annealing.

Keywords: Cryogenics; Silicon detectors

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1. Introduction

The Lazarus effect, described as charge collection efficiency (CCE) recovery of heavily irradiated silicon detectors when operated at cryogenic temperatures, was first observed in 1998 [1] and is under study by the RD39 collaboration at CERN. Based on this discovery, the RD39 collaboration has proposed cryogenic operation for experiments where, due to harsh radiation environments and high background, radiation hardness is required. Though several studies have proved the radiation tolerance of silicon detectors at cryogenic temperatures, following room temperature irradiation, no previous investigation has studied the behaviour of detectors irradiated "in situ" at low temperatures. In this work, effects of low temperature irradiation will be presented, and using displacement damage normalisation equivalent to 1 MeV neutron fluence, comparisons are made with previous works where the irradiation was performed at room temperature.

2. Experimental set-up

The results reported here were obtained from a silicon detector irradiated at 83 K with 450 GeV protons at the CERN-SPS up to a fluence of $(1.2 \pm 0.5) \times 10^{15}\,\mathrm{p\,cm^{-2}}$. The Al/p+/n/n+/Al implanted silicon pad detectors were processed at BNL (New York, USA) on a 400 μm thick 4 kΩ cm float-zone substrate. The diodes were square pads with active area $1.5 \times 1.5\,\mathrm{mm^{-2}}$ configured as a 3×3 array. The upper central pad was exposed to a dose of $1.2 \times 10^{15}\,\mathrm{p\,cm^{-2}}$, with 450 GeV protons. This would correspond to a 1 MeV neutron fluence of about $6 \times 10^{14}\,\mathrm{n\,cm^{-2}}$ [2]. However, this conversion is based only on extrapolation of existing data, since no damage conversion factors for particles of such high energy are available in the literature. At this extreme dose, operation at cryogenic temperatures ensures negligible leakage current, making it possible to perform CCE measurements on the detector. For these, it was necessary to insert trigger scintillators into the beam and hence the beam intensity was lowered to 10^5 p/spill at 300 GeV by inserting an aluminium target 118 m upstream from the detector. A continuous flow liquid nitrogen cryostat housed the test diodes. The sample holder was kept in an ultra high vacuum chamber and was connected to a cold copper finger. The sample was then cooled by thermal conduction down to 83 K. The proton beam entered the cryostat via two 100 μm stainless steel windows aligned with the test detector. Two scintillators, external to cryostat, were used to provide coincident triggers for the detection of minimum ionising particles (MIPS). During operation, the temperature was monitored using a LabVIEW based slow control system. The detector under test was read out with a charge amplifier (shaping time constant of 2 μs) placed outside the cryostat. The pre-amplifier noise of ~2500 electrons FWHM was determined by the capacitance of the 30 cm coaxial cable between the detector and the amplifier input. The signal was connected to an oscilloscope (LeCroy 9350), which was used to build histograms of the charge spectrum. A compressor in the experimental hall controlled the liquid nitrogen flow rate into the cryostat. This flow contributed microphonic noise to the system which made low noise measurements difficult.

3. Current–voltage characteristic

The current–voltage characteristics for the irradiated pad under reverse bias was measured with a Keithley 487 electrometer, polarising the guard-ring at the same voltage of the pad in order to measure only the bulk current. The maximum applied voltage was 500 V. As shown in the Fig. 1, the leakage current at 300 K is dominated by the generation component, being proportional to the depletion depth, hence to the square root of the bias voltage, for voltages lower then the full depletion voltage.

The generation current, at the full depletion voltage, is also related to the fluence by the following empirical relation [3,4]:

$$\frac{I(\phi) - I_0}{Sd} = \alpha\phi_{\mathrm{eq}} \qquad (3.1)$$

where $I(\phi)$ is the leakage current after a fluence ϕ_{eq} (fluence equivalent to a 1 MeV radiation), I_0 is

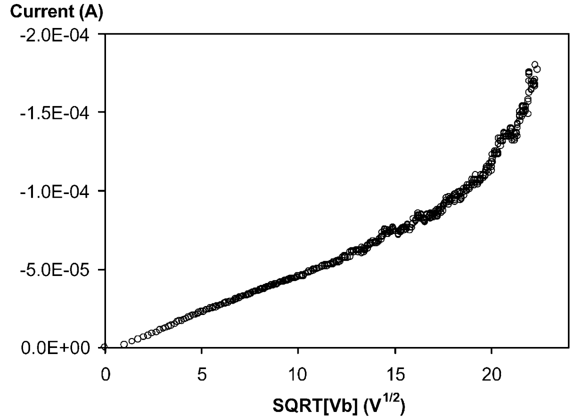

Fig. 1. Current–voltage characteristic measured at 300 K in reverse bias for the pad irradiated up to 1.2×10^{15} p/cm^2. The relationship between the current and the square root of the applied potential is linear until the breakdown.

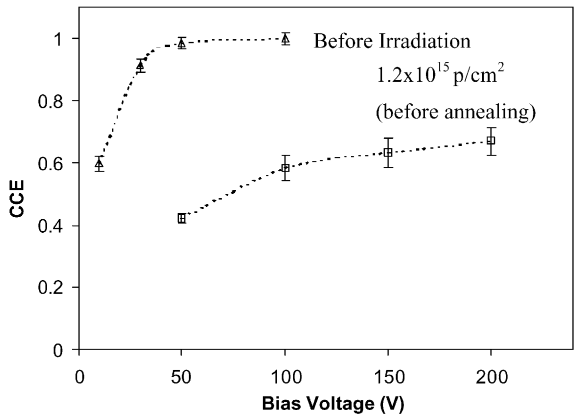

Fig. 2. Charge collection efficiency at different bias voltage. The two curves indicate the behaviour of the detector before the irradiation and after the maximum dose (1.2×10^{15} p cm^{-2}), at 83 K. For the1.2×10^{15} p cm^{-2} curve are displayed only the initial values.

the initial leakage current, S is the surface of the detector and d is the depleted thickness. The constant of proportionality, α, is generally called the leakage current damage factor, dependent on the annealing state and temperature.

Due to the diode breakdown, it has been impossible to observe the presence of a saturation knee at the depletion voltage, which, according to the empirical relation expressed before, could give then an estimation of the equivalent 1 MeV neutrons absorbed dose.

The leakage current was also measured at 80 K, showing a negligible value within the resolution of our set up.

4. CCE results

Once the system had been cooled to 83 K, CCE measurements were taken. The signals were normalised to those from a fully depleted pad before the irradiation, which achieves 100% CCE at 50 V, as shown in the Fig. 2. For the irradiated pad, each measurement was performed after the detector had been left at 0 V for a few minutes, to allow de-polarisation. In fact, the electric field in a damaged bulk of the silicon detector, and its time dependence, are strongly related to the spectrum of the deep levels present in the band gap [5]. It was therefore important to start measurements with the detector always in a stable condition. Then, having biased the detector, the CCE was monitored for about 1 h and found to have a stable value in time up to the dose of 6.5×10^{14} p cm^{-2}.

4.1. Voltage dependence

The CCE observed at different reverse bias voltages, increased as the voltage was increased. Starting from 100% CCE at 50 V for zero dose, the CCE is seen to decrease with the dose absorbed. At the fluence of 1.2×10^{15} p cm^{-2} appears also a time dependence of the CCE, with an initial value of the 42% right after the biasing at 50 V bias. At this dose, with the bias voltage increased to 200 V to improve the efficiency, an initial CCE of 67% was reached. The CCE increases with voltage within all the observed range, suggesting a higher value of the CCE for higher bias voltage. The increase with the voltage of the initial CCE follows a fast rise until 100 V and then a slower rise (see Fig. 2).

4.2. Annealing effects

After the maximum irradiation dose, the detector was warmed first at 160 K. After less then 1 h,

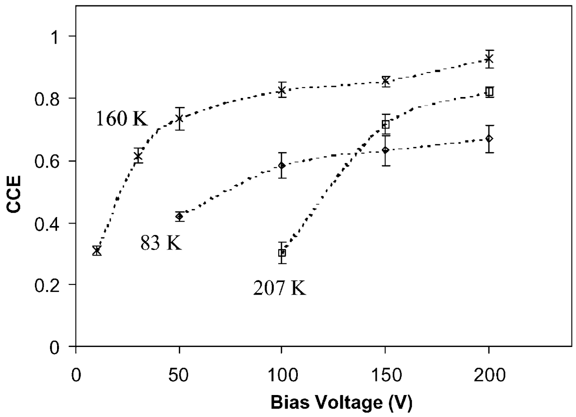

Fig. 3. CCE at the temperature of 160 and of 207 K compared with the one registered before warming up at $T = 83\,\mathrm{K}$. For all the curves the absorbed dose is $1.2 \times 10^{15}\,\mathrm{p\,cm^{-2}}$.

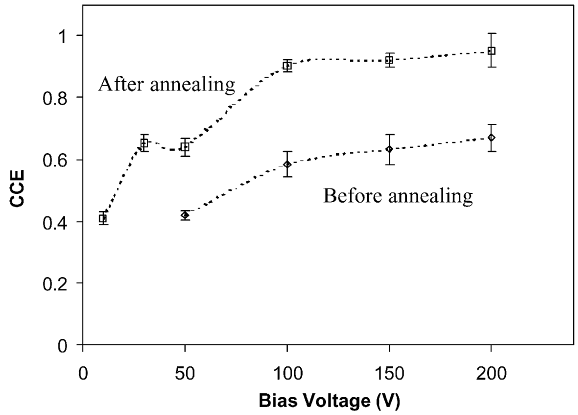

Fig. 4. CCE of the sample at 83 K after accumulating the maximum dose before annealing and at the end of the thermal cycle.

once measured the CCE, the detector was warmed again up to 207 K, and kept at this temperature for 1 h while making measurements. At 160 K, with a bias voltage of 200 V, the CCE reaches a value of the 95% and no degradation with time is registered. These measurements are shown in the Fig. 3. It is worth noting how the rising slopes of the CCE curves varies with the temperature .

Then the detector was cooled down again to 83 K. At the end of the thermal cycle, a recovery of CCE above the 60% level at 50 V bias is observed (see Fig. 4). With a further increase of bias to 200 V, the detector regains a CCE of 95%.

The sample was checked again after one year spent at room temperature. The test was done with the set up specified in Ref. [6]. The detector was biased at 190 V and the CCE was checked. A stable value of 53% was found which is compatible with the CCE measured at the maximum dose before the annealing.

4.3. Time dependence

It is interesting to note a time evolution of the CCE that takes place above fluences of $6.5 \times 10^{14}\,\mathrm{p\,cm^{-2}}$. This effect, though lightly apparent at $1.2 \times 10^{15}\,\mathrm{p\,cm^{-2}}$, is more evident after a partial annealing. Nevertheless, this CCE degradation with time seems not to compromise the beneficial annealing for which a stable value above

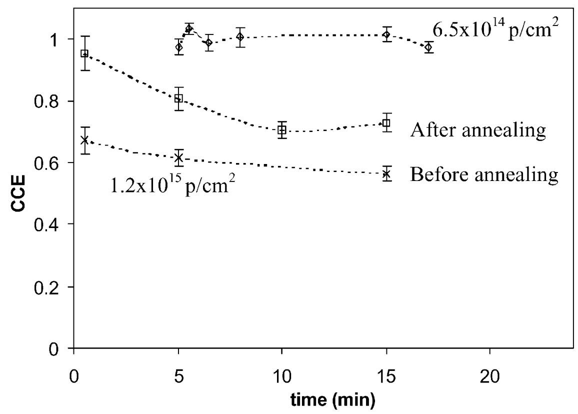

Fig. 5. Charge collection efficiency evolution of CCE with time at 83 K and a bias of 200 V for a dose of $6.5 \times 10^{14}\,\mathrm{p\,cm^{-2}}$ and for the maximum dose ($1.2 \times 10^{15}\,\mathrm{p\,cm^{-2}}$) before annealing and at the end of the thermal cycle.

70% CCE is observed at 200 V bias voltage (Fig. 5).

5. Discussion and conclusions

The CCE measured after the absorption of the maximum dose presents a value close to 60% of its original value. The degradation of the CCE with the accumulated fluence is due to the injection of negative charge into the depleted volume of the diode resulting from the irradiation. This first changes the bulk conductivity type and results in a high value of N_{eff} subsequently [7]. According to the relation:

$$V = \frac{e|N_{\mathrm{eff}}|d^2}{2\varepsilon\varepsilon_0} \tag{5.1}$$

a high value of N_{eff} requires a higher bias voltage to deplete the diode fully. For a partially depleted detector, the charge signal induced at the electrodes of a detector of thickness D will be proportional to $Q.\, d/D$ (Ramo's theorem), where Q is the generated charge and d is the thickness of the active layer. Considering MIPs, the generated charge will be proportional to (d/D), resulting in the CCE behaving like $(d/D)^2$. The presence of traps in the active volume induces another loss in the CCE [8]. In fact, the trapping of electrons and holes generated by the ionising radiation reduces their mean drift length, with a consequent loss in the signal, so that even for a fully depleted detector the CCE is lower than 100%. The operation at low temperature brings beneficial effects related to the increase of the emission time constant of the traps. A combination of two effects takes place: (a) partial neutralisation of the deep levels in the silicon band gap, which will no longer trap radiation-induced charge carriers and (b) a reduction of N_{eff} which allows full depletion at lower voltages. The experimental results presented in this work show that the CCE recovery of a heavily irradiated silicon detector when operated at low temperature is not affected by the temperature during irradiation. Moreover, if one were to compare the data shown in this work following an irradiation of $1.2 \times 10^{15}\,\mathrm{p}_{450\,\mathrm{GeV}}\,\mathrm{cm}^{-2}$ equivalent approximately to $6 \times 10^{14}\,\mathrm{n}_{1\,\mathrm{MeV}}\,\mathrm{cm}^{-2}$ [2], with the results following room temperature during irradiation [6], one would find a reasonable compatibility. Also, the fact that the reverse annealing does not affect the recovery of the CCE takes to the conclusion that the cooling is needed only during operation.

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References

[1] V.G. Palmieri, et al., Nucl. Instr. and Meth. A 413 (1998) 475.
[2] RD 48 Collaboration, V. Augelli, et al., CERN/LHCC 98-39, LEB Status Report/ RD48 21 October 1998.
[3] R. Wunstorf, Ph.D. Thesis, University of Hamburg, see also DESY FH1K-92-01 (1992).
[4] K. Gill, et al., Nucl. Instr. and Meth. A322 (1992) 177.
[5] V. Eremin, et al., Sov. Phys. Tech. Semicond. 8 (1974) 1157.
[6] K. Borer, et al., Nucl. Instr. and Meth. A 440 (2000) 5.
[7] Z. Li, H.W. Kraner, IEEE Trans. Nucl. Sci. NS-38 (1991).
[8] L. Bettie, et al., Nucl. Instr. and Meth. A 412 (1998) 238.