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Evidence for charge collection efficiency recovery in heavily irradiated silicon detectors operated at cryogenic temperatures

Vittorio Palmieri, Kurt Borer, Stefan Janos

Laboratorium fuer Hochenergiephysik, Universitaet Bern, Sidlerstrasse 5, 3012 Bern, Switzerland

Cinzia Da Viá

Department of Physics and Astronomy, University of Glasgow, Glasgow G128QQ, Scotland

Luca Casagrande

Laboratório de Instrumentação e Física Experimental de Partículas, av. E. Garcia 14, 1000 Lisboa, Portugal

Abstract.

Charge collection efficiency of 300 μm thick silicon detectors, previously irradiated with 2.23 10^{15} n/cm^2, has been measured at 4.2 K, 77 K and 195 K. The recovery measured at a bias voltage of 250 V leads to a most probable signal for minimum ionizing particles of 13000 electrons, preserving its fast characteristics (< 5 ns). Negligible difference is observed between 77 K and 4.2 K operation, while no recovery is measurable at 195 K. The samples were stored at room temperature and cooled only when operated.

Radiation damage in silicon detectors has been the subject of intensive studies in recent years in view of their use in LHC experiments at CERN. Different approaches have been followed by several groups in order to understand the physics of the radiation-induced damage [1]. The conclusions of these studies suggest to fix the working temperature of the inner silicon trackers of the two largest LHC experiments (ATLAS and CMS) slightly below 0 °C [2]. As long as this temperature is maintained, clusterization of primary lattice displacements is reduced and the lifetime of the detectors prolonged. However low temperature operation only delays bulk type inversion and does not prevent dramatic depletion voltage changes [3]. Moreover, if the radiation fluence approaches 10^{15} $n_{1MeV\ eq}/cm^2$, which is the anticipated irradiation of the innermost trackers after 15 years of LHC operation [4], the detectors become unusable [5].

Electrical characterization of irradiated detectors at cryogenic temperatures has been extensively studied, while Charge Collection Efficiency (CCE) is normally investigated only at room temperature and slightly below 0 °C. In this letter we report minimum ionising particle (mip) CCE of silicon detectors irradiated with 2.23 x 10^{15} n/cm^2 and afterwards operated at cryogenic temperatures. It will be shown that cryogenic cooling produces relevant recovery of the CCE when compared to operation at room temperature or close to 0 °C where the CCE is practically unmeasurable. It is important to stress that the investigated devices are cooled only during operation and otherwise stored at room temperature.

Moderate cooling is normally applied to irradiated silicon detectors to lower the leakage current and to inhibit "reverse annealing" [6]. At cryogenic temperatures, however, the trapping and de-trapping of carriers in radiation induced levels cause modifications of the detector electrical properties, such as the effective concentration of the ionised charges. This will in turn modify the electrical field distribution and therefore affect the CCE. Radiation-induced defect characterisation, at cryogenic temperatures, by means of Thermally Stimulated Current (TSC) [7] and Transient Current (TC) [8] techniques, has shown that the mobility of the carriers increases significantly leading to much faster output signals, while traps are inactive. In fact, at cryogenic temperatures, the de-trapping rate of electrons and holes is strongly affected by the reduced thermal energy. Trapping of drifting charges becomes the predominant effect, leading to the condition that a consistent fraction of deep-levels are filled and therefore inactive. Similar properties have been observed in the case of diamond detectors, in which the as-grown material already contains very deep traps. In this case, even at room temperature, neutralisation of deep traps is normally achieved by optical or electrical trap filling (*pumping*) [9].

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Float Zone (FZ) silicon detectors 300 μm thick, 0.7 x 0.7 cm^2 were irradiated for 30 minutes at TRIGA [10] up to 2.23 x 10^{15} n/cm^2 . Two different types of materials (oxygenated and non-oxygenated), currently under study by the CERN RD48 (ROSE) collaboration, were investigated. Both are n-type Al/n^+/n/p^+/Al implanted diodes. The as-grown resistivities are 1.8 kΩ-cm and 2.7 kΩ-cm for the oxygenated and the non-oxygenated materials respectively. The characterization of similar samples is described in [11].

The CCE measurements were performed at three different temperatures (4.2 K, 77 K and 195 K) immersing a cryogenic insert, described elsewhere [12], in liquid He, liquid N_2 and solid CO_2 respectively. The set of measurements for each detector always started at 4.2 K and was subsequently increased to 77 K and 195 K in two steps. At 4.2 K rather long (~10h) leakage current stabilization was necessary, while at higher temperatures one hour was sufficient. Mips charge distribution was measured at different bias voltages at the three temperatures for each irradiated detector. Non-irradiated detectors from the same wafer were used as reference and measured in exactly the same conditions. The bias voltage was varied from 50 V up to 250 V (the maximum value allowed by our set-up). Mips selection from a ^{106}Ru source was obtained using an additional silicon diode detector behind the test sample to provide a trigger. The trigger signal was amplified by a fast charge amplifier, while the signals from the detector were amplified by a charge amplifier with 2 μs shaping constant (AMPTEK 225, ~6000 e^- FWHM noise) and subsequently sent to a multi-channel analyzer. The large noise was mainly due to the 150 pF capacitance of the coaxial cable from the detector in the cryostat to the amplifier. The fast current signal of the detector was also measured directly with a low noise FET input voltage amplifier (5 ns risetime, 5 μV rms noise) connected to a digital oscilloscope (Tektronix 620B) in averaging mode. The detectors leakage current was continuously measured by a picoammeter (Keithley 697) for different bias voltage settings.

Fig. 1 shows the charge distribution for mips recorded at 77 K for (a) non-irradiated and (b) irradiated, silicon oxygenated diodes at 250 V bias voltage. As expected, we measure a reduction of the collected charge for the irradiated detector. It is worth stressing that the non-irradiated detectors show 100% CCE at full depletion voltage for all temperatures. The mips fast current signal of the irradiated silicon oxygenated diode at 250 V bias voltage is shown in fig. 2. This measurement was limited by the 5 ns risetime of the voltage amplifier. Similar results from the non-oxygenated detectors were obtained in the same experimental conditions. No appreciable changes were observed in either type of detectors when comparing operation at 77 K and 4.2 K.

The CCE (normalized to the corresponding non-irradiated detectors) of the irradiated samples, (a) oxygenated and (b) non-oxygenated, is shown in fig. 3 as a function of the bias voltage. The oxygenated diode, at 250 V bias voltage, shows a CCE of 0.52 ± 0.05 and 0.48 ± 0.05 at 4.2 K and 77 K respectively. Under the same bias conditions, the corresponding values for the non-oxygenated detector are 0.45 ± 0.05 and 0.47 ± 0.05. At 195 K the signals of the irradiated samples were indistinguishable from the pedestal. This is not surprising since, at this temperature, TSC measurements show that most of the radiation induced traps are still active.

Our results demonstrate that cryogenic operation of heavily irradiated silicon detectors leads to a significant recovery of the CCE. No significant difference was found between 77 K and 4.2 K. The measured values are expected to improve once a suitable mechanism of additional trap filling (*pumping*) is applied. Work in this direction is currently in progress. Concerning the read-out, conventional semiconducting electronics operates successfully at 77 K. In the context of high energy physics experiments, for example, interesting results have been achieved for the ATLAS liquid argon calorimeter [13]. In particular, at this temperature, bipolar circuits are expected to survive bulk radiation damage for the reasons discussed in this letter. For operation at 4.2 K it is possible to rely on Nb-based Josephson superconducting circuits which have already been shown to be the ultimate in radiation-hard technology [14]. Although a liquid He cooling system requires some sophistication, a much simpler picture applies for liquid N_2 where cooling pipes, like those proposed for the LHC experiments, could be used in combination with additional thermal insulation.

We conclude that cryogenic temperature operation allowed, for the first time, to obtain a mip signal (most probable dE/dx) of 13000 electrons for a 300 μm thick semiconductor detector irradiated above 10^{15} n/cm^2. This remarkable result was not affected by room temperature storage of the unbiased detectors.

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Figure Captions

Figure 1. Charge distributions for mips recorded at 77 K for (a) non-irradiated and (b) irradiated. silicon oxygenated diodes at 250 V bias voltage.

Figure 2. Mips current signal from the irradiated silicon oxygenated diode amplified by a fast low-noise (5 ns rise time, 5 μV rms noise) voltage amplifier and acquired by a digital oscilloscope in averaging mode. The detector bias voltage was 250 V.

Figure 3. CCE for irradiated detectors, (a) oxygenated and (b) non oxygenated, normalized to the corresponding non-irradiated ones, as a function of the applied bias voltage. Error bars include estimated systematic errors. The curves are drawn as guides to-the-eye.

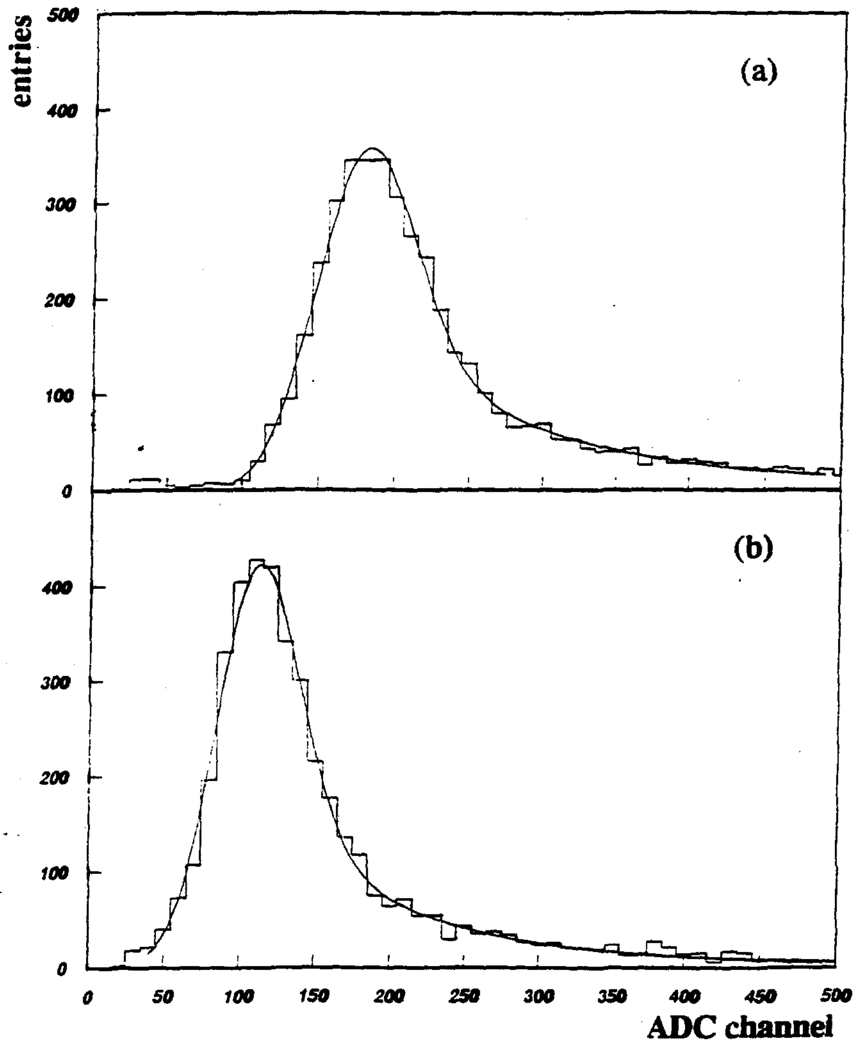
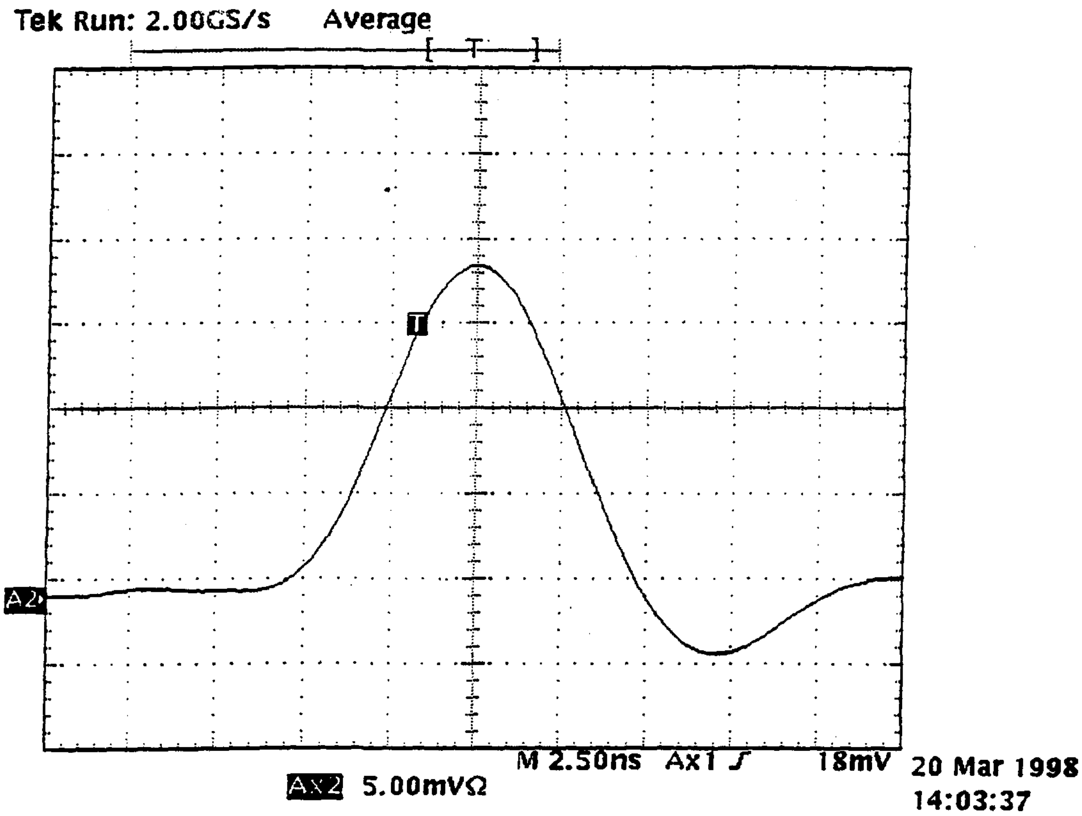

entries
500
400
300
200
100
0
(a)
(b)
0
50
100
150
200
250
300
350
400
450
500
ADC channel

Figure 1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T
A2
M 2.50ns Ax1 ∫ 18mV
Ax2 5.00mVΩ
20 Mar 1998
14:03:37

Figure 2

360

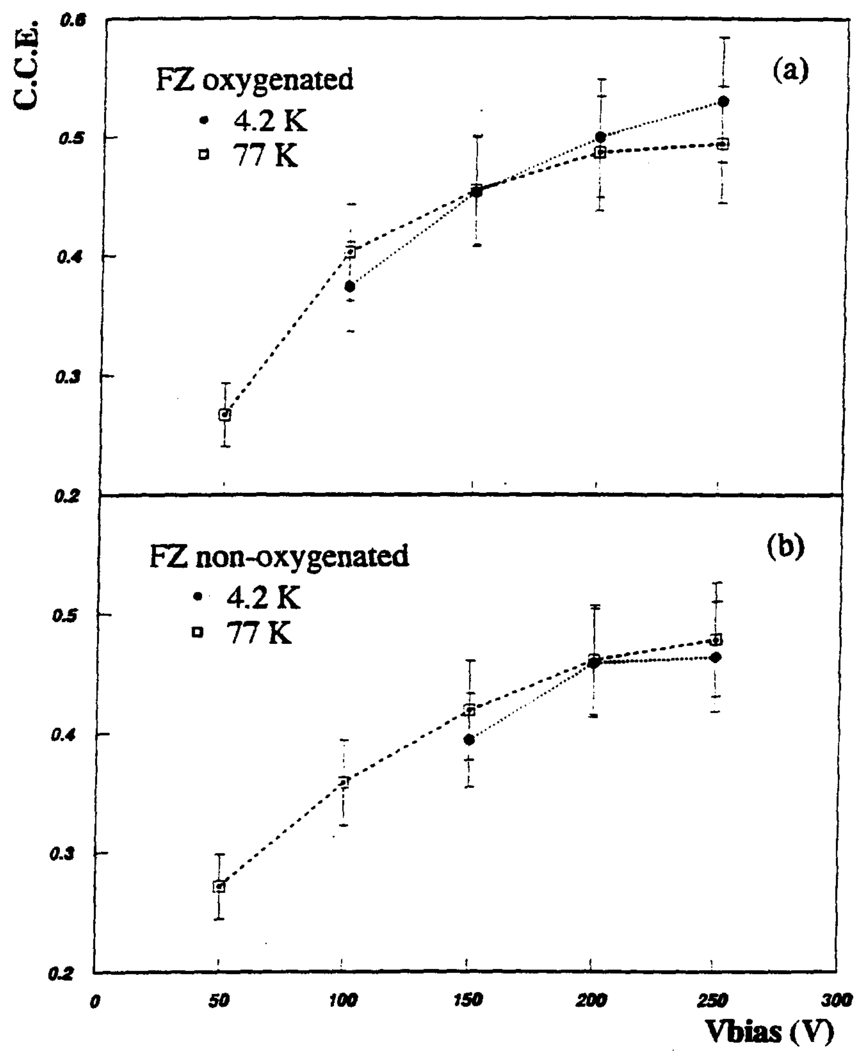
C.C.E.
FZ oxygenated
• 4.2 K
▫ 77 K
(a)
FZ non-oxygenated
• 4.2 K
▫ 77 K
(b)
0.6
0.5
0.4
0.3
0.2
0
50
100
150
200
250
300
Vbias (V)

Figure 3