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Review on the development of cryogenic silicon detectors

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The RD39 Collaboration

Abstract

In this paper, we report on the performance of heavily irradiated silicon detectors operated at cryogenic temperatures. The results discussed here show that cryogenic operation indeed represents a reliable method to increase the radiation tolerance of standard silicon detectors by more than one order of magnitude. In particular, a 400 μm thick "double-p" silicon detector irradiated up to $1 \times 10^{15}\,\mathrm{n/cm^2}$ delivers a mip signal of about 27 000 electrons when operated at 130 K and 500 V bias. The position resolution of an irradiated microstrip detector, and "in situ" irradiation of a pad detector during operation in the cold are also discussed. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Lazarus; Cryogenic; Silicon; Detectors

1. Introduction

It has been shown [1] that heavily irradiated silicon detectors, no longer operational at room

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temperature, show a dramatic recovery of the charge collection efficiency (CCE) when they are operated at cryogenic temperatures. This experimental observation is often referred to as the "Lazarus effect". This phenomenon has been further investigated by the CERN RD39 Collaboration [2], which studies cryogenic silicon detectors, in view of their use in applications requiring extreme radiation hardness. The results presented here show that indeed cryogenic operation represents a reliable technique to enhance the radiation tolerance of silicon detectors by more than one order of magnitude.

This paper is organised as follows. In Section 1, we report on the results obtained with single-diode structures irradiated to different fluences. Results from a "double-p" silicon detector, which shows unprecedented charge collection efficiency, are also presented. In Section 2, the position resolution of an irradiated double-sided microstrip detector operated at cryogenic temperatures is discussed. The question of what happens to silicon detectors, which are irradiated while operated in the cold is discussed in Section 3.

2. Results on diodes

We have investigated DC-coupled high-resistive (4–7 kΩ cm) Al/p^+/n/n^+/Al structures processed at BNL. In all cases, simple processing technology involving at most three mask steps was used. A single guard-ring surrounded the $5 \times 5\,\text{mm}^2$ sensitive area. The samples were irradiated (at room temperature) with neutrons at the TRIGA nuclear reactor of the J. Stefan Institute. All fluences in this paper are given as equivalent of 1 MeV neutrons.

At 77 K, the leakage current is strongly suppressed and measured to be less than 1 nA for all detectors up to 500 V reverse bias. Such a low current is observed also under forward bias in the case of samples irradiated above $5 \times 10^{14}\,\text{n/cm}^2$, thanks to the high-bulk resistivity. The samples were tested using minimum ionising particles (mip's) from a ^{90}Sr source. A 1 μs shaping time charge amplifier was used to read out the signals. The CCE was determined normalising the most probable value of the recorded charge spectrum with that of a non-irradiated sample. The errors shown in the figures include the systematic uncertainty on the sample thicknesses.

Fig. 1 shows the temperature dependence of the CCE under reverse (left) and forward (right) bias. For all samples, the CCE increases with decreasing temperature and peaks around 130 K. In the case of the most irradiated sample, a CCE of ~20% is achieved for 250 V applied bias. In reverse bias, the CCE decreases with time, reaching the stable values

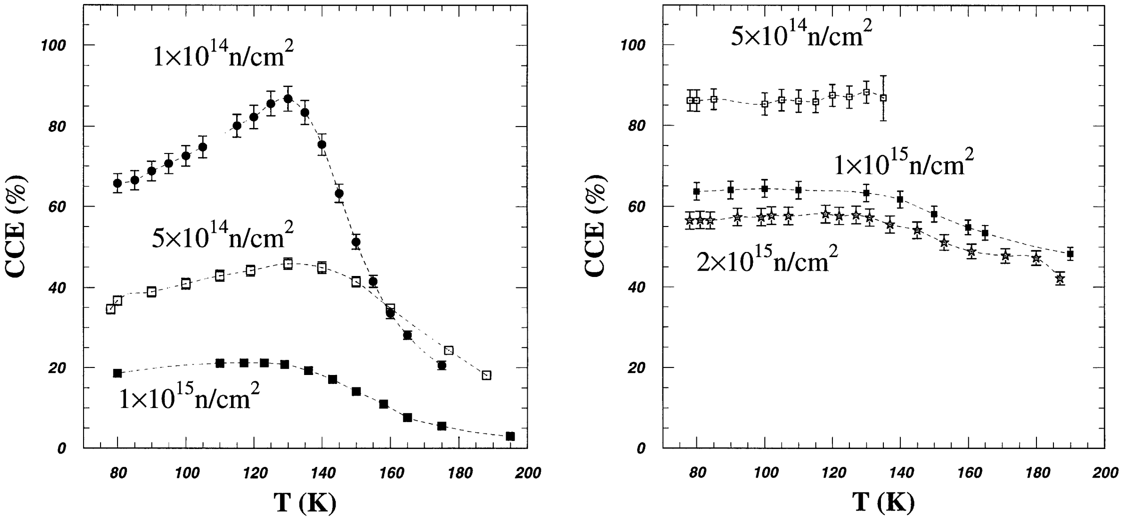

Fig. 1. CCE as a function of temperature for (left) reverse and (right) forward bias operation.

shown in the figure. This phenomenon is typical of materials reach in deep-level traps (such as heavily irradiated silicon) and is similar to the "polarisation" observed in germanium detectors [3].

In forward bias, the CCE does not decrease with time and stays to values that are about three times higher than in reverse bias. The high CCE values recorded at higher temperatures are in agreement with results obtained in the case of moderate cooling [4]. Nevertheless, the measurements above 200 K were characterised by a large leakage current, which induced noise such that it was not possible to perform a proper Landau fit of the recorded charge spectrum.

One could think of using a reverse biased detector until the resistivity of the bulk is such that forward bias can be applied. Unfortunately, this option requires bipolar readout electronics and bias voltage supply. Alternatively, one could consider the use of special devices designed to take full advantage of the operation in the cold. We have investigated the performance of an Al/p$^+$/n/p$^+$/Al-implanted silicon detector, hereafter named "double-p". Before irradiation, such a device behaves like two diodes connected in opposite direction. When irradiated beyond bulk inversion, the double-p detector is expected to become ohmic-like, and consequently have a time-independent CCE.

The 400 μm thick double-p detector was irradiated up to $1 \times 10^{15}\,\mathrm{n/cm^2}$. Also in this case the leakage current at 77 K was below 1 nA in the bias range ± 500 V. Fig. 2 shows the CCE as a function of the detector bias at different temperatures. As for the standard diodes, the highest value of CCE is achieved at 130 K. At 500 V, the unprecedented CCE of ~80% is achieved for a detector irradiated to such a dose. Contrary to what was expected, the CCE is not stable in time. This is due to the fact that the device preserves same of the original double diode behaviour. Nevertheless, at 200 V, for example, the CCE

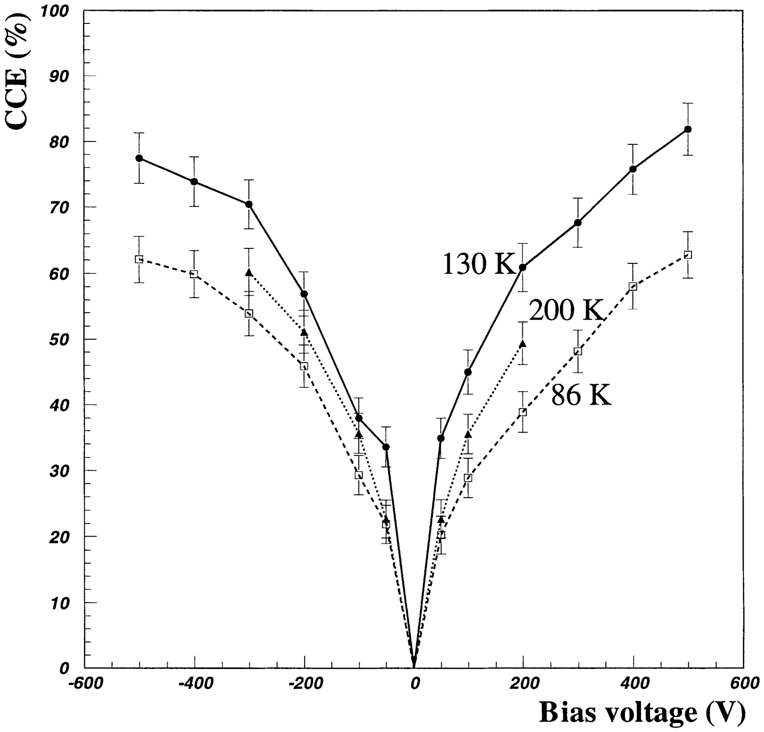

Fig. 2. CCE of the double-p detector as a function of the detector bias, for different operating temperatures. As for the standard diodes, the highest CCE values are recorder at 130 K.

decreases from the initial value of ~60% to only ~40%, while for the standard diode (irradiated to the same fluence) it goes down to ~20%.

3. Results on microstrips

In order to prove that cryogenic silicon detectors can indeed be used for tracking purposes, we have tested a rejected module of the DELPHI vertex detector [5]. This consists of two AC-coupled double-sided microstrip detectors daisy chained together and wire bonded to a double-sided hybrid carrier bus, equipped with 10 MX6 CMOS analog readout chips. The module, which has 2560 channels, covers a total sensitive area of $3.2 \times 10.8\,\mathrm{cm}^2$. The strip pitch is 25 μm on the p-side, with every second strip being readout, and 42 μm on the n-side. The tip of the detector was irradiated with 24 GeV protons at the CERN-PS. The inhomogeneous irradiation profile reached a maximum fluence of $\sim 3.5 \times 10^{14}$ protons/cm^2 on an area of approximately 1 cm^2.

The irradiated module was tested in a secondary 100 GeV muon beam of the CERN-SPS. Tracks were reconstructed using a telescope, which consisted of three stations of silicon microstrip detectors. The irradiated module was placed inside a cryostat downstream of the telescope together with a non-irradiated module used as reference. Throughout operation, the modules were kept at temperatures ranging from 115 to 140 K.

The CCE decreases with time, reaching a stable value of ~60% at 90 V detector bias, in agreement with the single-diode data. Fig. 3 shows the position resolution as a function of the CCE. The resolution on the n-side was found to be independent of the charge collection efficiency and to average around 12 μm. On the contrary, the p-side resolution deteriorates with decreasing CCE.

These results can be explained with the fact that, having been irradiated beyond type inversion, the junction depletes from the n-side. The carriers generate by ionising particles passing through the detector drift perpendicular to the electrodes. Since the field extends up to the n-strips, good track position resolution is achieved on this side. On the p-side instead the charges strop drifting when they reach the non-depleted region. Being the strip pitch sufficiently fine with respect to the non-depleted thickness of the detector, this results in a significant spread of the charge over a larger cluster.

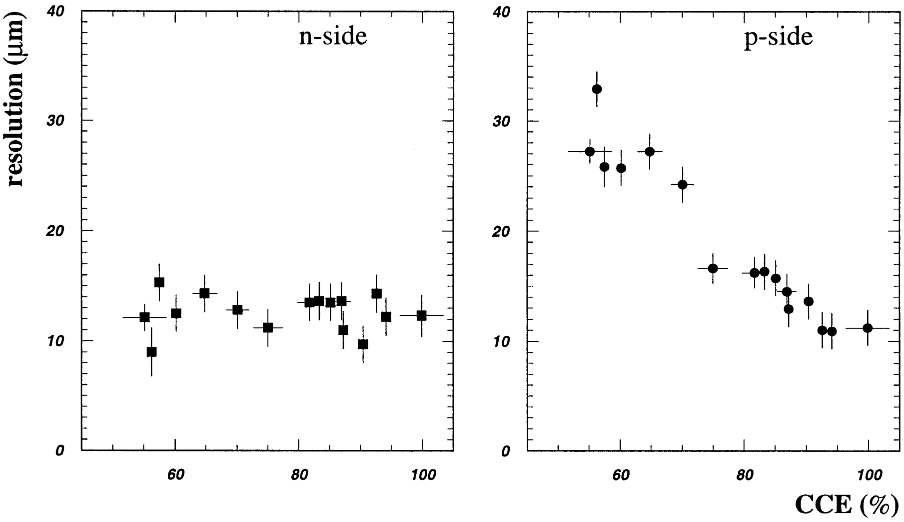

Fig. 3. Resolution as function of the CCE for the n-side (left) and p-side (right) of the irradiated DELPHI module.

4. Irradiation in the cold

A 400 μm thick silicon-pad detector was exposed to the CERN-SPS 450 GeV proton beam, while operated at a constant temperature of 83 K. The detector was irradiated and measured in a continuous-flow liquid-nitrogen cryostat, equipped with thin windows (200 μm thick stainless steel) in correspondence of the beam axis. The signals were readout by a 2 μs shaping time charge amplifier placed just outside of the cryostat.

During irradiation, the high-intensity proton beam (few 10^{10} protons per 2.5 s burst) was focused on the pad detector. Using a wire chamber placed just upstream of the cryostat and on-line monitoring of the detector, the beam size was adjusted to have a homogeneous irradiation on the $1.7 \times 1.7\,\mathrm{mm}^2$ pad area. During the CCE measurement, the beam intensity was lowered to $\sim 10^5$ protons per burst. Scintillator counters were used to select protons traversing the irradiated pad, and the corresponding charge spectrum was recorded. A total dose of about 1.5×10^{15} protons/cm^2 was reached.

At 83 K, the leakage current was below 1 nA up to 500 V. The charge collection efficiency as a function of the applied bias is shown in Fig. 4. After irradiation, the CCE at 200 V bias was around 60%. These results clearly indicate that there are no pathologies associated with the irradiation in the cold. Further work is in progress to study the sample performance after annealing.

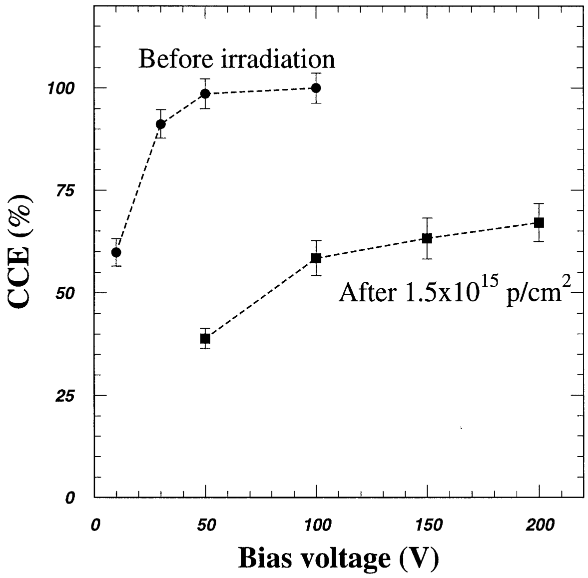

Fig. 4. CCE as a function of detector bias before and after irradiation at 83 K.

5. Conclusions

We have shown that heavily irradiated standard silicon detectors, no longer functional at room temperature, recover their performance when operated at cryogenic temperatures. A universal temperature of 130 K is found for the maximum value of the CCE. At this temperature, a 300 μm thick standard $p^+/n/n^+$ diode irradiated to $1 \times 10^{15}\,\mathrm{n/cm}^2$ shows a mip signal (most probable value) of $\sim$6000 electrons at 250 V bias. A 400 μm thick $p^+/n/p^+$-implanted silicon detector irradiated to the same fluence delivers about 27 000 electrons at 500 V bias.

Results from a test of an irradiated double-sided silicon microstrip detector show that a recovery of the CCE is accompainied by a corresponding recovery of the position resolution. No significant differences are found when the silicon detectors are irradiated while operated at cryogenic temperatures.

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