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Radiation hard cryogenic silicon detectors

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Abstract

It has been recently observed that heavily irradiated silicon detectors, no longer functional at room temperature, "resuscitate" when operated at temperatures below 130 K. This is often referred to as the "Lazarus effect". The results presented here show that cryogenic operation represents a new and reliable solution to the problem of radiation tolerance of silicon detectors. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

Finely segmented silicon detectors are the most common choice for close to interaction point tracking in high energy physics experiments. Due to the harsh environment, the effect of radiation induced damage in silicon represents a key issue in view of their long-term operation. Moderate cooling is applied to irradiated silicon detectors to lower the leakage current and to inhibit reverse annealing [1]. However, this kind of operation does not prevent the changes in effective doping concentration, implying a dramatic increase of the depletion voltage. When the radiation fluence approaches 10^{15} n/cm^2, standard detectors become unusable [2]. Sophisticated multi-guard-ring designs can be used to increase the maximum bias voltage which can be applied to a detector. Silicon detectors based on oxygenated bulk show a smaller increase of the depletion voltage when irradiated with charged particles [3].

An alternative way to improve the radiation hardness of silicon detectors is their operation at cryogenic temperatures. Indeed, it has been shown [4] that heavily irradiated silicon detectors, no longer functional at room temperature, recover their performance when operated at temperatures below 130 K. This experimental observation is usually referred to as the "Lazarus effect".

At very low temperatures, the de-trapping rate of charged carriers from radiation induced deep levels is strongly affected by the reduced thermal energy, leading to the situation in which an important fraction of traps remains filled, hence inactive. This prevents further trapping of carriers generated by particles traversing the detector and, therefore, the signal is not reduced. Moreover, the charged traps reduce the effective doping concentration thus reducing the full depletion voltage of the detector. This qualitative interpretation is in agreement with the available observations [5]. Furthermore, at cryogenic temperatures the leakage current becomes negligible. This facilitates the design of the front-end readout electronics in terms of noise requirements, and a simple readout scheme (like DC coupling) can be used. In this paper we present data obtained on silicon diodes irradiated at room temperature to fluences of 5×10^{14} and 2×10^{15} 1 MeV eq. neutrons/cm^2. We also present preliminary results on the irradiation of a silicon pad detector with 450 GeV protons during operation at 80 K.

2. Results on samples irradiated at room temperature

We have investigated the performance of two silicon (Al/p$^+$/n/n$^+$/Al) diodes irradiated at room temperature with neutrons to fluences of 5×10^{14} and 1×10^{15} n/cm^2, respectively. The 400 μm thick smaples has a sensitive area of 5×5 mm^2 surrounded by a guard-ring. Their resistivity before irradiation was around 4.5 kΩ cm.

The measurements were performed in a cryostat described elsewhere [6]. The samples were exposed to a radioactive source (^{90}Sr) and a trigger diode was used to select minimum ionising particles (MIPs). The detector signal was read out by a charge amplifier, the first stage of which was a GaAs FET operational down to 1 K mounted inside the cryostat. The noise of the amplifier was about 1500 electrons FWHM. The signal was shaped (1 μs shaping time) and sent to a multichannel analyser. The recorded charge spectra were fitted with a Landau distribution. The charge collection efficiency (CCE) was determined as the most probable value from the fit, normalised to the same value obtained for a non-irradiated detector of the same thickness operated above full depletion. The errors shown in the figures include the systematic errors due to the uncertainty on the detector thickness.

The current–voltage characteristic of the irradiated samples at 77 K showed a negligible leakage current (<1 nA) even when operated in forward bias up to 250 V. Fig. 1 shows the CCE of the samples as a function of the temperature. The measurements were only performed when the leakage current was reduced to such a value that the noise was below 2000 electrons FWHM. In the case of the sample irradiated with 5×10^{14} n/cm^2 operated in forward bias, this was only achieved for temperatures below $\sim$140 K. In reverse bias, the CCE improves with decreasing temperature until it reaches a maximum around

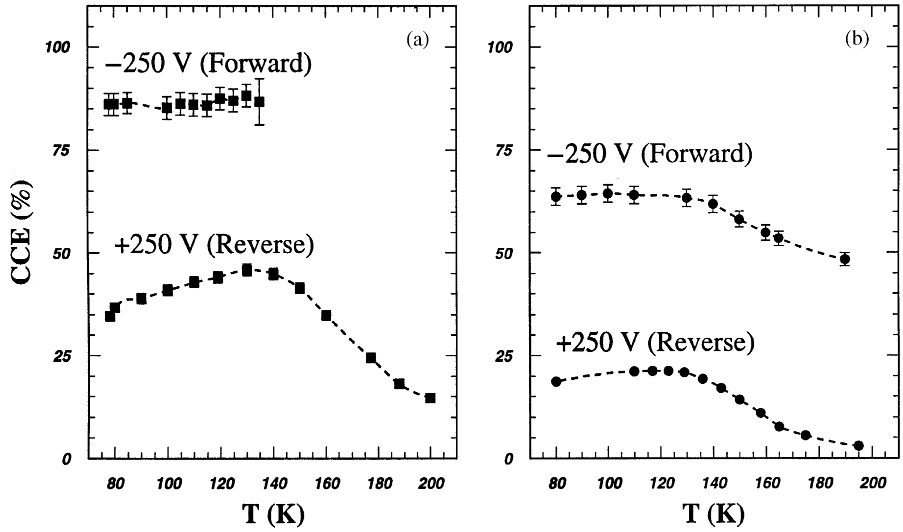

Fig. 1. CCE as a function of the temperature in reverse and forward bias operation after fluences of (a) $5 \times 10^{14}\,\mathrm{n/cm^2}$ and (b) $1 \times 10^{15}\,\mathrm{n/cm^2}$.

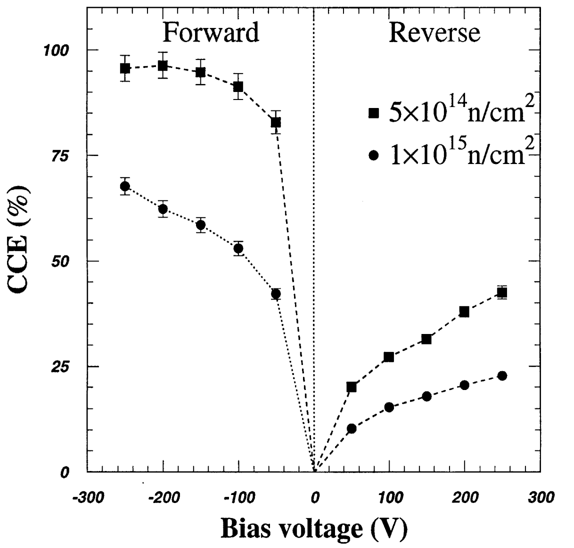

Fig. 2. CCE at $T = 77\,\mathrm{K}$ as a function of the bias voltage for the diodes irradiated at room temperature.

130 K. In forward bias, 2–3 times higher values of the CCE can be achieved also at higher temperatures, as long as the leakage current does not exceed tolerable values.

Fig. 2 shows the voltage dependence of the CCE in reverse and forward bias. The data shown in the figures correspond to measurements in stable conditions. In fact, it has been observed [6] that CCE in reverse bias decreases with time after the bias voltage is set, until it reaches a stable value. In conventional reverse bias operation, for the sample irradiated with the higherst fluence, an MIP signal of about 6500 electrons can be obtained. In forward bias there is no time dependence of the CCE and $\sim 100\%$ CCE can be achieved with 200 V after a fluence of $5 \times 10^{14}\,\mathrm{n/cm^2}$. The same result can be obtained in reverse bias in presence of short wavelength light [6].

3. Results from a sample irradiated at 80 K

A 3×3 silicon pad detector matrix was placed inside a cryostat in the CERN-SPS 450 GeV proton beam line. Each pad had a sensitive area of $1.5 \times 1.5\,\mathrm{mm^2}$. The sensor thickness was 400 μm. Two movable scintillators were used for triggering single protons for the CCE measurements. We used a liquid nitrogen continuous flow cryostat. The sample holder was kept in an ultrahigh vacuum chamber and was connected to a cold copper finger. The sample was then cooled by thermal conduction. The cryostat had two windows for the beam made of 100 μm thick stainless steel. In correspondence of the windows, the cryostat sample chamber had two 50 μm thick Al sheets acting as thermal radiation shield.

The beam was always centred on one of the pads. It had Gaussian shape in both transverse coordinates, with $\sigma_x \sim \sigma_y \sim 1$ mm at the detector. Therefore, the dose across the irradiated pad can be considered as rather uniform. The detector signal was read out by a charge amplifier placed outside the cryostat. The noise of the amplifier was ~2500 electrons FWHM, determined mainly by the 30 cm coaxial cable between the detector and the amplifier input. The signal was then fed into an oscilloscope with histogramming function, which recorded the charge spectra. The charge collection efficiency of the pad was measured using a low intensity beam, in between the high beam intensity periods of irradiation.

Fig. 3 shows the CCE of the irradiated pad as a function of the bias voltage. We assumed that before irradiation the pad was fully depleted and we normalised to this vlaue the CCE measured after the irradiation. After a dose of 1.5×10^{15} protons/cm^2 a CCE of 60% (most probable value) at 200 V bias volatge has been measured. It is worth mentioning that, contrary to the case of the irradiation at room temperature, these data show a negligible time dependence of the CCE.

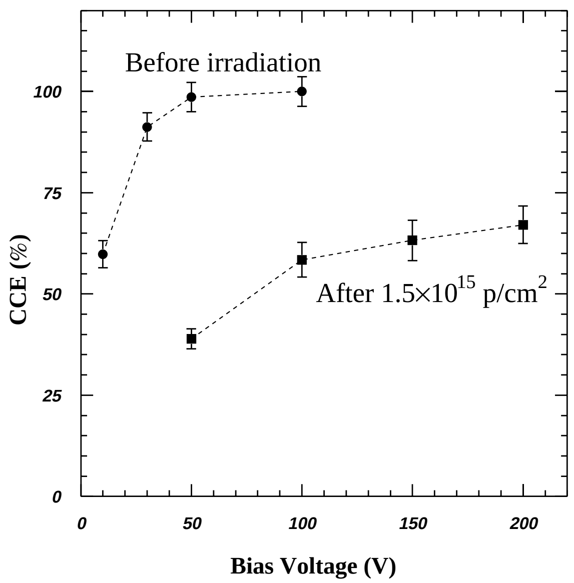

Fig. 3. CCE as a function of the bias volatge for the pad irradiated at 80 K.

One expects that stable defect generation in the silicon bulk is different from room to cryogenic temperatures. Since the detector was always operated at 80 K, we can reasonably assume that there is no annealing effect in the data. A complete understanding of the phenomenon is envisaged and work is currently in progress on this subject.

4. Conclusions

We have shown that the CCE of heavily irradiated silicon detectors recovers when the operating temperature is below 130 K. In the case of conventional reverse bias operation, an MIP signal of ~6500 electrons can be obtained from a 400 μm thick detector irradiated with 1×10^{15} n/cm^3. Furthermore, at very low temperatures forward bias operation becomes possible. In this case, a CCE of ~100% and ~60% can be achieved for samples irradiated with 5×10^{14} and 1×10^{15} n/cm^2, respectively.

Preliminary results on a silicon pad detector irradiated at 80 K indicate that there are no pathologies associated with the irradiation in the cold. It is important to stress that in the case of cryogenic operation, since the reverse annealing does not play a significant role [6], the devices only need to be cooled during operation and can otherwise be kept at room temperature.

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