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Radiation hard position-sensitive cryogenic silicon detectors: the Lazarus effect

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Abstract

The discovery of the so-called Lazarus effect, namely the recovery of the charge collection efficiency (CCE) of irradiated silicon detectors by means of cryogenic cooling has entailed an increasing interest in the behavior of silicon detectors at cryogenic temperatures. We have measured the CCE of a silicon p–i–n diode detector previously irradiated with an equivalent fluence of 1×10^{15} n/cm^2 neutrons of 1 MeV energy. The charge collection efficiency has been measured at 77 K, showing that the low-temperature operation considerably decreases the bias current. This is also the case when forward voltage bias is applied, which then becomes a suitable option. In this condition, the sample shows a charge collection efficiency in excess of 65% at 250 V corresponding to a most probable signal for a minimum ionizing particle of 21 000e$^-$. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Irradiated silicon detectors; Cryogenic detectors; Lazarus effect

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1. Introduction

In the past few years many groups of physicists have concentrated their efforts on improving the radiation hardness of silicon detectors and related readout electronics in view of their application at future experiments that will take place at the CERN-LHC (large hadron collider) (see for e.g. Ref. [1]).

A new development, which is based on the operation of silicon at cryogenic temperatures, represents a valid alternative to the standard radiation hardening techniques. The so-called Lazarus effect, consisting in the charge collection efficiency (CCE) recovery of heavily irradiated silicon detectors when operated at cryogenic temperatures, has been observed and studied since the beginning of 1998 [2]. The underlying mechanism of this effect consists in the neutralization of electron and hole traps formed by radiation-induced defects by means of low-temperature operation. At room temperature the trapping and de-trapping processes severely affects the CCE mechanism. When the devices are operated below 130 K, the de-trapping time is strongly prolonged due to the reduced thermal energy. In other words, the trapped carriers are frozen into the traps, and this in turn leads to a favorable manipulation of the radiation-induced space charge [3].

It is worth mentioning that at cryogenic temperatures the mobility of the carriers is dramatically increased while the leakage current becomes negligible. These effects contribute to improving the CCE value. Many tests made on irradiated conventional detectors, processed out of standard high resistivity (few kΩ cm) silicon substrates, have shown that the CCE depends not only on the radiation fluence value, but also on the temperature, the bias voltage and time eventually leading to 100% recovery up to a fluence of 5×10^{14} n/cm^2 [4]. Moreover, similar results in terms of overall performance recovery have also been observed in segmented devices [5].

2. Experimental results

In this paper we report preliminary results of recent tests of a silicon p–i–n diode detector irradiated up to an equivalent fluence of 1×10^{15} n/cm^2 neutrons of 1 MeV energy. The device was a Al/p$^+$/n/n$^+$/Al implanted silicon detector processed at BNL (New York, USA) out of 400 μm thick float-zone substrates with a resistivity of about 4 kΩ cm. The diode was irradiated with neutrons at a TRIGA reactor (Ljubljana, Slovenia). During and after irradiation the sample was stored at room temperature for several months and therefore can be considered reverse annealed. The CCE was measured for different voltage biases at a fixed temperature of 77 K. The experimental set-up used for the measurements consists of a vacuum tight cryogenic insert described elsewhere [6] immersed in a liquid nitrogen bath. The CCE was measured using minimum ionizing particles (MIPs) from a ^{90}Sr beta source triggered by a non-irradiated silicon detector placed behind the diode under test. The most probable value of the collected charge in the detector was determined by fitting the charge spectrum by a Landau distribution function. An example of the recorded histograms with the fitted Landau function is shown in Fig. 1. The CCE was then obtained normalizing the value resulting from the fit to that measured from a similar

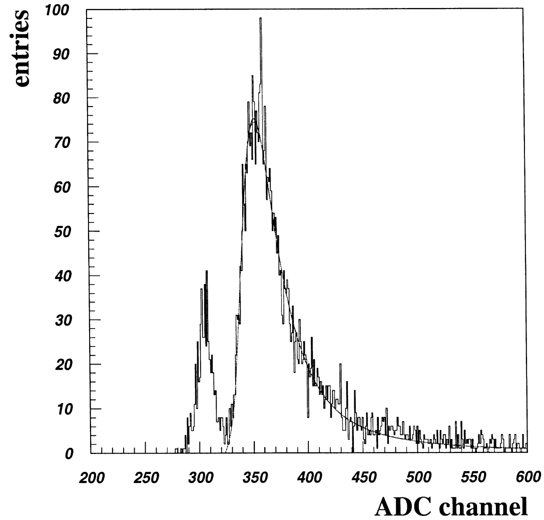

Fig. 1. A typical histogram obtained with the irradiated detector (fluence 1×10^{15} n/cm^2) at 77 K, with 250 V reverse bias. The left peak is the pedestal.

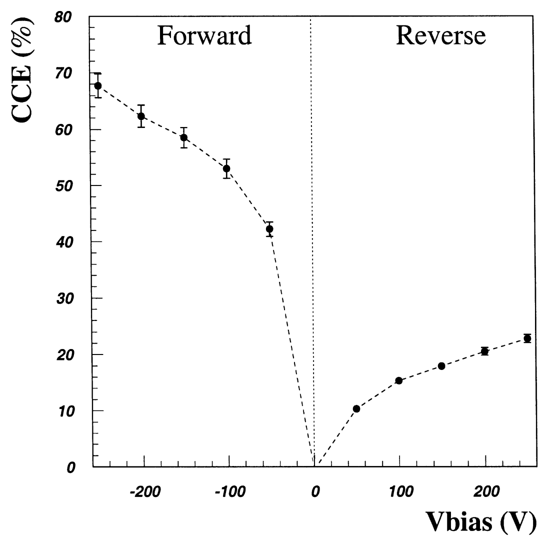

Fig. 2. Charge collection efficiency for the irradiated detector as a function of forward and reverse voltage bias at 77 K. The values for reverse bias are the stable ones.

non-irradiated detector measured under full depletion conditions. Since for heavily irradiated silicon detectors operated at cryogenic temperatures the very high bulk resistivity limits the bias current also in the forward direction, the sample could be measured from −250 V to 250 V in 50 V steps. Fig. 2 shows the CCE at 77 K (stable values) as a function of bias voltages. The CCE is better in the forward bias operation mode and at −250 V reaches the value in excess of 65% corresponding to a most probable signal for MIP of 21 000e^-. The reverse bias CCE values suffer from a significant degradation in time and the stable values are much reduced [4].

3. Conclusions

The results presented in this paper demonstrate that silicon detectors irradiated to high doses, once cooled at cryogenic temperatures, recover most of their operating performance. At 77 K it has been observed that the CCE value under forward bias reaches 65%, corresponding to a most probable signal for a minimum ionizing particle of 21 000e^-. This remarkable result relies on bias voltages below 250 V. Moreover, operation at cryogenic temperatures completely removes the leakage current, eventually allowing forward bias operation. The discovery of the Lazarus effect allows to achieve a higher radiation hardness, simply using standard silicon detectors cooled with liquid nitrogen. A systematic study of the silicon properties at cryogenic temperatures under different experimental conditions is currently in progress in the framework of the CERN-RD39 collaboration.

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