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One-cm-thick Si detector at LHe temperature

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Abstract

A silicon p-i-n diode of thickness 1 cm has been studied experimentally at liquid helium temperature. This preliminary study is aimed at the construction of a much bigger detector to detect low energy neutrino events.

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Keywords: Silicon detectors; Cryogenics; P-i-n diode; Depletion; Charge trapping

1. Introduction

High purity silicon is nowadays available at a moderate price and is mostly used at room temperature where the maximum achievable depletion is of the order of a few millimeters. In this work we demonstrate that at LHe temperature a few centimeters depletion layer can be obtained, with a mechanism that is totally different with respect to the method used with standard detectors, where a high bias voltage is applied. In fact, for temperatures smaller than 10 K the detecting material is totally free of carriers due to the freeze-out effect [1] and in this case it is no more necessary to apply high reverse bias voltages to deplete the detector volume. We also show that, in agreement with the results obtained by Penn et al. in Refs. [2–4], effects of charge trapping are absent if an electrical field of the order of a hundred V/cm is applied to the detector.

Silicon can thus be used to build bulk detectors (and not only surface barriers detectors or Si(Li) detectors, which are available up to only 1 cm thickness) with a large sensitive mass, which is necessary to increase the rate of events of low energy (~MeV) neutrino interaction. For example, to study the $\nu - e^-$ scattering 1 ton of active material is needed, whereas for the ν-nucleus scattering events approximately 100 kg could be enough.

Supported by the high mobility value of electrons and holes (close to $10^6\,\mathrm{cm}^2/\mathrm{Vs}$ [5]) and a large electron mean free path (of the order of 10 μm [6]) at this temperature, our final aim is to build a time projection chamber (TPC) with a large silicon ingot, with the possibility to obtain charge amplification in the vicinity of micropad structures.

Development of dark matter ionisation/thermal hybrid detectors with large dimensions has been studied in Refs. [7–9], but differently from the detector studied in this work, they are used also as bolometers and operated in the millikelvin range.

Note that the electronic noise has not been minimised yet in these preliminary measurements.

2. Experimental set up

A bulk cylinder (30 cm thickness, diameter of 10 cm) of floating zone crystal grown silicon has been bought from the Wacker company. The resistivity given by the manufacturer is $\rho \simeq 14\,\mathrm{k\Omega\,cm}$ at room temperature. The ingot has been cut and polished in slabs of 1 cm thickness

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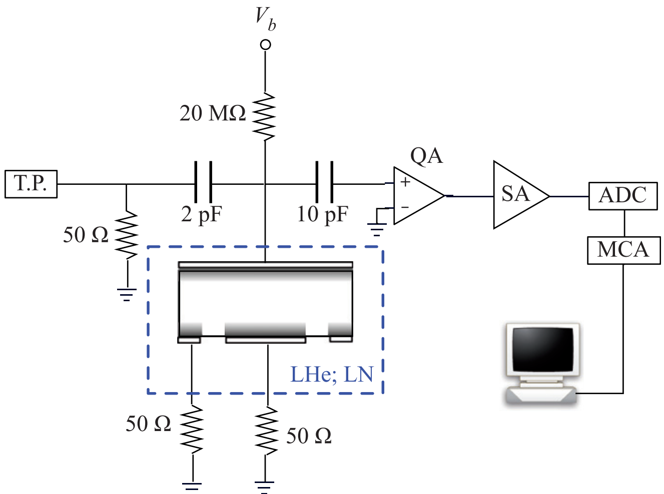

Fig. 1. Layout of the experimental setup. The signal generated inside the detector's volume is observed through a charge amplifier QA (model 142PC, Ortec) and further amplified by a shaping amplifier SA (SILENA 7612). The test pulse TP allows injection of signals for calibration.

and one of these has been used to fabricate three p-i-n diodes, with a p^+ boron diffused contact and a n^+ phosphorus diffusion, both approximately (1300 ± 100) nm thick. A 1 μm thick Al electrode was evaporated on both sides.

Each detector of 30 mm diameter has a central electrode of 22 mm diameter on the top side, surrounded by a guard ring. On the rear side the electrode is continuous.

The silicon wafer stabilised at a temperature of $T = 4.7$ K, inside a chamber with He gas at a pressure of a few mbar. The chamber is anchored to a LHe dewar. The setup is stable in temperature during measurements, which can be performed during a day.

The experimental scheme used during the tests is shown in Fig. 1.

3. Measurements and results

Currents flowing through the active volume and surface currents have also been measured at 77 K and LHe temperature as shown in Fig. 2. The leakage current measured at 77 K is four orders of magnitude greater than the current measured at LHe temperature; note that the current flowing through the central electrode is of a few pA till a bias voltage of 400 V and the current voltage characteristic curve is linear. From the quasi-ohmic behaviour of the polarised detector at 4.7 K, a bulk resistance of $T\Omega$ can be calculated.

The capacitance versus voltage measurements are shown in Fig. 3. The data obtained show progressive depletion at LN temperature with applied bias voltage V_b, whereas at liquid helium temperature the constancy of the measured capacitance confirms the expected freeze out of carriers.

The linearity of the detector response has been confirmed with an applied voltage of 250 V using three different sources, ^{137}Cs, ^{60}Co ^{22}Na (see Fig. 4).

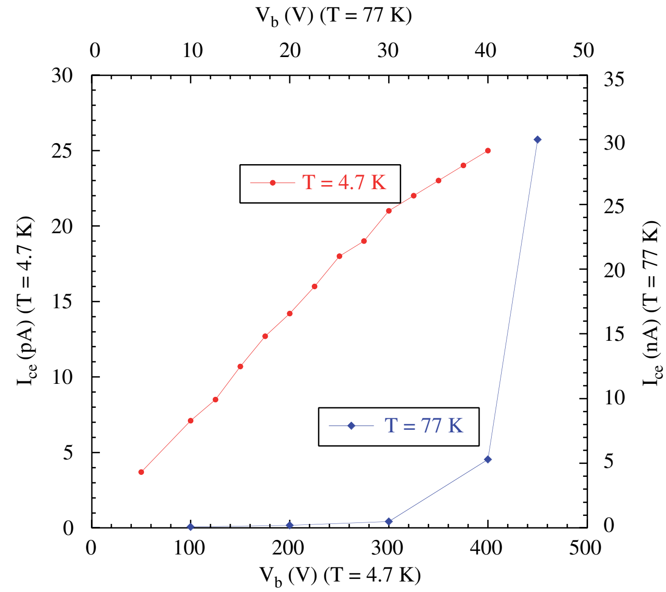

Fig. 2. Comparison between the current flowing through the central electrode I_{ce} at 4.7 and 77 K.

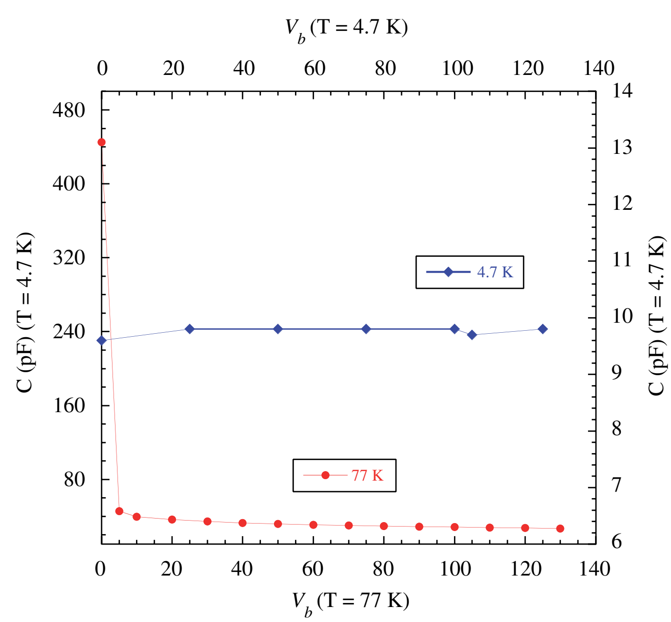

Fig. 3. Comparison between the capacitance measured at 4.7 and 77 K.

To show that inside the detector at LHe temperature charge collection is complete even with a low bias voltage, the following tests have been performed:

(1) measurement of the events rate in the detector in the presence of a ^{137}Cs radioactive source and measurement of the position of the Compton edge for different applied voltages;
(2) acquisition of a few hundreds of cosmic ray events;
(3) study of the signals corresponding to the energy release of alpha particles from an ^{241}Am source.

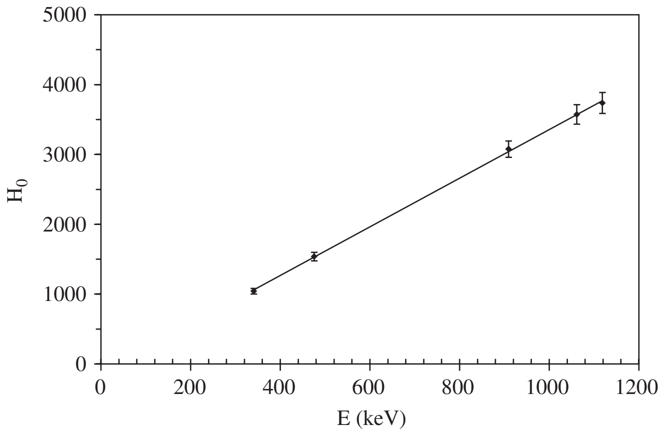

Fig. 4. Linearity of the detector response. H_0 is the centroid of the photopeak.

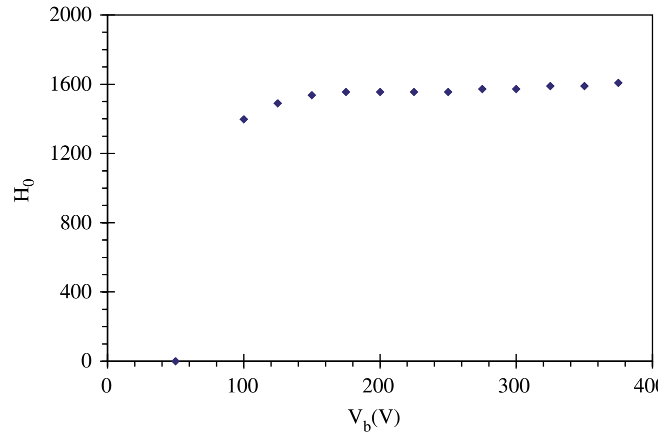

Fig. 6. Compton edge position versus bias voltage at 4.7 K. H_0 is the centroid of the photopeak.

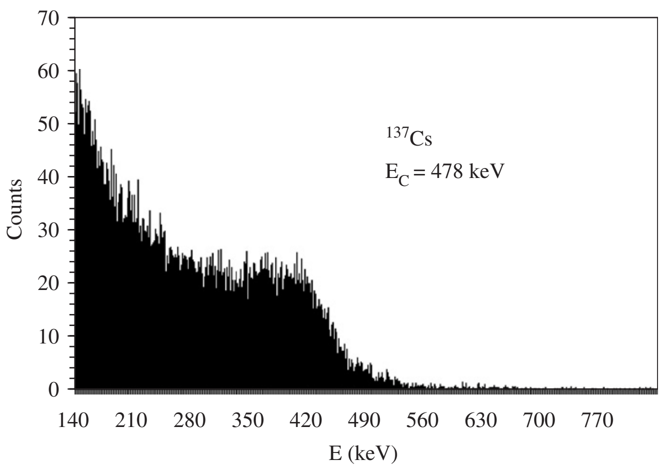

Fig. 5. Typical spectrum of a ^{137}Cs.

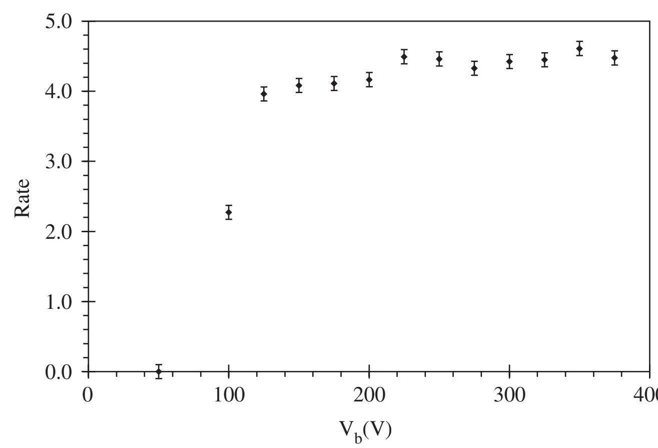

Fig. 7. Measured rate of events in the energy range $E_c \pm 3\sigma$ for a fixed interval of time.

3.1. ^{137}Cs source measurements

We studied the depletion in the entire bulk of the detector measuring the Compton edge position ($E_c = 478\,\text{keV}$) in the ^{137}Cs spectrum, for different bias voltages as shown in Fig. 6. A typical spectrum is shown in Fig. 5. The maximum pulse height ($H_0 = 1550 \pm 60$ corresponding to 478 keV) is achieved at approximately 120 V (Fig. 6). Calibration of the measurement system was accomplished injecting in the 2 pF capacitor in Fig. 1, the charge equivalent to the energy release in the detector. Another proof of total charge collection in the active volume at LHe temperature is given by the measured rate of events registered during a fixed interval of time ($\sim$1000 s) in the energy range $E_c \pm 3\sigma$, where σ has been obtained from the Gaussian distribution obtained differentiating the Compton edge. The plot shown in Fig. 7 is in agreement with the results obtained before: trapping effects are absent for $V_b \geqslant 120\,\text{V}$ at LHe temperature.

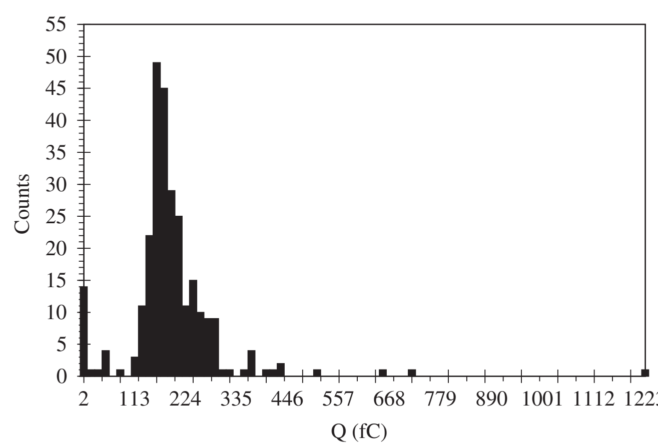

Fig. 8. Minimum Ionising Particle spectrum for $V_b = 250\,\text{V}$.

3.2. Cosmic rays events acquisition

The silicon wafer was mounted parallel to the earth surface and coincidence selection of the events was achieved through a scintillator set under the LHe cryostat.

The spectrum obtained at 4.7 K with a bias voltage $V_b = 250$ V is shown in Fig. 8: the peak value of 166 fC (±20%) corresponds to a MIP (Minimum Ionising Particle) in 1 cm thick silicon. The right tale in the histogram is due to the $\cos^2\theta$ distribution of the cosmic rays.

4. Conclusions

In this work we have studied the behaviour of a silicon detector of 1 cm thickness at cryogenic temperature, following preliminary studies with other different detectors operated at cryogenic temperatures [10]. We have demonstrated that massive silicon radiation detectors can be depleted from free carriers with the mechanism of the freeze out of the carriers, and good indications of the absence of charge trapping effects have been obtained.

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