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Ionization Measurements of SuperCDMS SNOLAB 100 mm Diameter Germanium Crystals

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Abstract Scaling cryogenic Germanium-based dark matter detectors to probe smaller WIMP-nucleon cross-sections poses significant challenges in the forms of increased labor, cold hardware, warm electronics and heat load. The development of larger crystals alleviates these issues. The results of ionization tests with two 100 mm diameter, 33 mm thick cylindrical detector-grade Germanium crystals are presented here. Through these results the potential of using such crystals in the Super Cryogenic Dark Matter Search (SuperCDMS) SNOLAB experiment is demonstrated.

Keywords Germanium crystals · Charge transport · Dark matter detectors

For the SuperCDMS Collaboration.

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1 Introduction

The Cryogenic Dark Matter Search (CDMS) experiment [1, 2] employs semiconductor crystals to perform direct searches of Dark Matter in the form of Weakly Interacting Massive Particles (WIMPs) [3]. The present generation of germanium crystals are cylinders of diameter 3″, height 1″ and mass 607 g. The detectors are operated at cryogenic temperatures of 50 mK at the Soudan Underground Laboratory, USA, and event-by-event discrimination between electron and nuclear recoils is achieved through simultaneous collection of charge and phonon signals [1, 2, 4, 5].

A future 100 kg target mass CDMS experiment will be commissioned at the SNOLAB facility in Sudbury, Canada [6]. Scaling the current generation of crystals poses significant challenges in the form of increased labor, cold hardware, warm electronics and heat load. These issues can be alleviated through the development of larger crystals. In an initial stage of the research and development effort, two 100 mm diameter, 33 mm thick cylindrical detector-grade germanium crystals of mass 1.37 kg have had charge electrodes patterned on one detector face in the form of four concentric rings.

Results of the ionization measurements of these detectors are presented here.

2 Detector Fabrication & Housing Design

Two 100 mm diameter, 33 mm thick detector-grade (impurity level $\sim 10^{10}$ atoms/cm^3) germanium n-type crystals of orientation [001] have been purchased from Umicore [7], with a dislocation Etch-Pitch-Density (EPD) of $\sim$3000 cm^{-2}. Each crystal has been etched, polished and cleaned in an ultrasonic bath prior to photolithography [8]. Thin films are deposited on both sides in the following order: 40 nm of amorphous silicon; 20 nm of aluminum; and 20 nm of tungsten. One side of each crystal is patterned and the tungsten and aluminum wet-etched to define 4 charge electrodes as a set of concentric rings as shown in Fig. 1. The electrodes are separated by 400 µm wide trenches, from which the conductive amorphous silicon film is etched out. The rings' dimensions are such that a crystal volume of 64.3 cm^3 lies under each electrode, thus ensuring a comparable response from each charge channel. Each electrode consists of a grid of 2 µm wide wires at a pitch of 40 µm. A uniform grid is present on the opposite side to the electrodes.

The housing is similar in design to that currently employed for the present generation of germanium crystals [9], scaled to encase a larger crystal. The crystal is placed within a hollow cylindrical copper hexagon of side length 2.42″ and inscribed circle radius 2.1″. Wire bonds running from each electrode connect to two Device Interface Boards (DIBs) on opposite faces of this hexagon. Top and bottom lids are then placed on this structure to protect the crystal and bonds during transportation and operation.

The top lid has been designed to fasten to a conventional CDMS tower, thus minimizing the amount of additional cold hardware to be fabricated to facilitate the testing of these detectors. Vacuum coaxial wires stretch from each DIB to the tower. The gap between the tower and coaxial wires is bridged by an extender plug. The remaining cold readout system is identical to the conventional CDMS design [9].

3 Ionization Measurements & Results

Four ^{241}Am sources, of activity 1 μCi each, are arranged in a source holder such that each lies above an electrode as shown in Fig. 1. Each source is collimated by way of a lead disc with a 0.008″ diameter hole, translating to an approximate event rate of 20 Hz. The source holder housing is identical to that of the detector described above. The structure is fastened together with M2 threaded rods that screw into the top lid.

The assembled tower is mounted within a cryostat and cooled to 50 mK with an Oxford Instruments Kelvinox 100 [10] dilution refrigerator. The detector is controlled and readout with two prototype SuperCDMS Detector Control and Readout Cards (DCRCs) connected to a computer running the LabVIEW-based data acquisition software. The DCRC is a new design of electronics to control and operate CDMS detectors, significantly simplifying the room-temperature electronics used by the experiment. It includes analog electronics to control and amplify four Quasiparticle-trap-assisted Electrothermal-feedback Transition edge (QET) sensors [11] with Superconducting Quantum Interference Device (SQUID) [9] amplifiers, and two ionization channels with Junction Field Effect Transistor (JFET) [9] amplifiers. The phonon and charge signals are digitized, processed and stored in Synchronous Dynamic Random Access Memory (SDRAM). Power, control and data readout are provided by a single Category-5 cable. For the purposes of these measurements, only signals from the ionization channels are recorded. Each DCRC is connected to a single DIB through the cold readout hardware described in [9], and a timing link is established between the two boards to synchronize triggering.

The raw data files are transferred to the Linux cluster, where they are processed using the standard CDMS analysis software package. An algorithm selects noise events from the first 500 random triggers at the start of each data series to build Power Spec-

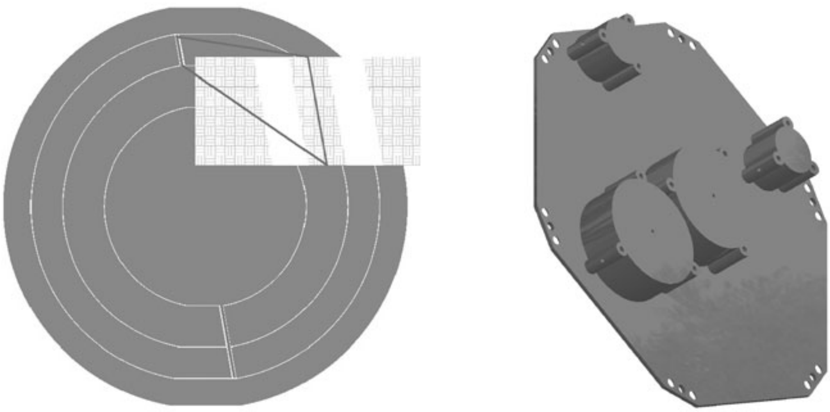

Fig. 1 (*Left*) Mask used to pattern four charge electrodes as a set of concentric rings (*gray grid*) on one side of crystal. Sections of the two inner electrodes extend through (*white*) gaps in the second and third electrodes, as illustrated in the *inset*, which depicts a magnified view of one of these interstices. This brings them closer to the Device Interface Boards (DIBs), to which they are wire bonded for readout. Additional wire bonds bridge these gaps, reconnecting the ends of each broken ring. (*Right*) Source holder housing four ^{241}Am 1 μCi sources, positioned such that each lies above the center of an electrode

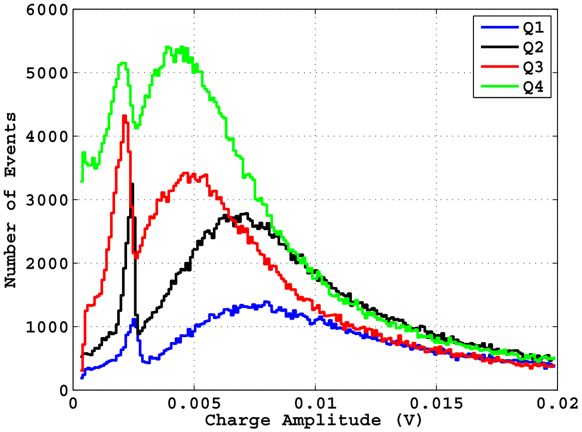

Fig. 2 (Color online) Charge energy spectra from each electrode at a uniform bias voltage of −4 V. The peaks due to 60 keV gamma-rays from the ^{241}Am sources above each electrode are visible. The spectra only include those events that exhibit the largest signal in their respective electrode

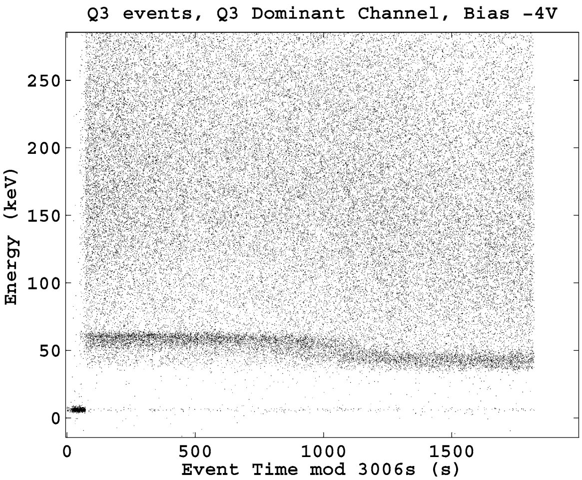

Fig. 3 Charge signal in Q3 as a function of time at a uniform bias voltage of −4 V. A sudden drop is seen after approximately 15 minutes due to charge trapping in the bulk of the crystal. The charge signals from a number of 30 minute long runs, separated by 6 s and 20 minutes of flashing and cool-down time respectively for a total run length of 3006 s as described in the text, have been superimposed on each other in the plot. This indicates that flashing the crystal with LEDs successfully restores neutralization

tral Densities (PSDs) for each channel. The PSDs are then used in an optimal filter algorithm in an effort to remove noise, and fits to an ideal pulse template generated analytically are performed on the pulses in the frequency domain. A basic cut on the χ^2 value from these fits allows for the removal of poorly fitted pulses.

Each electrode is given a designation of Qn, where n is an integer from 1 (central electrode) to 4 (outermost electrode). Typical charge energy spectra at a uniform bias voltage of −4 V are shown in Fig. 2, where the peaks due to 60 keV gamma-rays emitted from the ^{241}Am sources are clearly visible in each electrode. The event rate increases with distance from the center, due in part to self-shielding effects. However, the peak position seems to decrease with electrode radius, indicating a reduced charge collection efficiency if the response of the charge collection electrodes is assumed to be identical. This small radial dependence could easily be removed by the position correction algorithm that is standard in the CDMS data analysis [1, 2].

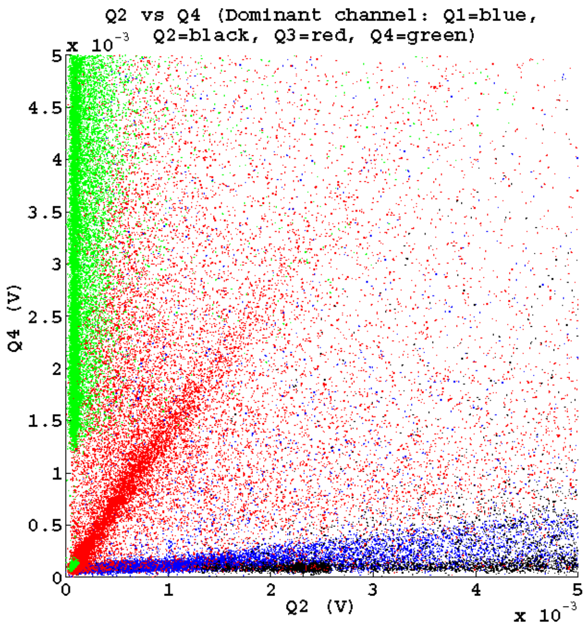

Fig. 4 (Color online) Cross talk between the Q2 and Q4 electrodes. Events where Q3 is the dominant channel lie on the diagonal

The relatively poor energy resolution in Fig. 2 can be partly explained by the rapid drop in neutralization after 15 minutes of operation as shown in Fig. 3 (another cause is that for complete charge collection, signals from all four charge channels should be added together). This is due to charge trapping in the bulk of the crystal, the reasons for which are given in more detail by [12, 13] and references within. To combat this degradation the electrodes are grounded after 30 minutes and the detector is flashed with four Light-Emitting Diodes (LEDs), each at a current of 0.6 mA, in 100 µs bursts separated by 5 ms, for a total of 6 s. The detector is then left to cool down for 20 minutes to base temperature before data acquisition is started again. This process is similar to that currently in use with conventional CDMS detectors, and successfully restores the crystal to its optimal state allowing for good quality data to be taken.

Cross-talk between the electrodes is evident in Fig. 4, where the signal in Q4 has been plotted as a function of that in Q2. Events on the diagonal have the largest signal in Q3. Monte Carlo simulations of the interactions of gamma-rays from ^{241}Am sources indicate that most of this cross-talk appears to be electrical in nature at depths of approximately 6 mm. However, physical charge sharing between electrodes is also expected for events in the bulk [12, 13].

The bias voltage was varied across the detector to investigate charge collection efficiency. At every bias, a Gaussian function is fit to the 60 keV peak in the summed charge spectra from all four channels. The mean of the peak is used as a measure of the charge collection efficiency, and is depicted in Fig. 5. At bias voltages greater than 2 V and less than −2 V, the mean of the 60 keV peak begins to plateau at unity within errors. Thus, good charge collection efficiency is witnessed at these bias voltages.

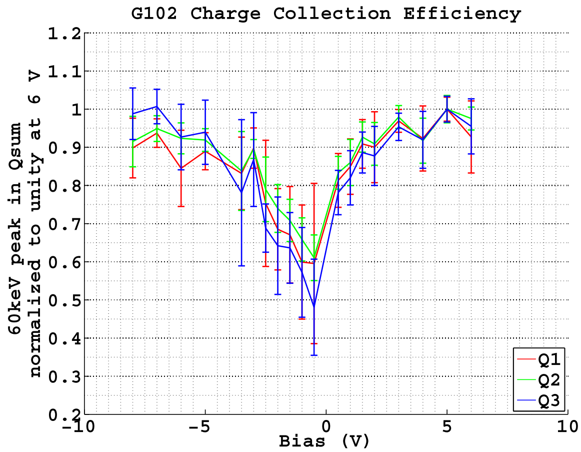

Fig. 5 (Color online) Charge collection efficiency as a function of bias voltage normalized to unity at 6 V. Events where Q4 exhibits the dominant signal are vetoed

4 Conclusions

The measurement shown in Fig. 5 agrees with past measurements on 1 cm thick crystals [14], which revealed that approximately 0.5 V bias is needed to achieve complete charge collection. In particular, to maintain the same electric field strength for 3.3 cm thick crystals, a bias voltage of 1.7 V would be required, which is consistent with Fig. 5. Therefore the larger germanium crystals tested in this paper have the necessary charge collection efficiency in order to be operated as dark matter detectors.

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