Nuclear Inst. and Methods in Physics Research, A 904 (2018) 15–22

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

Performance of the first 150 mm diameter Cryogenic silicon ionization detectors with contact-free electrodes

N. Mast [a,*], A. Kennedy [a], H. Chagani [a], D. Codoluto [a], M. Fritts [a], R. Harris [b], A. Jastram [b], R. Mahapatra [b], V. Mandic [a], N. Mirabolfathi [b], M. Platt [b], D. Strandberg [a]

[a] *School of Physics & Astronomy, University of Minnesota, Minneapolis, United States*
[b] *Department of Physics and Astronomy, Texas A&M University, United States*

ARTICLE INFO

Keywords:
Cryogenic
Semiconductors
Silicon
Ionization
Contact-free
150 mm

ABSTRACT

Cryogenic semiconductor detectors operated at temperatures below 100 mK are commonly used in particle physics experiments searching for dark matter. The largest such germanium and silicon detectors, with diameters of 100 mm and thickness of 33 mm, are planned for use by the Super Cryogenic Dark Matter Search (SuperCDMS) experiment at SNOLAB, Canada. Still larger individual detectors are being investigated to scale up the sensitive mass of future experiments. We present here the first results of testing two prototype 150 mm diameter silicon ionization detectors. The detectors are 25 mm and 33 mm thick with masses 1.7 and 2.2 times larger than those currently planned for SuperCDMS. These devices were operated with contact-free bias electrodes to minimize leakage currents which currently limit operation at high bias voltages. The results show promise for the use of such technologies in solid state cryogenic detectors.

1. Motivation

Although the effects of dark matter have been observed for over eight decades [1], the nature of dark matter remains unexplained. Comprising roughly 85% of all matter [2], this nonbaryonic matter has several potential candidates, with Weakly Interacting Massive Particles (WIMPs) garnering much focus by direct dark matter detection experiments. Results from these experiments as well as by the CMS [3] and ATLAS [4] experiments at the LHC have constrained the simplest supersymmetric WIMP models, which favor 10–100 GeV/c^2 WIMP masses, shifting interest to more recent models that suggest a WIMP mass below 10 GeV/c^2, such as asymmetric dark matter [5]. In the SuperCDMS experiment, sensitive solid state particle detectors are used to search for the small energy deposited by WIMP-nuclear recoils. To increase sensitivity to these new WIMP parameter spaces, larger payloads of more sensitive detectors must be deployed.

One method to increase sensitivity by lowering detector energy threshold relies on the Neganov–Trofimov–Luke effect, in which work done by the applied electric field on the electron–hole pairs produced in the detector is converted into phonons along the drift paths of the charges [6,7]. SuperCDMS has developed detectors biased at 50–100 V [8] that take advantage of Neganov–Trofimov–Luke phonon production to lower the energy threshold of the experiment, and therefore improve its sensitivity to lower mass WIMPs. However, leakage currents through the detector can reduce its sensitivity when operated in this mode, as observed at the 70 V operating bias of the CDMSlite detector [9]. It has been demonstrated that high voltage biasing via vacuum-separated (contact-free) electrodes can dramatically reduce this leakage for small (56 cm^3) Ge devices [10].

The work presented here demonstrates the feasibility of such contact-free bias schemes with larger (450–580 cm^3) Si crystals. Although these tests do not include phonon readout, they are the first demonstration of such bias schemes used with the largest cryogenic Si particle detectors yet operated at temperatures below 100 mK.

2. Detector designs and experimental setup

To test the performance parameters of large diameter silicon (Si) crystals as well as the use of prototype contact-free detector designs, two ionization detectors were fabricated and tested using n-type, [100] orientation, high purity, high resistivity (>15 kΩ cm) Si crystals purchased from TopSil [11].

One crystal, which was 150 mm diameter and 33 mm thick, was used to construct a simple single-channel contact-free detector by mounting the bare crystal between two planar aluminum electrodes. This detector is denoted “S1501”. As shown in the left side of Fig. 1, the ionization signal was measured on one electrode (“Readout”) while the other was used to provide a voltage bias (“Bias”). The readout electrode could

---

[*] Corresponding author.
E-mail address: mast@physics.umn.edu (N. Mast).

https://doi.org/10.1016/j.nima.2018.07.004
Received 25 April 2018; Received in revised form 30 June 2018; Accepted 2 July 2018

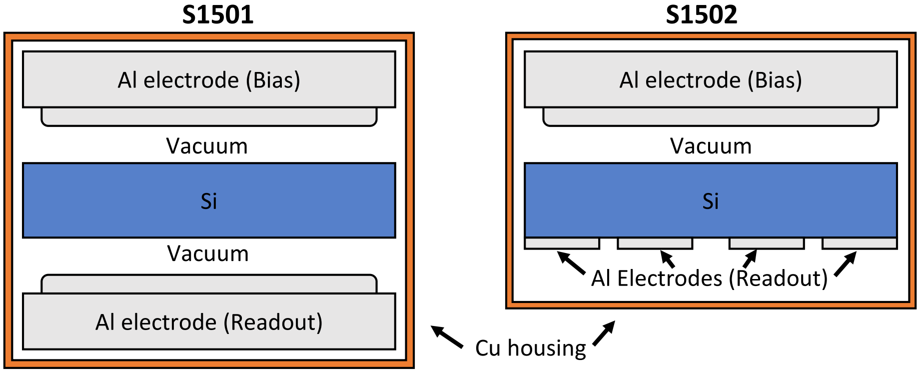

Fig. 1. *Left*: S1501 detector design with two aluminum electrodes (gray) surrounding a 150 mm Si crystal (blue) with a vacuum gap between faces. All pieces are secured within a copper housing with Cirlex clamps (not pictured). *Right*: S1502 detector design with a single vacuum gap for biasing and a set of deposited readout electrodes on the crystal surface. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

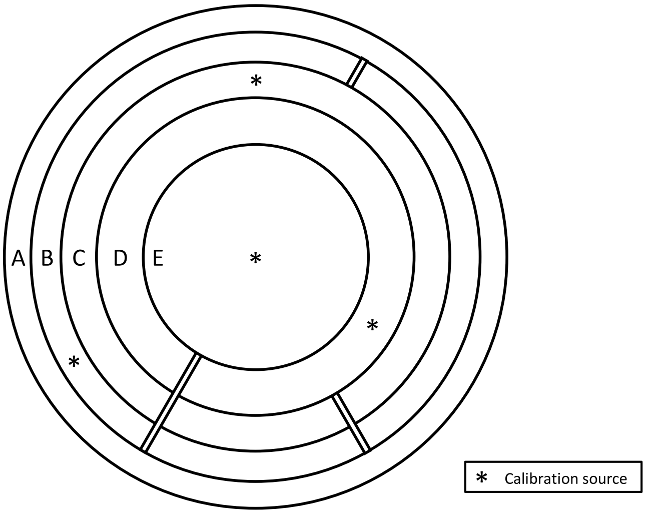

Fig. 2. S1502 ionization electrode channel map. Locations of the ^{241}Am calibration sources are marked. The segments of channels B and C are connected with wirebonds so that each forms a continuous annular electrode. Sections of the inner electrodes extend toward the detector radius to allow wirebond connections to readout electronics. The S1501 detector had a single, monolithic electrode with a single calibration source at the center.

also be biased up to ±12 V, but most often the readout electrode was grounded and the bias electrode provided a 0–100 V bias.

A second 150 mm diameter 25 mm thick crystal, denoted “S1502”, had five concentric electrodes of equal areas on one crystal surface as shown in Fig. 2. The electrodes were fabricated on one crystal face by depositing a layer of amorphous Si followed by a layer of aluminum while the opposite crystal face was left bare. The five channel geometries were then defined by wet-etching. Again, a planar contact-free electrode was mounted near the bare face to provide a bias voltage and the induced ionization signals were read out from the five deposited electrode channels.

The cylindrical aluminum electrodes, shown in Fig. 1, were comprised of a 150 mm outer diameter top lip, used to secure the electrode to its housing, and a solid 142 mm diameter cylinder which extended below the bottom edge of the lip. Each electrode was mounted with its flat face parallel to the crystal surface, with a gap of $\lesssim 1$ mm. As shown in Fig. 3, two shallow recesses along the radial periphery of the electrode face provided space for small circuit boards. Infrared (IR) at 940 nm and ultraviolet (UV) at 310 nm Light Emitting Diodes (LEDs) mounted on each board were used to periodically reset the detectors as discussed further in Section 4.2. The detectors were mounted and enclosed in housings machined from high purity copper. Mounting spacers were used to ensure that the contact-free electrodes and crystals were secured with the required small gaps. The voltage across the crystal, V_{cr}, was not the same as that applied to the detector as a whole, V_{tot} due to the voltage drop across the vacuum gap(s). They can be related by

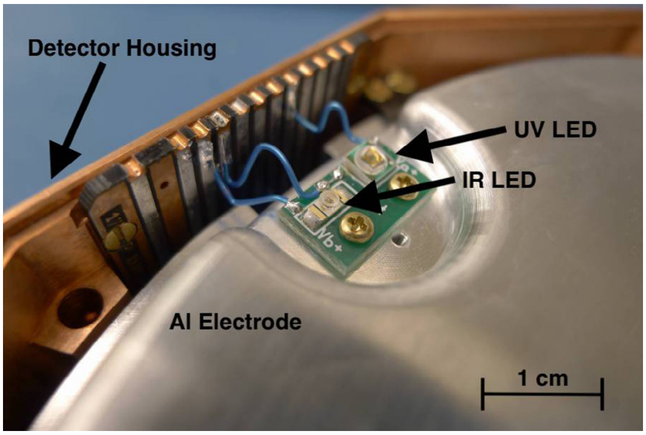

Fig. 3. Photo of LED board mounted on electrode.

$$V_{cr} = \frac{h}{h + \kappa d} V_{tot} \tag{1}$$

where h is the detector thickness, d is the total vacuum gap width, and $\kappa = 11.47$ is the relative permittivity of Si near 0 K [12]. This ignores any fringing fields or effects of the grounded detector housing.

The vacuum gaps of S1501 were measured to be 0.29 ± 0.03 mm and 0.40 ± 0.07 mm for the readout and bias sides respectively. These gaps result in $80\% \pm 2\%$ of the total bias field being applied across the crystal itself and a total detector capacitance of ~70 pF, which is comparable to typical SuperCDMS detector electrode capacitances of ~100 pF [13]. S1502 had a single gap of 0.9 ± 0.1 mm, giving $70\% \pm 3\%$ of applied bias across the crystal. With the different crystal thickness, vacuum gap and electrode geometry, the capacitance of each of the five readout electrodes to the bias electrode was reduced to ~20 pF. Direct measurement of the vacuum gaps was difficult and is the main source of uncertainty in the magnitude of the applied electric fields and in the expected signal magnitude.

The contact-free detector studies were performed at the cryogenic detector testing facility at the University of Minnesota in an Oxford Instruments Kelvinox 100 [14] dilution refrigerator, with a base temperature ranging from 75–95 mK. The detector housings were designed to fasten to a conventional CDMS-Soudan “tower” [15], thus minimizing the amount of additional cold hardware to be fabricated for these tests. Signals from the readout electrodes passed from the detector to the tower and first amplifier stage via a set of coaxial wires. For