Single Electron-Hole Pair Sensitive Silicon Detector with Surface Event Rejection

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We demonstrate single electron-hole pair resolution in a single-sided, contact-free 1 cm² by 1 mm thick Si crystal operated at 48 mK, with a baseline energy resolution of 3 eV. This crystal can be operated at voltages in excess of ±50 V, resulting in a measured charge resolution of 0.06 electron-hole pairs. The high aluminum coverage (~70%) of this device allows for the discrimination of surface events and separation of events occurring near the center of the detector from those near the edge. We use this discrimination ability to show that dark events seen in previous detectors of a similar design are likely dominated by charge leakage along the side wall of the device. We saw only a small reduction in dark event rate with this biasing scheme, further suggesting that sidewall and edge-dominated processes are responsible for the majority of these events.

Research into cryogenic calorimeters with eV-scale energy thresholds has grown in recent years, driven in large part by the needs of low background physics experiments, in particular direct detection of sub-GeV dark matter (DM) and coherent neutrino scattering measurements [1–6] and references therein. The recent demonstration of single electron-hole pair resolution in a cryogenic silicon crystal showed that the Neganov-Trofimov-Luke (NTL) effect [7, 8] can be leveraged to turn a calorimeter into a charge amplifier with single charge resolution by applying a bias voltage across the sensitive volume [1]. This means that a single detector can operate both as a highly sensitive eV-scale calorimeter, and complement high-resolution CCDs (Refs. [9, 10]) with phonon energy information when run in single-charge sensitive mode.

In the context of a rare event search, the optimal detector design will minimize both charge and energy resolution, and at the same time not introduce excessive backgrounds. Use of the NTL effect produces an additional low-energy background from ‘dark counts’ [1] [2], which can be produced by mechanisms including charge leakage through the interfaces between the electrodes and the bulk and through generation of unpaired excitations in the detector bulk or surfaces. If the process depends on electric field strength, a better energy resolution allows for lower field strength to be used to attain the same charge resolution, which allows for a reduction in dark counts. The contributions from interface leakage can be probed by using a contact-free biasing scheme, and with a device with a thinner substrate and thus better position resolution. In this paper, we present a detector with improved energy and position resolution compared to that discussed in Ref. [1] and explore the impact of contact-free operation on dark counts.

The data described in this paper were taken in a Veri-Cold Adiabatic Demagnetization Refrigerator (ADR), cooled to 48 mK. We fabricated a silicon detector 1 cm² × 1 mm in size. The top surface of the detector is instrumented with Quasiparticle-trap-assisted Electrothermal-feedback Transition-edge sensors (QETs) for phonon measurement. The QETs were arranged into inner and outer channels, as illustrated in Fig. 1. The bottom surface was polished but uninstrumented. The detector readout scheme is the same as that described in Ref. [11], with DC superconducting quantum interference devices (SQUIDs) operated in closed-loop mode. 300/168 QETs with critical temperature (Tc) ~ 63 mK in the inner/outer channel are connected in parallel with a 50 mΩ.

FIG. 1. A side view of the detector box mounted inside the ADR with the outer shielding removed. The inset picture shows the schematics of the detector used, together with the optical fiber and its field of illumination.
sorbed by the phonon sensors before the photons could reach the detector bulk, producing no electron-hole pairs to mediate NTL gain. The total energy measured by the QETs for an event where $n$ photons are absorbed in the bulk, and a mean of $\lambda_s$ photons are absorbed directly by the QETs on the surface, is given by

$$E_{QET} = \epsilon_{ph} n (E_\gamma + q_e f_{xtal} V_{applied}) + \epsilon_s E_\gamma \lambda_s,$$

where $\epsilon_s$ is the energy efficiency of surface events, $\epsilon_{ph}$ is the energy efficiency for events in the bulk (phonon energy efficiency), $E_\gamma = 1.95$ eV is the photon energy, $q_e$ is the electron charge, $V_{applied}$ is the voltage across the feedthrough, a 1 cm$^2$ copper square with the detector placed in the center. The copper square served as the high-voltage (HV) electrode. Four small pieces of cigarette paper $\sim 13$ µm thick were placed under the four corners of the detector to insulate the silicon crystal from the electrode. The vacuum gap between the silicon and the electrode depends on the thickness of the cigarette paper under a given amount of pressure at 48 mK, thus the voltage across the crystal needs to be calibrated. During operation, the HV electrode was voltage biased, while the ‘ground’ of the QET circuit was held at 0 V. This setup allowed for a nearly homogeneous electric field inside the silicon crystal. The detector assembly was placed in, and heat sunk to, a copper box that was designed to be light tight. The copper box was mounted on the base temperature stage of the ADR. A superconducting Niobium enclosure surrounds the copper box, serving as a magnetic shield.

For calibration purposes, we employ two photon feedthrough systems for optical photons and soft X-rays. First, a plastic optical fiber with a core diameter of 1 mm was fed through the detector box, with the gap between the fiber and the box filled with Eccosorb epoxy [11]. The plastic optical fiber was coupled to a single-mode optical fiber [12] through two pieces of KG-3 glass at 1.4 K. The single-mode fiber and the KG-3 glass filter were chosen to attenuate infrared photons from ambient and black body radiation from higher temperature stages [13]. The other end of the single mode fiber was connected to a vacuum feed-through at room temperature, then to a laser diode with a wavelength of 635 nm [14]. For the X-ray feedthrough, a 1 cm$^2$ square opening was cut on the copper box lid and re-sealed with a piece of aluminum foil 0.17 mm thick. The opening aligned with a Beryllium window installed on the ADR, serving as an X-ray input port. Multiple layers of Aluminized mylar sheets were placed between the opening and the Beryllium window at different thermal stages to block black body radiation from higher temperature stages while presenting minimal X-ray attenuation.

To calibrate the voltage drop across the crystal, establish an absolute energy scale of the signal, and measure the phonon energy resolution, the laser was pulsed with a fixed width of 500 ns and a frequency of $\sim 100$ Hz. The readout was triggered on the laser driver signal in order to read out zero-photon events, which are nominally below threshold. Multiple data sets were acquired at different crystal bias voltages and laser intensities.

Due to the $\sim 70\%$ overall QET coverage on the instrumented surface, and $\sim 90\%$ coverage near the center of the laser spot, significant photon energy was being absorbed by the phonon sensors before the photons could reach the detector bulk, producing no electron-hole pairs to mediate NTL gain. The total energy measured by the QETs for an event where $n$ photons are absorbed in the bulk, and a mean of $\lambda_s$ photons are absorbed directly by the QETs on the surface, is given by

$$E_{QET} = \epsilon_{ph} n (E_\gamma + q_e f_{xtal} V_{applied}) + \epsilon_s E_\gamma \lambda_s,$$

where $\epsilon_s$ is the energy efficiency of surface events, $\epsilon_{ph}$ is the energy efficiency for events in the bulk (phonon energy efficiency), $E_\gamma = 1.95$ eV is the photon energy, $q_e$ is the electron charge, $V_{applied}$ is the voltage across the
electrodes, and $f_{\text{stal}}$ is the fraction of that voltage drop across the detector bulk. Due to quantized number of electron-hole pairs produced, for sub-charge resolution, we can measure the mean number of photons absorbed in the bulk, $\lambda_{\text{Si}}$. As shown in Fig. 2b, the offset of the zero-photon peak ($n = 0$), which serves as a measurement of the surface absorption ($\epsilon_{\gamma} E_{\gamma} \lambda_{\gamma}$), is proportional to $\lambda_{\text{Si}}$, thus is linear in laser power and $\lambda_{\gamma}$. This allowed us to correct the measured energy scale for a given laser power, removing the average energy from surface energy depositions. Additional variance due to these surface events persists. For this reason, the laser power is tuned to provide $\lambda_{\text{Si}} \sim 0.4$ for the resolution studies. After correcting for surface energy depositions, we observed

$$E_{\text{QET}} - \epsilon_{\gamma} E_{\gamma} \lambda_{\gamma} = \epsilon_{\text{ph}} n \left( E_{\gamma} + q_{c} f_{\text{stal}} V_{\text{applied}} \right),$$

(2)

as shown in the upper panel of Fig. 2a. We used the intercepts at $V_{\text{applied}} = 0$ V with $n = 1, 2$ to calibrate the energy scale of this detector and to measure the energy efficiency, and used the slopes to calibrate $f_{\text{stal}}$. For this contact-free mounting scheme, the voltage across the crystal varied from 30% to 45% of the applied bias for different mounting techniques, but for a given run we find that this fraction is stable as long as charge buildup is mitigated.

Using this voltage calibration, we therefore inferred an energy efficiency of $\epsilon_{\text{ph}} \sim 27\%$, with a 95% confidence interval of 22% to 30%. This broad uncertainty is due to systematic uncertainties on the resistance values in the readout circuit, as well as uncertainties in the crystal bias calibration and surface absorption correction. The energy efficiency is significantly higher than that measured for the previous test device described in Ref. [1]. This is potentially due to the high aluminum coverage (70% as compared to 25%) leading to more efficient phonon collection, and the fact that this device is instrumented on only one side, while the back side of the crystal is left bare, acting as an athermal phonon reflector rather than a phonon sink.

The lower panel of Fig. 2a shows the laser calibration spectra in units of electron-hole pairs with a few example voltages applied across the detector. With more than 20 V across the crystal, we can resolve individual peaks at 99% confidence. We measure a baseline phonon resolution of 3 eV, and a charge resolution at 50 V of $\sim 0.06 e^{-}h^{+}$ pairs. This phonon resolution is 3–4 times better than that measured in Refs. [1, 2] due to the much higher energy efficiency, despite the fact that the $T_{c}$ of this device was 12 mK higher. This allows for comparable charge resolution at much lower voltage.

In order to calibrate the detector over a larger energy scale, and to probe position-dependent effects on our energy reconstruction, data were acquired using two sources. The first was a $^{55}$Fe source with two prominent X-ray lines at 5.9 and 6.4 keV, and the second was a $^{57}$Co source with a prominent 122 keV line. Due to the vacuum-gap design, this device is prone to charge buildup when subjected to the large charge production rate induced by the $^{57}$Co X-ray source. As electron-hole pairs are generated, they accumulate at the insulated surface, resulting in a counter voltage built across the vacuum gap that reduces the voltage across the crystal. A 0.2 V/br voltage gain decrease was observed in $^{57}$Co data at an event rate of $\sim 1$ Hz, consistent with the expected charge generated by this event rate. For a voltage bias of 50 V, this corresponds to a 0.4% decrease in energy resolution per hour, and can be corrected by interspersed laser calibration data as in Ref [2]. Grounding the HV electrode and warming up the detector to >20 K was found to neutralize this built-in potential, while grounding alone at 4 K was not always sufficient. Other neutralization methods are being investigated; in particular, we are studying how neutralization state and biasing history can affect the dark event rate. These studies will be discussed in a future work.

X-rays with energies below 100 keV have a mean free path much less than 1 mm in Si and Al. The $^{55}$Fe X-rays are therefore predominantly absorbed on the surface of the detector. Given that the sources face the high-coverage, instrumented side of the detector, this produces a large population of $^{55}$Fe X-ray hits on the QETs, rather than in the detector bulk. Fig. 3 shows the QET pulse integral compared to the pulse height obtained using an optimal filter [15]. While the pulse height is proportional to the energy in the small signal limit, the pulse duration begins to lengthen with smaller changes in pulse amplitude when the QETs approach the saturation regime, as shown in the insert of Fig. 3. This produces the flat portion of this curve. The proportionality between pulse height and integral therefore depends on the pulse shape. Fig. 5 shows that there are 3 distinct lines in the small-
FIG. 4. Radial partition, or the relative difference in energy absorbed by each channel, as a function of pulse height. Data shown from $^{57}$Co and $^{55}$Fe sources with no bias across the crystal, as well as laser and background (no source) data with a crystal bias of 50 V. A partition near $+/−1$ indicates an energy deposition entirely in the outer/inner channel, respectively. All events shown are those that pass the pulse-shape cut to remove surface events, described in the text. For events near the center of the detector (negative partition) the laser and background events are quantized, while non-quantized background events are restricted to the outer part of the detector. The dashed line represents the 50% efficiency cut separating inner from outer events, calibrated using the $^{57}$Co data.

signal region of different proportionality. Of these lines, only the upper one scales with voltage, which indicates that these are bulk events. Upon inspection, the lowest track is a population of square pulses generated by out of band RF pickup, which appears in the QET as a time-dependent and abrupt change in bias power. The middle class of events appear to be real QET events, but have a long secondary tail; the fact that they do not scale with applied voltage is consistent with these events occurring in or very close to the QETs, and are thus surface events. We can therefore remove this population with high efficiency by a selection criterion in this integral versus pulse amplitude space, taking advantage of pulse-shape information.

The 122 keV X-rays of the $^{57}$Co, unlike the 6 keV from the $^{55}$Fe, have a much longer mean free path in Si, and are more likely to Compton scatter than be absorbed in our thin Si substrate. This means that the $^{57}$Co events are primarily distributed uniformly in energy and position within the detector, with a range of energies between 0 and 50 keV. This provides us a means with which to study the energy partition between the inner and outer channels as a function of event energy. Fig. 4 shows the $^{57}$Co and $^{55}$Fe data in partition space for data taken at 0 V, along with laser and background events acquired at a crystal bias of 50 V. The long-lived thermal tails from the very high energy events from the $^{57}$Co source prevented us from triggering at the noise floor. The nearly vertical cutoff for the $^{57}$Co data around 0.4 µA results from a threshold trigger on the inner channel. Above this energy, the $^{57}$Co data demonstrates that the $^{55}$Fe events occur across the face of the crystal, and that by employing the pulse shape selection described earlier, the remaining events fill a single continuous band across the partition space as expected.

In the small-signal region, we extrapolated the partition down to zero. This shows that the laser events filled out the entire partition space, but biased towards the inner channel. This is due to the shape of the laser spot, as shown in the insert of Fig. 4. We found that the background events that are non-quantized are mostly contained near the outer channel. We used the $^{57}$Co data to construct a 50% efficient radial partition, shown by the dotted line in Fig. 4. By rejecting events larger than this partition requirement, we reject 95% of non-quantized dark events and 80% of quantized dark events, while keeping 90% of laser events. We observed no events above one electron-hole pair in the inner region of the detector. This suggests that, for this contact-free design, charge leakage towards the center of the detector is dominated by surface physics.

The rate of the events passing this partition cut appears to increase exponentially with voltage above ~70 V, suggesting an interface leakage component at high voltage. We did not operate above 50 V crystal bias for most of our tests due to the high voltage (~200 V) necessary to achieve these crystal biases, and thus we quote the charge resolutions for lower voltages despite qualitative improvement at higher voltage. The dark event rate passing the partition cut is strongly related to the voltage applied across the crystal, as well as the crystal biasing and neutralization history, and applying a strong electric field causes significant dark current immediately after the field is switched on. The dark event rate drops steadily immediately after reaching terminal bias, and stabilizes after a few minutes. At moderate voltages, however, the dark rate after stabilization is reduced by over an order of magnitude, and is influenced by the pre-biasing scheme of the detector. It is also somewhat lower than was seen in our previous device[2]. Longer exposures for calibration studies and another dark matter search will employ this partition pulse-shape rejection to further study the behavior of the inner and outer leakage events.

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[1] R. K. Romani, P. L. Brink, B. Cabrera, M. Cherry, T. Howarth, N. Kurinsky, R. A. Moffatt, R. Partridge, F. Ponce, M. Pyle, A. Tomada, S. Yellin, J. J. Yen, and B. A. Young, “Thermal detection of single e-h pairs in a biased silicon crystal detector,” Applied Physics Letters 112, 043501 (2018).

[2] R. Agnese et al., “First Dark Matter Constraints from a SuperCDMS Single-Charge Sensitive Detector,” Physical Review Letters 121, 051301 (2018).

[3] R. Strauss, J. Rothe, G. Angloher, A. Bento, A. Gütlein, D. Hauff, H. Kluck, M. Mancuso, L. Oberauer, F. Petricca, F. Pröbst, J. Schieck, S. Schönhert, W. Seidel, and L. Stodolsky, “Gram-scale cryogenic calorimeters for rare-event searches,” Phys. Rev. D 96, 022009 (2017).

[4] G. Angloher et al., “Results on MeV-scale dark matter from a gram-scale cryogenic calorimeter operated above ground,” European Physical Journal C 77, 637 (2017).

[5] Q. Arnaud et al. (EDELWEISS Collaboration), “Optimizing edelweiss detectors for low-mass wimp searches,” Phys. Rev. D 97, 022003 (2018).

[6] COHERENT Collaboration et al., “The COHERENT Experiment at the Spallation Neutron Source,” ArXiv e-prints (2015).

[7] P. N. Luke, J. Beeman, F. S. Goulding, S. E. Labov, and E. H. Silver, “Calorimetric ionization detector,” Nucl. Instrum. Meth. A289, 406–409 (1990).

[8] B. S. Neganov and V. N. Trofimov, “Colorimetric method measuring ionizing radiation,” Otkryt. Izobret. 146, 215 (1985).

[9] J. Tiffenberg, M. Sofo-Haro, A. Drlica-Wagner, R. Essig, Y. Guardincerri, S. Holland, T. Volansky, and T.-T. Yu, “Single-Electron and Single-Photon Sensitivity with a Silicon Skipper CCD,” Physical Review Letters 119, 131802 (2017).

[10] M. Crisler, R. Essig, J. Estrada, G. Fernandez, J. Tiffenberg, M. S. Haro, T. Volansky, T.-T. Yu, and Sensei Collaboration, “SENSEI: First Direct-Detection Constraints on Sub-GeV Dark Matter from a Surface Run,” Physical Review Letters 121, 061803 (2018).

[11] For more information about Eccosorb, a microwave energy dissipating material, see http://www.eccosorb.com/.

[12] For more information on the Thorlabs SM450 single mode fiber, see https://www.thorlabs.com/thorproduct.cfm?partnumber=SM450.

[13] These are the same optical fiber filters used in Ref [2].

[14] For more information on the Thorlabs LPS-635-FC laser diode employed, see https://www.thorlabs.com/thorproduct.cfm?partnumber=LPS-635-FC.

[15] N. A. Kurinsky, The Low-Mass Limit: Dark Matter Detectors with eV-Scale Energy Resolution, Ph.D. thesis, Stanford U., Dept. Phys. (2018).