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Toward single electron resolution phonon mediated ionization detectors

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Experiments seeking to detect rare event interactions such as dark matter or coherent elastic neutrino nucleus scattering are striving for large mass detectors with very low detection threshold. Using Neganov-Luke phonon amplification effect, the Cryogenic Dark Matter Search (CDMS) experiment is reaching unprecedented RMS resolutions of ~14 eV_{ee}. CDMSlite is currently the most sensitive experiment to WIMPs of mass ~5 GeV/c^2 but is limited in achieving higher phonon gains due to an early onset of leakage current into Ge crystals. The contact interface geometry is particularly weak for blocking hole injection from the metal, and thus a new design is demonstrated that allows high voltage bias via vacuum separated electrode. With an increased bias voltage and a×2 Luke phonon gain, world best RMS resolution of sigma ~7 eV_{ee} for 0.25 kg (d=75 mm, h=1 cm) Ge detectors was achieved. Since the leakage current is a function of the field and the phonon gain is a function of the applied voltage, appropriately robust interface blocking material combined with thicker substrate (25 mm) will reach a resolution of ~2.8 eV_{ee}. In order to achieve better resolution of ~ eV, we are investigating a layer of insulator between the phonon readout surface and the semiconductor crystals.

1. Motivation: ultra low threshold detectors for dark matter and coherent neutrino scattering detection

A large body of astrophysical observations point to the fact that 85% of the matter in the universe is not made of known standard model particles [1]. Understanding the nature of this dark matter is of fundamental importance to cosmology, astrophysics, and high energy particle physics. Although Weakly Interacting Massive Particles (WIMPs) of the mass 10–100 GeV/c^{2}have been the main interest of the majority of direct dark matter detection experiments, recent claims for signal, together with compelling new theoretical models, are shifting the old paradigm toward broader regions in the dark matter parameter space well below 10 GeV/c^2 [2].

Very low energy recoils and small interaction rates from these low mass WIMPs are expected, thus large mass detectors with very low threshold are highly desired. These very low threshold detectors are *sine qua non* for any attempt to detect very light mass (< 1 GeV/c^2) dark matter. They are also a necessary requisite for observing coherent elastic neutrino–nucleus scattering [3], a standard model process that has recently been proposed as a sensitive and flavor invariant probe for sterile neutrinos, neutrino magnetic moment and other HEP physics [4,5].

P. Luke had suggested to utilize very low noise readout designed for phonon mediated detectors to indirectly measuring ionization in semiconductor detectors [6]. The measurement principle is based on the fact that carriers drifting through crystals under an applied electric field release phonons whose total energy is proportional to the interaction energy as well as the applied bias voltage:

$$E_{Luke} = V_{bias}E/\epsilon. \tag{1}$$

Where E is the energy of the interaction and ϵ is the average energy necessary to produce electron and hole pairs. Since the total signal is proportional to the bias potential, in the absence of any leakage current, the Signal-to-Noise Ratio (SNR) improves proportionally to the bias and can be improved down to single electron-hole sensitivity. CDMSlite is using this very sensitive method to search for low mass dark matter and is currently the most sensitive experiment for WIMPs of masses <5 GeV/c^2 [7]. However, current generation CDMSlite detectors exhibit a leakage current for fields as low as 24 V/cm, thus single ionization sensitivity has not yet been realized. This early onset of leakage is in contrast with results from standard 77 K depleted Ge detectors that are usually operated with much larger fields (~1000 V/cm). Recent understanding of the CDMSlite interface shows that it is comprised of polycrystalline grain boundaries that allow charge leakage (to be published in parallel to this report). Here we report on our recent studies and success toward understanding this early onset of leakage

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current and our suggestions to improve ionization contacts for the ultimate single electron resolution detectors.

2. Bulk breakdown versus carrier injection through contact

We can think of three sources of excessive leakage current in CDMS detectors: Crystal break down, carrier injection through metal/germanium contact or conduction on non passivated free surfaces of detectors. The surface conduction is eliminated outright because of precise, clean crystal fabrication and handling. Furthermore, the amount of current leakage observed cannot be accounted for in surface current density without significant damage to the detector.

2.1. Ge crystal bulk breakdown

The first evidence in eliminating bulk crystal breakdown is the fact that such breakdown is catastrophic and irreversible. We observe that reverse biased detectors that have previously experienced significant leakage do not demonstrate high leakage when appropriately biased. The second set of evidence is in the low electric field ~30 V/cm at which high leakage is observed.

In a previous study we ruled out the breakdown in high purity Ge crystals by operating a Majorana prototype P-type Point Contact Ultra pure Ge detector (PPC) in the similar setup wherein we operate CDMS detectors [8]. A 17 g PPC prototype was equipped with a tungsten Transition Edge Sensor (TES) thermistor and both ionization and phonon measured up to 400 V as shown in Fig. 1. There were no sign of crystal breakdown despite large fields present in the vicinity of the point contact (up to 7000 V/cm). This clearly ruled out the crystal breakdown. We also verified that the phonons gain is a linear function of applied voltage up to our limited DC voltage supply circuit.

CDMS iZIPs interface structure is symmetric (amorphous–Si only), in contrast with LBNL PPC design wherein the positive and negative bias electrodes are interfaced with different material (amorphous–Si or amorphous–Ge) to the bulk (Fig. 1 Top left). A previous study by the LBNL group shows that the blocking properties of amorphous Si or Ge are different for different types of carriers and that amorphous–Ge better blocks holes than amorphous–Si [9]. However, these detectors are operated and tested at >77 K, well above freeze-out of Ge and high voltage operations at the low temperatures needed for phonon sensing may require different contacts.

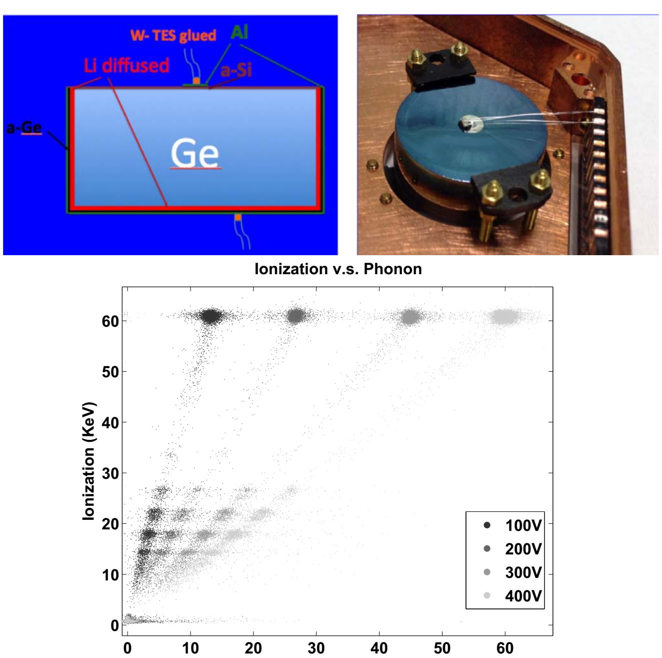

Fig. 1. (Top Left) Schematic of the PPC detector used in this work. The point contact is defined by a 3 mm diameter vapor-deposited aluminum disk on the amorphous silicon passivation layer. The face opposite of the point contact and the cylindrical surface have lithium diffused to a depth of ~1 mm coated with sputtered amorphous Ge followed by vapor-deposited aluminum. (Top right) Photo of the detector in its copper housing. The long wire bonds connect the point contact and the TES thermistors to the CDMS Digital Interface Board and corresponding cold electronics. (Bottom) Ionization versus phonon measurement for various bias voltages up to 400 V. The phonon signal increase proportional to bias while ionization signal remain constant as expected.

2.2. New contact geometry

To break CDMS design symmetry, we fabricated a detector wherein, we eliminate one interface and bias the detector with a flat aluminum electrode separated from the crystal via a small gap ~500 µm (Fig. 2). One face of a 0.250 kg Ge substrate was processed with athermal phonon sensors similar to CDMS ZIP detectors and was covered with athermal phonon tungsten (W) Transition Edge Sensors (TES). The phonon sensors are also acting as the ground for biasing purposes and are interfaced to the detector through a layer of α-Si. the other face of the detectors was left with bare polished Ge. The detector is biased via a gap of ~500 µm. The bias electrode was beveled to avoid the high fields associated with the sharp features at the edges of the electrodes. Since no carrier injection is expected from the contact-free face of the detector, this new biasing scheme allows for independent study of the Al/α-Si/Ge interface properties.

The detector was mounted with a collimated ^{241}Am source on the phonon face of the detector and was installed in Berkeley ^{3}He-^{4}He dilution refrigerator and cooled to <0.04 K. We discuss results from high voltage operation of this detector. A Light Emitting Diode (LED) with photon energies slightly above the Ge band gap was mounted close to the detector volume. By grounding the detector and pulsing the LED, large number of electrons and holes are generated to neutralize and reset the detector. Since the charge carriers that arrive to the bare face of the Ge has no path to leave the crystal, this LED pulsing is crucial in order to eliminate the accumulated charge and the counter electric field thereof.

3. Experimental results and discussion

Leakage current in the new contact-free geometry for both positive and negative bias polarities was measured. The phonon surface is always held at the ground potential. All the bias polarities mentioned in this paper are referenced to the phonon face electrode. Therefore, for the positive bias polarities the holes drift toward the phonon surface and electrons toward the bias electrode and vice versa. Since there is only one contact present in this detector design (phonon surface), we can study the polarity dependence of current leakage through Al/pc-Si/Ge with this device.

We use phonon noise performance as a metric to evaluate leakage. The carriers that are randomly leaking through the Ge electrode interface will also drift within the crystal volume producing Neganov-Luke phonons and will appear as an increase in phonon readout noise. We found this method of leakage current measurement much more sensitive than the standard ionization direct charge readout.

In clear agreement with the previous studies with PPC detectors, we observed a leakage asymmetry with respect to the bias polarity in this device. The detector sustains up to 350 V in positive polarity but exhibits significant leakage for negative polarity even for biases as low as 20 V shown in Fig. 3. In agreement with LBNL previous results, this suggests that the amorphous–Si interface is a much weaker blocking layer for hole injection from Al compared to electron injection from the same.

Since the detector is biased via a gap of ~500 µm, the actual potential across the detector (V_{Ge}) is smaller than the applied voltage ($V_{applied}$) by the ratio of detector capacitance (100 pF) and the gap. We use the phonon amplification gain for ^{241}Am 13.9 keV line