Bulk and Surface Charge Collection: CDMS Detector Performance and Design Implications

C.N. Bailey (for the CDMS and SuperCDMS Collaborations)

California Institute of Technology, Case Western Reserve University, Fermi National Accelerator Laboratory, Lawrence Berkeley National Laboratory, Massachusetts Institute of Technology, Queen's University, Saint Olaf College, Santa Clara University, Stanford University, Syracuse University, University of California - Berkeley, University of California - Santa Barbara, Texas A&M University, University of Colorado - Denver, University of Florida, University of Minnesota, University of Zürich

ABSTRACT

The Cryogenic Dark Matter Search (CDMS) searches for Weakly Interacting Massive Particles (WIMPs) with cryogenic germanium particle detectors. These detectors discriminate between nuclear-recoil candidate and electron-recoil background events by collecting both phonon and ionization energy from interactions in the crystal. Incomplete ionization collection results in the largest background in the CDMS detectors as this causes electron-recoil background interactions to appear as false candidate events. Two primary causes of incomplete ionization collection are surface and bulk charge trapping. Recent work has been focused on reducing surface trapping through the modification of fabrication methods for future detectors. Analyzing data taken with test devices shows that hydrogen passivation of the amorphous silicon blocking layer does not reduce the effects of surface trapping. Other data shows that the iron-ion implantation used to lower the critical temperature of the tungsten transition-edge sensors increases surface trapping, causing a degradation of the ionization collection. Using selective implantation on future detectors may improve ionization collection for events near the phonon side detector surface. Bulk trapping is minimized by neutralizing ionized lattice impurities. Detector investigations at testing facilities and at the experimental site in Soudan, MN have provided methods to optimize the neutralization process and monitor running conditions to maintain maximal ionization collection.

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CDMS

The Cryogenic Dark Matter Search (CDMS) uses Z-sensitive Ionization and Phonon (ZIP) detectors to measure both phonon and ionization energy. This dual measurement technique allows event-by-event discrimination between electron recoil background events, arising from residual radioactivity and cosmic rays, and nuclear recoil signal events, possibly produced by Weakly Interacting Massive Particles (WIMPs). CDMS's primary discrimination parameter is ionization yield, the ratio of ionization to phonon recoil energy, allowing for a rejection of electron recoil backgrounds from nuclear recoil events of better than 10,000 to 1. Ideally, ionization yield would provide complete discrimination of electron recoils. However, one of the most significant sources of background in CDMS detectors is due to charge trapping, which reduces the total ionization signal causing electron recoil background events to occur at lower ionization yield, looking like nuclear recoil signal events. Currently CDMS minimizes these effects through the use of phonon timing information to reject surface events and neutralization to minimize bulk trapping.

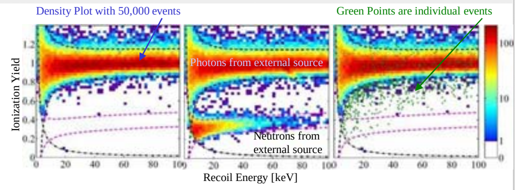

Figure 1 (a - left, b - middle, c - right): Ionization yield (ionization energy / phonon energy, primary discrimination parameter for CDMS) versus phonon recoil energy. The top band in all three plots is the electron recoil band while the bottom band is the nuclear recoil (or signal) band. 1a shows events only from an external gamma source. 1b shows events from both an external gamma and neutron source. 1c highlights surface events in green. These green points 'droop' into the lower signal band.

SURFACE EFFECT

Surface trapping creates a "dead layer," which is characterized by interactions with incomplete charge collection, along the flat detector faces. This surface trapping is caused by the back-diffusion of charge carriers into the adjacent ionization electrode. When a particle interaction occurs, freed electrons and holes gain kinetic energy. In order to separate and drift charge carriers to the electrodes, an applied electric field must overcome the initial kinetic energy imparted to the charge carriers.

If the interaction occurs near the detector surface the electric field is not strong enough to separate all the charge carriers before some reach the adjacent ionization electrode. Since these carriers do not drift across the crystal they do not contribute to the ionization signal, therefore causing a reduction in the measured ionization energy.

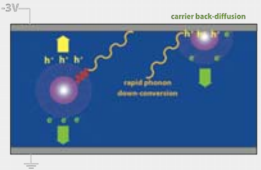

Figure 2: Cartoon depicting events occurring in the ZIP detector bulk (left) and surface (right).

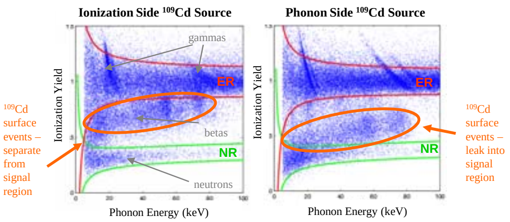

Figure 3: Ionization yield as a function of phonon recoil energy for calibration data from a Ge ZIP detector using an external ^{252}Cf and internal ^{109}Cd source. The ^{109}Cd source produces events which probe the detector surface layer creating the event population with low ionization yield between the upper electron recoil and lower nuclear recoil bands. Left: ^{109}Cd source (and surface events) on the ionization. Right: ^{109}Cd source (and surface events) on the phonon side. The phonon side surface events have worse ionization collection (lower ionization yield) than ionization side surface events.

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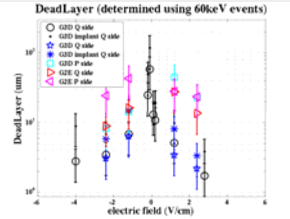

Figure 4: Dead layer as a function of applied electric field comparing G3D with G2E, demonstrating how G3D (no hydrogen in the aSi layer on either detector face) has the smallest dead layer for a given applied electric field. Comparison of the ionization side dead layers of G3D (black circle and blue star) and G2E (red triangle) illustrate how hydrogenating the ionization side aSi layer doesn't improve the dead layer while comparison of the phonon side dead layers of G3D (cyan square) and G2E (magenta triangle) show detector-to-detector variations between two detector faces that are nominally the same.

Comparison of G3D's non-implanted (black circle and blue star) and implanted (black dot and blue closed star) ionization sides show how iron-ion implantation creates a larger dead layer. Black and blue points represent data taken with G3D, only during separate data runs. Error bars on the data points represent 50\% variations to the determined dead layer. Based on the systematic error analysis, these error bars represent maximal variations.

HYDROGENATED AMORPHOUS SILICON

Previous experience with hydrogenated amorphous silicon (HaSi) blocking layers in early CDMS detectors indicates an improvement in ionization yield based surface event discrimination, thought to be due to the passivation of interface defects in the amorphous silicon (aSi), therefore increasing the layer's blocking ability and decreasing the detector dead layer. Three Ge test devices were fabricated and tested to determine the dead layers: one "control" device with no hydrogen added to the aSi layer on either detector face (G3D), one device with 20% hydrogen added to the aSi layer on the ionization face (G2E), and the final device with 8% hydrogen added to the aSi layer on the phonon face (G28B). These test results suggest that adding hydrogen to the aSi layer does not improve surface event ionization collection.

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IRON-ION IMPLANTATION

One hypothesis for the asymmetry is that it is due to the iron-ion implantation used on the phonon detector side to create appropriate and uniform tungsten superconducting transition temperatures. During implantation, the majority of the incident iron-ion flux strikes portions of the detector surface not covered by W and are suspected to cause damage to the Ge surface by adding acceptors and thus increasing the dead layer. To test this hypothesis, one of the test Ge devices (G3D) had half of its ionization side iron-ion implanted for comparison between the implanted and non-implanted ionization side dead layers. Testing this detector showed that the dead layer for the implanted half was systematically larger than the non-implanted half.

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NEUTRALIZATION

Bulk trapping reduces the ionization signal by trapping charge carriers at impurities caused by crystal lattice defects. To reduce the impact of bulk trapping, CDMS detector crystals have low impurity and dislocation concentrations. Operationally, data taking occurs on time scales shorter than the time when bulk trapping affects ionization collection. In addition, detectors routinely undergo a neutralization process to reduce the effects of bulk trapping.

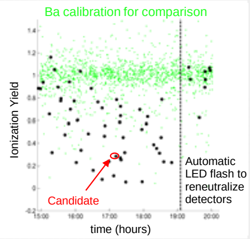

Figure 5: Ionization yield versus time for a WIMP search (black) and barium calibration (green) data series from the previous CDMS 2-tower Soudan data to illustrate how poor ionization collection (poor neutralization) can lead to leakage into the signal region. The barium calibration data shows good ionization collection and all lie at a yield = 1. This WIMP search data was accidentally taken with poor ionization collection and droops down from a yield of 1. The red circle is an event that was misidentified as a WIMP candidate due to this poor ionization collection. In the present analysis, this data would have been removed by quality cuts.

Evaluating the fraction of low yield events has proven to be a powerful method for establishing and comparing detector neutralization states. In particular, this quantitative figure-of-merit of detector neutralization allowed the development of a new data quality cut which removed any data sets that potentially suffered from poor detector neutralization, like the candidate event from the Soudan 2-tower data analysis, and real-time data monitoring to ensure stable detector neutralization. Finally, having this figure-of-merit also allowed investigations of detector neutralization at testing facilities and in situ at the experimental site which have provided methods to optimize the neutralization process.

CONCLUSIONS

The first 5-tower data runs of CDMS-II has resulted in a world leading WIMP-nucleon spin-independent cross section limit for WIMP masses above 44 GeV/c^2. As CDMS aims to achieve greater WIMP sensitivity, detector modifications have already been made to increase the target mass and reduce backgrounds. The studies discussed here, to reduce the detector dead layer, will impact further modifications to SuperCDMS detectors by implementing the use of selective iron-ion implantation which will reduce the phonon side dead layer. Neutralization studies have already led to improved background rejection, real-time monitoring (for better data quality), and optimizations to neutralization procedures. Further work at understanding charge transport in low temperature detector crystals will lead to further operational optimizations to maintain full ionization collection.

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