A SOLUTION TO THE DEAD LAYER PROBLEM IN IONIZATION AND PHONON-BASED DARK MATTER DETECTORS

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ABSTRACT

We report on a study of several different electrode technologies to avoid the “dead layer” problem in ionization and phonon-based dark matter detectors. We have found the most success with an amorphous blocking layer electrode structure, and have demonstrated background electron rejection of ≈ 95% above 20 keV.

1. INTRODUCTION

The CDMS dark matter experiment uses detectors which reject background electron recoils produced photons and electrons from the less-ionizing nuclear recoils expected for WIMP dark matter by simultaneously measuring the amount of ionization and phonons in a semiconductor detector at millikelvin temperatures (Ref. 1). The ionization measurement is different from standard detectors operating at 77 K. At these low temperatures kT is much less than the 10 meV excitation energy of impurities, so no thermally generated free-charge is present and the detector can be purposefully put into a neutralized state with very few ionized impurity sites. Charge collection is then very efficient at fields as low as ≈ 0.2 V/cm. (Ref. 2)

However, for many charge collection electrodes structures, events at the surface suffer from loss of charge in or near the contacts, a phenomena which has a qualitative analogue in 77 K detectors. Until recently CDMS has been limited by background electron events from contamination on or near the surface of the detectors, which, at energies of 10-50 keV, stop entirely in the first micron or so of this dead layer. There they lose just enough charge on average to be nearly indistinguishable from nuclear recoils (Ref. 3).

We report here on a study of the dead layer in several electrode structures. The devices studied were 1 cm^2 by 0.15 cm thick ultra-pure (n_a-n_d≈$6x10^{10}$ cm^{-3}) Ge detectors, to which were glued NTD Ge thermistor phonon sensors. We exposed the detectors to a ^{241}Am source, whose the 14, 18, 21 and 60 keV photons have attenuation lengths of 17, 31, 51 and 940 µm, respectively, thus providing a clean probe of the near surface region, and also directly to electrons from a ^{14}C beta source. At LTD7 we reported on similar measurements, but on fewer devices, and without the phonon measurement. (Ref. 3) The results discussed here represent a much deeper look at the dead layer problem, and, in part, a solution to it.

2. IMPLANTED CONTACTS

The first detectors used by CDMS had degenerately doped, ion-implanted contacts that had a severe dead layer (Ref. 3). For comparison, we first measured a device with these “standard” p^+-p-p^+ structures. The peak dopant density in the boron-implanted contacts is ≈ $1x10^{19}$ cm^{-3}, and extends over roughly 1500 Å. Figure 1 shows the charge yield, *y*, (the number of charges per eV of recoil energy) for photons from ^{241}Am. The charge-collection field was +0.6 V/cm. The polarity is referenced to the contact exposed to the source, and the field strength is the typical maximum used for previous full-scale CDMS detectors. Larger biases have not been possible on large detectors with p^+-p-p^+ contacts due to breakdown. Note

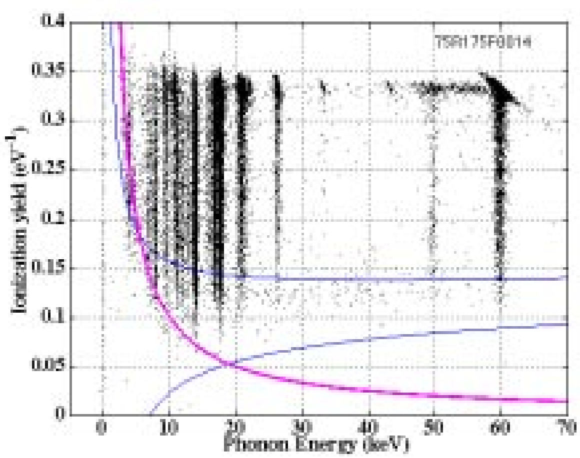

Figure 1. Ionization yield for a standard p^+ contact. The thin lines near 0.1 eV^{-1} indicate the region of nuclear recoils for energy resolutions typical on full-scale detectors. The thick line shows the approximate position of the charge trigger threshold.

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The dead-layer is readily apparent. Full charge collection gives y=0.33 eV^{-1}, and there are concentrations of photons at this value of y, especially at higher energy. However at each energy a vertical tail to lower values of y represents loss of charge for events nearer the surface. Some events near the surface are indistinguishable from nuclear recoils. A faint band of electrons near the top of the nuclear recoil band is visible, particularly between about 20 and 60 keV. These events are most likely electrons photo-ejected from material near the detector.

We next tested a "diode" device with a n^+-p-p^+ structure. At the interface between the bulk p material and the (phosphorous) implanted n^+ contact one would naively expect a p-n junction with extremely large (up to 100 V/cm) built-in fields. Instead we found the n^+-p electrode to have essentially the same behavior seen in figure 1 with a p^+-p electrode structure. This remarkable result shows that the neutralization we have long know exists in the bulk does, as one might expect, also apply to these near-contact regions. The resulting charge state is extremely non-equilibrium. In the bulk of the crystal, *the "Fermi level" is not a valid concept.*

This lack of a near-contact built-in field persisted despite numerous attempts to create space charge in the crystal with various biasing strategies. This result is disappointing in that a strong near-contact built-in field could be used to overcome the dead layer. Instead we believe that the band-edges of the implanted contacts are nearly lined-up with the band-edges in the bulk. Only the highest energy portion of the thermal distribution of the charge carriers in the contact can diffuse into the bulk (where they presumably fall onto impurity sites), resulting in a very small bending of the bands.

3. CHARGE RESPONSE PROFILE

This data can directly give us the fraction of full charge collection versus depth, or $q(x)$. We first select all the photons from a given line from the ^{241}Am source and project these on the charge axis to form dN/dq. The left side of

$$\int_0^q \frac{dN(q')}{dq'} d'q = \int_0^x \frac{dN(x')}{dx'} dx' \qquad (1)$$

can be evaluated from the data, while the right side is trivially integrated where $dN/dx = N_o/\lambda e^{-x/\lambda}$ and $\lambda(E)$ is known. This yields $x(q)$, hence $q(x)$.

In figure 2 we show $q(x)$ calculated from both the 14 and 18 keV lines from the data set of figures 1 and of figure 3 (which is discussed below). A measure of the reliability of this procedure is the quite good agreement between the two energies which have a factor of nearly two different penetration depths. The precipitous drop in $q(x)$ near x=0 is due to presence of events in figures (1) and (3) with very low charge. The naïve use of eqn (1) has attributed all of these to a depth << 1 µm. This is probably not correct. First, some of these events have low charge collection purely due to the finite resolution of the charge measurement. This can be corrected for in principle when applying eqn (1), but we have not yet done so. Second, the recoiling electrons from these events deposit energy in a region of some finite size on the scale of a fraction of 1 µm. The size of this region sets a lower limit on x, interpreted as the interaction point of the photon, for which the function $q(x)$ makes sense. In any case, these represent only a tiny fraction of all events.

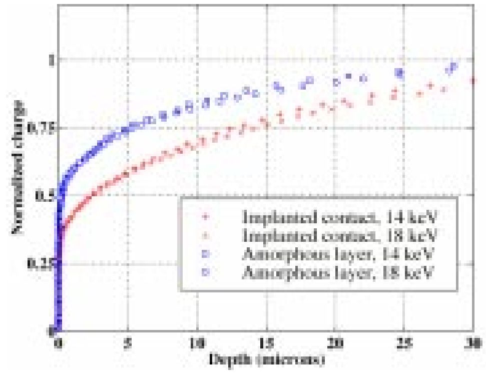

Figure 2. Fractional charge versus depth for the data of figures 1 and 3.

4. AMORPHOUS BLOCKING LAYERS

We next studied devices with a thin amorphous Si or Ge layer directly deposited on the Ge substrate and covered by a thin Al layer. Such structures are commonly employed to reduce similar (but much thinner) dead layers in 77 K semiconductor ionization detectors (Ref. 4). Even for these "standard" detectors, however, the physics of these structures is not know with certainty. Here we employ the working hypothesis that the amorphous layer, with an effective band gap nearly twice as large the bulk Ge, serves as a blocking layer between the bulk and the metallic electrode. Charges which would otherwise diffuse into the contact and be lost before being driven across the detector by the external field are instead reflected by this blocking layer. The layer has a small, but non-zero conductivity due to hopping conduction (on the order of GΩ/square) so that charges of the correct species that accumulate at a contact eventually tunnel through to the electrode.

In figure 3 we show the same measurement as figure 1, at the same charge-collection electric field, but obtained with such a device. The amorphous layer is 275 Å of sputtered Si, and is coated with ≈ 2500 Å of sputtered Al. There is obviously still a dead layer, but it has changed in an important way: the minimum charge collection for most events closest to the surface are well separated from the nuclear recoil band. There is also a fuzzy smear of events between 14 and 18 keV which may or may not be direct tails of the 14 and 18 keV photon distributions.

The improvement this device shows over the standard implanted contact is quite evident in figure 2. The implanted contact has q just barely above 0.3 near the surface; the amorphous layer device has q of roughly 0.5. Since nuclear recoils have $q \approx 0.3$ in Ge, thus this seemingly modest improvement is in fact crucial.

We repeated this measurement with the opposite polarity of electric field and obtained very similar charge collection. This tells us that there is no strong local built-in electric field near the contact. Once again this implies that the near-contact region is neutralized. In equilibrium one would expect strong built-in field due to a Schottky-barrier like structure which equilibrates the Fermi levels in the bulk and amorphous layers.

We then measured the charge collection of this amorphous-layer electrode for electrons from ^{14}C. Most electrons are well separated from the nuclear recoil band at energies as low as about 20 keV. Their charge collection is consistent with the $q(x)$ from the photon data at an energy-dependent depth of about 0.2-0.5 µm. Presumably this depth is a measure of the electron "track" length.

Additionally, as was seen with the photons of figure 3, there is a small tail of events with quite poor charge collection. This population turns out to be strongly dependent on the bias polarity. It is essentially absent for the polarity of figure 3, but much worse for the opposite polarity. This may result from a difference in the way electrons and holes interact with either the amorphous layer or the Al electrode. Or, it could also reflect built-in fields in the amorphous layer due to its (Schottky) interface with the Al. Such fields should depend on surface states and hence surface preparation, and also on the dopant type of the amorphous layer. If so, it might be possible to manipulate these fields in a favorable way.

An added benefit of the amorphous-layer contacts is that they allow full-scale devices to handle large electric fields without breakdown. The CDMS results presented at this conference were obtained with detectors with amorphous-layer contacts operated near 4 V/cm (Ref. 5). We therefore measured the electron response of the small device of figure 3 with this field. The main distribution of

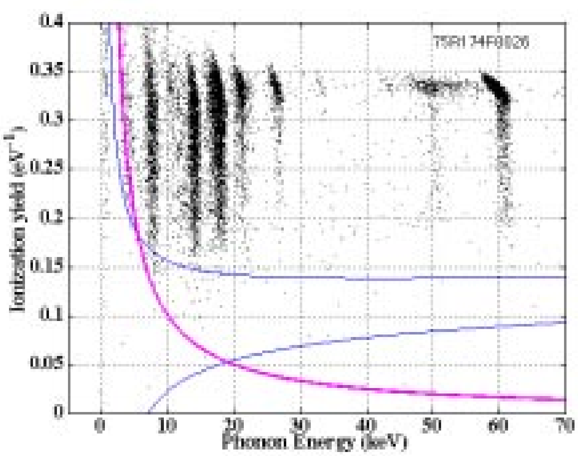

Figure 3. Charge yield measured with an amorphous-blocking layer based electrode.

electrons were well separated from nuclear recoils, and the electron rejection ability was dominated by the small tail of poor collection events. In the favorable positive bias direction the rejection was ≈ 95 % at 20 keV rising to much better than 99 % by about 45 keV; in the unfavorable bias direction it was ≈ 90 % at 20 keV and rose to 95 % at higher energies. By contrast, earlier standard-implant based detectors for CMDS had electron rejection capabilities on the order or 50 %.

5. CONCLUSION

Contacts based on a blocking amorphous layer are a powerful solution to the dead-layer problem, and have the potential for further improvements in the future. Already they have led to first important limits set by the experiment (Ref. 5) We are fighting the electron background problem in other ways as well. The next generation of CDMS detectors features an athermal phonon measurement which powerfully recognizes and rejects surface events. (Ref. 6). We have also made progress in the handling and packaging of detectors to minimize radioactive contamination. (Ref. 5). In addition, the non-equilibrium physics of these contact structures is interesting in its own right.

6. ACKNOWLEDGEMENTS

The authors would like to thank Paul Luke for many insights and suggestions, and B. Cabrera and S. Yellin for useful discussions. This work is supported by the Center for Particle Astrophysics, a NSF Science and Technology Center operated by the University of California, Berkeley, under Cooperative Agreement No. AST-91-20005, by the National Science Foundation under Grant No. PHY-9722414, and by the Department of Energy under contracts DE-AC03-76SF00098, DE-FG03-90ER40569, and DE-FG03-91ER40618.

REFERENCES

1. J.Hellmig *et al.*, these proceedings.
2. T.Shutt, *et al.*, *Phys. Rev. Lett.* **69**, 3531 (1992).
3. T. Shutt *et al.*, Proceedings of the Seventh International Workshop on Low Temperature Detectors. (1997)
4. See, for example, P. Luke, C.S. Rossington, and M.F. Wesela, *IEEE Trans. Nucl. Sci.* **41**, 4, 1074 (1994).
5. S.Golwala *et al.*, these proceedings.
6. R. M. Clarke, Ph.D. Thesis, Stanford University (1999).