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CdZnTe position-sensitive drift detectors with thicknesses up to 5 cm

A. E. Bolotnikov,^{1,a)} G. S. Camarda,¹ E. Chen,² S. Cheng,³ Y. Cui,¹ R. Gul,¹ R. Gallagher,⁴ V. Dedic,⁵ G. De Geronimo,¹ L. Ocampo Giraldo,⁶ J. Fried,¹ A. Hossain,¹ J. M. MacKenzie,² P. Sellin,⁷ S. Taherion,² E. Vernon,¹ G. Yang,¹ U. El-hanany,² and R. B. James¹

¹Department of Nonproliferation and National Security, Brookhaven National Laboratory, Upton, New York 11793-5000, USA

²Redlen Technologies, Saanichton, British Columbia V8M 0A5, Canada

³Department of Applied Physics, NYU School of Engineering, Brooklyn, New York 11201, USA

⁴Department of Physics, Ohio State University, Columbus, Ohio 43201, USA

⁵Institute of Physics of Charles University, Prague 12116, Czech Republic

⁶Department of Mechanical and Nuclear Engineering, Pennsylvania State University, University Park, Pennsylvania 16802, USA

⁷Department of Physics, University of Surrey, Surrey GU2 7XH, United Kingdom

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We investigated the feasibility of long-drift-time CdZnTe (CZT) gamma-ray detectors, fabricated from CZT material produced by Redlen Technologies. CZT crystals with cross-section areas of $5 \times 5 \text{ mm}^2$ and $6 \times 6 \text{ mm}^2$ and thicknesses of 20-, 30-, 40-, and 50-mm were configured as 3D position-sensitive drift detectors and were read out using a front-end ASIC. By correcting the electron charge losses caused by defects in the crystals, we demonstrated high performance for relatively thick detectors fabricated from unselected CZT material. © 2016 AIP Publishing LLC.

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CdZnTe (CZT) is an excellent medium for room-temperature semiconductor gamma-ray detectors.¹ Unfortunately, the inhomogeneity in the detector response caused by defects in the crystals limit the thicknesses of today's CZT detectors used for gamma spectroscopy to below approximately 15 mm. Recently, we demonstrated, by testing high-granularity 3D position-sensitive pixelated and virtual-Frisch-grid (VFG) detectors, that the response inhomogeneity can be corrected by (virtually) segmenting the detectors' volumes into large numbers of small voxels and equalizing the responses generated in each of them.^{2,3} For the position-sensitive VFG detectors, we achieved an energy resolution of $<1\%$ full width at half-maximum (FWHM) at 662 keV from detectors with thicknesses up to 25 mm. These results suggest that we might use even longer CZT detectors that would be particularly attractive for high-energy gamma-ray spectroscopy. Clearly, practical implementations of such devices are likely to impose certain limits on the device thicknesses. Here, we present our results from testing long (up to 5 cm) position-sensitive VFG detectors and highlight the main factors limiting the maximum thickness of CZT crystals that can be used for practical devices. We note that our ultra-thick VFG detectors closely resemble drift ionization chambers, particularly a drift cell originally proposed for gas-filled gamma-ray detectors.⁷

Detectors with a cross-section of $6 \times 6 \text{ mm}^2$ (thicknesses of 20-, 30-, and 40-mm) and a cross-section of $5 \times 5 \text{ mm}^2$ (thicknesses of 50 mm) were fabricated by Redlen Technologies from THM-grown CZT material. The bulk resistivity of the crystals was $>3 \times 10^{10} \Omega\text{-cm}$ and electron $\mu\text{-}\tau$ product was $>10^{-2} \text{ cm}^2/\text{V}$. This particular geometry is very convenient for making ultra-thick detectors, because

required crystals can be produced with high yield from thin wafers cut from a boule.

The details of device fabrication are described in our previous publications.^{2,4} The detectors are encapsulated in thin polyester shells that electrically insulate the crystal from the $5 \times 5 \text{ mm}^2$ pads (cut from a thin copper tape) glued over the polyester shell to each of the side surfaces near the anodes. The pads are virtually grounded via charge-sensitive preamplifiers. These charge-sensing pads look similar to the non-contacting or capacitive type electrodes originally proposed by McGregor and Rojeski⁵ and Montemont *et al.*⁶ for virtual Frisch-grid detectors. Here, their primary function is to provide position information on the electron clouds as they drift towards the anode. The side-surface conductivity ensures the formation of a slightly focusing electric field inside the long crystals, which steers electrons away from the side surfaces.

We employed a front-end ASIC, which provides both the amplitude and timing information, and data-acquisition system developed for our earlier detector arrays.⁴ Although it is not optimal for this device configuration, this ASIC is suited well for reading the positive signals from the anode and the negative signals from the cathode and four charge-sensing pads. The amplitudes from the four sensing pads were converted into X and Y coordinates of the interaction points as a weighted average of the signals from the two pairs of opposite pads. The timing information was used to evaluate the electron cloud's drift times, which can be converted into the Z coordinate. We could also use the cathode-to-anode ratio to independently estimate Z. It is worth mentioning that some corrections are required in order to evaluate the actual coordinates based on the measured values for X-Y-Z. However, using the configuration space described by the X-Y-Z coordinates does not affect the signal correction procedure described below.

^{a)}Electronic mail: bolotnik@bnl.gov

We tested between 6 and 8 detectors of each group except for 50-mm-thick detectors, for which we tested two detectors only. Each detector under test was placed inside an environmental chamber, and the measurements were taken at temperatures in the range of 17–18 °C. The cathode biases were between 3 and 9 kV (depending on the device's thickness and leakage current). The detectors were irradiated with an uncollimated ^{137}Cs source placed ~ 1 cm above the detector's cathode. The electronic noise was measured at the biased cathodes using the test-pulse signals. The FWHM of the test-pulse peaks were in the range of 3.2–3.5 keV, which is equivalent to 0.5%–0.6% FWHM at 662 keV. Testing each detector included two steps. First, we measured the pulse-height spectra from each voxel, and evaluated their photopeak positions. This information enabled us to generate a 3-dimensional correction matrix (lookup table) used to equalize the voxel responses. In the next step, we acquired a second set of data and processed it to evaluate the detector's response. For each event, the anode signal was multiplied by the correction value taken from the correction matrix in accordance with the measured X-Y-Z coordinates. Depending upon the detector's quality and its thickness, we used a correction matrix with dimensions between $10 \times 10 \times 50$ and $120 \times 120 \times 75$. Since the photopeaks of the corrected spectra are not accurately described by a Gaussian function, we evaluated the energy resolution by measuring the geometrical FWHM.

One of our primary concerns was applying a sufficiently high bias to create a strong electric field across the entire length of the detector. A similar problem exists for Si drift detectors;⁵ the space charge formed after the initial depletion of a detector prevents further development of the electric field over its entire thickness. In the case of high-resistivity CZT detectors, the formation of the space charge is governed by a different mechanism (ionization of deep levels), but its net result is similar. The electrical field strength decays towards the anode, and this effect is expected to be stronger in long, >2 cm, detectors. We were able to measure good responses from detectors up to 40-mm thick. However, in one 50-mm-thick detector, we observed a poorer response that correlated with a weak electric field near the anode. For the second 50-mm-thick detector, we measured strong signals and were able to obtain good energy spectra after corrections. Before corrections, the detectors showed a wide range of responses with energy resolutions ranging between 2% and 4% for 20-mm detectors, and up to 6% for 40-mm detectors at 662 keV. (Almost no photopeaks were measured in the case of 50-mm detectors.) After corrections, the energy resolutions improved well below 2% for all tested detectors, but the results still depended on the quality of the CZT crystals used for device fabrication.

Figure 1 summarizes the results obtained for the best detectors from each of the groups. The first two columns from the left show the spectra measured before and after corrections. The spectra representing each group are plotted on the same scale, so improvements in the energy resolutions are also seen as increases in the photopeak heights. After the corrections we achieved the corresponding energy resolutions of 0.76%, 1.06%, 1.10%, and 1.6% FWHM at 662 keV for the 20-, 30-, 40-, and 50-mm thick detectors.

Using the position information from each event, we could map the non-uniformities in the detector response. The third column in Figure 1 shows distributions of the photopeak widths (in relative units) over the detector area (X-Y coordinates). The widths were evaluated using drift-time-corrected spectra of the events interacting over entire thickness. The dark pixels indicate good regions corresponding to the narrowest widths, while the bright pixels represent poorer response regions with widened photopeaks. Using these maps, we could select the events from the good regions and plot their pulse-height distributions (the right-most spectra in Figure 1). For the good regions, the photopeaks' widths were in the range of 0.7%–0.85% FWHM at 662 keV. These results demonstrate that excellent energy resolution can be achieved with ultra-thick detectors of up to 40 mm, provided the crystals contain little or no big defects, such as those clearly seen in the response maps. In the case of the best 50-mm-thick detector, the best energy resolution of 1.6% was achieved at the cathode bias of 9 kV.

The round bright regions, seen in the response maps of the 30- and 40-mm thick detectors, represent well-known prismatic defects, which are particularly detrimental in thick detectors.⁸ These nearly spherical defects, the dimensions of which can exceed several hundred microns, and which are almost opaque to electron clouds, are formed during the annealing step and were sometimes present in the CZT in large concentrations. The fraction of the charge losses per interaction of the electron cloud with such defects can be so large that it is practically impossible to correct them without introducing substantial noise, which degrades the detector's overall response. Since the probability of finding prismatic defects in the crystals increases with thickness, it is more likely that thick detectors will be affected more by these defects. The charge losses due to prismatic defects also affect the photopeak efficiency and increase the Compton continuum, as is evident by comparing the energy spectra measured for 20-, 30-, and 40-mm thick detectors. The 20-mm-thick sample shows fewer prismatic defects, and its peak-to-Compton ratio has the highest value. In contrast, the peak-to-Compton ratio is notably lower for the 30- and 40-mm samples, particularly for the 40-mm sample, which has the highest number of prismatic defects.

Even though the second 50-mm-long detector showed a very uniform response over the crystal area, meaning that the crystal has no large prismatic defects, we were unable to improve its energy resolution to better than 1.6%. This could be explained by the significantly reduced electric field strength near the anode. We used the standard crossed-polarizer Pockels technique exploiting the electro-optic effect^{9,10} of the zinc-blende crystallographic structure of CZT to evaluate the internal electric-field distribution inside the 50-mm-thick detectors. Figure 2 shows the distributions of the electric-field strength evaluated for both 50-mm-thick detectors. As evident, in both detectors the field strength quickly decays towards the anode due to an accumulation of a positive space charge at defect levels, forming a dead layer through almost half of the detector volume in the case of detector 1. This region of low electric field showed considerably worse response compared to detector 2, in which case the electric field extended over the entire length of the

FIG. 1. Representative pulse-height spectra and response maps measured for the best 20-, 30-, 40-, and 50-mm long detectors. The first and second columns show the all-event spectra before (first column from left) and after (second column from left) corrections. The third column shows the distributions of the photopeak widths (in relative units) over the detector area (X-Y coordinates) after the corrections. The dark pixels indicate good regions with the narrowest photopeak widths, while the bright pixels represent poorer response regions with widened photopeaks. The right-most column shows the pulse-height spectra after correction evaluated for events from the good regions (dark areas in the maps shown in the third column from the left).

FIG. 2. Distributions of the internal electric field strength evaluated for the two 50-mm-thick detectors used in this study. The cathode bias is 8 kV.

detector. These results suggest that a low electric field in portions of the detector volume contributes to charge-collection non-uniformity and may be the main factor limiting the maximum attainable thickness of CZT detectors.

Long drift detectors allowed us to use the time-of-flight method to evaluate the electron lifetime (and $\mu\tau$ product) in our CZT crystals. We acquired a series of waveforms of the charge signals (after charge-sensitive preamplifiers) generated on the cathodes and the anodes for the 30- and 40-mm detectors at two different applied biases: 100 and 5000 V. Out of hundreds of acquired waveforms, we selected the cathode signals corresponding to the events with the longest drift time in the case of 100-V bias voltage and shortest in the case of 5000-V bias. The amplitude of the anode signal measured at 5000 V gives an estimate for the total amount of

the charge generated by the incident photon (we selected 662-keV photo-absorption events). We can neglect any charge trapping in this case. Combining this value with the amplitude and the drift time measured at 100 V, we estimated the electron lifetime to be $\sim 200 \mu\text{s}$, which corresponds to a $\mu\text{-}\tau$ product of $0.2 \text{ cm}^2/\text{V}$, assuming an electron mobility of $1000 \text{ cm}^2/\text{V}\cdot\text{s}$. Surprisingly, this value is significantly higher than the one evaluated based on the Hecht equation, which is about $0.02 \text{ cm}^2/\text{V}$.

Using the CZT crystals produced by Redlen, we demonstrated that high-granularity position-sensitive detectors with the ability to correct for response non-uniformities allow us to use crystals with thickness up to 50 mm. The main factor limiting the detector thickness comes from an inability to apply a sufficiently strong electric field over the entire length of the detector. The rapid decay of the electric-field strength towards the anode is caused by the accumulation of positive space charge, and it seems more critical than the limitations that arise from the response-correction techniques or the value of the $\mu\text{-}\tau$ product for the CZT used in this investigation. Based on the evaluated electron lifetime, high energy-resolution detectors with thicknesses up to 10 cm or even larger should be possible, if we can extend the electric field throughout the detector volume.

We found that, in the case of Redlen crystals, the performance is primarily affected by the content of prismatic defects. By selecting the regions relatively free of such defects, we were able to improve the energy resolution to below 0.8%, which means that minimizing the content of the prismatic defects is among the most important criteria in selecting CZT material for radiation detectors and for improving the quality of the crystals.

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