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An Effect of the Networks of the Subgrain Boundaries on Spectral Responses of Thick CdZnTe Detectors

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ABSTRACT

CdZnTe (CZT) crystals used for nuclear-radiation detectors often contain high concentrations of subgrain boundaries and networks of poligonized dislocations that can significantly degrade the performance of semiconductor devices. These defects exist in all commercial CZT materials, regardless of their growth techniques and their vendor. We describe our new results from examining such detectors using IR transmission microscopy and white X-ray beam diffraction topography. We emphasize the roles on the devices' performances of networks of subgrain boundaries with low dislocation densities, such as poligonized dislocations and mosaic structures. Specifically, we evaluated their effects on the gamma-ray responses of thick, >10 mm, CZT detectors. Our findings set the lower limit on the energy resolution of CZT detectors containing dense networks of subgrain boundaries, and walls of dislocations.

Keywords: CdZnTe detectors, virtual Frisch-grid detectors, crystal defects

1. INTRODUCTION

The performance of CdZnTe (CZT) nuclear-radiation detectors depends on the quality of the original crystals that often contain different kinds of subgrain boundaries and geometrical shapes, thereby inducing different levels of stress in the crystal lattice. Subgrain boundaries consist of linear dislocations arranged in planes, or in more complex three-dimensional surfaces. Based on their densities, they are classified as large-angle boundaries with high dislocation densities, to networks of poligonized dislocations, also called dislocation walls [1,2].

The presence of subgrain boundaries is a very common problem in today's commercial CZT material, regardless of the growth techniques employed, or the different vendors who supply them. It is a difficult, expensive task for vendors to identify subgrain boundaries since IR microscopy, their main screening technique, is inadequate for revealing dislocation-related defects; the most effective techniques are white X-ray beam diffraction topography (WXDT) and chemical etching of the crystals' surfaces (etch-pits density analysis). The main mechanism by which subgrain boundaries degrade carrier transport seemingly lies in the accumulation in the distorted areas around the subgrain boundaries of impurities and secondary phases that trap the carriers. and cause local variations of the electric field [3]. Previously, we investigated the roles of well-defined individual subgrain boundaries with interiors containing high dislocations-densities, finding that they induce significant strains in the crystal's lattice, which are easily observable with WXDT [3]. We demonstrated that such boundaries are particularly detrimental to the charge carriers' transport, and are unacceptable in CZT detectors. Here, we present our results from characterizing CZT material containing networks of subgrain boundaries with low dislocation-densities, such as poligonized dislocations and mosaic structures. Using the high-spatial resolution X-ray mapping system at BNL's National Synchrotron Light Source [4] we demonstrated their cumulative injurious effects on the spectral responses of thick, >10mm, CZT detectors.

2. EXPERIMENTAL

The main purpose of this work was to measure the spectral responses of thick detectors fabricated from high-resistivity high mu-tau product crystals, $>10^{-2}$ cm^2/V, containing dense networks of subgrain boundaries but with insignificant content of any other extended defects, such as Te inclusions, twins and grain boundaries. Hence, we ensured that any measured broadening of the photopeaks is attributable to these subgrain boundaries.

We evaluated performances of three crystals configured (confabulate means to chat) as virtual Frisch-grid detectors [5]. They were cut from the same area of a commercial CZT wafer specifically selected for its high content of the subgrain boundaries networks, and dearth of any other extended defects. Two samples measured 6x6x12 mm^3, and the third one was slightly longer, 6x6x15 mm^3. Before making the detectors, we carefully screened the polished and chemically etched parallelepiped detector blanks using transmission IR microscopy and WXDT [3,4]. We deposited two planar contacts on their shorter sides and encapsulated them inside ultra-thin polyester shells, as we described in Ref. [6]. A 4-mm wide shielding electrode (cut from aluminum tape) was placed on the side surfaces near the anode. During the measurements, we flood-illuminated the detectors with a ^{137}Cs source located ~1 cm above the cathode. Endicott charge-shaping preamplifiers read out the signals from the anode and the cathode, which then were digitized with a LeCroy WaveRunner. The stored waveforms were processed to evaluate the electron-drift times for each interaction event, and the amplitudes of the signals [7]; the latter were assessed by digital-pulse processing and then we applied a charge-loss correction. As we demonstrated previously [5], we can achieve an energy resolution of ~0.6% FWHM at 662 keV with detectors made from homogeneous crystals free from major defects. Therefore, any broadening of the photopeaks are attributable to the effects of the subgrain boundaries present in these detectors. To illustrate the anticipated spectral performance of the virtual Frisch-grid detectors, Fig. 1 shows the pulse-height spectrum measured from the best detector fabricated from a high-quality crystal free from subgrain boundaries and Te inclusions.

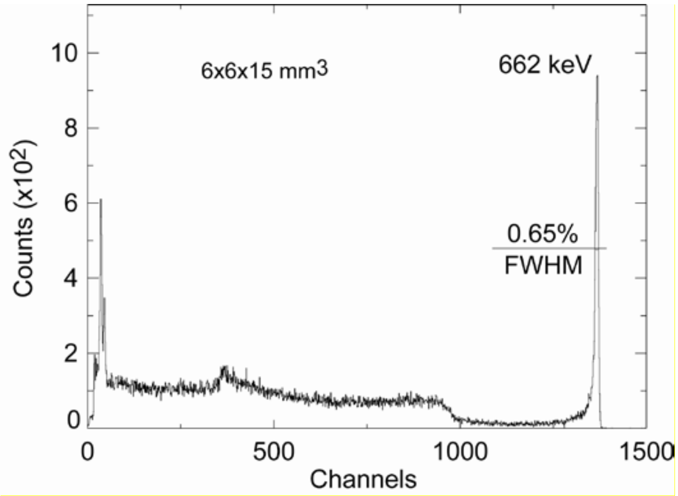

Fig. 1. Pulse-height spectrum measured from the best detector fabricated from a high-quality crystal free from subgrain boundaries and Te inclusions.

Through another type of study, viz., measurements of drift-time distributions of the electron clouds, we were able to assess the uniformity of charge transport. For this purpose, we used an alpha-particle source to generate ionization events close to the cathode, and digitized the output signals readout from the anode; in this case, we removed the shielding electrodes located near the detectors' anodes. Again, we applied digital pulse-processing to determine the drift times for interaction events randomly distributed over the cathode's surface.

3. RESULTS AND DISCUSSION

Figure 2 shows three sets of WXDT topographs of the four side-surfaces of the three CZT crystals used in these measurements; as evident, all three crystals are crisscrossed by networks of subgrain boundaries. Our etch-pit analyses of the samples indicated that most of these boundaries consist of the single-row dislocations. As we demonstrated previously, using X-ray response mapping of 2-mm-thin CZT planar detectors, such boundaries trap a very small fraction, ~1%, of the total charge from the electron clouds drifting across the boundaries [3]; thus, the total amount of the charge loss is of the same order-of- magnitude as a charge loss due to trapping by the point defects. However, the amounts of charge trapped by the subgrain boundaries fluctuate, so proportionally broadening the photopeaks in thick CZT detectors to the distances of electron-clouds' drift. . We also demonstrated, as with well-defined individual subgrain boundaries with a high dislocation density, that the charge losses can be attributed to impurities and secondary phases accumulated by the dislocations encompassed within their subgrain boundaries [8].

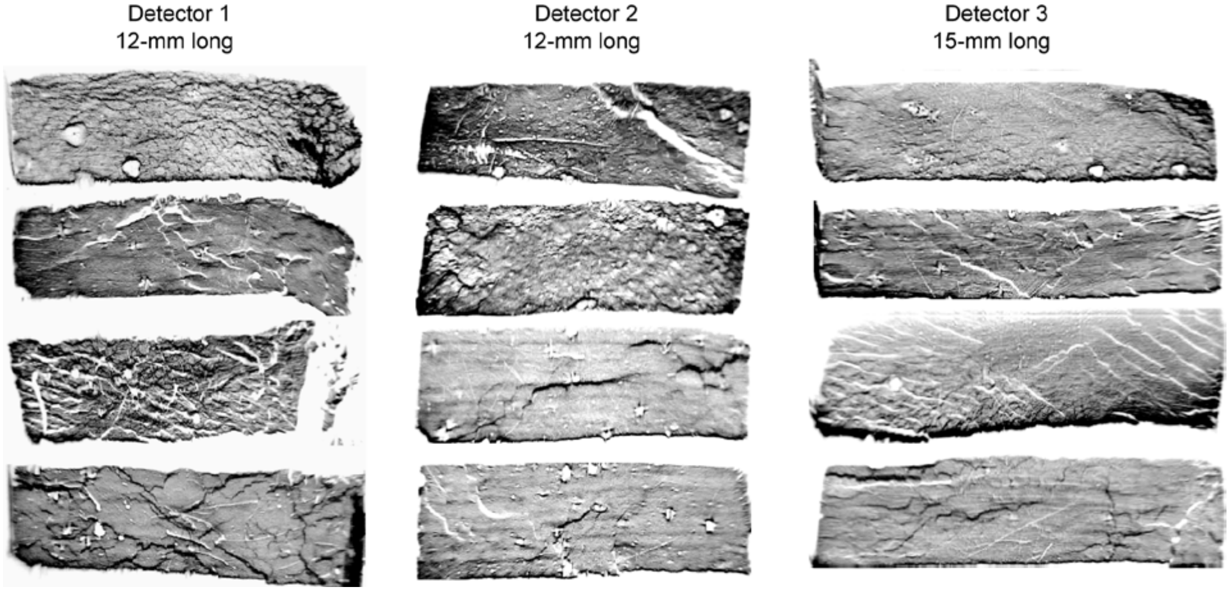

Fig. 2. WXDT images of the four side-surfaces of the detectors showing the subgrain boundaries exiting the crystals.

Figure 3 shows the spectral responses (top) and drift-time distributions (bottom) measured for detectors 1, 2, and 3 biased, respectively, at 2000, 1700, and 2000 V. We corrected these pulse height spectra for charge losses due to the trapping by the point defects. The responses measured from the 12-mm-long detectors were almost identical; we obtained nearly the same energy-resolutions of 1.3% at 662 keV and very similar drift-time distributions. Clearly, the response of the 15-mm long detector was notably stronger, possibly indicating a steep increase in the effect of the subgrain boundaries' network with the device's thickness. Thus, the width of the peak was broadened up 2.1%. We note that the electronic noise, evaluated by applying the test pulses during the spectral accumulations (not shown in the pulse-height spectra), was 0.6% and 0.8% at 662-keV for the 12- and 15-long detectors, respectively, which is small compared to the total widths measured with these detectors. Since these particular detectors had no defects other than networks of subgrain boundaries, we conclude that the cumulative effect of these networks is 1-2% to the total FWHM at 662 keV of the photopeaks in 10-15 mm thick detectors. This value sets the lower limit on the energy resolution of detectors made of the CZT crystals with the networks of subgrain boundaries and dislocation walls.

The spectral responses measured for the three detectors are correlated with the drift-time distributions. The subgrain boundaries act as the electrostatic potential barriers to the electron clouds, changing their speeds and drift directions. The vertical lines in the drift-time distributions indicate the theoretical (expected) times required for an electron cloud originating at the cathode to reach the anode and the drift time corresponding to the measured distribution maxima. The numbers indicate the values of the electron mobility (900, 770, and 870 cm^2/Vs, respectively) evaluated by assuming a uniform electric field inside the detectors and using actual applied biases. For a notable fraction of the events, the drift times are shorter than the theoretical limits. Such the events must be attributed to the electron clouds reaching the detectors' side surfaces, instead of the anode, where they become trapped. (State what you mean by a notable fraction)

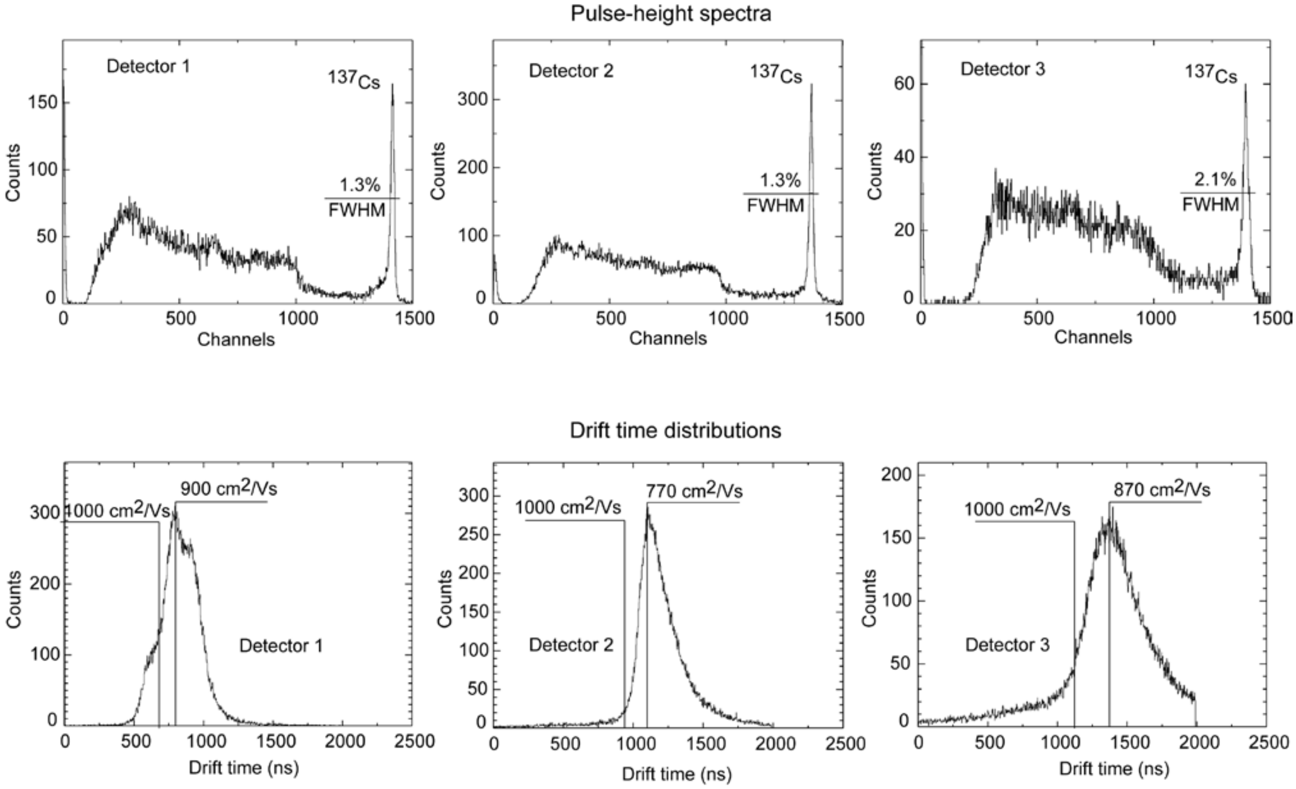

Fig. 3. Pulse-height spectra (top) and drift-time distributions (bottom) measured for the three virtual Frisch-grid detectors at the cathode biases of 2000-, 1700-, and 2000-V, respectively. The pulse-height spectra were corrected for charge losses caused by the trapping of impurities. The electronic noise, evaluated by applying the test pulses during while measuring the spectra, was 0.6% and 0.8% at 662-keV for the 12- and 15-long detectors, respectively, is small compared to the total widths measured with these detectors.

4. CONCLUSIONS

Subgrain boundaries are critical for the performances of CZT detectors; they accumulate impurities and secondary phases that affect their energy and spatial resolution. In this work, we evaluated three virtual Frisch-grid detectors fabricated from CZT crystals containing dense networks of subgrain boundaries but practically free from any other extended defects such as Te inclusions and grain boundaries. This allowed us to zero in on the cumulative effect of subgrain boundaries with low dislocation densities in thick, >10 mm, CZT detectors. We demonstrated that these networks of small subgrain boundaries are responsible for additional fluctuations in the collected charge, adding ~1-2% (at 662 keV) to the photopeaks' widths in thick detectors. Because of the presence of the subgrain boundaries in current commercial CZT material, today's CZT detectors with energy resolution of above 1% are typical, while < 1% detectors are uncommon. The effect of subgrain boundaries networks with low-dislocation density differs from that of well-defined subgrain boundaries with high-dislocation density that are very detrimental and cannot be tolerated in CZT detectors.

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