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Alpha Particle Response Characterization of CdZnTe

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ABSTRACT

The coplanar-grid as well as other electron-only detection techniques are effective in overcoming some of the material problems of CdZnTe and, consequently, have led to efficient gamma-ray detectors with good energy resolution while operating at room temperature. The performance of these detectors is limited by the degree of uniformity in both electron generation and transport. Despite recent progress in the growth of CdZnTe material, small variations in these properties remain a barrier to the widespread success of such detectors. Alpha-particle response characterization of CdZnTe crystals fabricated into simple planar detectors is an effective tool to accurately study electron generation and transport. We have used a finely collimated alpha source to produce two-dimensional maps of detector response. A clear correlation has been observed between the distribution of precipitates near the entrance contact on some crystals and their alpha-response maps. Further studies are ongoing to determine the mechanism for the observed response variations and the reason for the correlation. This paper presents the results of these studies and their relationship to coplanar-grid gamma-ray detector performance.

Keywords: CdZnTe, coplanar grid, semiconductor detector, gamma-ray detector, alpha particle

1. INTRODUCTION

The potential of CdZnTe for room-temperature gamma-ray detection with good energy resolution and efficiency has been demonstrated through many material and detector technology developments over the last decade.[1-10] The material has the desirable intrinsic properties of a wide bandgap necessary for room-temperature operation and a high average atomic number for efficient gamma-ray stopping. Furthermore, the CdZnTe material that is commercially available today exhibits negligible polarization effects, has a high bulk resistivity, and has reasonably good electron collection properties.[11] The material, however, continues to suffer from poor hole transport leading to large-volume detectors with poor spectroscopic performance when conventional detection techniques are used. Consequently, techniques in which the detector signal is almost exclusively derived from electron collection have become the most viable approaches for the successful application of CdZnTe to high-efficiency gamma-ray detection when good energy resolution is required. One of these *electron-only* approaches is the coplanar-grid charge-sensing technique.[4] This technique and its variations offer the advantages of nearly eliminating the hole collection problem, providing accurate and adjustable correction for electron trapping, producing uniform charge induction,[12,13] realizing near full-volume detection efficiency,[14,15] and requiring only simple conventional pulse-processing electronics. Coplanar-grid detectors 1cm^3 in size have achieved energy resolutions down to about 2% FWHM at 662keV, and complete hand-held detection systems have been produced from such detectors.[15]

Despite the accomplishments of the coplanar-grid and other electron-only techniques, the widespread application of CdZnTe remains hampered by the poor availability of large crystals with the uniformity required for high-resolution spectroscopy applications. Critical to the success of electron-only devices is spatial uniformity in electron generation and transport within the CdZnTe material. It is now well established that randomly-oriented grain boundaries can cause severe electron trapping and thereby substantially degrade the spectroscopic performance of these devices.[16] For this reason, crystals free of these grain boundaries must be selectively cut from the polycrystalline ingots typically produced. Once these grain boundary and other large-scale crystal defects such as cracks are eliminated through this selection process, small inhomogeneities in the electron generation and transport properties of the material remain. These small variations then typically limit the performance of the detectors produced from the material. We have used alpha-particle response measurements to characterize these electron generation and transport variations.[17,18] In one such method, an alpha-particle source is used to illuminate the cathode of a CdZnTe crystal that has been fabricated into a simple planar detector. Each alpha-particle interaction event in the detector generates a well-defined number of electron-hole pairs near the cathode. The collection of this charge produces an induced charge pulse on the detector electrodes that is almost entirely determined by the electron generation at the cathode and by the transport of the electrons through the entire detector length. The height of this pulse

then characterizes the electron generation at the cathode and the electron transport along the drift path. Nonuniformities in these properties are reflected in the alpha-response measurements as pulse-height variations. Consequently, a quick and accurate uniformity characterization of a crystal can be made by uniformly illuminating the full cathode area of the crystal and measuring the alpha-particle pulse-height spectrum. A spectrum that has a single sharp full-energy peak with little background indicates that the detector crystal is uniform in both the electron generation at the detector cathode and the electron transport throughout the crystal volume. We have demonstrated that such uniformity is necessary for a crystal to achieve a good gamma-ray spectroscopic performance when operated as a coplanar-grid detector.[18]

The alpha-particle characterization method just described can be used to screen material for high-resolution spectroscopy applications. However, the amount of highly uniform material currently available appears to be small, and even the best material that we have studied has measurable inhomogeneities that degrade spectroscopic performance. It is therefore necessary to determine the nature of these inhomogeneities and devise methods to eliminate them. To this end, we have used alpha-particle scanning along with other mapping techniques. Alpha-particle scanning is accomplished by finely collimating the alpha source so that only a small volume of the crystal is probed. The alpha-particle spectral response of the crystal can then be measured as a function of the source location along the cathode. In this way, a spatial map of the electron generation and transport can be made of the crystal thereby allowing the location of the inhomogeneities or the distribution of the variations to be determined in two dimensions. Furthermore, analysis of the induced charge pulses at each source location can provide information concerning the depth location and nature of the electron transport problems. Combining these alpha-response maps with maps of other material properties such as infrared transmission, photoreflectance, cathodoluminescence, and photoluminescence can allow the underlying cause of the inhomogeneities to be determined. As an example, we have observed a correlation between the presence of large (20 - 30 μm diameter) precipitates identified through infrared transmission microscopy and the degradation in the uniformity of the alpha-particle response.

In this paper, we review our work on alpha-particle characterization of CdZnTe and its direct relation to coplanar-grid gamma-ray detector performance. We first provide the details of our detector fabrication and characterization procedures. Following this, a section is devoted to demonstrating the validity of using the alpha-response measurements for studying material uniformity. The results from several different measurements are presented, all of which indicate that the measured alpha-response from a carefully prepared crystal depends on the bulk properties of the material rather than the properties of the electrical contact layer. Then, in Section 4, we present one of the more interesting findings from our alpha-particle scanning studies. This is the correlation between precipitates, alpha-response maps, and coplanar-grid detector performance. Finally, a summary of the paper is given in Section 5.

2. CHARACTERIZATION PROCEDURE

Our study has consisted of the characterization of a large number of commercially available CdZnTe crystals. Both high-pressure Bridgman (HPB) material obtained from eV Products[19] over the last four years and low-pressure Bridgman (LPB) material obtained from Yinnel Tech[20] within the last year have been analyzed. All of the results presented here from this study are from crystals approximately $1\times1\times1$ cm^3 in size. This size was chosen as a compromise between the desire for large volumes and the need for reasonable quantities of crystals free from random grain boundaries. This standardization of the sample geometry and the testing procedure to be described later is essential for evaluating and comparing different CdZnTe crystals and for tracking the progress made over time in the production of the material.

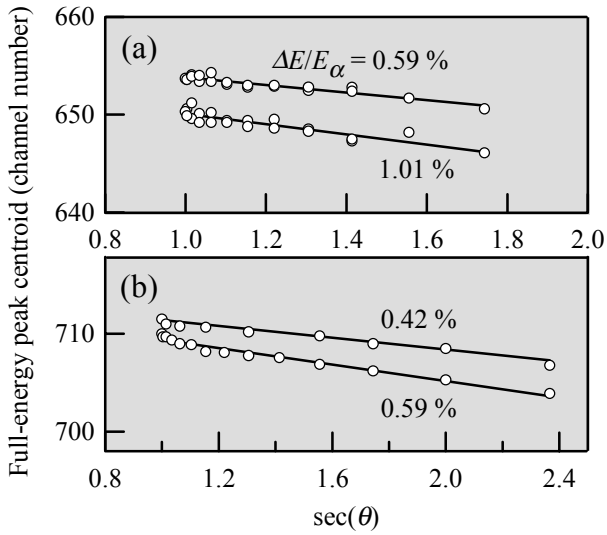
The value of the alpha-particle measurements can depend on the detector fabrication process and the characterization procedure as well as on the material properties themselves. Consequently, the details of both the detector fabrication and the alpha characterization are given here. The processing of each crystal consists first of lapping the crystal surfaces with a fine-grit alumina powder in water slurry on a glass plate. The scattering of light from the lapped crystal surfaces is dependent on the crystallographic orientation thereby allowing the identification of grain boundaries through simple visual inspection of the surfaces. We crudely categorize a boundary as either a *twin* if it is straight or *random* if it is not. The typically large electron trapping problems associated with random boundaries are well documented,[16] and nearly all of the crystals that we tested with such boundaries led to coplanar-grid detectors with performance problems that included substantial background counts, poor energy resolution, and poor photopeak efficiency. In contrast, the presence of twin grain boundaries typically did not directly lead to a poor coplanar-grid performance; though, these boundaries may sometimes be associated with electron transport nonuniformities that degrade the coplanar-grid energy resolution.[18] Consequently, the results in this paper are from crystals that have either no visible grain boundaries or only twin boundaries.

Following the lapped surface inspection, the crystal is mechanically polished with a water-based slurry of sub-micron alumina powder on a fabric pad in order to produce smooth surfaces. The crystal is then characterized using infrared transmission microscopy through which pipes, precipitates, and inclusions are identified. The fabrication of the crystal into a simple planar detector is continued by chemically etching the crystal in an approximately 2 % bromine-methanol solution in order to remove the surface damage introduced by the mechanical processing. Immediately following the etch, full-area Au electrodes approximately 80 - 90 nm thick are deposited onto two opposing detector surfaces through thermal evaporation. The completed planar detector is then mounted into a vacuum chamber where one of the detector electrodes is illuminated with alpha particles from an ^{241}Am source. A thin windowless alpha source is used, and the measurements are made under vacuum to ensure that the alpha particles entering the detector have a narrow energy distribution. A bias is applied across the detector to collect the electrons and holes generated by the alpha-particle interaction events within the detector. Finally, each of the charge pulses induced on one of the detector electrodes by the collection of the alpha-generated charge is measured with a charge-sensitive preamplifier and standard pulse-processing electronics chain. Using this configuration, the overall electron generation and transport uniformity of the material is characterized. This is accomplished by uniformly illuminating the full cathode area of the crystal with the uncollimated ^{241}Am alpha-particle source and measuring the resultant pulse-height spectrum at a typical detector bias of 1000 V. The spectral line shape and any background that may be present provide a measure of uniformity.

The measurement configuration just described is also used to extract both the electron and hole mobilities and lifetimes of the CdZnTe crystal. This technique has been described previously.[18] The transport properties extracted in this manner can be thought of as average values for the crystal. No clear correlation between these properties and the coplanar-grid gamma performance has been observed in our studies. This is not surprising since, for the case of electron transport, the coplanar-grid technique can accurately correct for the presence of uniform electron trapping. In principal, the magnitude of this uniform electron trapping could become a problem if it is large enough for the statistical fluctuations in the trapping to lead to a significant degradation in energy resolution. This, however, does not appear to be the case. The uniformity rather than the average value of the electron transport (and/or electron generation) seems to be the factor limiting the coplanar-grid detector performance. There is also no clear correlation with the average hole transport, which is not surprising since the dependence of the detector signal on hole transport is largely eliminated through the coplanar-grid charge-sensing technique. Some dependence on the hole transport could be possible, though, since if it is too poor, the trapped hole charge could lead to a polarization effect that would degrade resolution. Also, if the hole collection is too efficient, then the charge induction uniformity with depth is worsened when using the coplanar-grid technique, thereby degrading energy resolution.[16] Neither of these effects appears to be a limiting factor for the set of crystals analyzed.

Once the level of uniformity of a crystal is established through the full-area alpha-particle response, we investigate the nature of the inhomogeneities in the electron generation and transport using alpha-particle scanning. For this measurement, the alpha source is collimated to produce a beam diameter of about 0.3 mm, and the source is mounted on a scanning stage. In this way, the beam can be positioned anywhere along the cathode, and only a small region of the CdZnTe crystal is probed. LabVIEW code is used to control the stage scanning and the acquisition of pulse-height spectral information from a multichannel analyzer. The program moves the source to a specific location along the cathode, accumulates a pulse-height spectrum for a designated time (typically one-half hour), saves the spectrum, moves the source to the next location in the scan, and then repeats the process until a complete scan of a designated region is obtained. This results in the acquisition of a three-dimensional data set: spatial source positions of x and y, and channel number. Post-acquisition analysis software then allows various two-dimensional images to be formed from the three-dimensional data set. For example, a channel number region of interest can be selected about the alpha-particle peak, and the peak centroid within this region can be calculated at each source location. This then generates a full-energy-peak centroid image of the scanned region of the crystal. Shifts in the peak location or peak smearing to lower energies will be reflected in the centroid image and thereby provide a clear indication of nonuniformities. After the scan of the crystal is complete, the source is then positioned at various locations of interest, and induced charge signal analysis is performed. This typically consists of acquiring a set of induced charge signals that have pulse heights spanning the range of the full-energy-peak width. From this set of pulses, the origin of any peak broadening at that location in the crystal may be evident.

Following the above analysis of the crystal in the planar detector configuration, the crystal is reprocessed into a coplanar-grid detector and tested. This allows us to directly correlate the characteristics measured through the alpha-particle analysis (and other characterization techniques) to the gamma-ray detector performance of the crystal. The fabrication procedure is similar to that of the planar detector, except that the full-area anode is replaced with a coplanar-grid electrode structure that is defined by performing the Au evaporation through a shadow mask. The coplanar-grid pattern was designed for charge induction uniformity using three-dimensional electrostatic modeling and then later tested for uniformity through alpha-particle



(c)

Detector	$\Delta E/E_\alpha$ (%) Top contact	Bottom contact
HPB A	0.59	0.62
HPB B	0.74	
HPB C	0.89	
HPB D	0.8	1.01
LPB A	0.42	
LPB B	0.59	

Figure 1. Example contact thickness measurement data from **(a)** two HPB CdZnTe crystals and **(b)** two LPB CdZnTe crystals with evaporated Au contacts. The full-energy alpha-particle peak centroid measured with the planar geometry detectors is plotted as a function of the secant of the angle between the detector contact normal and the alpha-particle beam. An ^{241}Am alpha-particle source (5.5 MeV) was used, and the measurements were made at a detector bias of 1000 V. Ideally, such a plot is linear, and the fraction of energy lost in the contact dead layer is the ratio of the slope magnitude to *y*-axis intercept. **(c)** Measured fraction of energy lost by 5.5 MeV alpha particles in the contact dead layers of four HPB CdZnTe and two LPB CdZnTe crystals with evaporated Au contacts.

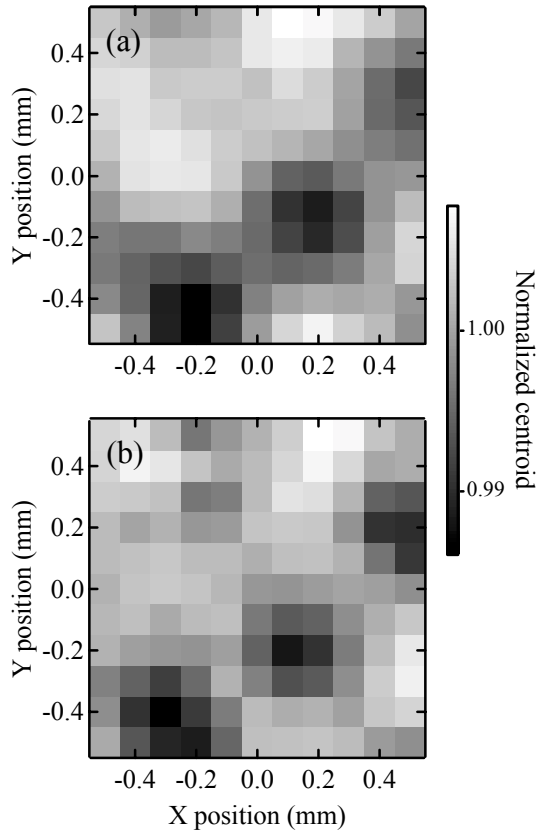


Figure 2. Alpha-particle peak centroid image of a HPB CdZnTe crystal **(a)** before and **(b)** after the cathode of the crystal was removed and then redeposited. An ^{241}Am alpha source was used to scan the cathode side of the crystal in a planar detector configuration while a bias of 1000 V was applied across the detector. The image before reprocessing was acquired with the source collimated to about 0.3 mm while that of the image after reprocessing was about 0.15 mm. The basic features are the same in the two images thereby indicating that these features are the result of the bulk crystal properties rather than variations in the properties of the cathode.

scanning measurements.[12,13,15] The completed coplanar-grid detector is placed inside a test chamber where it is illuminated with gamma rays from a ^{137}Cs source and operated as a differential-gain coplanar-grid detector.[13] The operating conditions of the detector are then optimized in order to produce the best possible 662 keV gamma-ray peak resolution.

3. VALIDATION OF ALPHA-PARTICLE RESPONSE TECHNIQUE

The use of alpha particles to characterize the electron generation and transport of CdZnTe crystals provides several advantages. First, the 5.5 MeV alpha particles from the ^{241}Am source used in our measurements produce large signals and a well-defined energy deposition and interaction region (within 20 μm of the entrance contact electrode).[21] This small interaction region near the entrance contact enables the characterization of the electron generation and collection properties alone. A deeper and more random energy deposition with depth, which would be present if high-energy gamma rays were used, would introduce a dependence of the measurements on hole collection and consequently would lead to a less accurate characterization. A near-contact energy deposition could be achieved with a low-energy gamma-ray source. However, the

resultant signal-to-noise level would be greatly reduced, and again, as a result, characterization accuracy would be degraded. A second advantage of alpha particles is that they are easily collimated and can therefore be used to probe small regions of the crystal. The source itself is also compact and easy to obtain, in contrast to accelerator-based sources of charged particles. Finally, the characterization procedure requires only a simple detector geometry and conventional pulse-processing electronics.

Despite the substantial advantages of the alpha-particle technique, some concerns need to be addressed. These relate to possible problems with electrical contact dead layers, obscured results from physical damage to the electrical contact, and charge loss due to recombination and trapping within the dense charge cloud created by an alpha particle. To address these concerns, we have made several measurements, all of which validate the use of the technique.

One concern is that energy straggling from a dead layer at the entrance contact or a nonuniform dead layer could lead to a substantial broadening of the alpha-particle full-energy peak. If such broadening is large, then the full-energy peak width will be a measurement dominated by the dead layer and not the material nonuniformity. To find out if a contact dead layer is a problem, we determined the energy loss in the dead layer of the entrance contact by measuring the alpha-particle pulse-height spectrum from a collimated alpha-particle source as a function of the angle between the detector and the alpha-particle beam. If we assume that the rate of energy loss of the alpha particles in the Au contact layer and any CdZnTe dead layer is constant, then the pulse height is given by the following

$$V_p = A\left(E_\alpha - \Delta E \sec(\theta)\right), \tag{1}$$

where A is a proportionality constant relating energy to pulse height, E_α is the alpha-particle energy, ΔE is the energy lost in the contact dead layer under normal incidence, and θ is the angle between the alpha-particle beam and the normal to the contact. Equation (1) is then fitted to the measured $V_p(\theta)$ data with AE_α and $A\Delta E$ as fitting parameters. The fraction of the energy lost in the entrance contact dead layer $\Delta E/E_\alpha$ is simply the ratio of these two fitted parameters. We have performed this measurement and analysis on four HPB crystals and two LPB crystals. The data and results of the analysis are shown in Figure 1, where we have taken the average pulse height to be the centroid of the alpha-particle full-energy peak. The average fractional energy lost in the contact dead layer of about 0.7 % is small and is approximately the same as the calculated loss expected from the Au layer of the entrance contact.[21] Energy broadening due to this dead layer should be substantially smaller than this energy loss. We therefore expect the broadening due to the dead layer to be insignificant compared to the typical broadening we observe due to material nonuniformity.

The results of another experiment performed to address the issue of contact dead layers are shown in Figure 2. The experiment consisted of scanning a region of a HPB crystal, removing the scanned cathode contact through polishing and etching, redepositing the cathode, and then rescanning that same region of the crystal. The two full-energy-peak centroid images of Figure 2 are from the scans taken before and after the cathode reprocessing. The basic features present in the two images are the same despite the entrance contact reprocessing. Consequently, the observed variations in centroid are not a result of physical electrode damage or electrode thickness variations.

One of the advantages of alpha particles, as described above, is that they deposit a large amount of energy within a small volume of the crystal. This property could also potentially be a disadvantage and is another concern to be addressed. Each alpha particle interaction in the CdZnTe crystal creates a dense column or plasma of electron-hole pairs. Under the influence of an applied bias, the electron and hole columns will begin to drift and separate. This separation of charge produces a field that opposes and slows down the charge collection process. The resultant longer collection time allows for more carrier losses from recombination and trapping thus leading to a smaller than expected signal. This is the so-called *plasma effect* that exists in the detection of heavy ions with silicon detectors.[22] If such a plasma effect is substantial or spatially nonuniform for the 5.5 MeV alphas in CdZnTe, then broadening of the alpha full-energy peak could be dominated by the plasma effect rather than bulk material nonuniformities. Furthermore, a substantial plasma effect could invalidate the contact thickness measurements, since the plasma-effect carrier losses could be a function of the angle θ between the charge column and the applied field. As a simple test of the impact of plasma-effect or other similar charge losses, we compared induced-charge-signal pulse heights generated by the alpha particles to those generated by 60 keV gamma rays. These low energy gamma rays generate a much less dense charge cloud than the alphas, and therefore should produce signals with a much weaker plasma effect. We performed this comparison with several different CdZnTe crystals (both HPB and LPB material). After normalizing the pulse heights by the energy of the particles, the average gamma-generated pulse height was found to be approximately 1 % greater than that of the alphas. This small difference is substantially accounted for by the alpha energy lost in the Au contact layer and demonstrates that plasma-induced charge losses should not be a problem in the alpha characterization of the material.

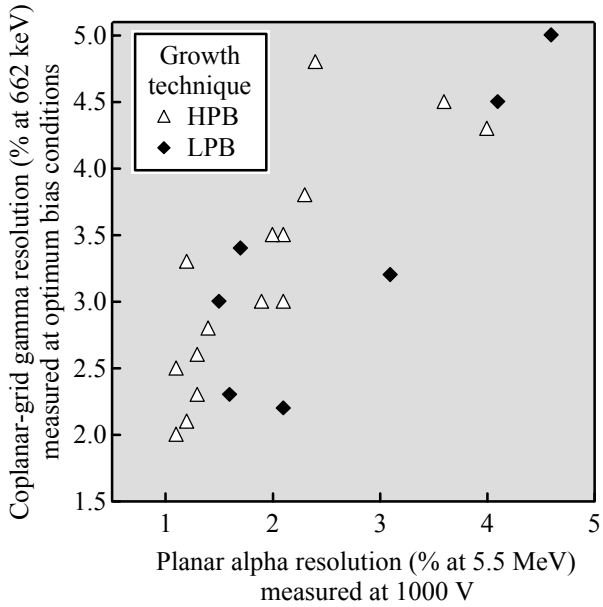


Figure 3. Measured coplanar-grid gamma-ray energy resolution at 662 keV plotted against the planar detector alpha-particle energy resolution at 5.5 MeV for 1 cm^3 CdZnTe crystals. The alpha-particle measurements were made at a bias of 1000 V whereas the gamma-ray measurements were made at biases that gave the best energy resolution.

Ultimately the value of a material characterization technique is dictated by how well its results relate to the gamma-ray detector performance of the material. In part, for this reason, we have evaluated the uniformity of many CdZnTe crystals through the alpha-particle spectral response of the crystals when in a planar detector geometry. These crystals were then reprocessed and tested as coplanar-grid gamma-ray detectors. A simple summary of this study is given in Figure 3. Here the coplanar-grid gamma-ray energy resolution at 662 keV obtained from the crystals is plotted against the planar alpha-particle energy resolution obtained with these same crystals. Despite the simplicity of the comparison, there is a clear correlation between the two measurements. If the electron generation and transport of a crystal is highly nonuniform as is indicated by a poor planar detector alpha-particle energy resolution, the crystal will then lead to a coplanar-grid detector with poor gamma-ray energy resolution. The simple alpha-response measurement can therefore be used to screen material for coplanar-grid detector applications. In practice, the single parameter of alpha-particle energy resolution alone is not sufficient to ensure uniformity, since an excellent full-energy-peak width can also be accompanied by considerable peak tailing or background counts. Such characteristics indicate crystal nonuniformity and must also be assessed in the material screening process. Furthermore, other factors can limit the gamma-ray performance of a crystal as a coplanar-grid detector. For example, some crystals exhibit unusually high electronic noise as coplanar-grid detectors when full bias is applied. The data from these crystals are not included in Figure 3 since this behavior prevents the proper optimization of the detectors. Nonetheless, the correlation of Figure 3 illustrates the value of the alpha measurements, and also implies that in many of the crystals the lack of uniformity in electron generation and transport is the limiting factor for the gamma-ray energy resolution obtained from the crystals.

To end this section, we note that the results presented here demonstrate the value of alpha-particle response measurements in the characterization of specific CdZnTe materials (HPB material from eV Products and LPB material from Yinnel Tech) fabricated using the process described in the previous section. The technique, however, may not be as useful for other materials and/or fabrication processes. As an example, a cursory investigation of LPB CdZnTe material obtained from Imarad Imaging Systems[23] revealed some problems. First, a crystal tested with indium contacts fabricated by Imarad produced anomalously large pulses with widely varying pulse heights when illuminated with alpha particles. One possible explanation for this is that trapped holes near the cathode lead to electron injection at that contact. These electrons do not necessarily recombine with the trapped holes because of the finite electron-hole recombination cross-section and the substantial applied field. These injected electrons can drift through the detector thereby resulting in a larger than expected pulse height. When an Imarad crystal was processed as described in the previous section, the contact thickness measurement

gave an anomalous result in that the peak centroid increased rather than decreased with θ. A comparison of the collected charge from an alpha interaction event in that same crystal to that of a gamma ray indicated a significant charge collection deficit for the case of the alpha event. From these measurements, we conclude that the alpha characterization technique does not appear to be an appropriate tool to analyze the uniformity of this material, and a more appropriate choice might be low-energy gamma rays.

4. ALPHA-PARTICLE SCANNING RESULTS

Alpha-particle scanning combined with pulse-height and induced-charge-signal analyses have proved useful for detailed investigations into the inhomogeneities of electron generation and transport in CdZnTe materials. In a previous study of HPB material,[18] we identified and mapped in three dimensions one type of nonuniformity, that of a change in the product of electron mobility and detector field. Based on measurements and numerical modeling, we determined that a sufficiently large extent of such variations would degrade coplanar-grid detector performance and that such a level of this type of nonuniformity does exist in some crystals. However, for the majority of the crystals that we have studied, the mobility-field variations observed are too small to account for the degraded coplanar-grid performance of the crystals. Nonuniformities apparently not explainable through simple mobility-field changes were also identified in the previous study. The more severe of these were observed to have substantial variations over small length scales (less than 1 mm), and crystals with this problem were found to perform poorly as coplanar-grid detectors. In an effort to understand the nature of these and other nonuniformities, we have continued our alpha-particle scanning studies. In particular, we have attempted to correlate the spatial dependence of the alpha response with spatial variations of other material properties. In this section, we present some of our recent findings from this study.

One approach to identify the dominant causes of spectroscopic performance degradation in CdZnTe materials is to analyze and compare crystals that have good coplanar-grid gamma-ray responses to those that perform poorly. Example measurements of this type are given in Figures 4 and 5. Here the results from an identical set of measurements made on two separate HPB crystals (labeled HPB 1 and HPB 2) are given. Plotted in part (a) of each figure is a full-area illumination alpha-particle spectrum acquired from the crystal when in a planar detector geometry. In part (b) of each figure, the coplanar-grid gamma-ray response of the crystal to a ^{137}Cs source is given. The alpha spectrum from crystal HPB 1 exhibits the desired single sharp full-energy peak with little background. As expected, this uniform crystal then achieves a good gamma-ray response as indicated by the 2.1 % FWHM energy resolution at 662 keV and the large peak-to-Compton ratio. In contrast to this is the response of HPB 2. The alpha spectrum again consists of a single peak; however, this peak is somewhat broad thereby indicating a lack of material uniformity. This nonuniformity is then the likely cause of the mediocre gamma-ray response of the crystal.

The HPB crystals that we have studied typically contain crystal defects such as pipes and Te precipitates or inclusions that are identifiable through infrared transmission microscopy. One possible explanation for the poor uniformity in the detector response is that these defects either directly or indirectly reduce charge generation or cause nonuniform electron trapping. To test this hypothesis and to better understand the performance degradation of crystal HPB 2, alpha-particle scans of HPB 1 and HPB 2 were taken. Part (c) of Figures 4 and 5 contain the full-energy-peak centroid images (in gray scale) extracted from these scans. Infrared images were also taken of the two crystals. The focal point of the images was chosen to be near the cathode surface of the crystal, though, depending on object size, objects millimeters deep into the crystal can still be identified in the images. These infrared images were processed to remove any slowly varying background and then converted to binary by choosing a threshold level that selects out the majority of in-focus objects in the images. For presentation purposes, these objects (black) were then expanded in size and outlined in white. The resultant processed infrared images are plotted as an overlay on the alpha-peak centroid images in Figures 4c and 5c. The regular array of gray pixels in each figure is the centroid image, and the black objects outlined in white are the regions of low infrared transmission. As a first observation, note that the centroid image of HPB 1 shows that the response of the crystal is relatively uniform over most of the scanned area with centroid variations of only about 1 %. The image of HPB 2 in contrast is clearly less uniform and contains regular variations of about 2 % in the centroid position over distances of less than 1 mm. This reaffirms the idea that the loss of gamma-ray spectral performance is a direct result of a lack of electron generation and transport uniformity as identified through alpha-particle response measurements.

A second observation from Figures 4c and 5c is that there is a clear correlation between the presence of certain defects identified through infrared microscopy and reduced alpha-peak centroid. Crystal HPB 1 is relatively free from identified defects and perhaps as a result has a relatively uniform alpha response. The objects in the form of horizontal lines in the

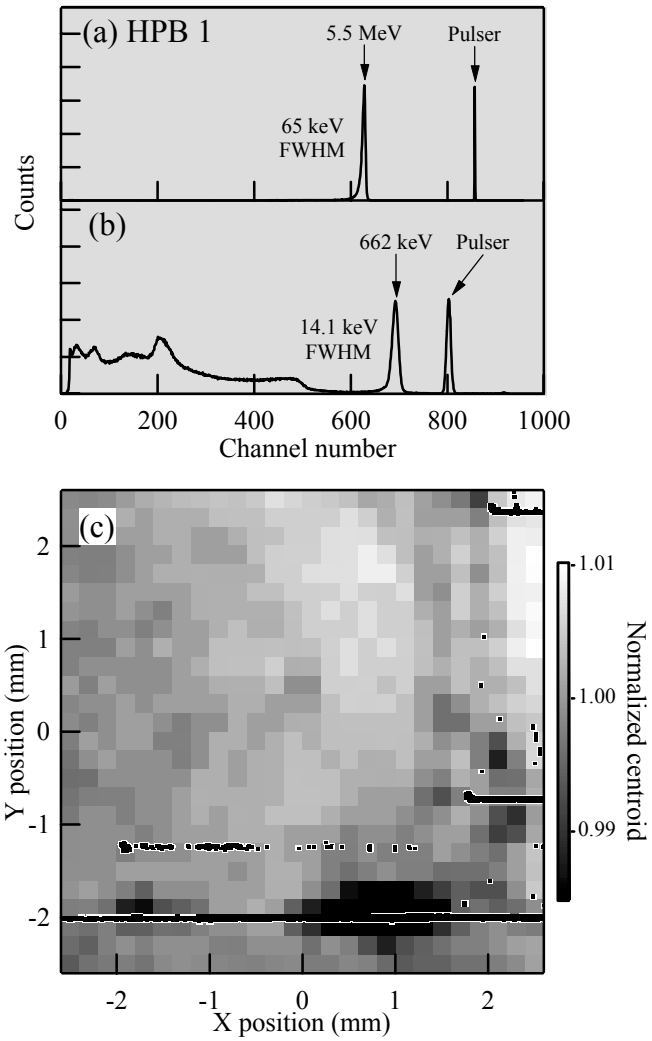


Figure 4. Measurements from the relatively uniform crystal HPB 1. **(a)** ^{241}Am alpha-particle pulse-height spectrum obtained with the crystal in a planar detector geometry. The detector bias was 1000 V. The source was uncollimated and illuminated the full cathode area of the crystal. **(b)** ^{137}Cs gamma-ray pulse-height spectrum obtained with the crystal in a coplanar-grid detector geometry. The bias across the detector was 1400 V and that between the grids was 39 V. The 662 keV gamma-ray peak to Compton ratio for this spectrum is 6.2. **(c)** Alpha-particle-peak centroid image of the center section of the crystal. An ^{241}Am alpha source collimated to about 0.3 mm was used to scan the cathode side of the crystal in a planar detector configuration while a bias of 1000 V was applied across the detector. Superimposed on top of this image are regions (black with white outline) of low infrared transmission.

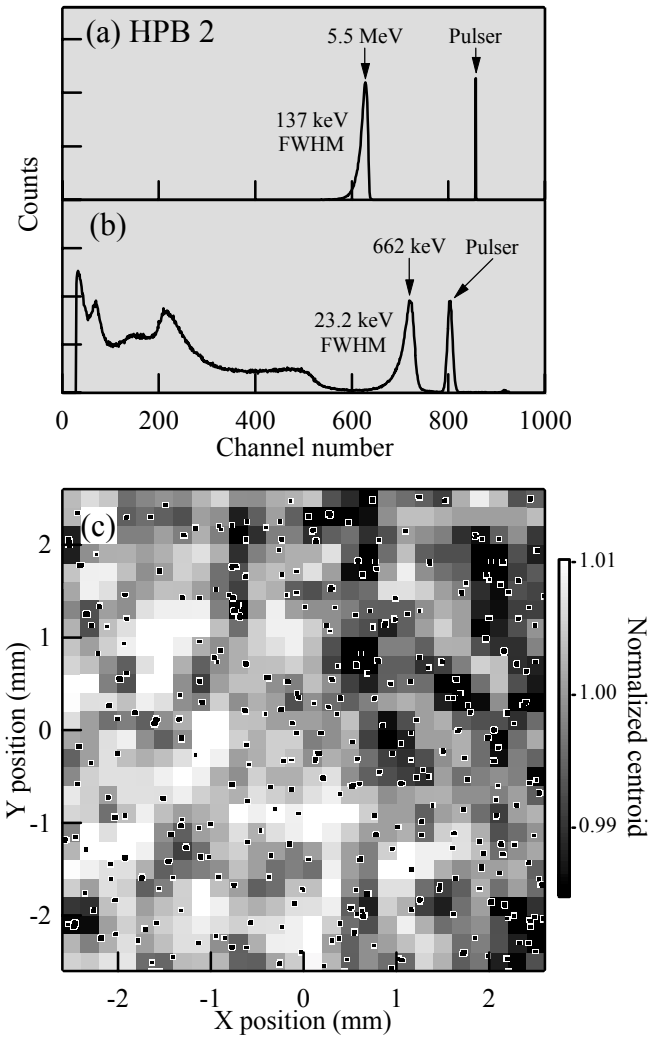


Figure 5. Measurements from the relatively nonuniform crystal HPB 2. **(a)** ^{241}Am alpha-particle pulse-height spectrum obtained with the crystal in a planar detector geometry. The detector bias was 1000 V. The source was uncollimated and illuminated the full cathode area of the crystal. **(b)** ^{137}Cs gamma-ray pulse-height spectrum obtained with the crystal in a coplanar-grid detector geometry. The bias across the detector was 1600 V and that between the grids was 65 V. The 662 keV gamma-ray peak to Compton ratio for this spectrum is 3.9. **(c)** Alpha-particle-peak centroid image of the center section of the crystal. An ^{241}Am alpha source collimated to about 0.3 mm was used to scan the cathode side of the crystal in a planar detector configuration while a bias of 1000 V was applied across the detector. Superimposed on top of this image are regions (black with white outline) of low infrared transmission.

infrared image are pipes.[11] It is not clear what influence these pipes have on the uniformity of the detector response. The pipe segments at y positions of 2.2 mm, -0.7 mm, and -1.2 mm appear to have little effect on the alpha-peak centroid. Respectively, these pipes are approximately 5.5 mm, 0 mm, and 8 mm deep into the crystal from the cathode surface. On the other hand, two pipes at the y position of -2 mm (2 and 3 mm deep into the crystal) are associated with regions of reduced centroid in the alpha response image. Induced charge signals (not shown) acquired at the alpha source location of x = 0.9 mm

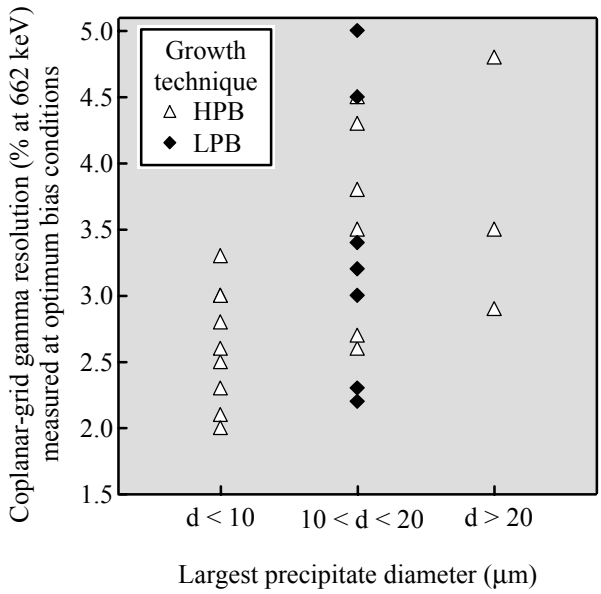


Figure 6. Measured coplanar-grid gamma-ray energy resolution at 662 keV plotted against the largest precipitate size observed to be distributed throughout the crystal used to make the detector. The precipitate sizes were determined through infrared transmission microscopy. The gamma-ray measurements were made at biases that gave the best energy resolution.

and y = -1.9 mm indicate that the reduced centroid is a result of a variable amount of electron trapping taking place at a depth in the crystal corresponding to the location of the pipes.

The infrared image of HPB 2 indicates that, unlike HPB 1, HPB 2 contains numerous defects approximately 20 - 30 μm in diameter dispersed throughout the crystal. These objects are most likely the often-identified Te precipitates or inclusions found in CdZnTe materials.[11] The data of Figure 5c indicate that there is a reasonably good correlation between the precipitate locations and reduced centroid of the alpha peak. It is not clear if the precipitates themselves are responsible for the degradation or if their presence is just correlated with other material defects that affect the detector signal. However, we can conclude that the degradation effects are correlated with the location of the precipitates and the effects extend beyond the physical volume occupied by the precipitate. To see this, realize that the alpha-particle probe beam is approximately 300 μm in diameter while the diameter of one of the larger precipitates is only 30 μm. If even several of these precipitates are contained within the alpha beam, the fraction of the beam area occupied by precipitates will still be less than 10 %. We see from an inspection of the scan data that the reduced centroid is due to a large fraction of the counts being shifted to lower energies. This indicates that a large fraction of the alpha events is affected. Therefore, the degraded region of the crystal must be larger than the cross-sectional area of the precipitates themselves. Another interesting observation is that the centroid image of HPB 2 correlates well with the infrared image when the infrared camera focus is set near the cathode surface of the crystal. The image obtained with the focus set near the anode (not shown) does not correlate well. In other words, the alpha scan correlates with the lateral precipitate distribution near the surface of the crystal where the alpha particles enter the crystal. This was also observed in the scan of a separate HPB crystal that also contained 20 - 30 μm diameter precipitates.

Precipitates are also present in HPB 1 as determined through infrared images. However, these precipitates are 10 μm or smaller in size and were too small to be identified in the processed image of Figure 4c. Many of these precipitates form string patterns in this crystal. A clear set of these strings are present near the cathode of the crystal and run nearly vertically along the right side of the scanned area (between x = 1.2 mm and 2.5 mm). This roughly corresponds to the slightly reduced centroid regions along the right side of the alpha response image of Figure 4c. This effect is however small compared to that observed in HPB 2.

Further evidence linking precipitates in HPB material to gamma-ray detector performance is given in Figure 6. Here we have categorized the crystals based on the largest size of precipitates found distributed throughout the crystal volume. We then

plotted as a function of this precipitate size the gamma-ray energy resolution obtained with the crystals as coplanar-grid detectors. The three crystals with large precipitates shown in the figure all have relatively poor gamma-ray responses. Even the best of these with a resolution of 2.9 % FWHM is not as good as the resolution implies since the full-energy peak contains some low-energy tailing. We have processed several other HPB crystals with such large precipitates. These crystals all have shown signs of performance problems during planar detector testing and were therefore not tested as coplanar-grid detectors. At the other extreme, the HPB crystals with the best gamma-ray detector responses are all free from distributed precipitates larger than about 10 μm in size.

At this point in our study, we are not able to definitely conclude that distributions of large precipitates in HPB material cause the degraded gamma-ray detector performance. There is only an observed correlation between the presence of such precipitates and a loss of electron generation or transport uniformity that then leads to a degraded gamma-ray response. The mechanism causing the reduced uniformity also remains to be determined. The likely possibilities include a reduction in the charge generation or enhanced electron trapping in the vicinity of a precipitate. These and other issues are being addressed by material studies that we are presently pursuing.

5. SUMMARY

The successful application of simple electron-only devices for high-resolution spectroscopy requires detector material that is highly uniform in both electron generation and transport. Our measurements illustrate that the variations of concern in CdZnTe material can be at the 1% level. Consequently, any useful characterization and analysis technique must be sensitive down to this level. We have shown that alpha-particle response measurements are capable of directly characterizing electron generation and transport uniformity at the accuracy required for this application. In this paper, we have demonstrated the validity of the alpha-response technique in the characterization of HPB (eV Products) and LPB (Yinnel Tech) CdZnTe material through a series of measurements. Both contact thickness measurements and a comparison of the signals generated by gamma-ray events to those of the alpha-particle events indicate that there are no anomalous contact electrode dead layers or near-contact effects present that would interfere with the alpha characterization. Furthermore, alpha-particle scans made of a crystal before and after the refabrication of the scanned cathode exhibit the same features. This then indicates that the alpha-particle response is indeed a probe of the bulk properties of the material rather than that of the electrical contact property variations. Another critical attribute of any useful characterization technique is that its results actually relate to the performance of the intended device. Such a relationship has been demonstrated for the alpha-particle technique through a direct correlation of the coplanar-grid gamma-ray performances of a large set of CdZnTe crystals to the alpha responses of these same crystals.

Through alpha-particle scanning combined with pulse-height and induced-charge-signal analyses, we have made detailed studies of the nonuniformities present in CdZnTe crystals free from random grain boundaries. From these and other studies, it is clear that multiple mechanisms play roles in the degradation of the gamma-ray performance of such crystals. One of our goals has been to determine which of these is dominant in limiting the performance of large-volume gamma-ray detectors. For some crystals, we have observed a clear correlation between nonuniformities in electron generation and transport, and the distribution of large precipitates in the crystals. These nonuniformities are most likely the dominant source of gamma-ray performance degradation in these crystals. We have not determined at this point if the precipitates themselves actually cause the degraded crystal properties. However, from a geometry argument alone, we can conclude that the region of degraded performance near a precipitate extends beyond the volume of the precipitate itself. Further studies are ongoing to determine the mechanism for the observed response variations and the reason for the correlation.

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