



BNL-82184-2009-CP

***Internal electric-field-lines distribution in CdZnTe
detectors measured using X-ray mapping***

**A.E. Bolotnikov, G.S. Camarda, Y. Cui, A. Hossain, G. Yang,
H.W. Yao, R.B. James**

Presented at IEEE Dresden 2008
Dresden, Germany
October 19-25, 2008

October 2008

Nonproliferation and National Security Department

Brookhaven National Laboratory

P.O. Box 5000
Upton, NY 11973-5000
www.bnl.gov

Notice: This manuscript has been authored by employees of Brookhaven Science Associates, LLC under Contract No. DE-AC02-98CH10886 with the U.S. Department of Energy. The publisher by accepting the manuscript for publication acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes.

This preprint is intended for publication in a journal or proceedings. Since changes may be made before publication, it may not be cited or reproduced without the author's permission.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or any third party's use or the results of such use of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof or its contractors or subcontractors. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.



Internal electric-field-lines distribution in CdZnTe detectors measured using X-ray mapping

A. E. Bolotnikov, *Member, IEEE* G. S. Camarda, Y. Cui, , *Member, IEEE* A. Hossain, G. Yang, H. W. Yao, and R. B. James, *Fellow, IEEE*

Abstract—The ideal operation of CdZnTe devices entails having a uniformly distributed internal electric field. Such uniformity especially is critical for thick long-drift-length detectors, such as large-volume CPG and 3-D multi-pixel devices. Using a high-spatial resolution X-ray mapping technique, we investigated the distribution of the electric field in real devices. Our measurements demonstrate that in thin detectors, <5 mm, the electric field-lines tend to bend away from the side surfaces (i.e., a focusing effect). In thick detectors, >1 cm, with a large aspect ratio (thickness-to-width ratio), we observed two effects: the electric field lines bending away from or towards the side surfaces, which we called, respectively, the focusing field-line distribution and the defocusing field-line distribution. In addition to these large-scale variations, the field-line distributions were locally perturbed by the presence of extended defects and residual strains existing inside the crystals. We present our data clearly demonstrating the non-uniformity of the internal electric field.

Index Terms—CdZnTe, radiation detectors, crystal defects

INTRODUCTION

RECENTLY, we employed a highly collimated x-ray beam [1] to study spatial variations of the responses of CdZnTe (CZT) detectors with micron-scale resolution. The x-ray mapping system we developed for such measurements allowed us to investigate the effects of different types of microscopic defects on their performance (see the most recent publication in Ref. [2]). The system also gave us the opportunity to map the electric-

field line distribution in CZT devices that we report in this paper.

The ability to maintain a desired electric field inside a CZT device is important for assuring its expected performance and functionalities. If the actual distribution of the field lines differs from the anticipated one based on the electrodes' configuration, then the charges generated by incident particles might be driven towards wrong electrodes, or become trapped in "dead" regions, e.g., near the side surfaces.

We can represent a typical CZT detector as a rectangular crystal block with contacts deposited on two opposite facets. The cathode usually is a monolithic contact that covers the entire area of the facet, while the anode may have one of the patterns that identify a particular type of device: pixel, coplanar grid, or strip. A constant lateral electric field is expected to ensure uniform efficiency in charge collection over the entire device's area down to the very edges. However, when a CZT detector (considered as metal-semiconductor-metal structure with two back-to-back Schottky barriers) is biased, a space charge is formed between the anode and cathode due to the charging/ionization of deep levels, which may create a non-uniform distribution. This modifies the electric-field distribution on a large scale, and may introduce significant local variations. Because of the space charge, the electric field is expected to be changing in the z-direction, as in any other depleted semiconductor.

There are limited experimental data on this subject [3]. The Pockels electro-optic effect (PE) was employed to investigate the

Manuscript received June 29, 2008. This work was supported by U.S. Department of Energy, Office of Nonproliferation Research and Development, NA-22. The manuscript has been authored by Brookhaven Science Associates, LLC under Contract No. DE-AC02-98CH1-886 with the U.S. Department of Energy.

A. E. Bolotnikov, G. S. Camarda, Y. Cui, A. Hossain, G. Yang, H. W. Yao, and R. B. James are with Brookhaven National Laboratory, Upton, NY 11793 USA (phone: 631-344-8014; e-mail: bolotnik@bnl.gov).

distribution of the internal electric field within CZT radiation detectors [4-9]. Utilizing the slight birefringent optical property of a CZT crystal under bias, the Pockels effect showed that most such distributions in CZT detectors were non-uniform, and were related to crystal defects and grain boundaries [5]. Based on the PE data, an energy band model was proposed to describe the internal electric-field distributions in CZT detectors [6]. However, many more investigations are needed to understand the internal E-field distributions in relation to the CZT detector's performance, its crystal defects and fabrication procedures. Several groups [5,9] reported that the electric-field strength in CZT detectors is highest near the cathode and decreases towards the anode side, consistent with the accumulation of the positive ions. In contrast, CdTe detectors apparently exhibit an opposite behavior: electric-field strength increases towards the anode [10]. The formation of the positive space charge in CZT detectors was found to be consistent with the analysis of I - V curves measured for 2-mm thin planar detectors with a small geometrical-aspect ratio (thickness-to-width ratio) [11]. By fitting the I - V curves, the concentration of the positive ions was estimated as $\sim 10^{10} \text{ cm}^{-3}$, while the concentration of the free carriers in high-resistivity CZT material is only $\sim 10^5 \text{ cm}^{-3}$. As an example, at such space-charge densities, the reduction of the electric field is expected to be $\sim 15\%$ in a 2-mm thick detector biased at 200 V. In CZT detectors with large aspect ratios, >1 , it is very likely that the variations of the electric field may not be described by a simple linear function because of the possibility of non-uniform accumulation of space charge.

The electric-field strength also can vary laterally, especially inside the devices with large aspect ratios. The conditions near the edges can differ from those in central regions of the device, causing poor charge-collection near the device's edges, called the edge effect. For peripheral events the charge-collection efficiency may be impaired because of the proximity of the side surfaces where the drift velocity is smaller than in the bulk, and the concentration of traps higher. To avoid this effect, the vector of the electric field near the side surfaces should point away from them. In other words, on a large scale, the electric field should be slightly "focusing" in

the direction towards the anode to provide high collection efficiency near the side surfaces. Theoretically, such conditions should naturally exist inside CZT crystals with positive space charge [12]. Indeed, the electric-field distribution is determined by the boundary conditions i.e., the electrostatic potential distribution on the device's side surfaces, which, in turn, are determined by the surface conductivity. If the surface potential decreases between the cathode and the anode faster than the potential along the device's axis, a "defocusing" field is generated inside the device thereby diminishing the detector's performance. In the opposite case, a "focusing" drift-field will form inside the device that steers the electrons toward the anode. Because of the high surface conductivity, the surface potential is almost independent of the bulk and changes linearly between the cathode and anode levels. At the same time, the bulk potential decreases as a sub-linear function due to the presence of the positive space-charge. Thus, theoretically, these two effects inevitably should produce a "focusing" field that is more favorable for the CZT detectors. However, in practice, the distribution of the electric field is not always as predicted, based on the above considerations.

Using a highly collimated x-ray beam, available at BNL's NSLS, we routinely characterize the responses of CZT devices of different configurations. Although the main goal of these measurements is to study the influence of the crystal defects on charge-transport properties, we can also map the distribution of the electric-field lines and their local variations. In this paper, we present the results from such mapping that we carried on two CZT pixel detectors, one thin and one thick. Our goal is to emphasize the surprisingly strong discrepancies between the expected and actual field-line distributions in high-quality commercial CZT detectors.

Experimental

The details of the high-spatial resolution x-ray mapping system used in these studies are described elsewhere [2]. Briefly, we employed a monochromatic (10-30) keV x-ray beam with a spot size of less than $25 \times 25 \mu\text{m}^2$ to generate free carriers and study charge transport in CZT samples. For each position of the beam, a pulse-height spectrum was collected and evaluated to locate a central gravity of the peak, which is

proportional to the fraction of the collected charge originally generated near the cathode. These values, plotted as a 2D map, represent the device's response. This system allows us to carry out a variety of measurements, including mapping the distributions of the electric field lines in different types of CZT detectors. Here, we discuss the line maps obtained from two commercial $1 \times 1 \times 1 \text{ cm}^3$ 4×4 pixel detectors (D1 and D2) that are representative of two limiting cases of the CZT device's behaviors. The pixel contacts were interconnected together in a way to form two electrodes somewhat resembling a chessboard (Fig. 1). In our discussion, we will call them black and white contacts. The charge signals, generated by the x-ray beam pointed in a particular location of the

cathode surface, were read out using only one electrode while the second one was grounded. In the ideal case of a uniform electric-field distribution inside a crystal, a raster scan over the entire area of the device would generate a response map with a pattern identical to those of the electrode used to read the signals. A distorted pattern measured from a real device would signify the deviation of the actual electric-field distribution from uniformity. A standard eV Products preamplifier was used to read the signals, which were further shaped and amplified with a standard research amplifier. During the measurements, we applied a negative 1000 V bias to the detectors' cathodes.

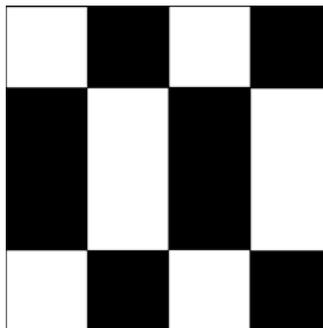


Fig. 1. Electrode patterns (black and white) formed by interconnecting individual pixel contacts.

Results and discussion

Fig. 2 (a-d) shows the response maps measured for the detector D1: (a) The black contacts are grounded, (b) the same as (a) but after applying a filter to highlight the pixels' boundaries, (c) all pixels are connected to form a monolithic contact used to read signals, and, (d) the same as (c) but after filtering to highlight the local variations in the detector's response caused by Te inclusions and twin boundaries. The dark colors represent the areas where weak signals were detected. Note, that when the grounded electrode collects electrons from the electron cloud, small signals still are induced by the electrons trapped in the bulk. The light colors represent strong signals

induced by the electrons collected by the electrode used to read the signals (except for small regions corresponding to the crystal's defects). To see more clearly the deviations of the actual electric-field distribution from uniformity, we have overlaid a grid indicating the geometrical boundaries of the actual pixels. We note that crystal defects, such as inclusions and twin boundaries, also appear as dark areas. For example, a twin boundary is located in the crystal's upper left corner. The electric field, distorted by this boundary, steers electrons to the side surfaces where they become trapped. The individual inclusions are dispersed everywhere within the crystal. Also, there is a network of inclusions (or dislocations) near the upper edge of the crystal.

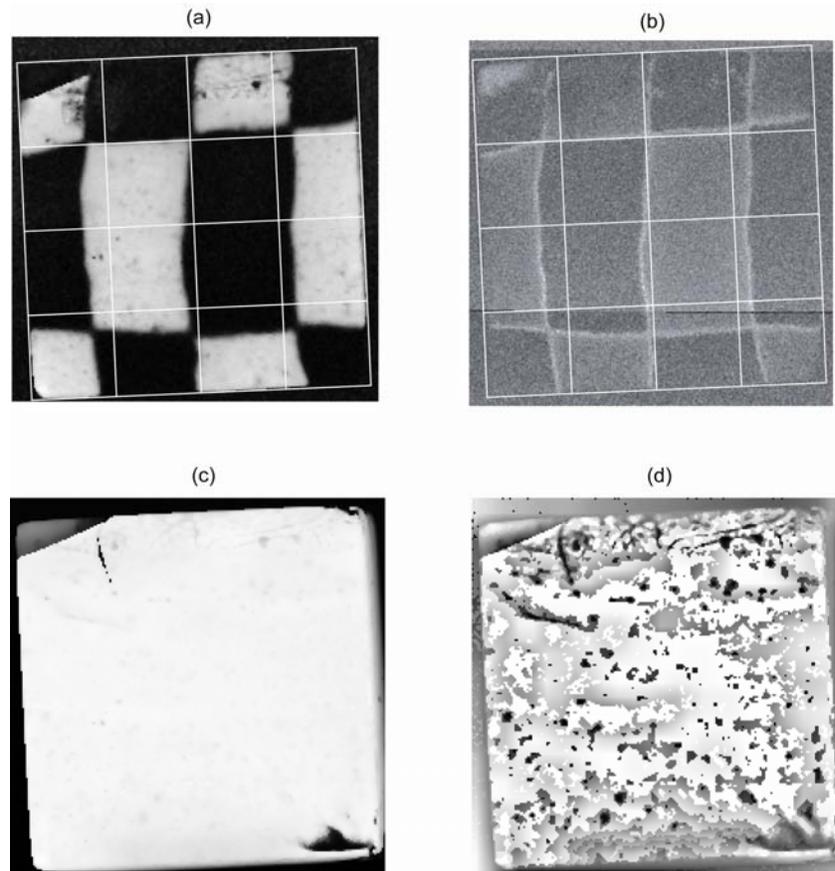


Fig. 2. Response maps acquired for detector D1: (a) Black pixels are grounded, (b) same as (a) but after applying a filter to highlight the pixels' boundaries, (c) all pixels are connected to form a single contact used to read signals, and, (d) same as (c) but after filtering to highlight the areas with defects (inclusions and twin boundaries). The grids represent the geometrical locations of the pixel contacts. The step size is $50\ \mu\text{m}$, and the total scan area is $\sim 12 \times 12\ \text{mm}^2$.

Comparing the apparent footprints of pixels and actual pixel clearly reveals that the electric field inside the thick CZT crystals is far from uniform. Fig. 2(a) shows that the apparent footprints of the pixels adjacent to the crystal's edges are notably smaller than their actual sizes. On the other hand, the apparent footprints of four central pixels stretch beyond their actual boundaries, while their internal boundaries are correctly located in the middle of the detector. Such patterns indicate that electron clouds originating at the cathode drift some distances laterally towards the center of the device before arriving at the anode. In other words, detector D1 has a "focusing" electric field, causing electrons drift along the

pathways schematically shown in Fig. 3(a). (The electron trajectories in Fig. 3 (a,b) were calculated based an exact solution of the Dirichlet problem in a 2D case.) The apparent locations of the contacts are shown on the cathode side are obtained by the backward projecting of the actual contacts along the electron trajectories. The "focusing" electric field is expected if the electrostatic potential in the bulk of the crystal changes faster (from the cathode and anode) than the potential along its side surfaces. This can occur when there is a positive space-charge in the sample. Because of the "focusing" field, the detector D1 shows good response from the entire area of the crystal down to its very edges, as illustrated in Fig. 2(c).

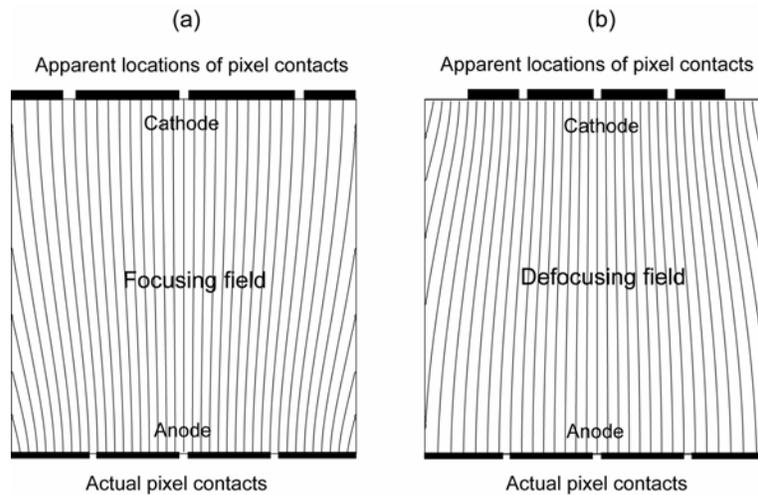


Fig. 3. Electron trajectories modeled for a CZT sample, 1-mm thick by 1-mm wide with an infinite third direction, illustrating the “focusing” (a), and “defocusing” (b) fields in the detectors D1 and D2, respectively.

Fig. 4 are response maps similar to those shown in Fig. 2 but measured for the detector D2: (a) Black contacts are grounded, (b) white contacts are grounded, (c) all pixels are connected together as a single contact to read signals, and, (d) same as (c) but after filtering to highlight local variations in the detector’s response. The detector D2 represents a

“defocusing” electric field, for which the field lines are bent towards the side surfaces of the crystal (Fig. 3(b)). The apparent pixels near the edges, in Figs. 4(a) and (b), are significantly smaller than their actual sizes.

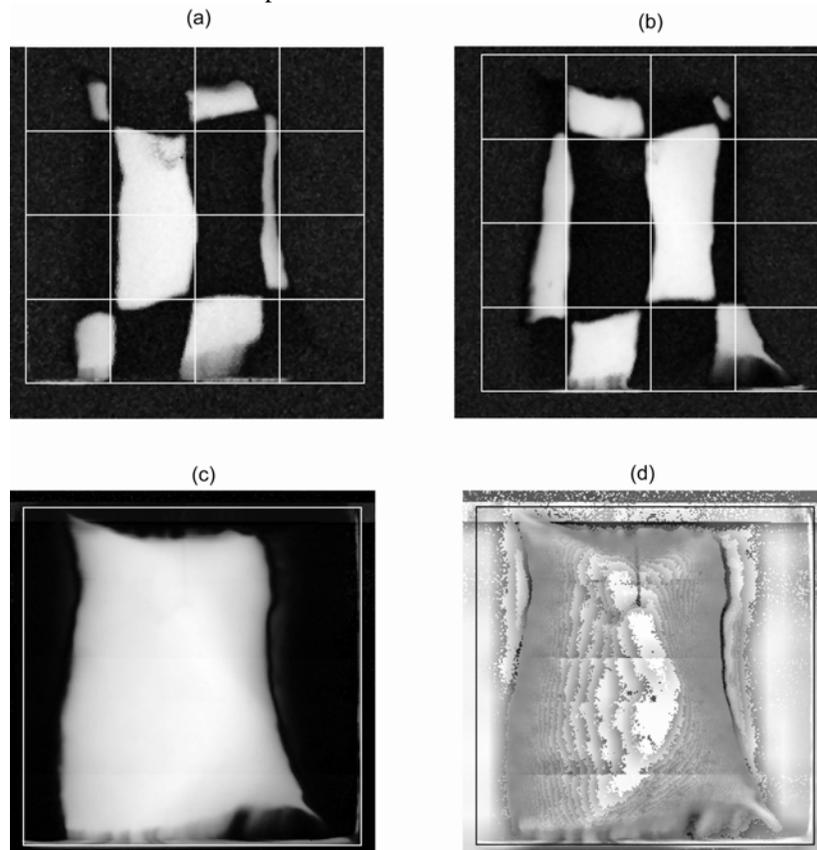


Fig. 4. Response maps measured for the detector D2: (a) Black pixels are grounded, (b) white pixels are grounded, (c) all pixels are connected together and used to read signals, and, (d) same as (c) but after filtering to highlight the extended defects. The grids represent geometrical locations of the contacts on the anode side. Spatial resolution is $50\ \mu\text{m}$, and the total scan area $\sim 12 \times 12\ \text{mm}^2$.

In fact, the field lines are so strongly bent that some of the edge pixels do not collect any charges, while some central pixels have reduced footprints. This is because all the electrons generated at the cathode above these pixels are driven to the side surface, where they become trapped. In other words, this detector D2 suffers from the edge effect caused by the “defocusing” electric field distribution inside the crystal. Following the same considerations we applied to the previous case, one can conclude that the detector D2 has negative space charge. Clearly, a “defocusing” electric field causes an undesirable charge loss near the device’s edges in thick CZT detectors. As discussed in the introduction, to avoid this edge effect the electrostatic potential on the side surfaces

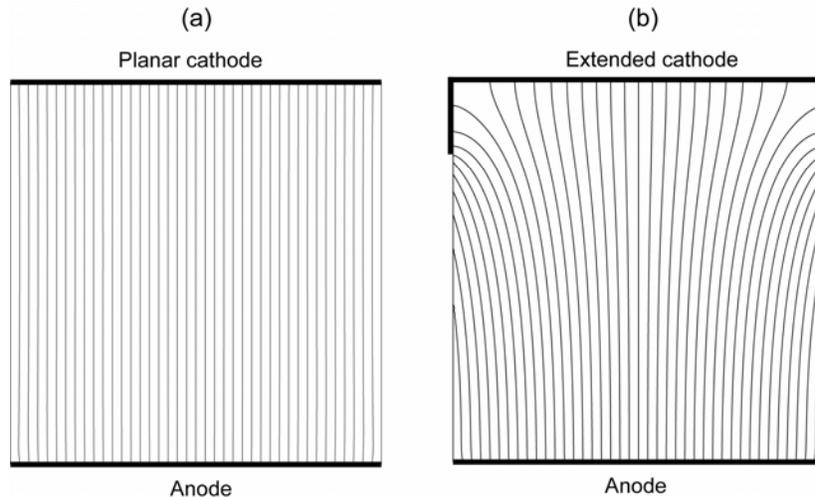


Fig. 5. Comparison between the electron trajectories calculated in a 2D approximation for a detector, 1-cm thick by 1-cm wide with an infinite third direction, with two cathode geometries: (a) Conventional, and, (b) with the extended cathode. A linearly changing potential on the side surfaces and no space-charge accumulation were assumed. The cathode extends 2 mm along the side surfaces.

So far, we discussed two possible cases of the global distribution of the electric-field lines inside CZT crystals, illustrated in Figs. 2 and 4. These same figures also indicate local variations of the electric field that can be seen in the response maps as wavy boundaries and chipped pixels. We attribute some of these variations to the inclusions and twins that are clearly apparent in the filtered response map (d) of detector D1. However, there are no defects seen for the detector D2, even though the maps were generated with higher resolution, in 25 μm steps. Also, the typical size of the local field variations is notably larger than the average size of the inclusions. From these findings, we conclude that certain material (bulk and surface) defects do not trap charge but affect the local electric field. The most reasonable candidates for such defects could be strains in the crystals, and associated with them, dislocations networks that locally accumulate the space charge.

Conclusion

A uniform electric field is especially critical for thick long-drift-length detectors, such as large-volume CPG and 3-D multi-pixel devices. It should be considered as a real factor degrading performance of CZT detectors. Using a high-spatial

resolution X-ray mapping technique, we investigated the distribution of the electric field in real devices. Our previous measurements demonstrate that in thin, <5 mm, CZT detectors, the electric field lines have a tendency to bend away from the side surfaces (the focusing effect). However, in thick detectors, >10 mm, the distribution of field lines depends on the polarity and distribution of the space charge accumulated inside the biased device, and on the electronic properties of the side surfaces that define the boundary conditions for the electrostatic potential. If the potential on the side surface decreases (in absolute values) more slowly than in the bulk, a “focusing” electric field is expected. In the opposite case, the field will be a “defocusing” one that engenders a loss in collection charge near the edges.

should change slower than that in the bulk. This can be achieved by slightly extending (by 2-3 mm) the cathode electrode on the side surfaces, as in the CAPture device [13,14]. To illustrate the idea, Fig. 5 compares the electron trajectories, which coincide with electric field lines when no space charge taken into account (for simplicity), calculated in a 2D approximation for a detector, 1-cm thick by 1-cm wide and an infinite third direction, with two cathode geometries: (a) Conventional, and, (b) with an extended cathode. In both cases, we assumed that the potential on the side surfaces changes linearly from the cathode voltage down to zero, and no space charge accumulates in the bulk.

We also found local parturiciencies in the electric field that could be related to the presence of extended defects and the residual strains existing inside the crystals. However, more measurements are needed to prove.

REFERENCES

- [1] G. A. Carini, A. E. Bolotnikov, G. S. Camarda, G. W. Wright, L. Li, and R. B. James, “Effect of Te precipitates on the performance of CdZnTe detectors”, *Appl. Phys. Lett.* 88, p. 143515, 2006.

- [2] G. S. Camarda, A. E. Bolotnikov, Y. Cui, A. Hossain, S. A. Awadalla, J. Mackenzie, H. Chen, and R. B. James, "Polarization Studies of CdZnTe Detectors using Synchrotron X-ray Radiation", submitted to IEEE Trans. Nucl. Sci., 2008.
- [3] James L. Matteson, Wayne Coburn, Fred Duttweiler, William A. Heindl, George L. Huszar, Philippe C. Leblanc, Michael R. Pelling, Laurence E. Peterson, Richard E. Rothschild, and Robert T. Skelton, "CdZnTe arrays for astrophysics applications", *Hard X-Ray and Gamma-Ray Detector Physics, Optics, and Applications*, edited by Richard B. Hoover, F. P. Doty, Proceedings of SPIE Vol. 3115, pp. 160-175, 1997.
- [4] R. Guenther, "Modern Optics", John Wiley & Sons, Inc. pp 569-590, 1990.
- [5] H. W. Yao, R. B. James, E. Y. Lee, R. W. Olsen, H. Hermon, and R. J. Anderson, "Optical Studies of the Internal Electric Field Distributions, Crystal Defects and Detector Performance of CdZnTe Radiation Detectors", SPIE Proceedings, 3446, pp. 169-178, 1998.
- [6] H. W. Yao, R. J. Anderson, and R. B. James, "Optical Characterization of the Internal Electric Field Distribution under Bias of CdZnTe Radiation Detectors", SPIE Proceedings, 3115, pp 62-68, 1997.
- [7] H. W. Yao, R. J. Anderson, R. B. James, and R. W. Olsen, Mater. "Optical Studies of the Internal Electric Field Distributions of CdZnTe Detectors Under Bias Conditions", Res. Soc. Symp. Proc. 487, pp 51-57, 1998.
- [8] H. W. Yao, R. B. James, and E. C. Erickson, "Optical Engineering and Characterization of the Internal Electric Field of CdZnTe Radiation Detectors", SPIE Proceedings 3768, pp. 330-338, 1999.
- [9] M. A. Hossain, E. J. Morton, and M. E. Özsan, "Photo-Electronic Investigation of CdZnTe Spectral Detectors", IEEE Trans. Nucl. Sci., V. 49, No. 4, pp. 1960-1964, 2002.
- [10] A. Cola, I. Farella, A. M. Mancini, and A. Donati, "Electric Field Properties of CdTe Nuclear Detectors", IEEE Trans. Nucl. Sci., V. 54, pp. 868-872, 2007.
- [11] A. E. Bolotnikov, S. E. Boggs, C. M. Hubert Chen, W. R. Cook, F. A. Harrison, and S. M. Schindler, "Properties of Pt Schottky Type Contacts On High-Resistivity CdZnTe Detectors", *Nucl. Instr. Meth.*, A482, pp. 395-407, 2002.
- [12] A. E. Bolotnikov, N. M. Abdul-Jabbar, S. Babalola, G. S. Camarda, Y. Cui, A. Hossain, E. Jackson, H. Jackson, J. R. James, A. L. Luryi, and R. B. James, "Optimization of virtual Frisch-grid CdZnTe detector designs for imaging and spectroscopy of gamma rays", Proceedings of SPIE Conference on Hard X-Ray and Gamma-Ray Detector Physics IX, Vol. 6706, edited by R. B. James, A. Burger, L. A. Franks, San Diego, CA, pp. 670603-1-13.
- [13] K. Parnham, C. Szeles, K. G. Lynn, R. Tjossem, "Performance Improvement of CdZnTe Detectors Using Modified Two-Terminal Electrode Geometry," in *Hard X-ray, Gamma-Ray and Neutron Detector Physics*, Proceedings of SPIE, Vol. 3786, pp. 49-54, 1999.
- [14] C. Szeles, D. Bale, J. Grosholz, Jr., G. L. Smith, M. Blostein, and J. Eger, "Fabrication of High Performance CdZnTe Quasi-Hemispherical Gamma-ray CAPTURE™ Plus Detectors", in *Hard X-Ray and Gamma-Ray Detector Physics VIII*, edited by Larry A. Franks, Arnold Burger, and Ralph B. James, Proceedings of SPIE Vol. 6319, pp. 63190B-1 - 63190B-1, 2006.