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Low-Cost Cadmium Zinc Telluride Radiation Detectors Based on Electron-Transport-Only Designs

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Low-Cost Cadmium Zinc Telluride Radiation Detectors Based on Electron-Transport-Only Designs

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Abstract

The goal of this project was to utilize a novel device design to build a compact, high resolution, room temperature operated semiconductor gamma ray sensor. This sensor was constructed from a cadmium zinc telluride (CZT) crystal. It was able to both detect total radiation intensity and perform spectroscopy on the detected radiation. CZT detectors produced today have excellent electron charge carrier collection, but suffer from poor hole collection. For conventional gamma-ray spectrometers, both the electrons and holes must be collected with high efficiency to preserve energy resolution. The requirement to collect the hole carriers, which have relatively low lifetimes, limits the efficiency and performance of existing experimental devices. By implementing novel device designs such that the devices rely only on the electron signal for energy information, the sensitivity of the sensors for detecting radiation can be increased substantially. In this report we describe a project to develop a new type of "electron-only" CZT detector. We report on our successful efforts to design, implement and test these new radiation detectors. In addition to the design and construction of the sensors we also report- in considerable detail- on the electrical characteristics of the CZT crystals used to make our detectors.

Acknowledgment

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Preface

Semiconductor detectors have long been used as γ -ray and x-ray spectrometers. The detector materials that provide the best efficiency and energy resolution require cryogenic cooling for their operation. This places considerable constraints on the application of these materials for field portable and long term monitoring systems. In the last few years several semiconductor materials have emerged that allow room-temperature operation which relax the constraints imposed by cooling requirements. Unfortunately, these materials are not yet mature and still have significant shortcomings such as poor carrier transport properties, low yield, and non-uniformity. These factors limit both the maximum volume that can be utilized as a spectrometer, which limits the efficiency of the overall spectroscopic system, and the maximum energy resolution achievable with systems based on these materials.

One of the most promising of the room-temperature semiconductor detectors is Cadmium Zinc Telluride (CZT). This material has a high average atomic number and high resistivity. These properties give this material good radiation absorption characteristics and low leakage currents which are favorable for low noise/high energy resolution applications. The most significant drawback of CZT is the insufficient supply of high quality crystals for spectroscopic systems. This circumstance results from both uniformity issues and carrier transport properties. Even the best material available exhibits diminished hole collection characteristics which reduces the effective volume of the device to a few percent of the physical volume.

Several novel designs have been introduced over the past few years that rely on the acceptable electron charge collection properties and block the hole contribution. These designs, known as single carrier devices, allow the utilization of lower quality material, although the material must still be uniform, to achieve both improved energy resolution and higher efficiency. The theory and application of these devices will be reviewed in this paper along with some guidelines for the selection of a particular design. The material uniformity issues will also be discussed along with a discussion of a material screening capability that has been developed.

Summary

The goal of this project was to develop a new type of gamma ray spectrometer based on cadmium zinc telluride (CZT). Our intention was to use a new design of CZT detector, which we called a lateral unipolar device, as the design for the improved detector. We succeeded in achieving our overall goal and demonstrated a detector with exceptional energy resolution for energetic photons (> 200 keV). Progress in the project was limited however, by our inability to reliably fabricate the unipolar devices. Part of our poor fabrication record could be attributed to our fabrication facilities being constructed during the time period of this development program (our CZT fabrication facilities here at Sandia/CA are only now becoming fully operational). Another component to our fabrication problems was the limited state of CZT fabrication technology in general. CZT is not silicon and every aspect of device fabrication requires a small development effort in and of itself; there are few if any standard fabrication procedures with CZT. Our intention on the project had been to focus on design, but in practice a great deal of time was spent attempting to fabricate devices and on selecting and characterizing CZT material for eventual device use. Despite these problems, we remain very optimistic that the concepts embodied in our unipolar device design will improve the state of the art in room-temperature gamma-ray detectors. Much work remains to be done before the unipolar concept can be employed commercially, but it is now clear what that work should be. Future efforts utilizing this device concept (or ones similar to it) should focus on devices built from single crystal material. In our view, single crystal material is hard to come by and not representative of the bulk of commercial material, but single crystal material is a far more efficient platform for testing unipolar device concepts. It can be very difficult to unfold design issues when the material is heterogeneous.

Nomenclature

ADC	analog to digital converter
CAMAC	computer automated measurement and control
CZT	cadmium zinc telluride
FWHM	full width half maximum
MCA	multi channel analyzer
NIM	nuclear instrumentation module
PHS	pulse height spectrum

Low-Cost Cadmium Zinc Telluride Radiation Detectors Based on Electron-Transport-Only Designs

I Introduction

This report is divided into three main sections: Device Design, Materials, and Experimental Results. In the Device Design section immediately following this introduction, we review the design of conventional planar semiconductor radiation detectors, review the modern electrostatic theory for analyzing these devices (the “weighting potential” concept), and finally we discuss the operating principle of the new device we designed and how it compares with other modern unipolar device designs. Next, in the Materials section of this report, we discuss the necessary electrical characteristics the CZT crystals must satisfy, and back up our assertions with some computer simulations of anticipated device response for particular starting material characteristics. Finally, in the Experimental Results section, we report on our measurements of the electrical characteristics of CZT crystals and report on the performance of the devices we fabricated as radiation detectors.

II Device Design

II.A Background

II.A.1 Ideal Planar Device Operation

A brief review of the operation of an ideal semiconductor detector will clarify the proceeding sections. In this section we will consider a detector with infinite carrier transport properties and resistivity. The simplest detector configuration is a planar device of thickness d , with electrical contacts on opposite faces of the crystal as shown in Figure 1. A DC bias is applied to the detec-

Figure 1: Diagrammatic representation of the operation of a planar semiconductor radiation detector. The transport of electrons and holes arising from a single photon interaction are shown.

tor producing a constant electric field within the crystal. When a photon interacts within the crystal, the number of charge carriers generated (electrons + holes) is proportion to the energy of the incident photon. These charge carriers then separate and drift, by the electric field, inducing charge on each of the contacts. It is important to remember that the charge induced on the contacts is a result of the motion of the carriers through the potential. If an electron moves through a potential difference ΔV , a charge of $-q\Delta V/V_{bias}$ will be induced on the contacts (where q is the ele-

mentary charge). Thus if an electron originates at the position $x = d$ (at the cathode) and drifts across the entire device to the anode, $\Delta V = V_{\text{bias}}$ and the entire charge on the electron will be induced on the contact. If, on the other hand, the electron was produced halfway through the device at $x = d/2$ it would only fall through 1/2 of the total potential on the device and induce half as much charge on the contact. Note that in this latter example the electron makes it to the anode yet a charge of only $-q/2$ was collected. Continuing with the last example of charge created midway through the device, if an electron and hole were generated at $d/2$ the hole would travel towards the cathode. The hole would induce a charge of $+q(-\Delta V/V_{\text{bias}}) = -q/2$ on the anode. Thus the motion of the electron and the hole from a position midway through the device leads to the seemingly trivial result that the total charge induced on the anode is equal to the elementary charge q . Continuing with this type of analysis we see that as long as both charges make it to the contacts the total charge induced on the anode is always $-q$. Another way of stating this result is to say that the “charge induction map” for the ideal detector is a constant (equal to unity); no matter where in the device we introduce an electron-hole pair we always induce a charge $-q$ on the anode. It is well known that the number of electron-hole pairs produced by ionizing radiation in a semiconductor is linearly proportional to the energy deposited by the radiation. Thus the ideal planar detector is potentially an excellent spectrometer: The charge induced on the contact (and measured with a charge sensitive preamplifier) is proportional to the energy deposited by the radiation and independent of the position of interaction in the crystal. Unfortunately, detectors constructed from wide bandgap semiconductors do not behave ideally. The electrons and holes generated in real semiconductor crystals often do not drift all the way to the anode or cathode. The transport properties of the holes is often much lower than the transport properties for electrons. The difference in transport properties gives rise to the effect known as hole tailing which will be discussed in the next section.

II.A.2 Hole tailing in planar devices

Hole tailing refers to a distribution of energies measured for a single photon energy that results in a “tail” in the measured pulse height spectrum. This distribution is the result of an interaction position dependence of the measured charge due to the incomplete collection of the holes.

Hole tailing will occur when the drift length of the holes (λ_h) is smaller than the physical device dimensions. If we assume that the electron drift length is greater than the device thickness d , (electrons always make it to the anode) then we can understand qualitatively how hole-tailing arises. If we revisit the example of the last section where an electron-hole pair is created at $x = d/2$, we see (as before) that the charge induced on the anode by electron motion $-q/2$. However, now that the hole is trapped it only induces a smaller charge $\sim -q\lambda_h/2d$ on the anode. Thus when holes are trapped the amount of charge induced on the anode depends on the position of interaction in the detector. The charge induction map is not constant. More quantitatively, the hole drift length may be written as,

$$\lambda_h = \frac{\mu_h \tau_h V}{d}, \quad (1)$$

where μ_h is the mobility, τ_h is the carrier lifetime, V is the detector bias, and d is the detector thickness. A similar equation can be written for the electron drift length. The charge collected as a function of position can be written as,

$$Q(x) = Q_0 \left[\frac{\lambda_e}{d} \left(1 - \exp\left(-\frac{d-x}{\lambda_e}\right) \right) + \frac{\lambda_h}{d} \left(1 - \exp\left(-\frac{x}{\lambda_h}\right) \right) \right], \quad (2)$$

where Q_0 is the total charge generated. The charge collected as a function of position for typical carrier transport properties in CZT is illustrated in **Figure 2** along with the resulting noise free pulse height spectrum. In this figure Γ is taken to be the point at which the amount of charge col-

Figure 2: Charge collection versus position in a planar semiconductor the detector (left), and corresponding noise free pulse height spectrum (right).

lection drops to 10% of the maximum and the origin of the x axis is located at the cathode.

The effects of hole tailing are twofold. First, the energy resolution of the resulting spectrometer is reduced due to the error introduced into the measured charge. It is often the case that the tailing is so severe that no spectroscopic capability is observed. The second effect of hole tailing is a reduction in the efficiency of the device, only a few percent of the physical volume of the detector near the cathode contributes to the counts observed in the photopeak.

II.A.3 Unipolar Devices

The difference between the electron and hole transport properties in CZT poses an interesting problem. The electron properties are adequate for spectroscopic applications but the hole transport properties limit the performance. If one could design a device that derived its charge induction primarily from the electron transport then large volume, high energy resolution spectrometers could be fabricated. This would allow the use of relatively inexpensive and available CZT material thereby making inexpensive CZT spectrometers possible. An approach that has proven successful is to design a detector such that the charge induction as a function of position is localized. Consider a hypothetical detector that is 1 cm^3 with the charge induction localized to 1 mm^3 in the center of the top face (anode). Assume that the detector is configured such that the electron drift length is a few cm and that the hole drift length is a few hundred microns. These conditions are easily achievable in currently available CZT material. The holes from any interaction outside this localized charge induction region will not contribute to the measured signal. Electrons created from interactions outside the localized region will travel toward the anode eventually traversing the "sweet spot" and give full contribution (ignoring trapping effects). This process is illustrated in **Figure 3**. Devices that operate in this manner are called unipolar devices because they only track one carrier type. The design of a unipolar device requires knowledge of the charge induction as a function of position within the detector. A useful construct that allows the designer to visual-

Figure 3: Illustration showing hole traversal with no contributed charge (a), electron traversal with no contributed charge (b), and electron traversal through localized region giving full charge induction (c).

ize and modify the charge induction map is the weighting potential. This concept will be discussed in greater detail in the next section.

II.A.4 The weighting potential concept

As discussed previously, the motion of a unit charge through a potential difference ΔV , will induce $q\Delta V/V_{\text{bias}}$ on the contacts. If one generates a non-constant electric field, such that the field or potential is concentrated near the anode, most of the induced charge will occur during the traversal of the high field region. Such a device would be more sensitive to electron contribution. If illuminated from the cathode, most interactions would occur outside the region of localized potential. The holes would drift a short distance but contribute little charge to the measured signal while electrons could traverse the crystal easily. Thereby traveling through the localized potential and contributing their complete charge. This configuration inhibits the contribution from the holes and removes most of the interaction position dependence observed in planar CZT spectrometers.

The next question is how to localize the potential to a small region near the anode. A brief review of some simple electrostatic field configurations will give a set of easily understood examples. Any introductory electrostatics book will give three examples that can be solved analytically, the infinite conducting plane, the infinite conducting wire and the point source. The field from an infinite plane is a constant and this gives rise to the linearly varying potential in a standard planar CZT configuration. We have already discussed this geometry and it is clear that interaction position dependence is a significant problem in these devices. The field from an infinite wire is inversely proportional to the distance from the wire which results in a potential that varies as the inverse natural log of the distance from the wire. A device of this geometry will have a localized potential near the anode and is a good step in the right direction. The field for the final example, the point source, varies as the inverse of the distance squared from the source. This results in a potential that is inversely proportional to the distance from the contact. This design gives the best localization.

The reader may have realized that simply creating a highly localized potential is not sufficient to create a high energy resolution spectrometer. A highly localized potential means that the field just a short distance from the anode drops to a very low value. Any carriers created in this region

will have a significantly lower velocity and thus their collection time will increase dramatically. This can manifest itself as carrier trapping for both electrons and holes which will again give a charge collection dependence on interaction position.

The introduction of a second isolated source of electric field can be used to increase the average field in the device while maintaining the localized potential on the collecting contact. This additional contact is often called the non-collecting or steering contact. With careful device design the fields within the detector can be engineered such that the carriers never encounter a region of low field while still localizing the weighting potential close to the anode. As an example consider a rectangular CZT crystal with a thin strip in the center. The resulting potential distribution from this contact is shown in **Figure 4**. This figure illustrates the highly localized potential near the

Figure 4: Visualization showing localized potential (left), and addition of non-collecting contacts to increase average field (right). This visualization was created by solving Laplace's equation for the two different boundary conditions using a finite element method.

anode. If an additional contact is added to the rest of the top face of the crystal the resulting potential distribution can be found by superposition and is also shown in **Figure 4**.

II.B Device Design Approaches

The overall goal of this research and development program was to develop a new type of unipolar radiation detector. The particular design we chose to use was called a "lateral contact device". Before we discuss the lateral contact device however, it is useful to review the properties of all other design approaches that have been mentioned in the literature. This review will allow us to compare and contrast the various design features of these new devices.

II.B.1 Coplanar Grid Device

The first unipolar semiconductor radiation detector is generally attributed to P. Luke at Lawrence Berkeley National Laboratory. Although other devices with asymmetrical weighting potentials predate Luke's design, his was the first successful high performance detector, and led to the accelerated interest in this approach. The Luke design, known as a "coplanar grid" is shown in **Figure 5**. The coplanar grid device is a three terminal device consisting of two anodes and a cathode. The two anodes are operated at different potentials to favor electron collection at the anode at highest potential. Electrons and holes induce a charge on both anodes over much of the volume of the device. However, as electrons enter the near field of the anodes they veer towards the higher potential anode leading to a distinctly different collected charge. By subtracting the sig-

nal from the low potential anode from the high potential anode the weighting potential can be effectively localized toward the anodes. The disadvantage of this design is that it requires two amplifiers read-out the strips. The two amplifiers add to system complexity, and increase the noise

Figure 5: Diagram showing a “Co-Planar Grid” design. One anode contact is given a slightly larger bias to cause preferential collection of electrons on one set of contacts. The device isolates the electron signal by subtracting the signals from the two anode connections.

added to the system. Since the noise from the two amplifiers is uncorrelated, it adds in quadrature resulting in an increase in system noise level. Despite this drawback, the Coplanar device is the most successful unipolar device developed to date.

II.B.2 McGregor “Etch Trench” Device

Another approach to unipolar device operation was first suggested by McGregor, now at the University of Michigan. McGregor’s device which he termed an “etch trench” design is conceptually very similar to the gridded gas tubes attributed to Frisch. The etched trench design makes use of a series of buried trenches inside a semiconductor crystal to shield the anode from moving charges between the grid and cathode (**Figure 6**). The trenches, which would be formed by etch-

Figure 6: Diagram showing the “Etched-Trench” device. This device can be categorized into two regions. The lower region is the interaction region in which ideally, all interactions would occur. The upper region, above the grid, is the sensing region. This device isolates the electron signal by sensing the motion of electrons between the grid and the anode.

ing channels in a semiconductor crystal would have an electrode material deposited at their base. In principle the operation of the Etch Trench device is identical to a Frisch Grid Gas detector. Electrons and holes produced by radiation interactions between the cathode and the grid (the majority of the volume of the device) would induce no charge on the anode until they had passed the grid. After passing the grid, electrons would then deposit their full charge in moving between the grid and the anode. In the parlance of electrostatic theory, the grid localizes the weighting potential of the anode to the region between the grid and anode. Of course, any interactions that occur between the grid and the anode would exhibit "hole tailing" effects just as in a planar detector. However, if the volume of the device between the grid and anode is a small fraction of the overall device volume, contributions from the grid anode region would be minimized.

To our knowledge the etch trench device has never been successfully demonstrated; devices have been constructed but they did not perform better than standard planar devices. There are two obvious drawbacks to the etch trench design. The first drawback is a practical one; the etch trench device is difficult to construct: it requires exotic fabrication procedures (etch trenching, and deposition at the base of the grid). Another major drawback of the etch trench device is theoretical in nature. From depictions of the device it would appear that many of the field lines from the cathode would terminate on the grid. Thus many of the electrons produced in the region between the grid and the cathode would terminate their trajectories on the grid without inducing any charge on the anode. The termination of electron trajectories would cause a serious reduction in the efficiency of the device. If we assume that there are no fixed charges in the bulk of the semiconductor, we can get an intuitive understanding of the efficiency problem from basic electrostatic theory. From electrostatics we know that all field lines originating at the cathode must terminate on the anode or on the grid (we'll assume that there are no other conductors close to the device). The efficiency at collecting charge at the anode must be approximately equal to the number of field lines terminating at the anode versus the total number of field lines emanating from the cathode. Using this line of reasoning, and Gauss's law of electrostatics we know that the number of field lines terminating on the grid is proportional to the mutual capacitance between the grid and cathode and the potential difference between them. Similarly, the number of field lines terminating on the grid is proportional to the mutual capacitance between the grid and the cathode and the potential difference between them. Thus in order to minimize the number of field lines terminating on the grid its area must be made very small; yet to provide effective shielding of the grid cathode region the density of strips must be high (the strip pitch must be much smaller than the grid cathode spacing). In gas detector parlance, an efficient grid is said to be "transparent" and is achieved by a density of very fine wires; such a topology would be exceedingly difficult to achieve with the etch trench approach. One improvement that might be made on the trench concept would be to simply cut very thin channels in a crystal (perhaps with a wire saw) and then apply the grid by flossing thin wires into the slits; such an arrangement might lead to an efficient design. However, a "trench" with any sizable width, with an evaporated contact at its nadir would be a very inefficient device.

In summary, the buried trench device invented by McGregor effectively localizes the weighting potential close to the anode by employing a grid as is used in gas detectors. Unfortunately the only achievable designs, from a practical device construction point of view, would be very inefficient because of electrons collected by the grid.

II.B.3 Lateral Contact Device

A variation of a gridded design was invented at Sandia/California to address the limitations inherent in the etch trench device. We have called this detector design a lateral contact device. A

depiction of this device is shown in **Figure 7**. Examination of **Figure 7** reveals that the device implements a grid by placing a contact on a surface of the device located laterally with respect to the anode. The primary advantage of this design over the etch trench design is that it is easier to con-

Figure 7: Diagram of the “Lateral Contact” device. This device can be categorized into two regions. The region below the grid is the interaction region and ideally, all interactions would occur in this region. The portion above the grid is the sensing region which actually measures the charge. This device isolates the electron signal by sensing the motion of the electrons between the grid and the anode.

struct. Thin strips of metal can be deposited on the lateral surface of the device using standard fabrication processes. Of course, the lateral contact device potentially suffers from the same drawback as the etch trench device in that the grid can become a major sink for electrons. However, applying a very thin lateral contact is easier with the lateral contact device. Another potential problem with the lateral contact device (and also present in the etch trench device) is the requirement for high quality semiconductor surfaces. The potential difference between the grid and anode should be as high as possible (again to minimize field lines terminating on the grid). Often the limitation in achieving this potential difference is controlled by leakage current or electrical breakdown on the surface of the device.

II.B.4 Small Pixel Devices

Perhaps the simplest class of unipolar detectors are the “small pixel” devices developed principally at the University of Arizona at Tucson. These devices rely on the fact that the weighting potential of a small electrode is very localized provided the electrode is surrounded by other electrodes. The simplest implementation of the small pixel device is an array of closely spaced rectangular anodes on side of a semiconductor slab with a contiguous single cathode on the other side of the slab. The small pixel design is capable of excellent performance, but can only be made efficient by reading out many pixels in parallel. While this approach is excellent for high resolution gamma ray imaging, it is a poor choice for gamma ray spectroscopy as the order of 100 channels of independent readout electronics per cm^2 of detector area are required.

A single element version of a small pixel device was recently developed commercially by Digirad of San Diego, CA. A diagram of a Digirad “Spectrum Plus” detector is shown in **Figure 8**. As **Figure 8** indicates the Digirad detector consists of a single circular anode surrounded by a “non collecting” electrode at a less positive potential than the anode. The principal

drawback of the Digirad approach would appear to be the poor efficiency of the device. It would seem that most of the field lines arising from the cathode in the Spectrum Plus device terminate on the non-collecting electrode. Sandia has recently purchased some of these devices but as of this

Figure 8: Diagram showing the small pixel device. The small area of the collecting contact with respect to the non-collecting contact localizes the weighting potential to an area very near the collecting contact. This causes the signal to be primarily derived from a small volume very near the collecting contact which gives rise to single-carrier operation.

writing no efficiency measurements have been performed with these devices.

II.C Development of a Performance Metric

II.C.1 Overview

Before an optimized radiation detector can be designed, it is necessary to quantify which performance characteristics of a detector should be optimized. In general, optimization would require a detailed knowledge of the specific application in which the detector would be used. This detailed knowledge would allow some optimum compromise to be made between various detector characteristics. For instance, a trade-off between sensitivity and operating power consumption might be required in one instance, whilst a trade-off between size and energy resolution might be required in another application. Thus, it is clearly impossible to optimize a detector for all possible applications and it is impossible to state- absolutely- which of the many performance characteristics of a detector should be maximized and which should be “traded off” in a particular detector design. However, it is also extremely difficult in any development effort, such as the one described here, to quantify progress without specifying some performance metric. Our solution to this parameter optimization dilemma was to search for two operating characteristics of the detector which were simultaneously of the most general importance yet were also the most “orthogonal”. By orthogonal we mean characteristics which tend to maximally trade-off. The two detector characteristics which most closely met these criteria were: the energy resolution and the active volume of the detector. It is well known that as the active volume of a room-temperature semiconductor detector grows, the energy resolution degrades. The active volume of the detector determines detector efficiency and the energy resolution of the detector determines the ability of the detector to separate gamma-rays from different radio-isotopes. Continuing with our metaphor from linear algebra, we can say that active volume and energy resolution- more than any other two parameters- span the space of radiation detector applications more effectively than any other

two parameters. Thus, our metric for performance was to obtain the best trade-off between energy resolution and active detector volume and compare our results with those obtained with conventional semiconductor radiation detectors. Before we begin evaluating various detector designs versus this performance metric we will define in more precise terms what we mean by “energy resolution” and “active volume”. The definition of these terms, and some of the ambiguities associated with them, are discussed in detail in the next two sections of this report.

II.C.2 Energy Resolution

In pulse height spectroscopy, the energy resolution of a detector is usually defined as the full width at half maximum (FWHM) of a gamma-ray photo-peak. The photo-peak (or full energy peak in the case of multiple Compton interactions) is intrinsically much narrower (< 1 eV) than our detector energy resolution could ever possibly be. Thus, the width of a radioisotopic gamma line- particularly an isolated line like the 662 keV emission of ^{137}Cs - is a measure of the response function or impulse response to a delta function of energy deposited by a gamma-ray photon. In a conventional gamma-ray pulse height spectroscopy system, such as a scintillation detector or a cryogenically cooled germanium detector, the peaks in the pulse height spectrum produced by gamma interaction in the detector are very close to Gaussian in shape. Since a Gaussian can be completely determined by its amplitude and width, conventional detector spectral resolution is conveniently described by one parameter (usually the full width at half maximum because it is easy to measure experimentally). Care must be used in using line width to describe energy resolution in a gamma ray detector built from room temperature semiconductor materials. Room temperature semiconductor detectors frequently exhibit very asymmetrical peaks in their pulse height spectra due to trapping effects. When the peaks in the pulse height spectra are asymmetric and possess “tails”, using the width of the peaks alone as a measure of the energy resolution in the detector is misleading. Energy resolution, from a gamma-ray spectroscopists point of view, may be thought of as the ability to distinguish closely spaced lines in a gamma ray spectrum. However, when comparing the resolution of two detectors- one with Gaussian peaks versus one with asymmetric tailed peaks- the situation arises where two detectors will have different resolving capabilities despite having the same FWHM of lines in their respective pulse height spectra. The situation is illustrated in **Figure 9** and **Figure 10**. These figures were generated by computer simulation, which enabled us to generate pseudo-spectra with the same integral and width but generated by convolution with different response functions. As **Figure 9** and **Figure 10** show, the ability to resolve distinct gamma-ray peaks is also effected by the shape of the response function as well as its width. Note also in **Figure 9** and **Figure 10** that the apparent efficiency is much different for detector with different response functions. Unfortunately the practice of defining the resolving capability of radiation detectors using a single statistic (usually FWHM) continues in the literature; even when describing detectors with a decidedly asymmetric response function. For comparison purposes (with other detectors reported in the literature), we will use the FWHM of a gamma-ray photo-peak as one measure of the energy resolution of a radiation detector. However, we will use the width parameter (FWHM) in conjunction with efficiency measurements which should provide a more meaningful metric of detector performance in a spectroscopic application. This issue- the relation of line width and efficiency- will be discussed in more detail in the next section of this report.

Figure 9: Plot showing a simulated pulse height spectrum from a hypothetical CZT detector irradiated with photons from a ^{133}Ba source. The solid line represents the response from material with good charge collection properties for both electrons and holes. The dashed line represents the spectrum resulting from a detector with typical electrical properties in which the hole transport properties are much lower than the electron properties. Notice how a significant number of “counts” are distributed throughout the tails of each peak.

Figure 10: Plot illustrating the loss of resolving capability when hole tailing is present. The same statistical broadening factor was used for each spectrum but the second peak is barely resolvable when hole tailing is present. A significant factor is the spreading of counts that belong in the photopeak across lower energy values.

II.C.3 Efficiency

Another important performance characteristic of a radiation detector is the efficiency with which it measures radiation incident on the detector. Although the concept of detector efficiency appears initially to be very simple, in practice there are ambiguities associated with its determination. The concept of detector efficiency for a quantized radiation source (counts) is intrinsically simple; the efficiency may be defined as the number of counts scored by the detection system versus the incident particle flux on the detector. Indeed, for a detector with a Gaussian response function it is simple to determine the efficiency of the detector as a function of incident gamma ray energy. For the simple Gaussian case the amplitude and width of the Gaussian can be determined and the area under the peak can be accurately inferred. The area under this peak would correspond to the number of measured events in the detector. However, in the case of the highly asymmetric peaks frequently encountered with room-temperature semiconductor materials, the total area under the peak cannot be inferred without a detailed knowledge of the detectors response function. Furthermore, in the case of asymmetric peaks from semiconductor detectors, the low energy tail of the photo-peak may extend below the "Compton edge" (the maximum energy deposited by a photon scattering 180 degrees off of an electron); in this situation it would be impossible to measure the number of counts under the complete "photopeak" when it becomes intertwined with events produced by Compton scattering in the crystal. Similarly, the low energy tail of an asymmetric photopeak may extend well below the "noise" (a Gaussian distribution centered at zero amplitude in the pulse height spectrum). To resolve the ambiguities associated with measuring the efficiency of a detector we propose using the "spectroscopic efficiency" of the detector as the detector efficiency parameter. The spectroscopic efficiency, is simply the number of counts that lie within an amplitude range of width equal to the FWHM and centered on the maximum in the photopeak. An example of our use of spectroscopic efficiency is illustrated in **Figure 11**. Note that when spectroscopic efficiency is used, the efficiency of the detector is no longer necessarily equal to the stopping efficiency of the detector for a particular class of events. For instance, the number of counts in the "photopeak" of a semiconductor used to detect 662 keV photons from a ^{137}Cs source would be equal to the number of photoelectric interactions occurring in the detector plus the number of multiple interactions that terminate in a photoelectric event (and deposit the full energy of the photon) for an ideal detector. Although, from a theoretical point of view, the spectroscopic efficiency might appear to be somewhat of an abstraction, in practice it is very sensible. A gamma-ray spectroscopist does not necessarily care about how many interactions occur in a detector, instead she or he is only concerned with the number of good events that occur close to the full-energy peak.

In the case of our definition of spectroscopic efficiency, the number of events in the photopeak is not necessarily equal to the number of interactions that deposited the correct amount of energy (the interaction efficiency of the detector). The ratio between the spectroscopic efficiency, and the interaction efficiency should be equal to the ratio of the active volume of the detector to the physical volume of the device. This seemingly trivial equivalence of ratios is important in the development of devices. In the course of this project, we were able to develop theoretical methods for computing the active volume of a detector, but when devices are measured experimentally it is always easier to measure the spectroscopic efficiency (as opposed to the active volume). Thus using the equivalence of volume and efficiency ratios allowed a comparison of theoretically predicted response with measured performance.

In summary, to evaluate the utility of new designs and to measure the performance of devices in the laboratory it was necessary to define performance metric against which we could define

progress. The metric we adopted consisted of two parameters, the spectroscopic efficiency and the width of “peaks” in the gamma-ray pulse height spectrum. Together these two parameters allowed us to judge progress, as well as assess the utility of devices built during this project.

Figure 11: Plot showing the distribution of counts between the photopeak and the rest of the pulse height spectrum from a high quality CZT detector for ^{137}Cs . The photopeak was defined as a symmetric window around the photon energy of 662 keV. The window size was determined by fitting the upper half of the photopeak to a gaussian and finding the energy at which the intensity dropped to 1% of the maximum. This value was doubled and applied symmetrically around the 662 keV photopeak energy. In this case about 4% of the counts appear in the photopeak. The majority of the counts outside the photopeak for large photon energies arise from events not associated with hole tailing; Compton and backscatter events are two of the major contributors.

III Materials

III.A Requirements for a Unipolar Device

III.A.1 Effect of non-uniformity on Device Performance

The dependence of the measured charge on position of interaction is not completely eliminated even in perfect unipolar devices. An example showing the effects of charge transport properties in uniform devices will be examined to show the strong dependence of any device on transport properties. Consider two ideal unipolar devices, in which the weighting potential is completely localized to the anode. This configuration is impossible to realize but will serve as an important illustration of the effects of carrier trapping. A hypothetical detector of this design would be insensitive to any hole contribution and would only measure the electron signal when the electrons reached the anode. The electrical property that most strongly affects this design is

the electron lifetime which determines how many of the electrons generated by a photon interaction actually reach the anode. The electron trapping will cause an interaction position dependence on the measured charge. Each of the two ideal devices are 1 cm thick and have a bias of 2000 V applied. The electron mobility is assumed to be $1000 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$ which is typical of good quality CZT. One detector has an electron lifetime of $3 \mu\text{s}$ which is also typical of good quality CZT. The second device has an electron lifetime of 0.3 ms which is currently unobtainable in CZT. A photon source giving uniform absorption such as ^{137}Cs is used for these calculations. The difference between the maximum and minimum charge measured for each of the devices will be number of electrons trapped during their traversal across the device. An interaction at the anode will undergo almost no electron trapping and the actual number of electrons generated will be measured. An interaction near the cathode will suffer from electron trapping during carrier traversal of the device. This will result in a 15% difference in measured charge for the first device with typical CZT electrical properties. This implies that even a perfect uni-polar device fabricated from the best available CZT will not be able to achieve the desired 1% energy resolution for detector thicknesses of 1 cm. These issues are discussed in much greater detail in the literature. The second device, would only give a 0.2% change in the measured charge, implying that the electron lifetime must be significantly improved to achieve 1% energy resolution for large volume detectors. The PHS resulting from these two devices is shown in **Figure 12**. A device configured in this manner

Figure 12: Plot showing the simulated pulse height spectrum resulting from two ideal uni-polar devices with differing electron lifetimes. The photon interaction was uniform in both cases. The solid line shows the pulse height spectrum resulting from material with a (presently unobtainable) electron lifetime of 0.3 ms. The variation of the charge collected in this device would be approximately 0.2%. The dashed line represents the pulse height spectrum resulting from material with an electron lifetime of $3 \mu\text{s}$, which is typical of presently available high quality CZT material. The measured charge variation in this device would be approximately 14%.

would require an electron lifetime of $50 \mu\text{s}$ to achieve 1% energy resolution at 662 keV. Methods have been developed to correct for electron trapping but these methods always require increased system complexity and cost.

Thus we see that an important material characteristic necessary for unipolar device operation is good electron transport. Typical crystals of CZT that were measured as part of this project had a $\mu\tau$ product of electrons of 1 to $3 \times 10^{-3} \text{ cm}^2\text{V}^{-1}$. In a typical average electric field of 1000 V/cm this translates to an average electron drift length between 1 and 3 cm . Thus we should be able to build devices between 1 and 3 mm thick and have about a 1% resolution broadening due to electron trapping. In addition we desire the uniformity of the electron transport properties to be better than 10% across the material.

III.A.2 Polycrystalline Material- the effect of Grain Boundaries on Device Performance

Up until this point in our discussion of material properties we have assumed that the material from which we construct our detector is single crystal and that no variations in the electron transport occur across this single crystal. Unfortunately however, commercially available CZT substrates are usually polycrystalline in nature. The grain boundaries that separate the crystallites that compose the substrate introduce a gross inhomogeneity in the material used to make the device.

The effects of a simple grain boundary will be explored in this section. A real device may have a complex mix of different defects but a thorough investigation of a simple defect is much easier to analyze. Consider an ideal unipolar device, like the one described in the previous section. This device only measures the signal once an electron reaches the anode as mentioned before. We will discuss two variations of a single boundary within the crystal. This boundary divides the detector into two regions cutting diagonally from the anode to the cathode as shown in **Figure 13**. A simulation was first performed with no boundary in the detector to provide a baseline for comparison. In all three cases the detector was 1 cm thick with an applied bias of 2000 V . The electron mobility for both regions was $1000 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$ and the electron lifetime for grain 1 was $3 \mu\text{s}$. Uniform photon interaction throughout the thickness was assumed like that achieved with ^{137}Cs . The PHS resulting from the simulation of the uniform case is shown as (a) in **Figure 13**. The effects of electron trapping are again observed in the PHS as the broad peak with about 15% variation in measured charge.

The first boundary example assumes that half of the detector material, that which is below the grain boundary, is inactive and will not contribute to the measured charge. This geometry will cause a preferential sampling of the detector near the anode, resulting in a PHS that is skewed toward full charge collection. An example of the resulting PHS is shown as (b) in **Figure 13**. This geometry will also affect the efficiency of the detector. Interactions occurring within the inactive region will not result in any measured signal, therefore the efficiency will be halved which also can be observed in the PHS. This type of a defect would not strongly affect the energy resolution but the efficiency would suffer.

The second boundary example involves two grains with different electron lifetimes. The electron lifetime of grain 1 is $3 \mu\text{s}$ as before but now the second grain has an electron lifetime of $1 \mu\text{s}$ or a factor of three difference between the two. These values of electron lifetime are both reasonable for currently available CZT material. Now the region below the boundary will exhibit much greater electron trapping causing the measured charge to vary by as much as 40% . The resulting PHS is shown as (c) in **Figure 13**. The same 40% charge variation would occur if the material was uniform with an electron lifetime of $1 \mu\text{s}$, but in this case the PHS is distorted by the effects of the two different electron lifetimes.

In this section we have considered the effect gross crystalline grain boundaries would have on the performance of a unipolar radiation detector. We found that- depending on the electrical properties of the grain boundary- a variety of undesirable effects could occur. Grain boundary degra-

dations could range from catastrophocly degrading to a spectrometer to causing only a mild change in the efficiency of a unipolar device. The magnitude of the degradation will be determined by the size of the grains in the crystal and the electrical properties of the grain boundaries.

Figure 13: Figure showing the effects of a boundary defect on an ideal unipolar device. The simulation parameters that remained constant for all three cases were as follows: device thickness of 1 cm, bias of 2000 V, electron mobility of $1000 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$, and uniform photon absorption throughout the device. The simulated pulse height spectrum for a uniform single crystal device with an electron lifetime of $3 \mu\text{s}$ is shown as (a). A device with half of its volume inactive is given as (b) in which the pulse height spectrum is skewed toward interactions near the anode, which gives maximum charge collection. The third example (c) shows the simulated pulse height spectrum from a detector with two grains in which the electron lifetime is $3 \mu\text{s}$ and $1 \mu\text{s}$ respectively. The charge variation will be dominated by the region with lower electron lifetime giving a variation of approximately 40% and distorting the pulse height spectrum significantly.

III.A.3 Measurement of Theoretical non-uniformity

The range of effects induced on a unipolar device by material inhomogeneities are so great that they would mask any changes intentioned by device design. For this reason we embarked on a program to measure the magnitude of the inhomogeneities in the CZT substrates we were to use for detector fabrication. We knew that the approach we would use to measure inhomogeneities would employ a planar device geometry (the details of the apparatus will be discussed in a subse-

quent section of this report). However, it was important to determine if we could interpret the inhomogeneities in a planar detector and use this information to assess the damage these features would induce in unipolar devices. In this section we consider- theoretically- what effects we would expect to observe from homogeneities in a planar device.

Consider two separate detectors which are identical except for the electron lifetime (which is $3\text{ }\mu\text{s}$ and $1\text{ }\mu\text{s}$ for detector 1 and detector 2 respectively). In this example the detectors are configured in a planar geometry with a thickness of 1 cm and an applied bias of 2000 V . The electron mobility, hole mobility and hole lifetime are equal for both detectors at $1000\text{ cm}^2\text{V}^{-1}\text{s}^{-1}$, $50\text{ cm}^2\text{V}^{-1}\text{s}^{-1}$, and $1\text{ }\mu\text{s}$ respectively. A simulation was performed to generate the noise free PHS for each detector under uniform photon absorption (**Figure 14**). The results show that a factor of

Figure 14: Plot of two simulated pulse height spectra resulting from standard planar detectors with uniform photon absorption. Notice how the maximum charge collected decreases with lower electron lifetime. The detector with reduced electron lifetime appears to give a better pulse height spectrum but bear in mind that only 80% of the charge is actually collected. This reduced charge collection efficiency would cause significant reduction in the signal to noise ratio for lower energy photons.

three difference in electron lifetime causes significant electron trapping which drops the maximum amount of charge measured. It appears that the detector with lower electron lifetime actually gives a better spectral result but there are several factors not accounted for in this simulation. First, you are losing signal to noise because you are only collecting a fraction of the charge generated. A photopeak that was just above the noise level of the system for a device with long electron lifetime would be lost in the noise for a detector with shorter electron lifetime. Also, the Compton edge and backscatter peak are neglected in these simulations. A detector exhibiting reduced charge collection would compress the PHS into lower channels and reduce the spectral distance between the photopeak and the other dominant peaks, complicating spectral analysis.

The natural extension of the example discussed above is a planar CZT detector consisting of multiple crystal grains. We have chosen two simple examples to illustrate the effects of this gross

material non-uniformity. The simplest example that can be imagined is a single detector with a diagonal boundary crossing the detector, dividing it into two separate regions. Two variations of this configuration were simulated, one in which half of the device was inactive and had no charge transport capability. The second simulation examined the effects of two grains, one with lower quality but not completely inactive. An initial simulation was performed to provide a baseline for comparison in which the detector consisted of a single grain with typical charge transport properties for CZT. In each case the detector was 1 cm thick, a bias of 2000 V was used, and uniform photon absorption was assumed. The material properties for the baseline calculation were: electron mobility = $1000 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$, electron lifetime = $3 \text{ }\mu\text{s}$, hole mobility = $50 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$, and hole lifetime = $1 \text{ }\mu\text{s}$. The resulting PHS and device configuration is given in **Figure 15** as (a). This example shows the expected phototpeak with a significant low energy tail caused by the dependence on interaction position.

The results from the detector with the inactive region (**Figure 15** (b)) were simulated with the same properties as the baseline example except that no charge transport was allowed across the boundary or in the inactive region. The resulting PHS shows a complete loss of energy resolution and one half of the efficiency expected. A detector with this type of defect would not be useful as a spectrometer and would suffer from limited efficiency even as a counter.

The detector with two different charge collection properties (**Figure 15** (c)) will give a convolution of the PHS from each separate region. The energy resolution is not completely lost but the spectrum becomes highly distorted making spectral analysis or photon energy identification very complicated, especially if multiple photon energies are present. In this case the efficiency is not compromised but spectroscopy would be difficult. These calculations show that the effects of inhomogeneities on a planar detector may encompass a great range (as they did for the unipolar case considered in the previous section). These calculations also indicate that- in general- it would not be possible to unfold the range of defects and inhomogeneities in a detector by considering only the total output of a planar detector. To completely unfold the inhomogeneities in the CZT substrate we will have to scan the sample; the expected results of a scanning an inhomogeneous sample with a scanned radiation beam are discussed in the next section.

Figure 15: Plot showing the simulated effects of a crystalline boundary on a planar CZT detector. The boundary divides the detector in half, running diagonally from the anode to the cathode. The detector was 1 cm thick with an applied bias of 2000 V. The electron mobility, hole mobility, and hole lifetime were kept constant for each simulation at $1000 \text{ cm}^2 \text{V}^{-1} \text{s}^{-1}$, $50 \text{ cm}^2 \text{V}^{-1} \text{s}^{-1}$, and $1 \mu\text{s}$ respectively. The spectrum resulting from a uniform detector with an electron lifetime of $3 \mu\text{s}$ was simulated for comparison (a), and shows significant hole tailing. A detector with half of its volume inactive (b) shows complete loss of energy resolution in the resulting spectrum. Interactions within the inactive region will not contribute any charge causing the efficiency to drop by half. The third simulation shows a detector with electron lifetimes of $3 \mu\text{s}$ and $1 \mu\text{s}$ for grain 1 and grain 2 respectively. The resulting pulse height spectrum is highly distorted which would complicate spectral analysis.

III.A.4 Expected Scanning Results

We have shown the overall effects on the PHS resulting from various crystalline features in a CZT radiation detector. In the ideal situation we would be able to examine the PHS from a detector and determine what types of defects exist within the crystal. This approach is impractical because there are usually several defect types within one detector which makes reconstruction of these causes difficult. We have the capability to locally examine the detector response through a gamma-response mapper which will be discussed in greater detail later in this report. This allows us to examine the overall spatial response and possibly isolate some of the defects discussed earlier. Therefore, a careful examination of the expected PHS from a region localized to a

single defect type will allow later comparison between experimental results and theoretical expectations. We have again chosen two examples of a boundary type defect due to its simplicity in simulation and explanation. The following two examples will discuss the local response as we scan a collimated photon source across a crystalline boundary.

The first example is of a detector with a diagonal boundary separating half of the detector. The lower half possess typical charge transport properties and the upper half is inactive. These simulations were performed for a 122 keV collimated photon source which requires that we account for the preferential attenuation towards one side of the detector. It is assumed that the detector is 2 mm thick, is illuminated from the cathode, and has a bias of 200 V applied. These particular choices mimic the configuration of the physical setup we have produced to map detectors. A diagram of the detector geometry is shown in **Figure 16**. The position of the boundary within the crystal will move from the anode to the cathode as the photon source is scanned from left to right for the detector in **Figure 16**. A series of simulated PHS are shown as a function of boundary position within the detector. The maximum amount of charge collected drops as the “active” thickness decreases, as expected, due to the decreasing distance the carriers are capable of traveling. In addition, the efficiency drops due to the increasing fraction of the thickness that is inactive. However, these calculations are instructive because they show that a unique signature is formed if we scan a radiation beam over a grain boundary between an active (good electron transport properties) crystal grain and an inactive crystal grain (poor electron transport properties).

Figure 16: Figure showing the expected pulse height spectrum as a collimated photon source is translated across the detector. The upper half of the detector is inactive and does not contribute to the measured charge. The active thickness of the detector decreases as the photon source moves from left to right limiting the distance that carriers can move within the crystal, resulting in a reduction in the amount of measured charge.

The next example assumes the same geometry as before but this time the upper half of the detector exhibits lower charge collection properties (**Figure 17**). A similar scan for this configuration would show gradual transformation between two different spectral responses as given in **Figure 17**. Again, the calculations illustrated in **Figure 17** show that a unique signature would be formed when we scan across a grain boundary in a planar detector configuration; in this instance

the grain boundary separates a grain of good electron transport characteristics from a crystallite with poor electron transport characteristics.

Figure 17: Figure showing the expected pulse height spectrum as a collimated photon source is translated across the detector. The upper half of the detector has a $\mu\tau_e$ product of $5 \times 10^{-5} \text{ cm}^2\text{V}^{-1}$ which reduces the amount of charge collected. As the photon source is moved from left to right the contribution from each grain varies linearly, resulting in a transformation between the pulse height spectrum of grain 1 to the pulse height spectrum of grain 2.

The simulations described in this section clearly indicate that scanning a planar detector with a radiation beam may elucidate the nature of defects in the substrates used to make detectors. In the next section we describe the apparatus we developed during this project to scan detectors, followed by a discussion of the results obtained with this apparatus.

III.B System Developed for Material Screening

The mapping system consists of three basic components: a translation mechanism, signal processing and acquisition hardware, and a finely collimated photon source. Pulse height spectroscopy is performed at each spatial point, which gives a local measure of detector performance.

The translation hardware consists of a two-axis stage and motion controller capable of micron resolution. The actuators utilize electrical encoding of the linear output shaft ensuring excellent precision and repeatability.

Pulse height spectroscopy is achieved via a four channel ADC with local histogram memory controlled by a CAMAC dataway. Each channel possesses a dedicated nuclear spectroscopic electronics chain including a shaping amplifier and pre-amplifier. A pulse height spectrum (PHS) is acquired via the histogram memory for each ADC channel; however, for the results presented in this paper, only a single spectroscopic channel was necessary. A block diagram of the experimental setup is shown in **Figure 18**.

The collimator was designed to have a 200 μm beam diameter with a working distance of a few mm, and was designed for use with the 122 keV photons from ^{57}Co . Unfortunately, ^{57}Co produces a high background due to its 692 keV photon emission. The intensity of this emission line is several orders of magnitude lower than the 122 keV emission but the current configuration of the

collimator does not adequately attenuate the high energy photons. This allows the 692 keV photons to flood irradiate the sample while the 122 keV line is limited to a small area.

Figure 18: Block diagram showing equipment setup for the system designed to measure the spatial response of detectors (and substrates used to make detectors) to the 122 keV photons from a ^{57}Co source.

A second source of significant background illumination was the Pb fluorescence (79 keV) from the collimator. This photon source was also flood distributed due to the inadequate absorption of the 692 keV photons from ^{57}Co . A shield of Sn/Cu was added to absorb the fluorescence and significantly reduced the Pb fluorescence peak.

Mapping is achieved by translating the sample under the collimated photon source as shown in **Figure 19**. The photon source remains fixed while the sample, mounting hardware, and preamplifier are moved. The sample is configured in a standard planar geometry which requires only two electrical contacts. This configuration eliminates the need for any mechanical access ports allowing a closed sample container which is important for noise considerations. One disadvantage of a planar geometry is that it conceals any information about the spatial distribution of the leakage current or local noise variation.

Figure 19: Diagram showing the physical configuration of the sample and collimated ^{57}Co source.

The apparatus described in this section was intended to scan substrates of CZT (configured in a planar configuration) to determine their suitability for use in unipolar device construction. In the next section of this report we discuss the results obtained with this apparatus and later analyze these results in the context of the theory discussed previously.

IV Experimental Results

IV.A Material Screening

IV.A.1 Measurements

Fifteen CZT samples were examined for this study. All samples were tested in a planar configuration and the material grade ranged from “counter” to “select discriminator”. Attempts were made to keep the experimental conditions constant for each of the samples examined. The sample bias was chosen to achieve a field of 1000 V/cm within the detector. The detector was mounted in a brass sample holder with a Be window and the cathode of the sample was illuminated with the collimated ^{57}Co γ -source. The spatial response was measured at a resolution of 250 μm with an acquisition time of 45 seconds per spatial point. The shaping time and gain setting of the shaping amplifier were kept constant for each sample at 1 μs and 1000 respectively. The pulse height spectrum acquired for each point was 1024 channels in length and was stored for later analysis.

The data set obtained from the mapping system presented some unique visualization possibilities including both the spatial response and the spectral response. The spatial response is achieved by selecting a channel “window” and then plotting the counts contained within that window for each spatial point in a 2-dimensional map. All of the pulse height spectra from each sample were compressed into 128 channels such that selection of any one of these compressed channels represented a window of 8 channels in the original PHS. The compression was performed to reduce the computational requirements when viewing the data. the count/window representation allows the uniformity of the detector to a particular photon energy range to be examined. The second representation, the spectral response, is useful for determining the spectroscopic capability of a particular region of the detector. This view is achieved by selecting a spatial window and summing the individual PHS obtained at each sampling position into one spectrum representing the region defined by the spatial window. This operation was performed on the original spectra of 1024 channels rather than the compressed spectra to maintain the maximum resolution. The two complimentary representations will be exemplified in the following sections.

Infrared transmission images were also obtained for each sample. After the sample was examined with the mapping system; the contacts were removed and the IR image was taken with a CCD camera. These images were taken to compare the spatial uniformity with any defects observed in the IR images, examples will be shown later in this paper.

IV.A.2 General Data Analysis

The spatial uniformity and spectral quality of each sample were examined using a consistent method. A great deal of variation was found both in single samples and between the entire collection of samples. A detailed analysis of one detector will be presented to clarify the analysis methods and the type of results found. A 1 cm^2 x 2 mm “counter” was chosen for this example because it showed large variations. The first step in the analysis was to examine the overall γ -response of the detector. All of the individual PHS were compressed to 128 channels and summed into one spectrum (**Figure 20**). This spectrum represents the result that would be obtained if the detector was operated in a standard nuclear spectroscopic system. This detector has very poor spectroscopic performance with a very small photopeak and a very large low energy tail (**Figure 20**). The next step was to determine if this poor spectroscopic response was due to overall low quality material or if there was a particular region that was degrading the performance. The spatial

response was examined to answer this question. Two channels were chosen for analysis and are indicated in **Figure 20** as vertical lines. The upper channel was chosen to highlight regions of the

Figure 20: Overall spectral response showing the poor spectroscopic quality of the detector. Also shown are two indices used to generate spatial response maps.

crystal that contribute to the photopeak and similarly the lower channel was picked to identify regions giving poor response. From these two channel indices, spatial maps were generated and are given in **Figure 21**. Two regions can be seen in the top map that contribute a larger number of

Figure 21: Two-dimensional maps of the spatial response for the two regions indexed in **Figure 20**. The left map represents the count contribution to the low energy tail and the right map shows the counts contributing to the photopeak. The majority of the counts in the photopeak are generated in the lower third of the detector.

counts to the lower channels indicating poor response. One spatial region is in the top-right area of the detector and the other runs diagonal near the bottom of the sample. It is likely that these regions give poor spectral response and they will be examined later in this section. The bottom map shows that the majority of the counts in the photopeak were generated in the lower third of the sample suggesting that this region actually has good spectroscopic performance. Three regions were selected to examine the local spectral response indicated as (a), (b), and (c) in **Figure 21**. Each region was 2 mm² in area and the individual spectra within the region were summed into one PHS. The spectra resulting from these three areas are shown in **Figure 22**. Region (c) gives a broad irregular response in which no photopeak is observed. Region (b) exhib-

its a small photopeak but the energy resolution is poor. And region (a) has respectable spectroscopic response even though the overall quality of the detector was given as “counter”. From this analysis it is obvious that the overall poor spectroscopic quality of the entire detector is caused by specific regions within the detector and not by overall poor quality material. It is worth mention that out of all of the samples examined, this “counter” grade detector had one of the best spectral responses when comparing 2 mm² regions.

Figure 22: Pulse height spectra resulting from the regions indicated in the spatial response maps of Figure 21. Notice the complete loss of energy resolution in region (c).

IV.A.3 Defects Diminishing Charge Collection

The most common feature observed in the samples examined was a region in which the magnitude of the charge collected is reduced from that which is expected. In some instances the pulse height spectrum maintained its shape and was simply shifted to lower channels (energy). There were also cases in which the shape of the pulse height spectrum was not maintained and the resulting PHS contained a broad irregular peak at low channel numbers. In these cases any energy resolution was completely lost. An example of attenuated charge collection is shown in **Figure 23**. The spatial map was generated by selecting a channel index at the shoulder of the PHS

Figure 23: Plot showing the spatial distribution of counts in the photopeak. The 2 mm² areas indicated were used to examine the spectral response.

attributed to the 122 keV photons. This sample was a 10 mm² x 2 mm “select counter” grade detector. As in the previous example, this detector also showed a large region that was diminishing the overall energy resolution of the detector. The two regions indicated in **Figure 23** give the spectral response plotted in **Figure 24**. The entire left half of the detector showed reduced charge

Figure 24: Pulse height spectra resulting from the regions highlighted in **Figure 23**. Region (a) shows lower charge collection efficiency and energy resolution.

collection and lower energy resolution than the opposite half of the detector. In addition, the left half of the detector possessed a large density of crystalline defects. These defects can be seen in the IR transmission image of **Figure 25**. Regions showing reduced charge collection can almost always be linked to the existence of defects within the detector crystal. Previous studies suggest that these defects decorate a crystal boundary [4].

Figure 25: IR transmission image of the detector crystal. A high density of defects can be seen in the left half of the crystal which corresponds to the region with lower charge collection efficiency.

IV.A.4 Charge Channeling Defects

A second type of feature that was observed is the charge channeling feature. The channeling behavior was observed as a region with a deficit of counts relative to other regions of the detector. Unlike the charge reduction features, channeling features did not strongly affect the resulting pulse height spectrum. Additionally, regions of devices that exhibited channeling showed a spatial dependence on the pulse height index used to generate the spatial response map. The channeling

feature will shift spatial position as the pulse height index for the spatial map is swept. An example of this type of behavior is shown in **Figure 26**.

Figure 26: Pulse height spectrum integrated over the detector area (top). Spatial response maps showing the contribution to the photopeak (bottom right) at channel 92, and to 75% of the photopeak (bottom left) at channel 69. A linear grayscale was applied with black representing the lowest counts. Note the line defect that exhibits a spatial position dependence on the selected channel.

These factors suggest that there is a thin region within the detector that is channeling charge from one position to another. The low energy tail in the CZT pulse height spectrum is due to a interaction position dependence on the collected charge, presumably, by examining successive windows in the pulse height spectrum, we are examining successive slices into the depth of the detector. Therefore, the spatial variation of the channeling feature suggests a planar structure that is inclined to the surface of the detector. Consider the hypothetical example in **Figure 27** representing a detector with an electrically active planar defect.

Figure 27: Diagram illustrating a hypothetical detector containing a planar crystalline defect. Interactions on the cathode side of the defect (a) will be “channeled” along the defect contributing the expected charge. Interactions on the anode side (c) will be collected normally. Interactions within the defect (b) will become trapped, attenuating the measured charge.

the planar defect will be affected, causing a smaller amount of charge to be collected. As we choose different indices in the low energy tail of the pulse height spectrum, we are sampling

counts resulting from different interaction depths. Therefore, the spatial position of the observed feature will shift position in the 2-dimensional detector response map.

Attempts to find the crystalline defect responsible for this feature were unsuccessful. No crystalline defects could be found in the IR transmission image given in **Figure 28**. Therefore, it is

Figure 28: IR transmission image showing an irregular region with a high density of defects (a), several line defects which do not affect the spectral response (b), and the lack of any obvious crystalline defects that may lead to the charge channeling effect.

likely that this type of response is caused by a crystalline defect that is not easily identified by IR transmission analysis. Twinned regions of the crystal are known to be difficult to detect by IR and might be responsible for the channeling behavior we observed.

A region containing a high density of defects is found where the charge collection is obstructed. This region is indicated by the label (b) in **Figure 28** and corresponds to a horizontal band in the lower portion of the spatial response maps.

The dark lines found in the IR image are attributed to defects known as “pipes” which are formed by Ar or Cd vapor bubbles during the growth process. It is believed that they have no effect on detector performance unless they short the detector contacts together [5].

IV.A.5 Grain Boundary Example

We have observed a large range of defect characteristics in the spatial detector response of CZT crystals. Often, it is difficult to attribute a particular result to one specific type of crystalline defect, suggesting that we usually see a convolution of several defect types. Occasionally we do find a characteristic response that matches the results expected from one of the defects discussed in this report. One such response, that arising from a suspected grain boundary, is illustrated in **Figure 29**. The top map shows the contribution of each spatial point to the photopeak of ^{57}Co . Several regions can be seen in which the material exhibits poor charge collection. A series of PHS were examined at 0.5 mm steps in the region designated by a box in the lower center of the map. This region crosses from an area with good charge collection into an area giving poor charge collection. The resulting progression of spectra are given in the lower plot of **Figure 29**. In the top spectra we see the expected PHS for CZT with reasonable charge collection properties. As the scan progresses the photopeak begins to move into lower channels and a second peak at very low channel numbers begins to appear. This continues as we proceed with the scan until the original photopeak has completely disappeared leaving only the second peak. This response resembles the instance of an inclined grain boundary which separates regions with different charge collection properties. We have observed several instances where the experimental results agree with the the-

oretical expectations. The mapping apparatus has proved successful both for material screening and providing insight into some of the defects occurring in commercially available CZT detectors.

Figure 29: Spatial map of the gamma response (^{57}Co) measured for a $10 \times 10 \times 2 \text{ mm}^3$ CZT detector indicating the counts present in the photopeak for each spatial point (top). Pulse height spectra observed as the photon source is translated over the region indicated (bottom). This response resembles that which is expected for an inclined grain boundary with each grain possessing different charge collection properties.

IV.B Performance of Unipolar Devices

Up until this point we have discussed the theory of operation of unipolar devices, and the measured performance of CZT substrates intended for use in unipolar detectors but operated in a conventional planar configuration. In this section we discuss the measured performance of unipolar CZT detectors operated as gamma-ray pulse height spectrometers. Most of the results presented in this section are from a single lateral contact device. Many other lateral contact devices were designed and fabricated during the project but none worked as well the one discussed here. Part of the reason for lack of success with other devices was our lack of experience with device fabrication. As of this writing, however, we have seen a considerable improvement in our CZT detector fabrication capability. We anticipated fabricating many more unipolar devices in the near future.

Another reason for our low yield of working unipolar devices was the quality of the substrates used to fabricate the detectors. As the results in the last section of this report show, the homogeneity of commercially available CZT crystals could stand improvement. In particular, the polycrystalline nature of the commercial CZT substrates is - in many cases- very detrimental to unipolar device operation. Nonetheless, the biggest factor limiting our yield of unipolar devices was our own fabrication procedures. As we will see in the following sections even our best working device was fabricated on very nonuniform material; indicating that the lateral contact design was somewhat forgiving with respect to substrate uniformities.

IV.B.1 Uni-Polar Operation

One of the most important tools we used in the analysis of unipolar device behavior was the use of multiparameter pulse height spectroscopy systems. In a multiparameter system, two or more coincident signals are digitized simultaneously. The numbers resulting from the digitizing of the two signals are then used to increment a value in a two dimensional matrix in computer memory; the address of the location in the matrix is given by the values from the digitizer. An example of multiparameter pulse height spectrum taken from a unipolar device is shown in **Figure 30**. To generate **Figure 30** a $10 \times 10 \times 2 \text{ mm}^3$ lateral contact unipolar device was irradi-

Figure 30: Multi parameter plots showing the Cathode response vs. the Anode response for low field operation (a), and high field operation (b) with 662 keV photon illumination from ^{137}Cs . Note the high level of electron trapping observed in the low field plot which appears as a diagonal line intersecting the x-axis at channel 120.

ated with photons from a ^{137}Cs source (662 keV). The pulses from both the anode and the cathode were digitized and the resulting two-dimensional histograms are visualized in **Figure 30**. When interpreting **Figure 30**, note that a “projection” of the data toward one of the axes would result in

the “single” pulse height spectrum for that particular channel. For instance, by summing the data in **Figure 30** downward toward the abscissa the pulse height spectrum for the anode would be obtained (such a pulse height spectrum is shown in **Figure 31**). Conversely, summing the data in **Figure 30** toward the ordinate would produce the singles pulse height spectrum for the cathode. Note the extreme performance difference between the cathode and anode observed in **Figure 30**; the vertical line is the 662 keV photopeak of ^{137}Cs .

Another interesting feature of the two-dimensional pulse height spectrum in **Figure 30** is that spatial information about the position of interaction can be obtained from the multi-parameter spectrum. Under the assumption that the anode weighting potential is localized to the region between the grid and the anode, we would expect the ratio of the pulse height from the anode to the pulse height from the cathode to indicate the position of interaction between the grid and the cathode. In **Figure 30** (a) the position sensitivity is clearly demonstrated because we can see the effect of electron trapping in this low-field regime of operation. In the photopeak region of **Figure 30** (a) we see that the high anode pulse heights correspond to low cathode pulse heights; exactly what would be expected if electrons get trapped as they drift longer times (and distances) toward the grid-anode region. By contrast, in **Figure 30** (b), we see that when the detector is operated in high field mode the trapping is greatly reduced. Thus, we see that the lateral contact unipolar device is capable of sensing the position of interaction (in one dimension) by purely electronic means. This position sensing capability might prove very useful in some radiation detection applications such as “gamma cameras” or other imaging devices.

IV.B.2 Energy Resolution

The overall goal of this research program was to produce a simple to operate device capable of improved energy resolution when operated as a gamma-ray pulse height spectrometer. **Figure 31** illustrates a pulse height spectrum obtained from a lateral contact unipolar device demonstrating this capability. The pulse height spectrum shown in **Figure 31** was obtained by irradi-

Figure 31: Plot showing the pulse height spectrum for ^{137}Cs at 662 keV measured with the “Lateral Contact” device. The energy resolution at this energy was measured at 1.4% which is a significant improvement over commercially available CZT spectrometers.

ating a $10 \times 10 \times 2 \text{ mm}^3$ lateral contact device with 662 keV photons from a ^{137}Cs source. The device was operated with 1100 V potential difference between anode and cathode, and a 200 V difference between the anode and grid (the grid was at ground potential). The device was operated using a technique we developed called “cathode gating”. Cathode gating operates by gating the ADC (reading the anode) only when there is significant pulse produced in coincidence at the cathode. Although the cathode gating scheme sounds complex it is very easy to implement in the laboratory; a preamp and comparator is used on the cathode electrode, but no computer or digital signal processing is involved.

It is worth noting that the pulse height energy resolution shown in **Figure 31** is much better what can be obtained from a commercial CZT spectrometer (usually commercial CZT spectrometers have 100% FWHM at 662 keV due to the low energy tail from hole trapping), and far better than a conventional NAI(Tl)/PMT scintillation spectrometer ($\sim 7\%$ FWHM at 662 keV) energy resolution.

IV.B.3 Efficiency and Spatial Response

Because we had observed extreme non-uniformity in the CZT substrates we tested, we were interested in the uniformity of response of the lateral contact unipolar device. **Figure 32** shows a spatial response measurement taken on a $10 \times 10 \times 2 \text{ mm}^3$ lateral contact unipolar device. The measurements visualized in **Figure 32** were taken with the apparatus described in section III.B of this report. In examining **Figure 32**, note that two distinct pulse height groupings were observed in **Figure 32** corresponding regions (grains) of different electron transport in the material. Note also in **Figure 32** that portions of the device appear “dead”; virtually no pulses arise from that region of the detector when selectively irradiated with gamma rays.

In summary, our testing of the unipolar devices indicated they were capable of very good energy resolution; far superior to commercially available CZT detectors. However, we were limited in our analysis of these devices by our inability to fabricate the lateral contact unipolar devices reliably. Furthermore, the inhomogeneities of the crystals we used to fabricate our detectors also limited their performance.

Figure 32: Map showing the spatial response of the detector contributing to the 122 keV photopeak (top). The left half of the detector was inactive which reduced the overall efficiency of the detector. The right half of the detector shows a preferential charge collection near the grid which we attribute to charge traveling to the grid rather than the anode for interactions closer to the cathode. The superfluous peak observed in the overall pulse height spectrum can be attributed to the region indicated (d) and is compared to (a) where the local efficiency is a maximum (lower left). Two regions near the cathode are compared, (b) and (c), to show the effects of efficiency loss and resolution loss (lower right).

V Conclusions

The goal of this project was to develop a new type of gamma ray spectrometer based on cadmium zinc telluride (CZT). Our intention was to use a new design of CZT detector, which we called a lateral unipolar device, as the design for the improved detector. We succeeded in achieving our overall goal and demonstrated a detector with exceptional energy resolution for energetic photons (> 200 keV). Progress in the project was limited however, by our inability to reliably fabricate the unipolar devices. Part of our poor fabrication record could be attributed to our fabrication facilities being constructed during the time period of this development program (our CZT fabrication facilities here at Sandia/CA are only now becoming fully operational). Another component to our fabrication problems was the limited state of CZT fabrication technology in general. CZT is not silicon and every aspect of device fabrication requires a small development effort in and of itself; there are few if any standard fabrication procedures with CZT. Our intention on the project had been to focus on design, but in practice a great deal of time was spent attempting to fabricate devices and on selecting and characterizing CZT material for eventual device use. Despite these problems, we remain very optimistic that the concepts embodied in our unipolar device design will improve the state of the art in room-temperature gamma-ray detectors. Much work remains to be done before the unipolar concept can be employed commercially, but it is now clear what that work should be. Future efforts utilizing this device concept (or ones similar to it) should focus on devices built from single crystal material. In our view, single crystal material is hard to come by and not representative of the bulk of commercial material, but single crystal material is a far more efficient platform for testing unipolar device concepts. It can be very difficult to unfold design issues when the material is heterogeneous.

VI References

- [1] Z. He, "Investigation of Detector Performance of Position Sensitive CdZnTe Detectors," presented at the IEEE Nuclear Science Symposium, Albuquerque, NM, 1997.
- [2] K.J. Matherson, et al, "Progress in the Development of Large-Area Modular 64 x 64 CdZnTe Imaging Arrays for Nuclear Medicine," present at the IEEE Nuclear Science Symposium, Albuquerque, NM, 1997.
- [3] P.N. Luke, Single-Polarity Charge Sensing in Ionization Detectors using Coplanar Electrodes," *Appl. Phys. Lett.*, Vol. 65, pp. 2884-2886, 1994.
- [4] J.R. Heffelfinger, D.L. Medlin, and R.B. James, "Analysis of Grain Boundaries and Te Precipitates in CdZnTe Grown by High-Pressure Bridgman Method", *MRS Symposium Proceedings*, Vol. 487, pp. 33-38, 1998.
- [5] C. Szeles and E. Eissler, "Current Issues of High-Pressure Bridgman Growth of Semi-Insulating CdZnTe", *MRS Symposium Proceedings*, Vol. 487, pp. 3-12, 1998.
- [6] F.P. Doty, private communication, November 1998.
- [7] H.H. Barrett, J.D. Eskin, and H.B. Barber, "Charge Transport in Arrays of Semiconductor Gamma-Ray Detectors", *Phys. Rev. Letters*, Vol. 75, no. 1, pp. 156-159, 1995.
- [8] D.J. Wagenaar and R.A. Terwilliger, "Effects of induced charge in the kinestatic charge detector", *Medical Physics*, Vol. 22, no. 5, pp. 627-634, 1995.
- [9] C.L. Lingren, B. Apotovsky, J.F. Butler, R.L. Conwell, F.P. Doty, S.J. Friesenhanh, A. Oganesyan, B. Pi, and S. Zhao, "Cadmium-Zinc_Telluride, Multiple-Electrode Detectors Achieve Good Energy Resolution with High Sensitivity at Room-Temperature", *IEEE NSS/MIC Conference Record*, Albuquerque, NM, 1997.
- [10] J.D. Eskin, H.H. Barrett, H.B. Barber, and J.M. Woolfdnden, "The Effect of Pixel Geometry on Spatial and Spectral Resolution in a CdZnTe Imaging Array", *IEEE NSS/MIC Conference Record*, San Francisco, CA, 1995.
- [11] J.D. Eskin, H.B. Barber, and H.H. Barrett, "Variations in pulse-height spectrum and pulse timing in CdZnTe pixel array detectors", *Proceedings of the SPIE*, Vol. 2859, pp. 46-49, 1996.

ON THE ACTIVE VOLUME OF CADMIUM ZINC TELLURIDE GAMMA-RAY SPECTROMETERS

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ABSTRACT

In this paper we develop quantitative models to predict the active volume of cadmium zinc telluride (CZT) detectors operated as gamma-ray pulse height spectrometers. Three cases are considered: a conventional planar detector, a unipolar device, and a detector in which electronic signal processing has been applied to correct for charge trapping effects. We find that existing detectors are very limited in their maximum attainable active volume, but unipolar devices with charge correction show promise for producing large active volume devices.

INTRODUCTION

Cadmium Zinc Telluride gamma ray detectors are being used with greater frequency as crystals of this material become more available. When considering the use of a CZT detector in a new application, it is often desirable to know the efficiency of the detector for the radiation to be detected. The first step in determining the efficiency of a CZT detector towards penetrating gamma-rays is to determine the active volume of the detector. Often, it is assumed that the active volume of the detector is the same as its physical volume. However, when CZT detectors are used as pulse height spectrometers the active volume of the detector is often much less than the physical volume of the detector. The difference between the active volume and the physical volume is due to charge trapping effects.

In this paper we compute the expected efficiency of the CZT gamma ray spectrometers under various circumstances. In particular we compute the active volume of a planar detector as a function of material parameters and operating conditions. Next we compute the active volume of a unipolar charge sensing or "electron only" type of device. Finally we compute the expected efficiency of a device employing electronic methods to compensate for charge trapping.

Before we begin our discussion of the efficiency of a CZT detector we wish to define precisely what we mean by "active volume" in a spectroscopic detector. Consider the hypothetical pulse height spectrum shown in **Figure 1** due to monoenergetic photons interacting uniformly throughout the detector and producing Q_o of charge with each interaction. The pulse height spectrum arising from this hypothetical interaction may be thought of as some function $p(Q)$, which represents the probability of measuring a given charge on the contact of the detector. Note that for a perfect detector $p(Q)$ would be a delta function at Q_o . The active volume (Vol_{eff}) of the detector, from a pulse height spectroscopy point of

Figure 1: Hypothetical pulse height spectrum resulting from a monoenergetic photon interaction producing Q_o of charge. The peak width is denoted as Γ .

view, is proportional to the ratio of events under the peak to the total number of interactions occurring in the detector. More rigorously,

$$Vol_{eff} = Vol_{physical} \int_{Q_o - \Gamma/2}^{Q_o + \Gamma/2} p(Q) dQ, \quad (1)$$

where $Vol_{physical}$ is the physical volume of the device, and Γ is the width of the peak. Using this simple result we can now compute the effective volume of a detector under various circumstances.

Planar Detector

The simplest type of CZT radiation detector is the planar detector, formed by the application of contacts on opposite parallel faces of a CZT sample. In a planar detector of thickness d , the charge collection efficiency, η , as a function of position in the detector, x , is given by [1],

$$\eta(x) = \frac{\lambda_e}{d} \left(1 - \exp\left(-\frac{d-x}{\lambda_e}\right) \right) + \frac{\lambda_h}{d} \left(1 - \exp\left(-\frac{x}{\lambda_h}\right) \right), \quad (2)$$

where λ_e and λ_h are the drift length of electrons and holes respectively. If we assume that the electric field in the detector is a constant and extends across the entire detector, then the drift length of electrons is given by

$$\lambda_e = \frac{\mu_e \tau_e V}{d}, \quad (3)$$

where V is the potential difference across the detector, μ_e is the drift mobility and τ_e is the trapping time of electrons. A similar expression may be written for holes.

With a knowledge of the charge collection efficiency as a function of position in the detector, we can compute the active volume of the detector. For any well behaved charge collection distribution, we would expect the most probable value of charge collection to be equal to the maximum charge collection value. Thus computing the active volume of a planar detector reduces to finding the position in the detector where the charge collection is at a maximum and finding the distance from this point to where the charge collection falls to $Q_{max} - \Gamma$ of its value (Figure 2). For a planar

Figure 2: Charge collection versus position in detector (left), and corresponding noise-free pulse height spectrum (right). Note: $Q(x) = \eta(x)Q_0$

detector the maximum value of the charge collection efficiency occurs at, x_{max} (4)

$$x_{max} = \frac{\lambda_h}{\lambda_e + \lambda_h} d, \quad (4)$$

$$\eta_{max} = \eta(x_{max}) = \frac{\lambda_e + \lambda_h}{d} \exp\left(-\frac{d}{\lambda_e + \lambda_h}\right). \quad (5)$$

The active thickness of the detector for the planar case can be computed by solving the following equation for x over the range $\{0 < x < d\}$.

$$\eta(x) = \eta_{max} - \Gamma \quad (6)$$

In general, the roots to equation (6) must be found numerically. Later in this paper we give an analytic approximation, equation (8), useful under common circumstances. For a realistic planar CZT detector ($\lambda_e > d > \lambda_h$) equation (6) has at most two solutions in the range 0 to d . We denote these solutions x_1 and x_2 then the active thickness of the detector is simply.

$$x_{active} = |x_1 - x_2| \quad (7)$$

If η_{max} is close to the cathode then equation (6) may have only one solution in the range 0 to d . Under these circumstances the single solution is the active thickness. Of course, for a planar detector, once the active thickness is known the active volume can be computed from it by simply multiplying by the area of the device.

Using the above formalism, and assuming a constant electric field in the detector, we have computed the active volumes of some typical planar CZT detectors and some results are shown in **Figure 3**. Note that the active volume of typical devices is much smaller than the physical volume. Note too that thin devices have a greater relative active volume, as should be expected since - in the constant field case - the ratio of the drift length to the device thickness goes as V/d^2 . Thus two stacked detectors can often give more active volume than a single element device of greater physical thickness. When computing the results shown in **Figure 3** we truncated the solution to exist only if the field in the detector was less than 2000 V/cm. Our laboratory experience has shown that is very difficult to build devices that can withstand a field greater than 2 kV/cm with current technology.

It has been noted [2] that when the drift length of both carriers becomes much less than the thickness of the device, relatively uniform charge collection results. In principle this would appear to offer a method for producing more active volume in a detector. In practice, however, when the effects of photon transport and noise are considered, it becomes apparent that reducing the drift length of the carriers is not a practical solution to increasing the active volume. For instance, con-

Figure 3: Active detector thickness as a function of bias for three different device thickness.

sider a CZT detector used to perform pulse height spectroscopy on ^{137}Cs (662 keV photons). If the bias on the detector were reduced to where the charge collection is somewhat uniform throughout the detector, the maximum signal would be reduced to about 1/10 of the value of full charge collection. Assuming the total noise of the detector was 14 keV FWHM of noise referred to full charge collection (2% relative energy resolution), the noise would become 20% of the 662 keV peak at the reduced bias needed for uniform charge collection. At 20% energy resolution, the CZT detector would have little or no performance advantage over a scintillator based spectrometer system. To compute the proper effects of reducing carrier drift length it is necessary to convolve the expected charge pulse height spectrum with the Gaussian electronic noise expected in the detection system. However, for simplicity in estimation purposes, we recommend constraining the solutions of equation (6) such that the charge collection efficiency is always greater than about 0.6; under these conditions the convolution can be avoided and equation (6) can be used directly to estimate the active thickness of the detector. For the case of a detector operating with a constant electric field, an approximate solution to the active volume of the detector is given by the following expression

$$x_{active} = x_{max} + (\eta_{max} + \Gamma)d \exp\left(\frac{d - x_{max}}{2\lambda_e}\right) \quad (8)$$

This expression was obtained by approximating the charge collection efficiency as a function of detector position as a line between η_{max} , x_{max} and $\eta(d)$, d . Equation (8) may be used to predict the active volume of a detector based on measured charge carrier transport characteristics.

Unipolar Device

There has been a great deal of recent interest in the use of CZT gamma-ray spectrometers based on unipolar or "electron-only" designs. Such devices promise to have a much larger active volume because only the trapping effects of electrons (not holes) diminish the performance of the device as a pulse height spectrometer.

Consider a somewhat idealized unipolar device where the weighting potential [3] of the anode is localized very close to the anode (under these circumstances charge is only induced on the anode when electrons travel very close to it). In this hypothetical unipolar device, trapping of electrons induces a distortion of the pulse height spectrum and corresponding decrease in spectroscopic efficiency. For the idealized unipolar device, the charge collection efficiency as a function of distance from the anode is simply given by,

$$\eta(x) = \exp\left(-\frac{x}{\lambda_e}\right), \quad (9)$$

where, x is the distance from the cathode and, as before, λ_e is the drift length of electrons. Since the charge collection is simply a monotonic decreasing function of distance from the anode, the active thickness of the device at a given resolution is given by,

$$x_{active} = -\ln\left(\frac{1 - \Gamma}{\lambda_e}\right). \quad (10)$$

Note that for a spectroscopic device with good energy resolution (Γ small), the active volume is simply $\Gamma\lambda_e$. Thus, for an electron only device made with present day material ($\lambda_{max} \sim 4$ cm), good energy resolution ($\Gamma < 0.1$) limits the active thickness to only about 4 mm maximum. How-

ever, as we discuss in the next section of this paper, electron only devices show much greater promise for large volume devices when electronic means are used to compensate for the electron trapping.

Compensation Electronics

A variety of methods have been proposed over the years to electronically compensate for the effects of charge carrier trapping [4-7]. Such methods offer the possibility of substantially improving the active volume of CZT gamma-ray detectors by "moving" pulses (with reduced amplitude from charge trapping) back into the full-energy peak. Most of the charge compensation methods developed to date rely on correcting the amplitude of the pulse based on its shape in the time domain. Implicit in the reasoning behind the charge compensation methods based on pulse shape is that there is a one-to-one correspondence between the position of interaction in the detector and the amount of charge compensation required. However, multiple interaction events (such as Compton scattering followed by photo-electric absorption) do not have a single position of interaction in the detector and thus cannot be properly corrected using charge compensation methods. Once detectors become substantially larger than 1 cm³, multiple interaction events become an important (even dominant) contribution to the full energy peak in a gamma-ray spectrometer. Thus, the deficiencies of conventional charge compensation techniques preclude their use in developing CZT detectors that could compete with germanium or scintillation detectors for efficiency. Nonetheless, conventional charge compensation techniques would be expected to boost the active volume of small detectors whose gamma-ray efficiency is dominated by photo-electric interactions. The active (photo-electric only) volume for a hypothetical charge compensation method can be derived by assuming that all of the trapped charge is placed back in the full-energy peak. At first glance this would seem to indicate that charge compensation would produce detectors whose entire physical volume is active. However when the additional noise broadening of the corrected charge is considered, the efficiency of a compensated device is diminished. In particular, the full energy peak in a compensated device may be thought of as composed of the sum of a series of Gaussian peaks with the same centroid but different standard deviations. Note that, in general, this sum of Gaussians peak would not itself be a Gaussian. The standard deviation due to each point in the detector is simply equal to the noise width (equivalent noise charge (ENC) divided by the charge collection efficiency at that point in the detector). In the limit, this sum of Gaussians becomes an integral,

$$V_{fraction} = \int_{Q_o - \Gamma/2}^{Q_o + \Gamma/2} \int_0^d \frac{\eta(x)}{ENC \sqrt{2\pi}} \exp\left(-\left(\frac{(Q - Q_o)\eta(x)}{2ENC}\right)^2\right) dx dQ. \quad (11)$$

In other words, charge compensation can correct the amplitude of a peak but it cannot change its relative width.

Charge trapping compensation methods can also be applied to unipolar devices as first suggested by He [8]. In the case of unipolar devices, it may also be possible to correct for multiple interaction Compton events. This possibility arises because multiple scatter events can be distinguished in unipolar devices. In an ideal unipolar device, no charge is induced on the anode until electrons drift into close proximity. Thus, multiple scatter events are distinguishable by the distinct (but close) arrival times of the induced charge pulses on the anode. Such a compensating system for multiple scatter events would be difficult to implement however, because it would necessitate short amplifier integration times to distinguish the distinct arrival of the pulses (tens of ns assuming an electron mobility of 1000 cm²/Vs and a average electric field of 1000 V/cm). At these short integration times the series white noise [3] of the amplifier would be rather large, and

the energy resolution would become dominated by noise. Despite these technical difficulties, a unipolar device capable of compensating multiple interaction events would offer the possibility of CZT detectors with active thickness of several centimeters, many times the active thickness achievable using other methods.

SUMMARY

We have computed the expected spectroscopic efficiency in CZT detectors under various circumstances. We found that conventional planar detectors available today have very small active volumes compared to their physical size. Planar detectors that are commercially available are limited in their active thickness to about 2 mm by hole trapping effects, irrespective of the physical thickness of the detector. Unipolar devices offer an increase of active volume but these devices too are also limited, in this case by electron trapping, to active thickness of less than about 5 mm. Of course, if the charge carrier transport properties of CZT crystals were to improve this would lead to an immediate improvement in achievable active volumes. The most promising approach to CZT detectors that could attain large active volumes would seem to be a unipolar device with some form of correction for electron trapping. If such a compensation mechanism could be implemented, and it was capable of correctly processing multiple interaction events, we could see CZT detectors with truly large active volumes ($> 10 \text{ cm}^3$).

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REFERENCES

1. W. Akutagawa and K. Zanio, Gamma Response of Semi-Insulating Material in the Presence of Trapping and Detrapping, J. Appl. Phys., Vol. 40, p. 3838, (1969).
2. G.F. Knoll, and D.S. McGregor, Fundamentals of Semiconductor Detectors for Ionizing Radiation, Mat. Res. Soc. Proc., Vol. 302, p. 3 (1993).
3. V. Radeka, Low-Noise Techniques in Detectors, Ann. Rev. Nucl. Part. Sci., Vol. 38, p. 217, (1988).
4. M. Richter and P. Siffert, High Resolution Gamma Ray Spectroscopy with CdTe Detector Systems, Nucl. Inst. and Meth. A, Vol 323, p. 529 (1994).
5. Y. Eisen, and Y. Horowitz, Correction of Incomplete Charge Collection in CdTe Detectors, Nucl. Inst. and Meth. A, Vol 353, p. 60 (1994).
6. J.A. Heanue, J.K. Brown, and B. Hasegawa, The Use of CdTe and CdZnTe for Pulse Counting and Current Mode Medical Imaging Applications, Nucl. Inst. and Meth. A, Vol. 380, (1996).
7. J.C. Lund, R. Olsen, J.M. VanScyoc, and R.B. James, The Use of Pulse Processing to Improve the Performance of CdZnTe Gamma-Ray Spectrometers, IEEE Trans. Nuc. Sci, Vol. 43, No. 3, p. 1411 (1996).
8. Z. He, Private Communication.

Fine-Scale Spatial Response of CdZnTe Radiation Detectors

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Abstract

Several studies have suggested that the uniformity of Cadmium Zinc Telluride (CZT) detectors play an important role in their performance when operated as gamma-ray spectrometers [1]. However the detailed gamma response of simple planar detectors as a function of position over the device area is largely unknown. To address this issue we have built a system capable of measuring the detector response with a resolution of $\sim 250 \mu\text{m}$. The system consists of a highly collimated ($\sim 200 \mu\text{m}$) photon source ($<150 \text{ keV}$) scanned over the detector using a computer controlled, two-axis translation stage. Fifteen samples configured as planar detectors were examined with the new apparatus. The material grade of the detectors examined varied from "counter" to "select discriminator". Two classes of spatial response variation were observed and are presented here. Infrared (IR) transmission images were also acquired for each sample and correlation between features in the pulse height spectrum and crystalline defects were observed.

I. Introduction

CZT radiation detector technology has matured rapidly over the last few years. Several new device designs have been demonstrated such as fine pitch imaging arrays [2] and single-carrier spectrometers [3]. All of these designs require a uniform response over the device area to γ -irradiation. Therefore it would be useful to be able to measure the spatial variation in the spectral response of commercially available CZT detectors. This system would allow screening of material for some of the novel device designs mentioned above, and for general research into the causes and possible solutions to the uniformity problems. A system has been built to explore these questions in detail. The method we used to analyze the pulse height spectra was very simple. The counts in one or two windows in the pulse height spectrum were evaluated at each position on the sample. More sophisticated analysis could be performed on the pulse height spectrum associated with each spatial point.

II. Experimental Setup

A. Equipment

The mapping system consists of three basic components: a translation mechanism, signal processing and acquisition hardware, and a finely collimated photon source. Pulse height spectroscopy is performed at each spatial point, which gives a local measure of detector performance.

The translation hardware consists of a two-axis stage and motion controller capable of micron resolution. The actuators utilize electrical encoding of the linear output shaft ensuring excellent precision and repeatability.

Pulse height spectroscopy is achieved via a four channel ADC with local histogram memory controlled by a CAMAC dataway. Each channel possesses a dedicated nuclear spectroscopic electronics chain including a shaping amplifier and pre-amplifier. A pulse height spectrum (PHS) is acquired via the histogram memory for each ADC channel; however, for the results presented in this paper, only a single spectroscopic channel was necessary. A block diagram of the experimental setup is shown in Figure 1.

Figure 1: Block diagram showing equipment setup for the mapping system.

The collimator was designed to have a $200 \mu\text{m}$ beam diameter with a working distance of a few mm, and was designed for use with the 122 keV photons from ^{57}Co . Unfortunately, ^{57}Co produces a high background due to its 692 keV photon emission. The intensity of this emission line is several orders of magnitude lower than the 122 keV emission but the current configuration of the collimator does not adequately attenuate the high energy photons. This allows the 692 keV photons to flood irradiate the sample while the 122 keV line is limited to a small area.

A second source of significant background illumination was the Pb fluorescence (79 keV) from the collimator. This photon source was also flood distributed due to the inadequate absorption of the 692 keV photons from ^{57}Co . A shield of Sn/

Cu was added to absorb the fluorescence and significantly reduced the Pb fluorescence peak.

Mapping is achieved by translating the sample under the collimated photon source as shown in Figure 2. The photon source remains fixed while the sample, mounting hardware, and preamplifier are moved. The sample is configured in a standard planar geometry which requires only two electrical contacts. This configuration eliminates the need for any mechanical access ports allowing a closed sample container which is important for noise considerations. One disadvantage of a planar geometry is that it conceals any information about the spatial distribution of the leakage current or local noise variation.

Figure 2: Diagram showing the physical configuration of the sample and collimated ^{57}Co source.

B. Measurements

Fifteen CZT samples were examined for this study. All samples were tested in a planar configuration and the material grade ranged from "counter" to "select discriminator". Attempts were made to keep the experimental conditions constant for each of the samples examined. The sample bias was chosen to achieve a field of 1000 V/cm within the detector. The detector was mounted in a brass sample holder with a Be window and the cathode of the sample was illuminated with the collimated ^{57}Co γ -source. The spatial response was measured at a resolution of 250 μm with an acquisition time of 45 seconds per spatial point. The shaping time and gain setting of the shaping amplifier were kept constant for each sample at 1 μs and 1000 respectively. The pulse height spectrum acquired for each point was 1024 channels in length and was stored for later analysis.

The data set obtained from the mapping system presented some unique visualization possibilities including both the spatial response and the spectral response. The spatial response is achieved by selecting a channel "window" and then plotting the counts contained within that window for each spatial point in a 2-dimensional map. All of the pulse height spectra from each sample were compressed into 128 channels such that selection of any one of these compressed channels represented a window of 8 channels in the original PHS. The compression was performed to reduce the computational requirements when viewing the data. The count/window representation allows the uniformity of the detector to a particular photon energy range to be examined. The second representation, the spectral

response, is useful for determining the spectroscopic capability of a particular region of the detector. This view is achieved by selecting a spatial window and summing the individual PHS obtained at each sampling position into one spectrum representing the region defined by the spatial window. This operation was performed on the original spectra of 1024 channels rather than the compressed spectra to maintain the maximum resolution. The two complimentary representations will be exemplified in the following sections.

Infrared transmission images were also obtained for each sample. After the sample was examined with the mapping system, the contacts were removed and the IR image was taken with a CCD camera. These images were taken to compare the spatial uniformity with any defects observed in the IR images, examples will be shown later in this paper.

III. Discussion

A. General

The spatial uniformity and spectral quality of each sample were examined using a consistent method. A great deal of variation was found both in single samples and between the entire collection of samples. A detailed analysis of one detector will be presented to clarify the analysis methods and the type of results found. A 1 $\text{cm}^2 \times 2 \text{ mm}$ "counter" was chosen for this example because it showed large variations. The first step in the analysis was to examine the overall γ -response of the detector. All of the individual PHS were compressed to 128 channels and summed into one spectrum (Figure 3). This spectrum represents

Figure 3: Overall spectral response showing the poor spectroscopic quality of the detector. Also shown are two indexes used to generate spatial response maps.

resents the result that would be obtained if the detector was operated in a standard nuclear spectroscopic system. This detector has very poor spectroscopic performance with a very small photopeak and a very large low energy tail (Figure 3). The next step was to determine if this poor spectroscopic response was due to overall low quality material or if there was a particular region that was degrading the performance. The spatial response was examined to answer this question. Two

channels were chosen for analysis and are indicated in Figure 3 as vertical lines. The upper channel was chosen to highlight regions of the crystal that contribute to the photopeak and similarly the lower channel was picked to identify regions giving poor response. From these two channel indices, spatial maps were generated and are given in Figure 4. Two regions

Figure 4: Two-dimensional maps of the spatial response for the two regions indexed in Figure 3. The top map represents the count contribution to the low energy tail and the bottom map shows the counts contributing to the photopeak. The majority of the counts in the photopeak are generated in the lower third of the detector.

can be seen in the top map that contribute a larger number of counts to the lower channels indicating poor response. One spatial region is in the top-right area of the detector and the other runs diagonal near the bottom of the sample. It is likely that these regions give poor spectral response and they will be examined later in this section. The bottom map shows that the majority of the counts in the photopeak were generated in the lower third of the sample suggesting that this region actually has good spectroscopic performance. Three regions were selected to examine the local spectral response indicated as (a), (b), and (c) in Figure 4. Each region was 2 mm² in area and the individual spectra within the region were summed into one

Figure 5: Pulse height spectra resulting from the regions indicated in the spatial response maps of Figure 4. Notice the complete loss of energy resolution in region (c).

PHS. The spectra resulting from these three areas are shown in Figure 5. Region (c) gives a broad irregular response in which no photopeak is observed. Region (b) exhibits a small photopeak but the energy resolution is poor. And region (a) has respectable spectroscopic response even though the overall quality of the detector was given as "counter". From this analysis it is obvious that the overall poor spectroscopic quality of the entire detector is caused by specific regions within the detector and not by overall poor quality material. It is worth mention that out of all of the samples examined, this "counter" grade detector had one of the best spectral responses when comparing 2 mm² regions.

B. Defects Diminishing Charge Collection

The most common feature observed in the samples examined was a region in which the magnitude of the charge collected is reduced from that which is expected. In some instances the pulse height spectrum maintained its shape and was simply shifted to lower channels (energy). There were also cases in which the shape of the pulse height spectrum was not maintained and the resulting PHS contained a broad irregular peak at low channel numbers. In these cases any energy resolution was completely lost. An example of attenuated charge collection is shown in Figure 6. The spatial map was generated by selecting a channel index at the shoulder of the PHS attributed to the 122 keV photons. This sample was a 10 mm² x 2mm "select counter" grade detector. As in the previous example, this detector also showed a large region that was diminishing the overall energy resolution of the detector. The two regions indicated in Figure 6 give the spectral response plotted in Figure 7. The entire left half of the detector showed reduced charge collection and lower energy resolution than the opposite half of the detector. In addition, the left half of the detector possessed a large density of crystalline defects. These defects can be seen in the IR transmission image of Figure 8. Regions showing reduced charge collection can almost always be linked to the existence of defects within the detector crystal. Previous

studies suggest that these defects decorate a crystal boundary [4].

Figure 6: Plot showing the spatial distribution of counts in the photopeak. The 2 mm² areas indicated were used to examine the spectral response.

Figure 7: Pulse height spectra resulting from the regions highlighted in Figure 6. Region (a) shows lower charge collection efficiency and energy resolution.

Figure 8: IR transmission image of the detector crystal. A high density of defects can be seen in the left half of the crystal which corresponds to the region with lower charge collection efficiency.

C. Charge Channeling Defects

A second type of feature that was observed is the charge channeling feature. The channeling behavior was observed as a region with a deficit of counts relative to other regions of the detector. Unlike the charge reduction features, channeling features did not strongly affect the resulting pulse height spectrum. Additionally, regions of devices that exhibited channeling showed a spatial dependence on the pulse height index used to generate the spatial response map. The channeling feature will shift spatial position as the pulse height index for the spatial map is swept. An example of this type of behavior is shown in Figure 9.

Figure 9: Pulse height spectrum integrated over the detector area (top). Spatial response maps showing the contribution to the photopeak (bottom right) at channel 92, and to 75% of the photopeak (bottom left) at channel 69. A linear grayscale was applied with black representing the lowest counts. Note the line defect that exhibits a spatial position dependence on the selected channel.

These factors suggest that there is a thin region within the detector that is channeling charge from one position to another. The low energy tail in the CZT pulse height spectrum is due to an interaction position dependence on the collected charge, presumably, by examining successive windows in the pulse height spectrum, we are examining successive slices into the depth of the detector. Therefore, the spatial variation of the channeling feature suggests a planar structure that is inclined to the surface of the detector. Consider the hypothetical example in Figure 10 representing a detector with an electrically active

Figure 10: Diagram illustrating a hypothetical detector containing a planar crystalline defect. Interactions on the cathode side of the defect (a) will be “channeled” along the defect contributing the expected charge. Interactions on the anode side (c) will be collected normally. Interactions within the defect (b) will become trapped, attenuating the measured charge.

planar defect. Any interactions within the region of the planar defect will be affected, causing a smaller amount of charge to be collected. As we choose different indices in the low energy tail of the pulse height spectrum, we are sampling counts resulting from different interaction depths. Therefore, the spatial position of the observed feature will shift position in the 2-dimensional detector response map.

Attempts to find the crystalline defect responsible for this feature were unsuccessful. No crystalline defects could be found in the IR transmission image given in **Figure 11**. Therefore, it is likely that this type of response is caused by a crystalline defect that is not easily identified by IR transmission analysis. Twinned regions of the crystal are known to be difficult to detect by IR and might be responsible for the channeling behavior we observed.

A region containing a high density of defects is found where the charge collection is obstructed. This region is indicated by the label (b) in **Figure 11** and corresponds to a horizontal band in the lower portion of the spatial response maps.

The dark lines found in the IR image are attributed to defects known as “pipes” which are formed by Ar or Cd vapor bubbles during the growth process. It is believed that they have no effect on detector performance unless they short the detector contacts together [5].

Figure 11: IR transmission image showing an irregular region with a high density of defects (a), several line defects which do not affect the spectral response (b), and the lack of any obvious crystalline defects that may lead to the charge channeling effect.

IV. Conclusion

The fine-scale spatial response of planar CZT detectors to gamma irradiation has been successfully measured. Large variations in the response have been observed and can be categorized into two classes, charge reduction and charge channeling. Charge reduction is observed as an attenuation in the magnitude of the measured charge from that which is expected. These effects correlate with regions within the detector exhibiting a high density of defects. In some instances this effect is so strong that energy resolution is completely lost. The second variation observed, charge channeling, does not significantly affect the energy resolution for the planar configuration used here. However, a pixellated detector will probably suffer significant performance degradation from a channeling feature. Interactions in one pixel may show up as counts in adjacent pixels [6]. Of the fifteen samples examined three showed a uniform response, three showed the effects of charge channeling, and eleven showed regions of charge reduction. There was no apparent correlation with material grade and spatial uniformity. The strong correlation of crystalline defects with regions of poor charge collection suggest that a simple IR transmission image would be very successful as a screening procedure. Any region containing a large number of defects visible in the image could be avoided when dicing the crystal, allowing a greater yield of higher quality material.

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VI. References

- [1] Z. He, “Investigation of Detector Performance of Position Sensitive CdZnTe Detectors,” presented at the IEEE Nuclear Science Symposium, Albuquerque, NM, 1997.
- [2] K.J. Matherson, *et al*, “Progress in the Development of Large-Area Modular 64 x 64 CdZnTe Imaging Arrays for Nuclear Medicine,” present at the IEEE Nuclear Science Symposium, Albuquerque, NM, 1997.
- [3] P.N. Luke, Single-Polarity Charge Sensing in Ionization Detectors using Coplanar Electrodes,” *Appl. Phys. Lett.*, Vol. 65, pp. 2884-2886, 1994.
- [4] J.R. Heffelfinger, D.L. Medlin, and R.B. James, “Analysis of Grain Boundaries and Te Precipitates in CdZnTe Grown by High-Pressure Bridgman Method”, *MRS Symposium Proceedings*, Vol. 487, pp. 33-38, 1998.
- [5] C. Szeles and E. Eissler, “Current Issues of High-Pressure Bridgman Growth of Semi-Insulating CdZnTe”, *MRS Symposium Proceedings*, Vol. 487, pp. 3-12, 1998.
- [6] F.P. Doty, private communication, November 1998.

Multi-Parameter High-Resolution Spatial Maps of a CdZnTe Radiation Detector Array

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Abstract

Resistivity results from a 48x48 pixelated CdZnTe (CZT) radiation detector array are presented alongside X-ray topography and detector mapping with a collimated gamma-ray beam. By using a variety of measurements performed on the same sample and registering each data set relative to the others, the spatial dependence of relationships between them was examined. The local correlations between resistivity and one measure of detector performance were strongly influenced by the positions of grain boundaries and other gross crystal defects in the sample. These measurements highlight the need for material studies of spatially heterogeneous CZT to record position information along with the parameters under study.

I. INTRODUCTION

The purpose of this work is to utilize a 48x48 pixelated $\text{Cd}_{0.8}\text{Zn}_{0.2}\text{Te}$ (CZT) radiation detector array to measure detector properties at high spatial resolutions[1]. Detector array results are combined with data from other tests including X-ray diffraction, photoluminescence, IR transmission imaging, and ^{57}Co gamma-ray mapping to provide a more comprehensive view of a single sample than has been available previously. This objective was prompted by some earlier work which sampled a few spots on a CZT crystal and suggested that increasing the number of samples would strengthen any conclusions relating to material parameters and performance as a radiation detector[2].

This paper presents a subset of our results by focusing on the leakage current measurements made with the imaging array and gamma-ray mapping done after the pixels were removed. By measuring the physical and electrical properties of the CZT crystal at spatial resolutions comparable to the detector array spacing, we were able to examine the relationship between the local characteristics of the crystal and its performance. From a practical standpoint, this information should be considered when selecting material for manufacturing radiation detectors[3].

To avoid possible confusion caused by some terminology we define two terms which are used throughout this paper. "Resistivity" is the term we use to describe the results of the leakage current measurements. We are aware that this term may not always correspond to the physical resistivity of the

CZT substrate material (in the case of blocking contacts for instance). Nonetheless, we use the term resistivity because it is a convenient way of expressing the leakage current—scaled for pixel geometry and operating bias—that can be compared with the results reported by others. Second, we define "detector performance" to mean the total number of counts in the pulse height spectrum within an energy window (range of pulse heights). We realize that the counts in an energy window does not define all aspects of detector performance, but it is often a useful indicator of charge collection properties.

II. EXPERIMENT

The first tests performed with the imaging array were a series of leakage current measurements as a function of bias voltage and temperature. The device, shown in Figure 1, is a $7\times 7\times 1.5\text{ mm}^3$ CZT substrate on which a 48x48 array of gold pixels was delineated by photolithography at $125\text{ }\mu\text{m}$ pitch. Visible on the opposite side is the continuous planar electrode. The detector array was indium bump bonded to a silicon multiplexer readout. This hybridized focal plane array was then wire bonded into a chip carrier. Several of these devices

Figure 1: 48x48 focal plane array wire bonded in a chip carrier. This array was designed for high speed readout and low temperature operation.

Figure 2: IR transmission photograph of the CZT crystal used in the 48x48 array. Pipes within crystal grains and small precipitates along boundaries are visible. Comparison with Figures 3 and 6 makes it easier to see some of these features. The five dark regions in the corners are remnants of the pixel array structure.

have been made and tested in a specially designed vacuum dewar that provides stable, controllable temperature of the devices as well as the front-end electronics. An external ADC, VME histogramming memory, and computer readout software convert the video signal from the array to histograms for each pixel[4].

The array readout technique integrates the charge induced on a pixel during each frame. Each unit cell of the multiplexer is sensitive to currents from thermally excited carriers as well as those from photon or particle interactions within a pixel's sensitive volume. At each voltage bias a leakage current measurement was obtained by noting the change in position of the "no-gamma" peak in the histogram for each pixel, relative to the zero bias offset. Currents were converted to resistivities assuming a fixed geometry for all pixels.

Later, the array was disassembled and most of the gold pixels were removed. A few were left as fiducial marks to register subsequent data sets. Although they are not reported here, these investigations included mapping with photoluminescence at room temperature and 4.2 K, electron microprobe, and triple axis X-ray diffraction. We present data from infrared imaging, X-ray topography, and ^{57}Co gamma-ray mapping.

The IR transmission photograph in Figure 2 was taken with a 35 mm camera using a close-up lens and Kodak HEI film. X-ray topographs were taken at UCLA after determining crystal orientation from Laue diffraction patterns generated from locations on both the front and back faces of the sample. The "front" refers to the (formerly) pixelated side. Figure 3 is a topograph of the front side and the companion sketch in Figure 6 distills the major crystal grain information revealed when all the X-ray and IR data are combined.

Figure 3: Double-crystal X-ray diffraction topograph (206 reflection). White areas are in the diffracting condition. In general, the dark areas in the lower portion of the image and extending into the middle are other crystal grains and twins. Except for twins, dark areas in the upper half are due to misorientation contrast since they are visible in other topographs.

The last test on this sample which we report here is the ^{57}Co gamma-ray mapping done at Sandia National Laboratory. Figure 4 shows the apparatus used. Single, planar, electroless gold contacts were deposited on both faces of the CZT crystal without removing the fiducial pixels. The detector was mounted inside a test box which rides on high-precision two-axis translation stages and is connected to the charge sensitive pre-amplifier and high voltage supply. Pulse signals were digitized by an Ortec ADC and histogramming memory package in a CAMAC crate. Gamma-ray spectra were recorded as a function of the position of collimator/source assembly over the detector.

The collimator is a stainless steel needle tube with a 200 μm inside diameter embedded in a 1 cm thick eutectic alloy of 44.5% lead and 55.5% bismuth. This alloy melts at 255 $^{\circ}\text{F}$ which makes fabrication easier and safer than if it were

Figure 4: Sandia Labs' ^{57}Co gamma-ray mapping apparatus.

pure lead. After cooling, the protruding tube was machined off leaving the inside of the tube relatively free of debris. A quick acid rinse cleared any remaining material inside the collimator bore. A custom ^{57}Co source with a 1 mm diameter active area was placed in a shielded source holder made of the same alloy and positioned over the collimator. Because a high activity ^{57}Co source was needed to get a sufficient count rate at 122 keV, the 570 and 692 keV gamma rays—for which shielding is relatively ineffective—contribute a significant number of counts in the pulse height spectra. Data acquisition is computer controlled by software written with LabVIEW. Further discussion and results involving this gamma-ray mapping apparatus are reported elsewhere in these proceedings[5].

III. RESULTS AND DISCUSSION

The results of the leakage current tests are presented in Figure 5. The histogram data were transformed into leakage currents and then into resistivities. Figure 5 is a rescaled map of these resistivity values where extremely high and low values have been clipped to allow more subtle features to be visible. Lighter areas indicate higher resistivities. Black areas are where no resistivity values were measured. Several hundred of those pixels for which we have no data had indium bumps that were delaminated from the multiplexer circuit. Typically, the delaminated pixels were on the periphery of the array. We cannot report resistivity values for many other pixels (a few hundred) which were mostly located between the delaminated pixels and the good pixels because they had leakage currents beyond the dynamic range of the readout electronics.

A depiction of the crystallographic information on this sample is shown in Figure 6. The two crystal grains studied by

X-ray topography on the front and back sides of the crystal are not the same grains. Referring to Figure 6, the diffraction condition was met on the front side in regions 1 and 5 and on the back in regions 4, 5, and 6. One notable missing piece of information is what direction the twins (clearly visible in Figure 3 as dark bands) extend into, and then possibly exit the crystal on the back side. Furthermore, we must allow that regions in both topographs which were not in the diffraction condition could be more than one grain themselves. Thus, in Figure 6 we have indicated with a question mark where an additional grain boundary may intersect the front surface which would mean the grain(s) of region 6 is different from the grain(s) of 3 and 4. We suggest that the grains are different and that regions 3 and 4 comprise a single grain which extends up and to the right as it enters the crystal. This grain then exits in regions 4, 5, and 6 on the back.

If the proposed configuration is correct, the perimeters of these sets of regions are connected by a grain boundary. The dotted line in Figure 6 indicates the extent of the boundary on the interior of the crystal. This boundary is visible in Figure 2 due to precipitates which often decorate such boundaries. A second grain enters in region 6 and exits out the side resulting in at least one additional boundary traversing the sample in this area. Many other grain configuration possibilities exist for this sample which cannot all be represented or investigated in this paper. We present one possible configuration and the supporting evidence. The square box in Figure 6 indicates the location of the pixel array and the only region imaged in Figures 5, 8, and 12. It will often be useful to refer to the boxed region in Figure 6 in the remainder of the paper.

Gamma-ray detection performance data from this array have been reported earlier along with various methods to improve the spatial and spectral resolution[6-8]. The pixels

Figure 5: Map of pixel resistivity at 30°C. Solid black areas are where no reliable resistivity data was found. Lighter regions indicate higher resistivity. Resistivity values in white areas have been clipped to increase grayscale contrast of more subtle features.

Figure 6: A representation, derived from the IR photo and X-ray topographs, of where known crystal grains intersect the front and back surfaces. The black square marks the location of the pixel array. See text for descriptions of other markings.

are sensitive mainly to one type of charge carrier because of their small size[4,9,10]. Hole tailing of the spectra caused by dissimilar charge transport properties for holes and electrons when photons interact throughout the detector is therefore reduced. However, because of non-localized charge production and transport, too much charge is spread to neighboring pixels to consistently generate the same induced charge on a pixel for photon interaction events within its volume. Consequently, the photopeak is degraded unless processing of the data is done to compensate. Nevertheless, we show here that pixel geometry is not the only factor which determines detector performance.

Unfortunately, limited gamma-ray performance data on the CZT sample were obtained while operated as an imaging array because it was damaged during testing. Instead, the sample was re-fabricated into a planar device by applying a continuous gold electrode on each side of the sample. Gamma-ray pulse height spectra as a function of position on the device were then measured using the mapping apparatus described earlier. Figures 7-9 show some results from these collimated ^{57}Co gamma-ray mapping studies. Two typical pulse height spectra acquired at locations marked A and B in Figure 6 are shown in Figure 7. The region between the vertical dotted lines is the integration window used to generate Figure 8, which is a grayscale map of the total counts recorded within this energy window at each point on the sample.

The feature that is immediately evident when interpreting Figures 7 and 8 is that crystal grain boundaries shift the photopeaks of the spectra to lower energies. The grain boundaries impede charge transport from one grain to the next. This results in less than maximum charge induction on the electrodes[11]. Since the gamma rays interact in the crystal on both sides of the grain boundary, we would expect to see duplicate photopeaks in the pulse height spectrum at the energy difference between the new energies of the original photopeaks and their energies measured at a location without a grain boundary. The 122 and 136 keV peaks unite and become one as they shift so there are only two peaks in the spectra—the original and the duplicate of the united photopeak. For an example, compare spectrum “A” in Figure 7 with spectrum “a” in Figure 9. Furthermore, with our mapping data we can infer the depth and slope of the grain boundary from the ratios between the energies of the original and duplicate photopeaks. This can be seen in the spectra shown in Figure 9 when referenced to their respective sampling locations in Figure 6. These data support our hypothesis about the position of the main grain boundary described earlier.

We also investigated if there were correlations between resistivity, crystal topography, and detector performance. Figure 10 shows a scatter plot comparing pixel resistivity and integrated counts within the energy window. This measure of detector performance is a reasonable representation of the charge transport efficiency at a given location on the detector. Correlations within scatter plot data such as this would be indicated by diagonal patterns; conversely, vertical and

Figure 7: Pulse height spectra of a collimated ^{57}Co source irradiating locations A and B shown in Figure 6. The dotted lines indicate the energy window used to produce the image in Figure 8.

Figure 8: Map of integrated counts within the energy window shown in Figure 7 as a function of position on the sample. The effect of both high angle grain boundaries and twins is obvious.

Figure 9: Pulse height spectra obtained at locations a, b, c, and d shown in Figure 6. This region contains a crystal grain boundary. The detector effectively behaves as two detectors whose relative thickness are proportional to their relative photopeak positions. The resulting spectrum is the superposition of the spectra from within each grain.

Figure 10: A scatter plot of integrated counts in the high energy window versus resistivity at 30°C suggests there may be small correlations, possibly in localized regions.

Figure 11: Enlarged version of previous plot where only pixels in the upper left corner are shown, clustered into groups according to their location on this scatter plot. See Figure 12 for a map showing how each lettered group is spatially distributed.

Figure 12: Locations of pixels plotted in Figure 11 according to their classifications by resistivity and detector performance. Black regions either do not have resistivity data or are not considered here because of location or the number of counts in energy window.

horizontal patterns describe uncorrelated parameters. Clearly, Figure 10 shows no obvious correlation between charge transport efficiency and resistivity. The lack of correlation is somewhat surprising since impurities in the bulk semiconductor might be expected to affect both resistivity and charge transport. It is possible that the presence of grain boundaries so dominates the charge transport that any possible correlations are overshadowed.

In order to study the relationship of resistivity to detector performance without the effects of grain boundaries we looked only at pixels in the upper left-hand corner of the device. In spite of the twins in this area, we concluded that it was the only region which could contain areas free of grain boundaries. Figure 11 is an enlarged version of the scatter plot for this region with the data grouped into several classes. The spatial distribution of these classes is shown in Figure 12.

Although there is some evidence for localized structure in groups C and B relating resistivity and performance, there are still no convincing indications that these quantities are correlated. Given that the measured resistivity varied by over an order of magnitude, the absence of a strong correlation indicates that we must look elsewhere for a mechanism to account for the detector performance variation. The dominant structure in Figure 11 is likely related to the twins in this part of the detector, as seen in Figure 12.

IV. CONCLUSIONS

The original motivation for this work was the possibility of gathering data at a large number of points on a CZT sample to determine what kinds of relationships exist between measured material parameters and the performance of radiation detectors constructed from this material. In particular, we wished to assess the influence of physical and electrical characteristics of a CZT crystal on the efficiency and energy resolution of a small pixel detector array made from that crystal. In this paper we focused on correlating a subset of our physical properties data (resistivity and crystal grain locations) with the pulse height spectra obtained from gamma-ray excitation. Because we knew the physical location from which each physical property datum was collected, and we were able to acquire a gamma-ray pulse height spectrum with similar position resolution, we could interpret the local correlations visible in this particular sample.

The measurements described in this paper were conducted on just one sample. However, this particular sample was so heterogeneous and the amount of data was so large that we can infer some general conclusions about the effects of CZT crystal properties on radiation detector performance. The most obvious conclusion is that grain boundaries, visible in IR transmission microscopy and X-ray topography, have an extremely deleterious effect on the radiation detector characteristics. The correlation of such a gross physical defect as a grain boundary with detector pixel performance is hardly surprising and has been noted by others[11]. Nonetheless, this seems to be the first instance that quantitative evidence linking

poor radiation detector performance with adjacent grain boundaries is presented.

A surprising conclusion of this work is that there was no evidence of a correlation between resistivity and our measure of performance, or charge transport efficiency. The dominant effects of the grain boundaries are so striking that the intra-grain response noted in this paper seems subtle in comparison. It seems clear that resistivity maps are poor indicators for selecting good crystals for detectors using a pulse electronics readout. Of course, such maps are useful in cases where integrating readout methods such as our multiplexer approach are used, since too much leakage current offset can drive individual pixels out of the dynamic range of the electronics.

Clearly the work presented here supports the conclusion that grain boundaries have a very large negative effect on the characteristics of radiation detectors, and single crystals of CZT should be used in manufacturing detectors whenever possible. We look forward to the opportunity to view detectors manufactured from more homogeneous crystals using the methods developed for this study. Such future investigations should enable us to obtain a better quantitative understanding of the relationship between material parameters such as resistivity and charge collection properties.

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VI. REFERENCES

- [1] H.B. Barber, et al., "Use of CdZnTe pixel arrays with multiplexer readout to map detector crystal properties," *1997 IEEE NSS/MIC Conference Record*.
- [2] J.E. Toney, et al., "Uniformity of $\text{Cd}_{1-x}\text{Zn}_x\text{Te}$ grown by high-pressure Bridgman," *Nuclear Instruments and Methods in Physics Research A*, vol. 380, pp.132-135, 1996.
- [3] J.C. Lund, et al., "Semiconductor material requirements of orthogonal strip detectors," *SPIE Proceedings*, vol. 3115, pp.190-198, 1997.
- [4] J.D. Eskin dissertation, Semiconductor Gamma-ray Detectors for Nuclear Medicine, University of Arizona, 1997.
- [5] B.A. Brunett, et al., "Fine-scale spatial response of CdZnTe radiation detectors," *1998 IEEE NSS/MIC Conference Record*.
- [6] H.B. Barber, et al., "Semiconductor pixel detectors for gamma-ray imaging in nuclear medicine," *Nuclear Instruments and Methods in Physics Research A*, vol. 395, pp.421-428, 1997.
- [7] D.G. Marks, et al., "A 48x48 CdZnTe array with multiplexer readout," *IEEE Transactions on Nuclear Science*, vol. 43, no. 3, pp.1253-1259, 1996.
- [8] D.G. Marks, et al., "Maximum-likelihood estimation for semiconductor detector arrays," *1997 IEEE NSS/MIC Conference Record*.
- [9] D.J. Wagenaar and R.A. Terwilliger, "Effects of induced charge in the kinestatic charge detector," *Medical Physics*, vol. 22, no. 5, pp.627-634, May 1995.
- [10] J.D. Eskin, et al., "The effect of pixel geometry on spatial and spectral resolution in a CdZnTe imaging array," *1995 IEEE NSS/MIC Conference Record*.
- [11] F.P. Doty, J.P. Cozzatti, and J.P. Schomer, "Characterization of bulk CdZnTe by IR transmission imaging," *SPIE Proceedings*, vol. 3115, pp.51-55, 1997.

DEVICE SIMULATION OF AN UNIPOLAR GAMMA-RAY DETECTOR

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ABSTRACT

The pulse height spectra from a new kind of unipolar gamma-ray detectors were predicted using a new three-dimensional simulation program developed at Sandia National Laboratories. The detectors were fabricated at Sandia and RMD Inc., and tested at Sandia. They were fabricated from $\text{Cd}_{1-x}\text{Zn}_x\text{Te}$ crystals and they were electron-transport-only devices. For the simulation, a successive overrelaxation method was used to determine the three-dimensional internal electric field within a detector, and to find the weighting potentials for the anode and the cathode. Uniform irradiation and ionization from a ^{137}Cs source was assumed, and the charge transport and the signal induction within the detector were numerically computed using the appropriate materials and design parameters. The simulation gave excellent agreement with experimental pulse height spectra, and it demonstrated the power of such a simulation to correlate the materials parameters and the device design to the actual detector performance.

INTRODUCTION

Room temperature gamma-ray detectors are rapidly gaining wide-spread use, due to their superior energy resolution and portability [1]. Recent advances have taken place both in their materials properties and design. One of the most exciting advances in this field is the advent of the unipolar devices [2-3]. Due to the larger mobilities, longer lifetimes, and smaller effective masses of electrons over holes, all of such unipolar devices are electron-transport-only devices, and these terms are used interchangeably. In these devices, the signal is determined by the motion of the electrons only, resulting in superior energy resolution over the existing planar detectors. However, due to the relatively complex three-dimensional (3-D) structures of these devices, detailed understanding of their behavior remains illusive. Analytical simulation of such a device is, in general, difficult to do properly, except in simplest cases where a high degree of symmetry exists.

In this manuscript, a 3-D numerical simulation of a new kind of unipolar device is described. Pulse height spectra were simulated using realistic materials parameters and device dimensions, and the simulated pulse height spectra are in excellent agreement with the experiment. The unipolar devices were fabricated at Sandia National Laboratories, California, and at RMD Inc. of Watertown, Massachusetts, and their design is schematically depicted in Fig. 1. (Ref. 4) On a parallelepiped CdZnTe (CZT) crystal, the cathode and the anode are placed at the opposite ends, as is usual for a conventional planar detector. However, in this unipolar device, a Au grid is evaporated at some short distance away from the anode, all the way around the detector, and it is grounded. The grid functions to shield the electric field of the cathode from the anode, while allowing the carrier transport of the electrons across the grid toward the anode. A detailed discussion of other unipolar devices can be found in Ref. 3 and other references therein. A further description of Sandia's unipolar device will be given elsewhere [5].

In this paper, a model of carrier transport and electrical signal generation within an unipolar device will be presented, followed by a description of the computational method used to predict the detector performance. Next, simulations for various grid positions will be discussed, relying on charge induction maps for the anode and the cathode to relate the features in the pulse height spectra to specific design parameters of the unipolar device. Then a comparison of an experimental pulse height spectrum from a unipolar device to a simulation will be made. Lastly, the effect of the electron lifetime on the simulated pulse height spectrum shape will be discussed.

Fig. 1. An unipolar γ -ray detector design. $+V_1$ is the dc anode bias and $-V_2$ is the dc cathode bias. The signal is measured from the anode in the single pulse mode, and, optionally, the cathode signal is used as a trigger for the anode signal, to improve the detector energy resolution.

MODEL OF CHARGE CARRIER TRANSPORT AND SIGNAL GENERATION IN A SEMICONDUCTOR RADIATION DETECTOR

When ionizing radiation interacts within a semiconductor radiation detector, it gives rise to an equal number of free electrons and holes near the point of interaction, and the electrons and the holes start to move under the influence of the electric field within the detector. If $Q_e(0)$ electrons are created at time $t=0$ and position $\mathbf{r} = \mathbf{r}_0$, the trapping of the charge carriers causes an exponential decay of the free charge carriers.

$$Q_e(t) = Q_e(0) \exp(-t/\tau_e), \quad (1)$$

where τ_e is the lifetime of the electrons. A similar expression can be written for the holes. In the following equations, we will omit the subscript e for the electrons, keeping in mind that the equations apply for both the electrons and the holes.

The motion of the free carriers can be characterized by their velocity, $\mathbf{v}$. In the typical low field condition, the velocity is a linear function of the electric field.

$$\mathbf{v}(\mathbf{r}(\mathbf{r}_0, t)) = \mu \mathbf{E}(\mathbf{r}(\mathbf{r}_0, t)), \quad (2)$$

where μ is the mobility and $\mathbf{E}(\mathbf{r}(\mathbf{r}_0, t))$ is the electrostatic field along the trajectory of the charges at the position $\mathbf{r}(\mathbf{r}_0, t)$ and time t . During their motion, the carriers experience an electrostatic force $\mathbf{F}$, given by

$$\mathbf{F}(\mathbf{r}(\mathbf{r}_0, t)) = Q(t) \mathbf{E}(\mathbf{r}(\mathbf{r}_0, t)). \quad (3)$$

Based on the principle of superposition, each electrode exerts a force that, summed together with the forces by all the other electrodes, gives the total force on the charge carriers. The force that the i th electrode exerts is

$$\mathbf{F}_i(\mathbf{r}(\mathbf{r}_0, t)) = Q(t) \mathbf{E}_i(\mathbf{r}(\mathbf{r}_0, t)), \quad (4)$$

where $\mathbf{E}_i(\mathbf{r}(\mathbf{r}_0, t))$ is the electric field in the configuration where the i th electrode is set at the biasing voltage, V_i , but all the other electrodes are grounded. It is convenient to introduce

$$\mathbf{E}_i^w(\mathbf{r}(\mathbf{r}_0, t)) = \mathbf{E}_i(\mathbf{r}(\mathbf{r}_0, t)) / V_i. \quad (5)$$

In this case, $\mathbf{E}_i^w(\mathbf{r})$ is the electric field when the i th electrode is set at 1 Volt and all the other electrodes are grounded. This electric field is called the weighting field, and the potential field associated with it is called the weighting potential [3]. The power expended by the moving particle on the i th electrode is $\mathbf{F}_i \cdot \mathbf{v}$, and this must equal the power induced on the external circuit, $i \times V_i$, where i is the current. Typically, V_i is kept constant, and hence

$$i(\mathbf{r}_0, t) = \mu Q(t) \mathbf{E}_i^w(\mathbf{r}(\mathbf{r}_0, t)) \cdot \mathbf{E}(\mathbf{r}(\mathbf{r}_0, t)). \quad (6)$$

The function that is the total charge, $q_i(\mathbf{r}_0)$ induced on the i th electrode by a radiation quantum interacting at the position $\mathbf{r}_0$ is called the charge induction map, and it is

$$q_i(\mathbf{r}_0) = \int_0^T i(\mathbf{r}_0, t) dt, \quad (7)$$

where T is the integration time of the measurement. In typical nuclear electronics, T is approximately equal to the shaping time of the spectroscopy amplifier. Equations (1) and (2) can be used to simulate the charge carrier transport, and Equations (5), (6), and (7) can be used to calculate the charge induced on each electrode. The pulse height spectrum for the detector can be obtained from the charge induction map. In a multichannel analyzer, the counts in the channel collecting charges between q_j and $q_j + \Delta q$ are determined by the equation

$$N_j = \int q(\mathbf{r}_0) \vartheta(q(\mathbf{r}_0) - q_j) \vartheta(q_j + \Delta q - q(\mathbf{r}_0)) d\mathbf{r}_0, \quad (8)$$

where ϑ is the Heaviside step function, and the integration is over the entire detector volume.

When combined with the solutions for the weighting fields and the total electric field, these equations allow for the simulation of the pulse height spectrum produced by the detector. A simulated pulse height spectrum can be directly compared to the experimental spectrum, and the charge induction map and the weighting fields can give insights into the operation of the device, by giving information on the spatially resolved response of the device to incident ionizing radiation.

The simulation can be applied to conventional planar detectors, but its real power is in simulating multiple electrode 3-D geometries, such as an unipolar device, that can not be readily treated by analytical models. In an ideal unipolar device, the charge induction map for the anode would be relatively large and uniform between the grid and the cathode, and it would be zero between the grid and the anode.

COMPUTATIONAL METHOD

The detector simulation divides naturally into two parts. The first part is the determination of the electrostatic field within the detector, and the second part is the calculation of the charge transport within the detector, along with the corresponding signal induced on the electrodes. Except in the simplest approximations, both parts require detailed 3-D numerical computations.

For our simulation, the electrostatic field within the detector was solved by applying a finite-element method called successive overrelaxation (SOR) to the Poisson equation [6]. In this method, the field is first discretized and a trial potential field is selected, then SOR is applied to the lattice space. Successive iterations result in a lowering of the total electrostatic energy of the field and convergence of the field. We defined a lattice space of $120 \times 120 \times 40$ and set the lattice spacing at 0.1 mm. Typically, 1000 iterations gave 1 part in 10^5 convergence of both the total electrostatic energy and the potential field at all points of the lattice. Periodic boundary conditions were assumed, and the detector was placed inside the boundary. For the results to be discussed here, $10 \times 10 \times 2$ mm³ detectors with various electrode geometries and voltages were placed 1 mm away from all the border faces.

The charge transport was numerically computed using Equations (1) and (2), and the corresponding charge induction maps were also numerically calculated using Equations (5) through (9). The transport parameters for the simulation were typical for commercially available CZT [7]. The CZT electron and hole mobilities are taken to be 1000 and 100 cm²/V/sec, respectively, and the electron and hole lifetimes to be 3 and 1 μ sec, respectively. The dielectric constant of the detector was assumed to be 10 (cgs units) and that for the surrounding medium was assumed to be 1, i.e. the value for air. For the simulation of the pulse height spectra, a shaping time of 1 μ sec and uniform irradiation and ionization by 662 keV γ -rays from ¹³⁷Cs was assumed.

COMPUTATIONAL RESULTS

For the detector schematically shown in Fig.1, one of the important design parameters is the grid-to-anode spacing, Δs . One should minimize Δs to obtain the largest active detector

volume, while allowing minimal sacrifice to the detector resolution. Four grid spacings of 1, 3, 5, and 7 mm from the cathode were modeled. In Fig. 2, the weighting-potential fields for the 3 mm case are shown. The anode, grid, and cathode biases are 275, 0, -1000 V, respectively. The weighting potentials show that the grid shields the anode and the cathode from each other, but there are distortions near the grid. Note that the equipotential lines push through the center region at the plane of the grid. This effect becomes more pronounced as Δs becomes smaller.

For the same boundary conditions as Fig. 2, Fig. 3 (a) and (b) show the charge induction maps for the anode, resolved of the electron and the hole contributions. The charge induction map for the electron can be seen to be fairly uniform between the cathode and the grid, characteristic of an unipolar device. However, near the grid, distortions can be seen, and $q(r_0)$ drops to zero nearly linearly between the grid and the anode. The charge induction map for the hole is nearly zero between the grid and the cathode, and it decreases nonlinearly from the anode to the grid, due to hole trapping.

Fig. 2(a) A contour map of the weighting potential for the anode, examined in the plane in the middle of the $10 \times 10 \times 2 \text{ mm}^3$ CZT detector. Each pair of contour lines separates 25 mV, the anode being at 1 Volt and the other electrodes being grounded. The potential is depicted in the lattice space, where 1 lattice unit is 0.1 mm. The grid is located 3 mm away from the anode and it is 0.1 mm thick. (b) The weighting potential for the cathode. Each contour line separates 25 mV.

Fig. 3(a) The charge induction map on the cathode due to the electron transport only, examined in the plane in the middle of the detector. (b) The charge induction map on the anode due to the hole transport only, scaled up for ease of viewing. The absolute magnitude of the charge induced by the holes is much smaller than for the electrons.

Recalling that $q(r_0)$ is the charge induced at an electrode, a detailed examination of the induction maps shown in Fig. 3 indicates that, even though $q(r_0)$ for the anode is fairly uniform between the grid and the cathode, it has a local maximum near the grid, due to the shorter distance to the anode and hence shorter transit time. Because of electron trapping, shorter transit times mean larger signals.

Some simulated pulse height spectra for various grid-to-anode spacings, $\Delta s'$, are shown in Fig. 4. For $\Delta s = 1$ and 3 mm, the electron peaks are seen to have sharp main peaks surrounded by broader tails. It was found by detailed examination of the charge induction maps that the sharp

main peaks are due to electrons originating from the region near the plane of the grid. More specifically, for $\Delta s = 1$ mm, the signal originates mostly from the region between ~ 2 and 4 mm away from the grid, on the cathode side of the detector. This region is relatively far away from the grid, because the close proximity of the grid to the anode causes the anode weighting potential to extend significantly beyond the grid plane. For $\Delta s = 3$ mm, it originates from the region between ~ 1 and 3 mm away from the grid, on the cathode side.

The broader tails in both the $\Delta s = 1$ and 3 mm cases originate from the regions near the grid and near the cathode. The larger inhomogeneity of the electric field near the grid causes the 1 mm case to have a much broader tail.

In the 5 mm case, a qualitatively different shape is seen. The inhomogeneity in the field that gave the sharp feature is no longer there, and this results in a relatively uniform charge induction map between the grid and the cathode. However, this is at the price of detection efficiency and decreased charge collection. The count under the electron peak in this case is only 24% compared to the 1 mm spacing case. Note that this is worse than one would expect based purely on detection volume considerations, which would predict a decrease to only 56%. The additional degradation is mostly due to increased electron trapping between the grid and the anode.

Fig. 4. The simulated pulse height spectra of the unipolar device described in the text with grid-to-anode spacings between 1 and 7 mm. The signal is taken at the anode. The peaks are due to photoelectric interaction of 662 keV γ -rays. A real spectrum would have additional features due to Compton scattering and electronic noise of the nuclear electronics.

In the 7 mm case, the electron peak broadens again, and the peak position moves to lower channels, both effects being mostly due to the electron trapping.

A comparison of the simulation and the experimental data is shown in Fig. 5. The experimental spectrum is discussed in detail in Ref. 5. For the experiment, a $10 \times 10 \times 2$ mm³ CdZnTe crystal was used. Two Au electrodes were evaporated on opposite 10×2 mm² faces as the cathode and the anode. The grid was 2 mm thick Au film located 1.5 mm away from the anode. The cathode was biased at -1301 V and the anode at +220 V. The anode signal was triggered off the cathode to select ionization events occurring between the grid and the cathode, to optimize the energy resolution.

Fig. 5. The simulated pulse height spectrum (solid line) and the experimental data (circles) for the unipolar γ -ray detector described in the text, taken from the anode with cathode triggering. The energy resolution is excellent, being $\sim 1.4\%$ FWHM. For the simulation of the pulse height spectrum, finer binning was done to match the experimental pulse height channel bin size, and the overall count per minute (cpm) was scaled to the experimental photoelectric peak.

The simulation was performed using the exact geometry, the typical CZT materials parameters, and the cathode triggering used in the experiment. It can be seen that the photoelectric peak is fit very well, even though there are no fitting parameters. The tail in the experimental spectrum may be lower due to a larger electron lifetime or a higher electron mobility.

To see the effect of the materials parameters on the pulse height spectrum, additional simulations were done. Fig. 6 shows a comparison of two simulated pulse height spectra, with the typical electron lifetimes of $3\ \mu\text{sec}$ and a shorter lifetime of $1\ \mu\text{sec}$. Cathode triggering was not used in these cases. Lower lifetime resulted in increased tailing and broadening of the photoelectric peak. It is clear that, by varying the materials parameters, one can get an even better fit than shown in Fig. 5.

Fig. 6. The simulated pulse height spectra for electron lifetimes of $3\ \mu\text{sec}$ (dashed line) and $1\ \mu\text{sec}$ (solid line). The shorter lifetime results in a longer tail and degraded energy resolution. Cathode triggering was not included in these cases.

CONCLUSION

In conclusion, simulation of Sandia's unipolar CdZnTe γ -ray detectors were performed. The simulated pulse height spectra for the electron-transport-only devices were in very good agreement with the experimental results. Detectors with various grid-to-anode spacings were simulated and found to have very different pulse height spectra. In addition, the electron lifetime was varied and also found have a significant effect on the pulse height spectra, demonstrating the importance of the device design and the materials properties on the performance of the electron-transport-only devices. In the future, simulations will be completed on other device structures, and detailed comparisons between the simulations and the experimental data will be used to optimize the device performance.

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REFERENCES

1. For a recent review, see Semiconductors for Room-Temperature Radiation Detector Applications, Proceedings of Materials Research Society Symposium, Vol. 302, edited by R. B. James, T. E. Schlesinger, Paul Siffert, and Larry Franks (Material Research Society, Pittsburgh, Pennsylvania, 1993).
2. For a discussion of the Frisch grid concept, which is akin to the unipolar device concept, see Knoll, G. F., Radiation Detection and Measurement, John Wiley & Sons, New York, 1979, pp. 178.
3. P. N. Luke, *Appl. Phys. Lett.* **65**, 2884(1994).
4. J. C. Lund (patent pending).
5. J. C. Lund, E. Y. Lee, N. R. Hilton, B. A. Brunett, F. Olshner, P. Bennet, K. S. Shah, H. Hermon, T. P. Viles, and R. B. James (to be published).
6. W. H. Press, S. A. Teukolsky, W. T. Vetterling, B. P. Flannery, Numerical Recipes in C, 2nd edition, Cambridge University Press, New York, 1992, pp. 866.
7. See, for example, M. Squillante in Semiconductors for Room-Temperature Radiation Detector Applications, Proceedings of Materials Research Society Symposium, Vol. 302, edited by R. B. James, T. E. Schlesinger, Paul Siffert, and Larry Franks (Material Research Society, Pittsburgh, Pennsylvania, 1993).

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