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ADVANCED RADIATION DETECTOR DEVELOPMENT

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PROGRESS REPORT

Advanced Radiation Detector Development
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Glenn F. Knoll, Project Director
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Since our last progress report, the project at The University of Michigan has continued to concentrate on the development of gamma ray spectrometers fabricated from cadmium zinc telluride (CZT). This material is capable of providing energy resolution that is superior to that of scintillation detectors, while avoiding the necessity for cooling associated with germanium systems. In our past reports, we have described one approach (the coplanar grid electrode) that we have used to partially overcome some of the major limitations on charge collection that is found in samples of CZT. This approach largely eliminates the effect of hole motion in the formation of the output signal, and therefore leads to pulses that depend only on the motion of a single carrier (electrons). Since electrons move much more readily through CZT than do holes, much better energy resolution can be achieved under these conditions. In our past reports, we have described a 1 cm cube CZT spectrometer fitted with coplanar grids that achieved an energy resolution of 1.8% from the entire volume of the crystal. This still represents, to our knowledge, the best energy resolution ever demonstrated in a CZT detector of this size.

We are continuing to develop the coplanar grid approach, and have made improvements in the specific grid pattern that we now favor. These improvements came about because our study of the existing pattern demonstrated that a slight imbalance in the induced charges on the two components of the grid resulted from an unavoidable asymetry in their placement on the crystal face. This imbalance turned out to be the principal limitation on the energy resolution that we reported earlier. As a result, we invested considerable analytical effort in a re-design of the grid to minimize this imbalance. Our analytic studies showed that a redesigned grid could reduce the effect of the asymetry to insignificant levels. A new generation of CZT 1 cm cube detectors was then fabricated and tested, with mixed results. While we were able to definitely see the improvement from the re-designed grid pattern, this new generation of detectors showed a much higher noise level than observed from the previous generation. Both were fabricated at Digirad laboratories, using ostensibly the same fabrication steps. The increased noise level in the second generation has prevented us from achieving the better energy resolution expected from the re-designed grid pattern. Once our initial measurements were completed, we returned these crystals for re-fabrication in the hope that this anomalous source of noise will be eliminated by reprocessing the devices. The exact origin of this noise has not yet been identified, nor have the personnel at Digirad been able to identify any change in the processing steps that could account for the very different observed behavior.

We therefore feel that a critical step in the further development of coplanar grid devices on CZT is a better understanding of the surface properties and electrode formation on this material. We are somewhat disappointed by the lack of consistency in the results obtained from the devices fabricated at Digirad, and are pursuing alternatives at this point. We are in discussions with personnel at NASA/Goddard laboratory involving the fabrication of new CZT coplanar grid devices at their facilities. We have past experience in working with this laboratory and feel that their surface processing techniques offer an alternative that should be investigated. We are also evaluating whether an effort on a more fundamental understanding of surface preparation and electrode formation on CZT should be undertaken here at The University of Michigan.

Past progress reports have also described our pioneering efforts at extracting depth information from CZT spectrometers through the use of a third output signal from the cathode. This new technique has now been widely adopted by other laboratories studying CZT spectrometers. Its advantage is that we are able to understand the variations in charge collection properties as a function of depth into the material, and are thus able to make 1-D corrections for trapping that inevitably occur. Because these corrections will be different at each depth, we are able to compensate for some of the variability in the composition of the original crystalline material.

Taking this concept one step further, we have embarked on a major effort to develop a fully three-dimensional CZT spectrometer that is capable of corrections not only with depth, but throughout the full volume of the detector. This has involved the fabrication of an 11 by 11 pixel pattern on the surface of a 1 cm^3 CZT crystal, and the separate readout of each of these 121 pixels through a recently developed low-noise integrated circuit. We then apply the same depth sensing technique described earlier to further resolve 20 separate layers that are parallel to the pixellated surface. The net result is that we have over 2400 voxels defined in the volume of the detector, each one of which can provide an independently measured pulse-height spectrum. This now allows us to make pulse height corrections not only as a function of depth, but also that can vary in a non-uniform manner throughout the detector volume. Two such 3-D spectrometers have now been fabricated and tested. First results are described in the papers that are attached to this report and have already shown excellent energy resolution from the entire volume of the device. To our knowledge, these are the first 3-dimensional semiconductor spectrometers ever successfully demonstrated, including the intensive development efforts in silicon and germanium over the past several decades.

Looking ahead, we are continuing to develop both the coplanar grid and the three-dimensional volume approach to overcoming the current limitations in CZT performance. We continue to feel that the 3-D electronic correction of the response in CZT, while adding to the complexity of the device, will prove to be more feasible for field instrumentation as the integrated circuits designed specifically for parallel readout of this type of devise become more mature. This is an area where the current growth curve is very steep, and we are in a good position to benefit from the more sophisticated ICs that are currently under development. We have established a collaboration with IDE Corporation which will yield the next generation IC that will greatly reduce the electronic noise level and expand the capability of our current CZT spectrometers.

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3-D Position Sensitive CdZnTe Gamma-Ray Spectrometers

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Abstract

Two 3-D position-sensitive room temperature semiconductor γ-ray spectrometers have been built using 1 cm^3 cubic CdZnTe crystals. The lateral coordinates of γ-ray interaction are obtained from the location of the $11(x)\times 11(y)$ pixellated anodes and the depth (z) is obtained from the ratio of the signals coming from the cathode and the anode. Energy spectra from 662 keV incident γ-rays have been collected from each of the $11(x) \times 11(y) \times 20(z)$ voxels in both of the CdZnTe devices. After corrections for electron trapping, the difference of weighting potentials in 3-D, and for the gain variation of the readout circuitry, energy resolutions of 1.70%(11.3 keV) FWHM and 1.84%(12.2 keV) FWHM were obtained at 662 keV γ-ray energy on the first and second detectors respectively, from the whole bulk for single-pixel events. Possible improvements in the detector performance are discussed.

1 Introduction

By combining 2-D position sensing using a pixellated anode array [1] yielding good energy resolution from the small pixel effect [2], and the depth sensing technique [3, 4] for electron trapping corrections, the first two 3-D position sensitive CdZnTe γ-ray spectrometers have been fabricated.

An 11×11 pixellated anode array was fabricated on one 10×10 mm surface of each 1 cm^3 cube CdZnTe crystal at NASA Goddard Space Flight Center. The details for the fabrication process to achieve good metal electrodes for wire bonding and high surface resistivity was published previously [5]. The (x,y) coordinates (in the plane parallel to the anode surface) of γ-ray interactions are obtained from the location of the pixel anode where electrons are collected. Instead of using an array of simple square pixel anodes [1], each square anode is surrounded by a common non-collecting grid which is biased at a potential lower than that of the pixel anodes [6]. As shown in Fig. 1, each pixel has a dimension of 0.7×0.7 mm, with a collecting anode of 0.2×0.2 mm at the center surrounded by a common non-collecting grid with a width of 0.1 mm. Since the non-collecting grid is biased at lower potential relative to that of the collecting anodes, electrons are guided towards the collecting pixel anodes. More importantly, the dimension of the pixel anode that is smaller than the pixel dimension enhances the small pixel effect and minimizes any induced signal from the movement of holes. The 11×11 anode array covers an area of 7.8×7.8 mm on the 10×10 mm CdZnTe anode surface. The gaps between the boundary of the non-collecting grid and the edges of the crystal facilitated fabrication, but resulted in an effective volume of peripheral pixels, especially the four corner pixels, that is larger than the volume of each of 9×9 central pixels. A picture of the CdZnTe detector wirebonded to the fanout board which is then wire bonded to the readout ASIC (VA1 chip) is shown in Fig. 2.

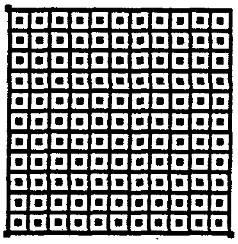

Figure 1: Top view of pixellated anode.

2 Depth Sensing

The γ-ray interaction depth between the cathode and the anode is obtained from the ratio of the cathode and the anode signals [3, 4]. This technique provides the depth (z) of the γ-ray interaction for single-site events, and

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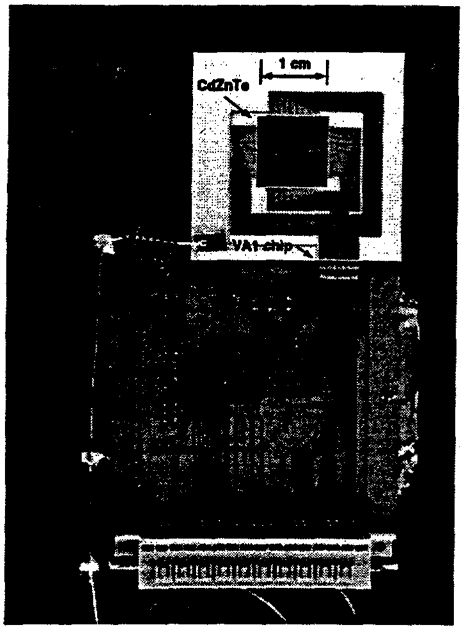

Figure 2: A picture of the detector system.

the centroid depth for multiple-site interactions, such as Compton scattering events.

In order to identify individual γ-ray interaction depths for multiple-site events, the signal from the non-collecting grid is read out using an A250 [7] charge sensitive preamplifier. When electrons generated by an energy deposition are deflected towards the collecting pixel anode near the anode surface, a negative pulse is induced on the non-collecting grid as shown in Fig. 3. A differential circuit provides a positive pulse corresponding to the negative drop of the non-collecting grid signal. A threshold circuit uses the differential output to produce a logic pulse when the differential signal is above the set threshold. The threshold circuit triggers the data acquisition system, and provides start and stop signals to a time-to-amplitude converter (TAC) so that the interval of drifting times of electron clouds can be measured. By combining the centroid depth, pulse amplitudes from each pixel anode and the depth interval between energy depositions, the depth of each individual energy deposition can be obtained.

Although the differential circuit can identify multiple γ-ray interaction depths, the TAC limits the number of interactions to two. Therefore, the current system provides γ-ray interaction depths for only single and two-site events. Events having more energy depositions than two can be identified by the number of anode pixels with recorded signals, but only the centroid interaction depth can be obtained. The threshold on the grid signal is relatively high at about 100 keV in the present measurements.

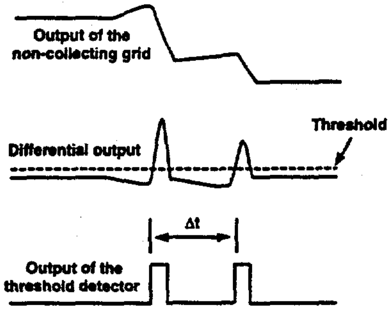

Figure 3: Illustration of depth sensing for multiple-site events.

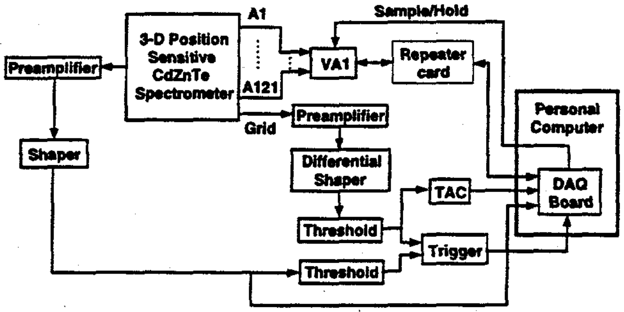

Figure 4: The schematic diagram of the data acquisition system.

3 Data Acquisition System

The data acquisition system is schematically shown in Fig. 4. Signals induced on the 11×11 pixel anodes are read out by a VA1 integrated circuitry [8] which has 128 channels of independent preamplifiers, shaping amplifiers and sample/holds. The cathode signal is processed by an A250 preamplifier followed by an EG&G Ortec 572 shaping amplifier with a shaping time constant of 0.5 μs. Since the sample/hold signal required by the VA1 circuitry holds the pulse amplitudes of all 128 channels simultaneously, the peak amplitudes of Compton scattering events will not be obtained correctly by the fixed sample/hold time due to different pulse peaking times. Because of the high threshold needed due to the poor signal-to-noise ratio of the grid signal, the trigger is instead taken from the cathode signal for low energy γ-ray events. By using the combination of the grid and the cathode triggers, γ-rays within the whole energy range can be collected. For simplicity, the grid trigger was used for higher energy γ-ray sources, such as ^{137}Cs, and the trigger from the cathode signal was used for low energy γ-rays, such as ^{241}Am, in our measurements.

4 γ-Ray Spectroscopy

Both 1 cm^3 cubic 3-D position sensitive CdZnTe spectrometers have been tested using a 10 μCi ^{137}Cs source

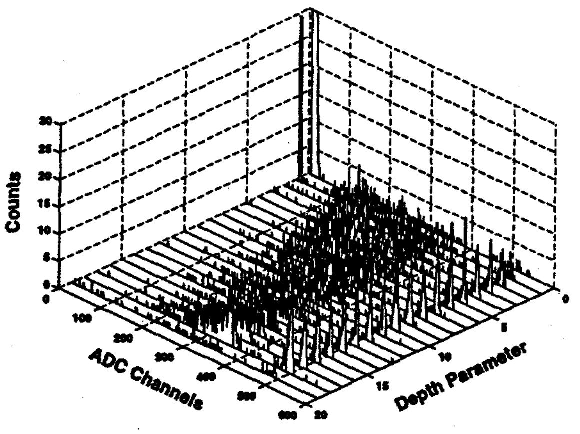

Figure 5: Energy spectra of ^{137}Cs obtained from pixel #6 of the first detector at different depths.

located about 5 cm from the cathode surface. The biases between the cathode and the anode were 2000 V and 1400 V for the two devices, and the biases between the pixel anodes and the non-collecting grid were 50 V and 30 V respectively. The lower voltages used on the second device were dictated by higher leakage currents which saturated the preamplifiers on the VA1 chip. Energy spectra were measured sorted by the number of pixels producing signals per incident gamma.

Fig. 5 shows the energy spectra obtained from pixel anode #6 of the first detector as a function of 20 γ-ray interaction depths ranging from near the anode surface to the cathode surface. Single-pixel events, including multiple interactions depositing energy within the column underneath one anode pixel, were selected for the spectra. The energy threshold for rejection of multiple-pixel events was ~10 keV. Since a depth resolution of less than 0.5 mm can be achieved at 662 keV γ-ray energy [4], spectra were binned into 20 depths. Thus each of the 2420 resolved voxels corresponds to a volume of about 0.7(x)×0.7(y)×0.5(z) mm in the detector.

The centroids of 662 keV photopeak amplitudes from each voxel were measured. Electron trapping can be observed from the significant decrease in pulse amplitude with increasing electron drift distance as shown in Fig. 6. The sharp drop in photopeak amplitude near the anode surface (depth parameter < 3) is caused by the non-linear weighting potential in the vicinity of the anode surface. The correction for electron trapping, the effect of the weighting potential, and the electronic gain variation is performed by applying a multiplicative constant to the pulse amplitude depending on the voxel and the energy deposition (if necessary), so that the photopeak centroids of all voxels are aligned at each γ-ray energy.

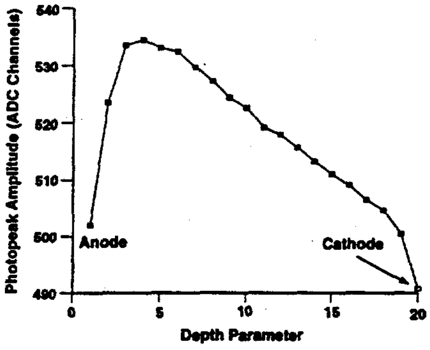

Figure 6: The centroids of ^{137}Cs photopeak amplitudes as a function of the depth parameter (1-20) from pixel #6 of the first detector.

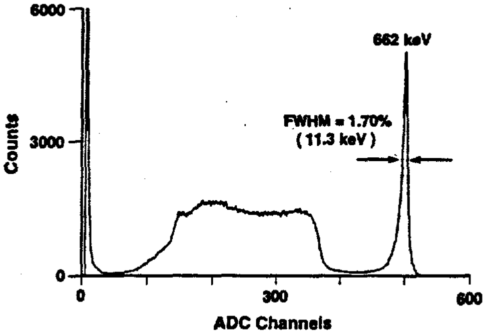

Figure 7: Energy spectrum of ^{137}Cs obtained from the whole bulk of the first detector for single-pixel events.

After these corrections, the energy spectrum of 662 keV γ-rays was obtained from the whole bulk for single-pixel events. The result, as shown in Fig. 7, yielded energy resolutions of 1.70% (11.3 keV) FWHM and 1.84% (12.2 keV) FWHM from the two devices.

Since there is a gap of ~1 mm left between the boundary of the non-collecting grid and the edges of the 1 cm square CdZnTe surface, the effective volume and the charge collection of peripheral pixels are different from that of central pixels. In order to isolate the detector performance from this edge effect, the energy spectra of 662 keV γ-rays were collected from just the central 9×9 pixels. Energy resolutions of 1.51% (10.0 keV) FWHM (see Fig. 8) and 1.74% (11.5 keV) FWHM were obtained from the two devices respectively.

The first detector was also tested at 60 keV using a ^{241}Am source located ~5 cm from the cathode surface. After the correction for electronic gain variation, an energy resolution of 11.3% (6.7 keV) FWHM was obtained (see Fig. 9).

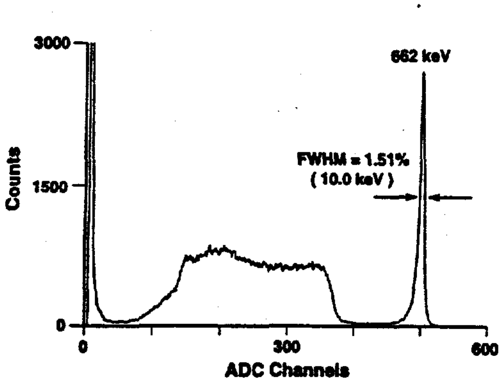

Figure 8: Energy spectrum of ^{137}Cs obtained from the central 9×9 pixels of the first detector for single-pixel events.

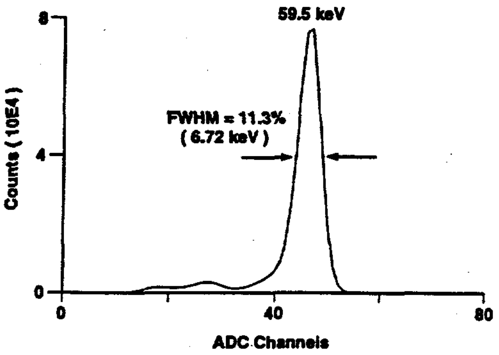

Figure 9: Energy spectrum of ^{241}Am obtained from the whole bulk of the first detector for single-pixel events.

5 Discussions

There are several factors which limited the detector performance. First, the VA1 chip was designed for very low leakage current at its inputs. The feedback FETs on the VA1 preamplifiers must be operated in an ad hoc status to prevent preamplifier saturation by the leakage current of even a few nA from each pixel anode. The electronic noise thus increased from ~3 keV to 6-7 keV FWHM. The electronic noise should reduce to ~3 keV FWHM if AC coupling or equivalent circuitry between the pixellated anodes and the VA1 chip replaces the DC coupling currently used. Second, the sample/hold signal required by the VA1 chip holds the pulse amplitude of all 128 channels simultaneously. For Compton scattering events, the peak amplitudes can not be correctly sampled due to the variable electron drifting times. This leads to significant degradation in energy resolution for multiple-pixel events. The energy resolution of ^{137}Cs for two pixel events was 3.7% (24.5 keV) FWHM on the first detector, which is significantly worse than that predicted from the results of single-pixel events. Third, while γ-ray Monte-Carlo simulations using GEANT3 [9] indicate that ~50% of 662 keV γ-ray interactions should be registered as single-pixel events when electron cloud size is not considered, only 25% and 15% of 662 keV γ-ray events were recorded as single-pixel events on the two detectors. This discrepancy indicates that the actual size of the electron clouds increases the fraction of multiple-pixel events. Since the energy resolution degrades when the number of pixels which record signals increases, the optimum pixel dimension should be large enough to minimize charge sharing between anode pixels, yet small enough to correct for the non-uniformity of the detector material and produce the small pixel effect.

Both 1 cm^3 cubic CdZnTe detectors were fabricated using discrimination grade crystals [10]. Significant material defects were observed within the bulk of the second device. These defects may account for the higher leakage current and the low fraction of single-pixel events compared with the first device (which showed a much more uniform γ-ray response within the detector volume). Thus we feel that the measured energy resolutions do not represent the limitations of future 3-D position sensitive CdZnTe spectrometers, especially for multiple-pixel events. Our initial investigation has been focused on the single and two-site interaction events, which account for ~60% of 662 keV γ-ray interactions collected.

6 Acknowledgments

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[8] IDE AS, Veritasveien 9, N-1322 Hovik, Norway.

[9] GEANT3, CERN, Geneva, Switzerland.

[10] eV Products, 375 Saxonburg Boulevard, Saxonburg, PA 16056, USA.

Effects of Charge Sharing in 3-D Position Sensitive CdZnTe Gamma-Ray Spectrometers

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Abstract

Two 3-D position-sensitive semiconductor γ-ray spectrometers operable at room temperature, have been fabricated using 1 cm^3 cubic CdZnTe crystals. Gamma-ray spectra have been obtained from $11(x)\times11(y)\times20(z)$ voxels, each corresponds to $\sim0.7\times0.7\times0.5$ mm in the detector volume. Individual spectra from each of the 2420 voxels were corrected for electron trapping, differences in weighting potentials, and the gain variation of the readout circuitry. Energy resolutions of 1.70%(11.3 keV) FWHM and 1.84%(12.2 keV) FWHM were obtained at 662 keV from the combined output of the entire volume for single-pixel events. Charge sharing between neighboring pixels has been observed and the sizes of electron clouds are estimated from these experimental data. An understanding of electron cloud dimensions is important for the design of future detectors using pixellated electrodes.

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1 Introduction

Gamma-ray spectrometers with 3-D position sensitivity are of interest in nuclear spectroscopy and imaging, γ-ray astronomy, medical imaging and high energy physics applications. CdTe, HgI_2 and CdZnTe have attracted attention for decades because of their high atomic number constituents desired for high stopping power and wide band-gaps needed for room temperature operation. However, widespread use of these devices has been hindered by charge trapping, material non-uniformity and polarization problems.

By combining 2-D position sensing using a pixellated anode array [1], which can yield good energy resolution from the small pixel effect [2], and the depth sensing technique [3, 4] that makes use of the low hole mobility in CdZnTe, two 3-D position sensitive CdZnTe γ-ray spectrometers have been fabricated using 1 cm^3 cubic crystals. Because of the small pixel effect [2], the induced charge on each pixel anode is dominated by the number of electrons collected by the anode. Therefore, the incomplete charge collection generally observed in conventional planar detectors due to severe hole trapping can be dramatically improved. The 3-dimensional position sensitivity not only provides imaging capability in the devices, but also permits voxel-specific corrections to be applied throughout the volume to accommodate non-uniform charge transport properties. To our knowledge, these are the first fully 3-dimensional γ-ray spectrometers fabricated from semiconductor crystals.

2 System Description

Each detector system [5] consists of a 10×10×10 mm CdZnTe crystal with an 11×11 pixellated anode array fabricated on the anode surface. Signals induced on pixel anodes are read out by an integrated circuit VA1 [6] which has 128 channels of independent preamplifiers, shaping amplifiers and sample/holds. The data acquisition system is based on a National Instrument ATMIO-16E ADC board. Each pixel of the anode has a dimension of 0.7×0.7 mm, with a collecting anode of 0.2×0.2 mm at the center surrounded by a common non-collecting grid electrode with 0.1 mm width. The 11×11 anode array covers an area of 7.8×7.8 mm on the 10×10 mm CdZnTe anode surface. The margins between the anode pattern and the edges of the crystal facilitated the anode fabrication, and can be reduced in future devices. The electrode fabrication was performed at NASA Goddard Space Flight Center [7], and wire bonding and detector assembly were carried out at Johns Hopkins University Applied Physics Laboratory.

The energy of a γ-ray interaction is obtained from the pulse amplitude from each anode pixel. The lateral position of the interaction is determined by identifying the pixel anode where electrons are collected, and the depth is obtained from the ratio of the cathode and the anode signals. The combination of signals from the cathode and the non-collecting grid electrode provides the trigger of the system [5] .

Both detectors have been tested using γ-ray sources [5]. Energy spectra were obtained from each of the voxels corresponding to a volume of about 0.7×0.7×0.5 mm in each device. The observed photopeak pulse height varies depending on electron trapping, the difference of weighting potentials and the variation of electronic gain of the VA1 chip. After aligning the centroids of the photopeak amplitudes of all voxels, the energy resolution can be dramatically improved. Energy resolutions of 1.70% (11.3 keV) FWHM and 1.84% (12.2 keV) FWHM were obtained at 662 keV γ-ray energy for the whole volume from the first and the second detectors respectively, for single-pixel events. The voltages applied between the cathode and the anode were 2000 V and 1400 V, and the biases between the pixel anodes and the non-collecting grid were 50 V and 30 V on the first and second detectors respectively. The energy threshold for rejection of multiple-pixel events was $\sim$10 keV. In order to observe the detector performance without the edge effect, energy spectra were collected from the central 9×9 pixel anodes, and the total energy spectra before and after the alignment of photopeak centroids are shown in Fig. 1 for comparison.

The first detector was also tested at 60 keV using a ^{241}Am source located $\sim$5 cm from the cathode surface. After correction for electronic gain variations, an energy resolution of 11.3% (6.7 keV) FWHM was obtained.

As summarized in our earlier paper [5], several factors limit the current detector performance, such as the saturation of the VA1 preamplifiers by leakage currents, the error in pulse peak sampling due to the fixed sample/hold timing of the VA1 chip, and the material defects within the CdZnTe crystals. Therefore, the measured energy resolutions certainly do not represent the limitations of future 3-D position sensitive CdZnTe spectrometers. We are presently limited by the timing characteristics of the VA1 chip to selecting single pixel events for best energy resolution since the sampling of multiple pixel events is not accurate. We present some results later for multiple pixel events, but the energy resolution is currently poorer for these cases.

By observing the variation of the photopeak counting rate as a function of the location of each voxel, the first detector shows a uniform detection efficiency within its active volume. In contrast, significant material defect was observed within about a third of the detector volume in the second device. Therefore, the first detector was used to carry out the following measurements.

3 3-Dimensional Position Sensing

The depth sensing technique [3, 4] provides the depth (z) of the γ-ray interaction for single-site events, and the centroid depth for multiple-site interactions, such as Compton scattering events. The current system can also provide individual interaction depths for two-site γ-ray interaction events by measuring the drift time interval between the two electron clouds [5].

In order to demonstrate the 3-dimensional position sensing capability of the system, an experiment was conducted as illustrated in Fig. 2(a). In the first 10 hour data collection, a 2.5 cm thick Pb collimator was located between a 10 μCi ^{137}Cs source and the detector. Since a portion of the 1 cm^3 cubic CdZnTe detector towards the cathode side was shielded by the shadow of the collimator, the photopeak counts of the voxels in the shadow was lower than those not in the shadow. Then the Pb collimator was removed, the second 10 hour data collection was carried out by keeping the ^{137}Cs source at the same location. The ratio of the photopeak counts with detector partly shielded to the counts without the Pb collimator is shown in Fig. 2(b). The counts along the vertical direction (y) were added together for better statistics. The ratio of the counts was used to cancel geometrical effects and γ-ray attenuation within the detector, and its value is normalized to a maximum of 64. The edge of the Pb collimator was clearly seen in Fig. 2(b). When the ratios of photopeak counts were calculated using the data from each of the 11 horizontal slices (a specific y value), similar attenuation results were obtained, but with poorer statistics due to the lower photopeak counts. The shadow of the edge of the Pb collimator was smeared in this image because of the long attenuation length of 662 keV γ-rays and the finite size of the ^{137}Cs source.

4 Observation of Charge Sharing

The energy spectra of 662 keV γ-rays incident from the cathode surface were sorted by the number of anode pixels producing signals per γ-ray event. The probability of a photopeak event as a function of pixel number was obtained from the entire crystal and the result is shown in Fig. 3. Monte-Carlo simulations using GEANT3 [8] were also performed under the assumption that the size of the electron clouds is negligible and no K-shell X-ray is generated. One can see that the fraction of single-pixel photopeak events actually observed is significantly lower than that of the simulation result. This shows that the dimension of electron clouds can not be neglected in comparison with the 0.7×0.7 mm anode pixel size. If we simply assume that the electron-hole pairs arrive at the anode within a circle of diameter of ϕ, a value of $\phi \approx 100$ μm can be estimated from the ratio of the measured single-pixel photopeak probability to that of the simulation at 662 keV.

There are several factors which can contribute to the size of the electron clouds when they are collected at the anode surface. They include the range of the primary photoelectron, the diffusion of charge carrier electrons, the range of K-shell X-rays (the range of X-rays from L, M, ... shells are very short), and Coulomb repulsion between electrons. Fig. 4 shows a simulation of the trajectory of a 662 keV photoelectron incident from (0,0,0) along the z axis. From the distribution of electron-hole pairs generated along the trajectory along the range of $\sim$100 μm, the increase of electron cloud size during the pulse collection time due to the Coulomb repulsion force between electrons can be calculated and is very small compared to this range. Therefore, the dimension of electron clouds are mainly determined by the first three factors.

In order to estimate the contribution from diffusion, the fraction of photopeak counts as a function of pixel number was obtained at 122 keV where the photoelectric effect dominates γ-ray interactions in CdZnTe. The experimental results at two interaction depths and two voltages between the cathode and the anode are summarized in Fig. 5. Again assuming that the electron clouds arrive at the anode with a diameter ϕ and that all interactions are photoelectric, the results shown in Fig. 5 lead to an estimate of $\phi = 41$ μm for interactions that occur near the anode, where the effect of diffusion is minimum. For interactions near the cathode, the additional effect of charge diffusion leads to values of 58 and 76 μm for applied voltages of 2000 V and 1400 V, respectively.

5 Conclusions

Two 3-D position sensitive room temperature γ-ray spectrometers were constructed using 1 cm^3 cubic CdZnTe crystals. Position sensing in 3-D was demonstrated and used to enhance the energy resolution obtained from the entire detector volume. The 3-dimensional data provides a powerful tool in studying the non-uniform charge collection properties of semiconductor crystals, and allows a new approach to overcoming some of the resulting limitations in their performance as spectrometers.

Significant charge sharing was observed between the 0.7×0.7 mm^2 pixels, and the results fit to a simplified model. In choosing the optimum pixel size for future detectors, several factors will need to be balanced. Small pixel size provides the best spatial resolution and enhance the small pixel effect that minimizes the effects of poor hole transport. However, the fraction of multiple pixel events will increase as pixel dimensions are reduced, increasing the electronic noise contribution to summed full-energy pulses. Better models of the charge sharing behavior will be an important help in the choice of optimum pixel size for future applications.

6 Acknowledgments

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Figure captions

Fig. 1: Energy spectra of ^{137}Cs obtained from the central 9x9 pixels of the first detector for single-pixel events.

Fig. 2: Demonstration of 3-dimensional position sensing of the device. (a) Top view of the experimental setup. (b) Ratio of the photopeak counts at 662 keV with detector partly shielded to the counts when detector was not shielded by a 2.5 cm thick Pb collimator.

Fig. 3: The fraction of photopeak counts versus pixel number. The size of the electron clouds was not considered in simulation.

Fig. 4: The trajectory of a 662 keV photoelectron obtained from Monte-Carlo simulation using EGS4.

Fig. 5: The fraction of photopeak counts versus pixel number measured at 122 keV γ-ray energy.

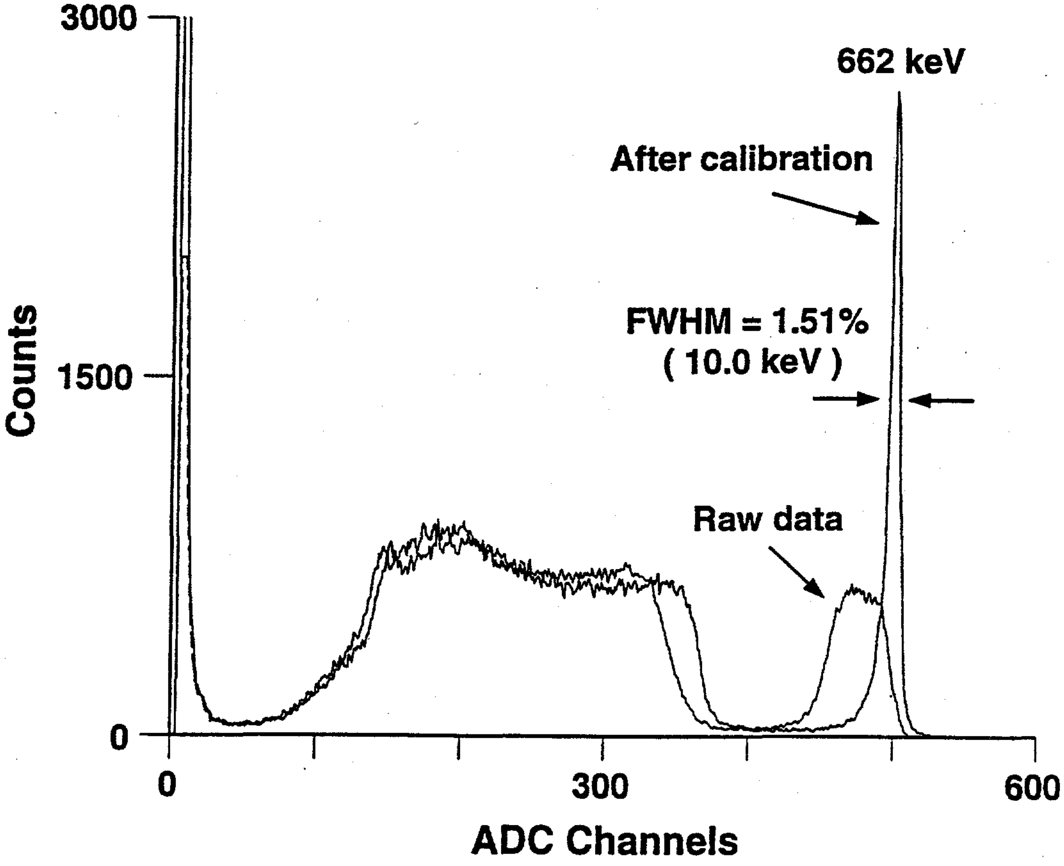
3000
1500
0
Counts
0
300
600
ADC Channels
662 keV
After calibration
FWHM = 1.51%
(10.0 keV)
Raw data

Figure 1:

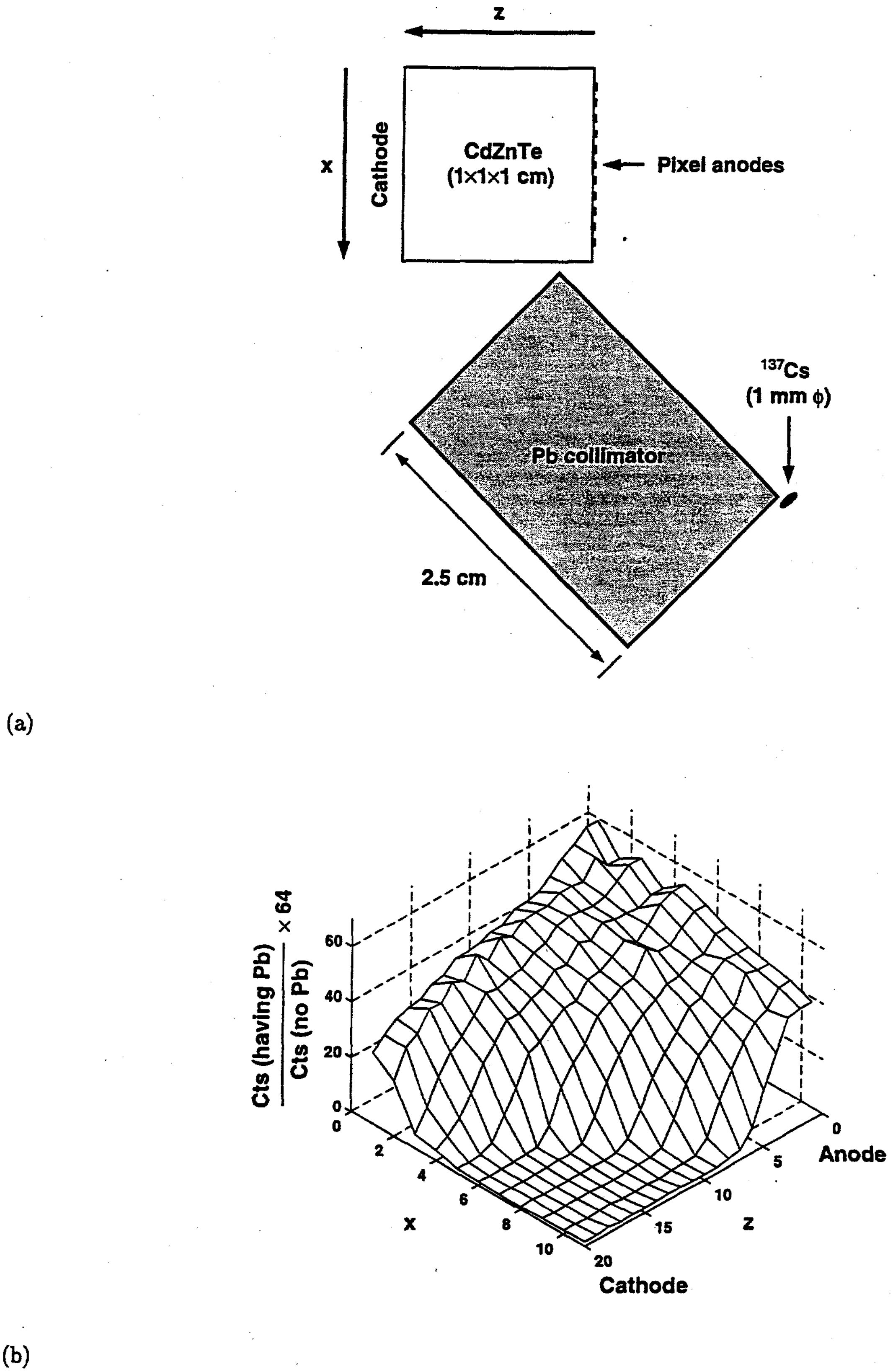
z
x
Cathode
CdZnTe
(1×1×1 cm)
Pixel anodes
137Cs
(1 mm ϕ)
Pb collimator
2.5 cm
(a)
Cts (having Pb) / Cts (no Pb) × 64
0
20
40
60
0
2
4
6
8
10
x
0
5
10
15
20
z
Anode
Cathode
(b)

Figure 2:

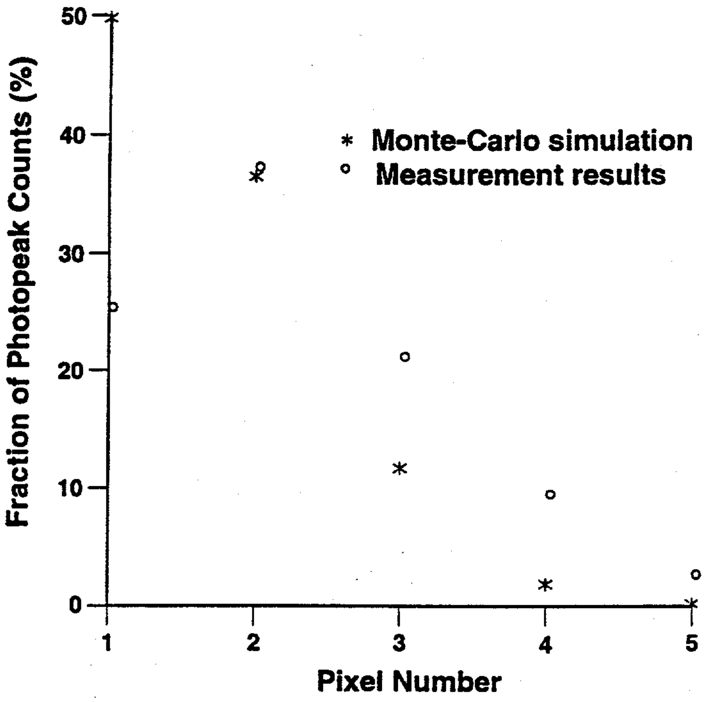
50
40
30
20
10
0
Fraction of Photopeak Counts (%)
* Monte-Carlo simulation
° Measurement results
1
2
3
4
5
Pixel Number

Figure 3:

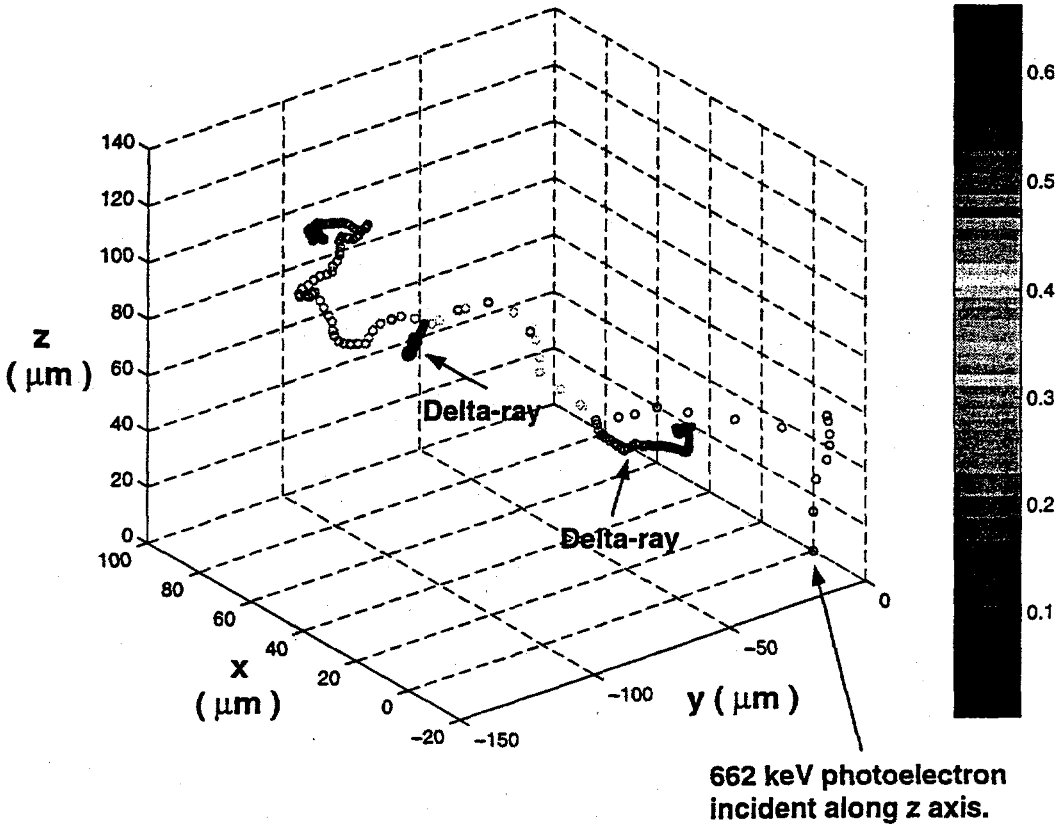
140
120
100
80
60
40
20
0
z
(µm)
100
80
60
40
20
0
-20
x
(µm)
-150
-100
-50
0
y (µm)
Delta-ray
Delta-ray
662 keV photoelectron
incident along z axis.
0.6
0.5
0.4
0.3
0.2
0.1

Figure 4:

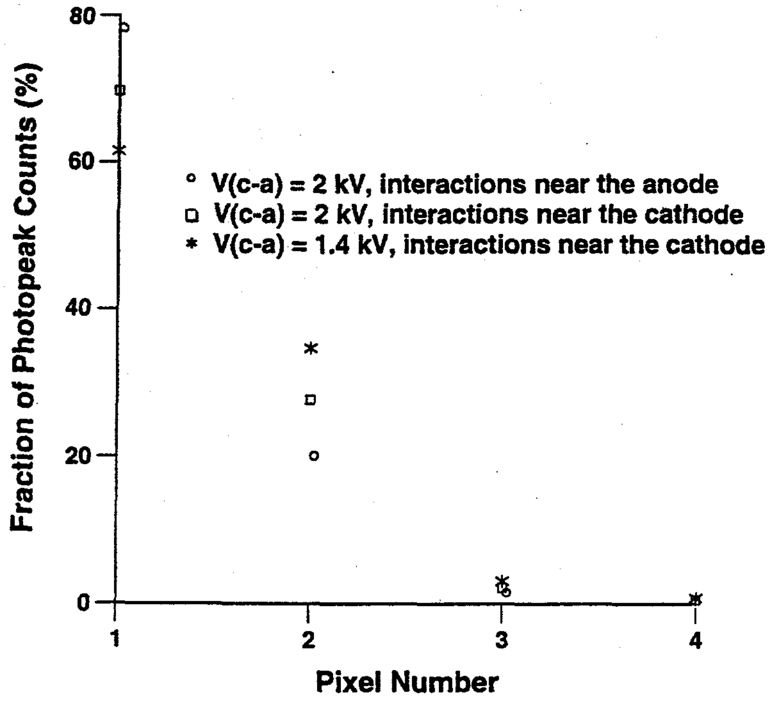
80
60
40
20
0
Fraction of Photopeak Counts (%)
1
2
3
4
Pixel Number
○ V(c-a) = 2 kV, interactions near the anode
□ V(c-a) = 2 kV, interactions near the cathode
* V(c-a) = 1.4 kV, interactions near the cathode

Figure 5: