Coplanar grid CdZnTe detectors for space science applications

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ABSTRACT

The characteristics and performance for two of the latest coplanar grid CdZnTe detectors, which use the third-generation coplanar grid design, will be discussed. These detectors, with dimensions of 1.5×1.5×0.9 cm^3 and 1.5×1.5×0.95 cm^3, were fabricated by Baltic Scientific Instruments, Ltd., using crystals from Yinnel Tech, Inc. The high $\mu_e\tau_e$ product measured for these crystals will lead to improved charge collection efficiency and better energy resolution. The spectroscopic performance obtained from the detectors, employing various methods such as depth sensing, radial sensing, and relative gain compensation, will be reported. Results from these measurements will give us insight into the material properties as well as the charge induction uniformity of the detector.

Keywords: coplanar grid, CdZnTe, depth sensing, radial sensing, gamma-ray spectroscopy

1. INTRODUCTION

CdZnTe has become a proven detection material with a high atomic number for good γ-ray stopping efficiency and a sufficiently large bandgap (1.7 eV) for room-temperature applications. The poor $\mu_h\tau_h$ product for this material makes it difficult to operate in a planar electrode configuration. However, the adverse effects of poor hole mobility can be ignored when utilizing in a single-polarity charge sensing mode. That is, by sensing the movement of electrons solely, the slow-moving holes will no longer act to degrade detector performance. In this way, the favorable properties of CdZnTe as a room temperature γ-ray detection device can be exploited, while mitigating the normally detrimental effect of poor hole mobility.

The method of single-polarity charge sensing in CdZnTe was first implemented by Luke[1] by way of the coplanar grid electrodes. These electrodes consist of two grids that when operated in a subtraction mode, produce a net signal that depends only on the movement of charge carriers very near to the grids. Thus, when operated as anodes, the coplanar grid electrodes will have a signal proportional to the number of electrons collected. Due to the effects of electron trapping, however, the number of electrons collected will be dependent on the depth of the γ-ray interaction, resulting in a depth dependent subtracted signal. In order to circumvent this dependency, Luke[1] introduced a means to compensate for the effects of electron trapping. This was done by applying a relative gain to one of the coplanar anode signals, introducing an artificial charge induction component to the subtracted signal that grows with increasing distance from the anodes. By selecting the optimal relative gain and assuming good material uniformity throughout the whole crystal, near-ideal electron trapping compensation can result.

Shortly after Luke's finding, He et al.[2, 3] proposed a method using depth sensing to correct for electron trapping. By taking the ratio of the cathode and subtracted signals, the interaction depth of the γ-ray event can be determined. This ability to sense the depth of the γ-ray interaction provides us the additional capability to obtain spectra as a function of interaction depth. Hence, by plotting the spectrum at each depth, we can clearly observe the shifting of the photopeak

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amplitude due to electron trapping. In addition, by aligning the photopeaks of each spectrum in our spectral analysis program such that the peak centroid values coincide, we can obtain the depth-corrected spectrum with improved energy resolution. This method has the advantage of achieving compensation for any depth-dependent variation in electron trapping or material properties. The depth sensing method allows us to obtain a 1-D spectral mapping of the detector, giving us additional knowledge of detector material properties and charge induction uniformity.

The design of the coplanar grid electrodes has undergone a number of modifications since conception. The original design, named generation 1, consisted of two simple coplanar grid electrodes. He et al.[2] observed significant energy resolution degradation near the coplanar anodes, which was later attributed to the weighting potential asymmetric effect[4]. In order to reduce this effect, the generation 2 design was proposed, which involves a boundary electrode surrounding the two interior coplanar anodes. The boundary electrode helps to both balance the weighting potential symmetry as well as absorb excess leakage current from the sides of the detector which allows for higher biasing and thus improved charge collection efficiency. With the addition of the boundary electrode, a significant improvement in energy resolution near the coplanar anodes was observed. Although the generation 2 design was superior to the previous configuration, He et al.[4] still recognized that the weighting potential symmetry could be improved further. This improvement can be achieved by adjusting the widths of the two outermost strips and three outermost gaps in order to minimize the difference in the coplanar grid weighting potentials. This new design was labeled generation 3 and again significantly better resolution near the coplanar anodes was observed in comparison to the generation 2 design. In fact, utilizing eV Products[5] detectors with our generation 3 design, better energy resolution was observed near the coplanar anode side than on the cathode side, a testament to the uniformity of the weighting potentials near the anodes. This paper discusses the characteristics and performance of detectors using CdZnTe crystals obtained from Yinnel Tech, Inc.[6], and fabricated into detectors by Baltic Scientific Instruments, Ltd.[7], (BSI) using the generation 3 coplanar grid electrode design.

2. DETECTOR DESIGN AND FABRICATION

Two CZT crystals grown by Yinnel Tech were fabricated into coplanar grid detectors by BSI using the generation 3 design.

2.1 Design of coplanar grid electrodes

The design of the coplanar grid electrodes was carried out using the 3-D electrostatic finite-element analysis software package Maxwell[8]. This package can easily simulate the weighting potential field for any electrode of interest. Because our goal is to achieve uniform response independent of the γ-ray interaction location, we sought to minimize the difference of the weighting potentials for the coplanar anodes. As a means of comparing design simulations, we used the following figure of merit value

$$FOM = \overline{|W1 - W2|} \; , \tag{1}$$

where W1 and W2 are the weighting potentials for either coplanar grid anode at some specified point within the simulation mesh. Smaller FOM values indicate better electrode design. In addition to the weighting potential symmetry, it is also very important to keep in mind the effects of detector capacitance, which is related to the amount of electronic noise observed in the system. Calculations of the capacitance were carried out using the well known C = Q/V equality in which Q is found using Gauss's law as shown in Equation (2),

$$\oint_s \vec{D} \cdot d\vec{s} \tag{2}$$

where $\vec{D}$ is the electric displacement vector and $d\vec{s}$ is the outer unit normal component for an infinitesimal area of the electrode surface. Substituting (2) into the capacitance relationship, one can easily calculate C. Although reducing the gaps would often times lead to a better FOM, this would also act to increase the detector capacitance in addition to introducing greater fabrication difficulties. By adapting a gap width of 300 μm and strip width of 150 μm in the central region from previous detectors, we made adjustments to the outermost gaps and strips and simulated a variety of different designs. Our final design is illustrated in Figure 1.

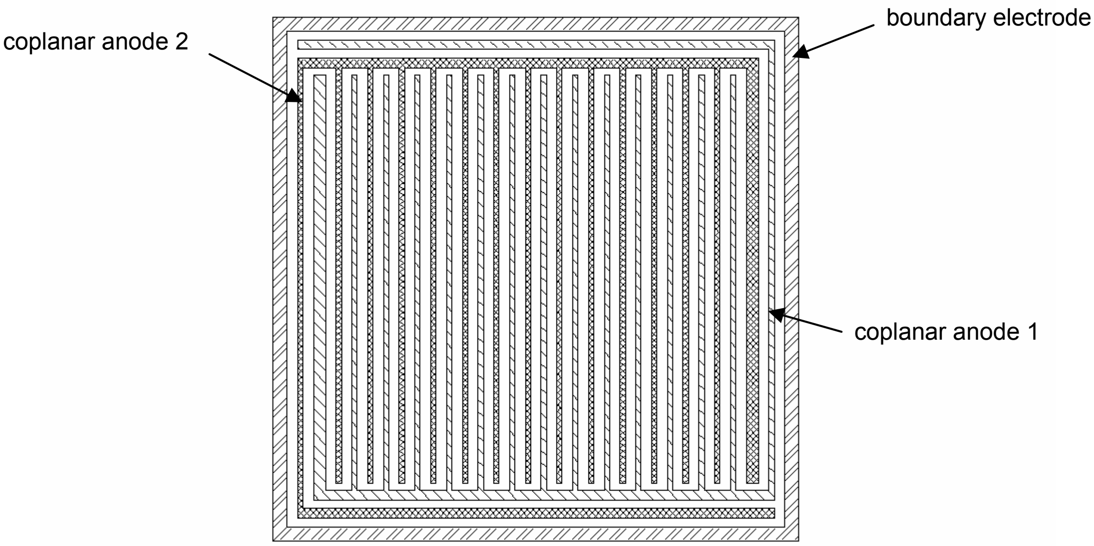


Figure 1. Generation 3 coplanar grid electrode design used in this study. The design dimensions are 15×15 mm^2 and it encompasses a boundary electrode surrounding two interior coplanar grid electrodes. The innermost strips and gaps are all of a uniform dimension whereas the two outermost strips and three outermost gaps are fine tuned to result in a more symmetric weighting potential profile.

2.2 Detector assembly

The coplanar electrodes have been fabricated on both sides of the detector to increase the chance for successful performance. To operate one side of the detector as a cathode, the 3 electrodes on that side are coupled together by connecting the corresponding signal wires together. The other side is then operated in the standard coplanar anode mode. With the advent of coplanar anodes on both sides of the detector we now have the added flexibility to select which side is to be operated as the anode and which side is to be operated as the cathode. This then assures us that the detector can be operated in a means to achieve the best performance.

The final sizes of the two detectors were 1.5×1.5×0.9 cm^3 and 1.5×1.5×0.95 cm^3, the former being labeled CZT2-4-1 and the latter CZT2-4-2.

3. ROOM TEMPERATURE MEASUREMENTS

3.1 Depth sensing and relative gain compensation results

The preliminary results obtained by BSI for these detectors were very promising. For both detectors, BSI measured higher interstrip resistance on one face (side A) than on the other (side B). So, in an effort to reduce the electronic noise due to leakage current, we initially selected side A to be the anode side. The testing equipment consisted of three Amptek A250 preamplifiers for converting the cathode, the collecting anode, and the noncollecting anode signals. In addition to the three preamplifiers, a variable-gain subtraction circuit as well as the detector itself were housed inside a metal box for the purpose of electromagnetic shielding. Standard NIM-bin modules were used for signal post-processing. Spectra acquired using the relative gain compensation method were simply read out from the subtraction signal with a gain applied between the two signal components. The depth sensing method requires the use of peak-hold circuitry to read out the cathode pulse amplitude together with the subtracted signal amplitude while the relative gain on the subtraction circuit is set to 1.

3.1.1 CZT2-4-2

We began by testing the CZT2-4-2 detector because it was found by BSI to be the better of the two detectors. Measurements were first carried out with the collecting anode set positive with respect to both the noncollecting anode and the boundary electrode, which were both set to ground. This biasing configuration results in charge carriers from the entire detector volume being collected by the collecting anode. Testing many different biasing configurations in the range of -800 V to -1500 V on the cathode and +30 V to +55 V on the collecting anode, the best energy resolution obtained using the depth sensing method for electron trapping compensation was 2.09% FWHM for 662 keV γ-rays. Using the relative gain compensation method, the best resolution obtained was 2.18%. We then switched the polarity of the anodes such that the noncollecting anode was biased negative with respect to the boundary electrode and the collecting anode. He et. al[9] has shown that this will help to achieve improved energy resolution since now the charge carriers will be collected from the central region of the detector. Again, testing a variety of bias settings, by using the depth sensing method the best resolution achieved for 662 keV γ-rays was 1.75% FWHM. Even better, using the relative gain compensation method the resolution obtained was 1.65%. The pulse height spectrum for this measurement is given in Figure 2. To our knowledge, this is the best resolution ever achieved for coplanar grid CdZnTe at room temperature operation.

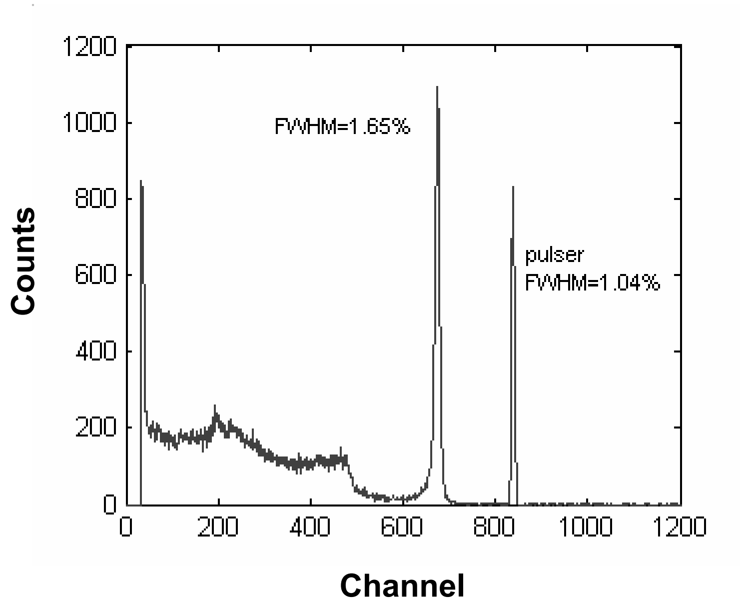
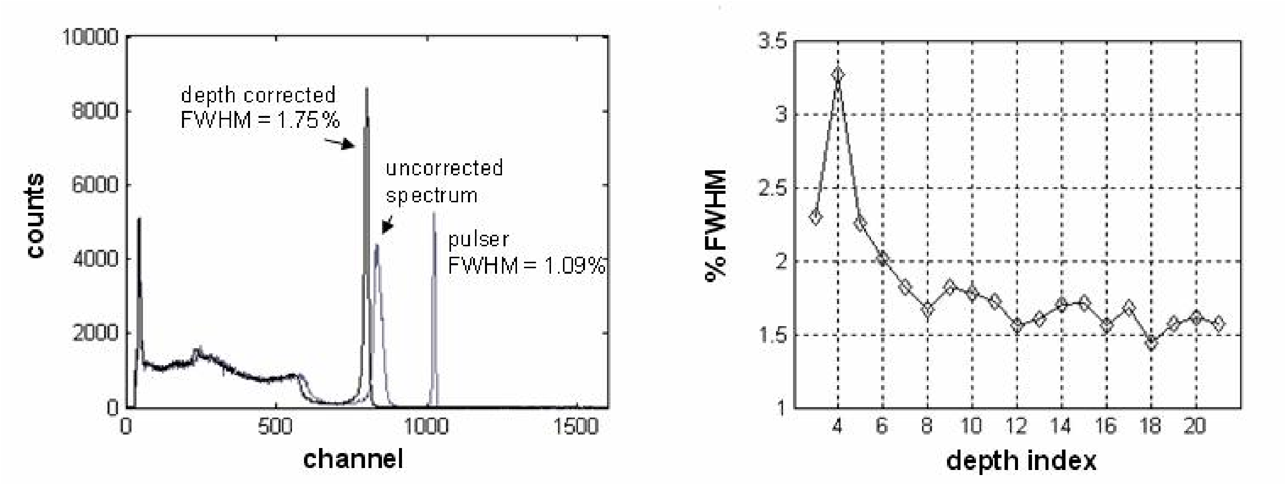


Figure 2. Energy spectrum for the CZT2-4-2 detector using the relative gain compensation method. Results in the range of 1.65% to 1.70% were consistently achieved.

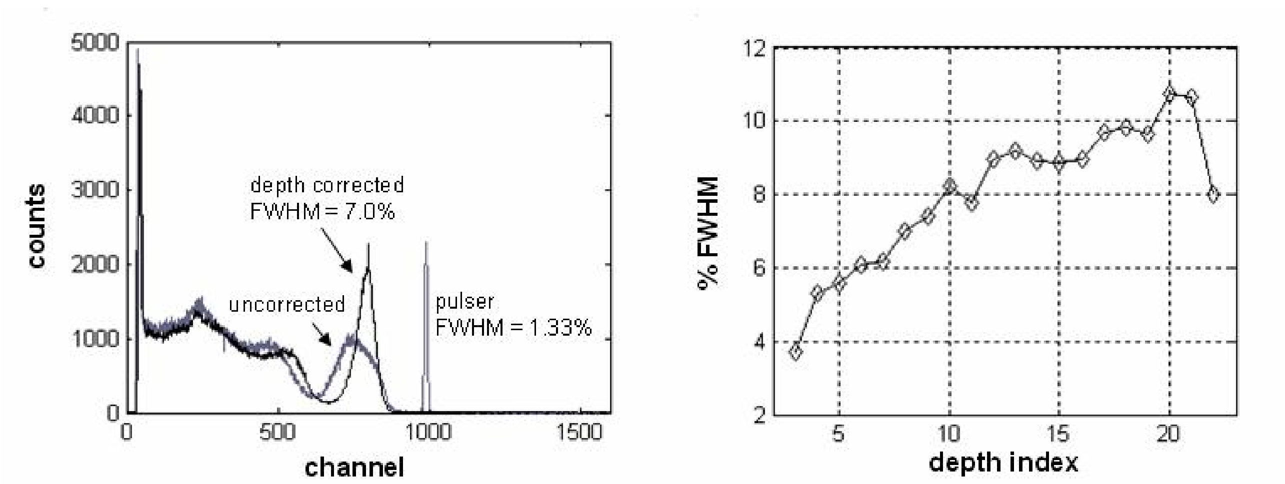
As was previously described, the depth sensing method for electron trapping compensation allows us to obtain energy spectra as a function of interaction depth. Figure 3(a) shows both the uncorrected γ-ray spectrum and depth corrected spectrum. Figure 3(b) illustrates the depth dependency for energy resolution in the detector where larger depth indices indicate increasing distance from the anodes. We find that the resolution remains fairly constant in the bulk of the detector, but then degrades significantly near the coplanar anodes. This effect was surprising to us, because of what we had observed earlier on an eV Products detector using a similar generation 3 coplanar grid electrode design[9] – namely, the effects of weighting potential asymmetry observed on the generation 2 detector were reduced on the generation 3 detector to the point where the best resolution obtained was very near the coplanar grid anode. The trend of energy resolution versus depth observed in Figure 3(b) indicates that perhaps the design of the coplanar grid used on the BSI detector had not been optimized to the extent of the previous generation 3 design.

The placement of coplanar grid electrodes on opposite faces of the detector allows us to reverse the biasing polarity such that the anode side becomes the cathode side and vice versa. So, testing the detector with opposite polarity such that side B now becomes the anode and side A the cathode, we observe very different results. That is, using the relative gain compensation method, we find the 662 keV resolution to be ~8%, and using the depth sensing method the resolution improves slightly to ~7% as shown in Figure 4(a). The dramatically poorer results in this biasing configuration were unexpected. We observe from the energy spectrum that the electronic noise, although greater, is comparable to the noise observed in Figure 3(a). So, the poorer performance is not dominated by the larger leakage current. From Figure 4(b) we observe linearly degrading resolution as a function of increasing depth from the coplanar anodes. This indicates that the degradation of energy resolution is related to the drift distance of electrons, leading us to conclude that this effect is due to a material bulk property. Because the trend observed is not consistent with that of Figure 3(b), this suggests that the detector properties are asymmetric with opposite polarities.



(a) (b)

Figure 3. Energy spectrum for the CZT2-4-2 detector acquired using the depth sensing method (a). Energy resolution as a function of depth index, where larger depth indices indicate increasing distances from the anodes (b).



(a) (b)

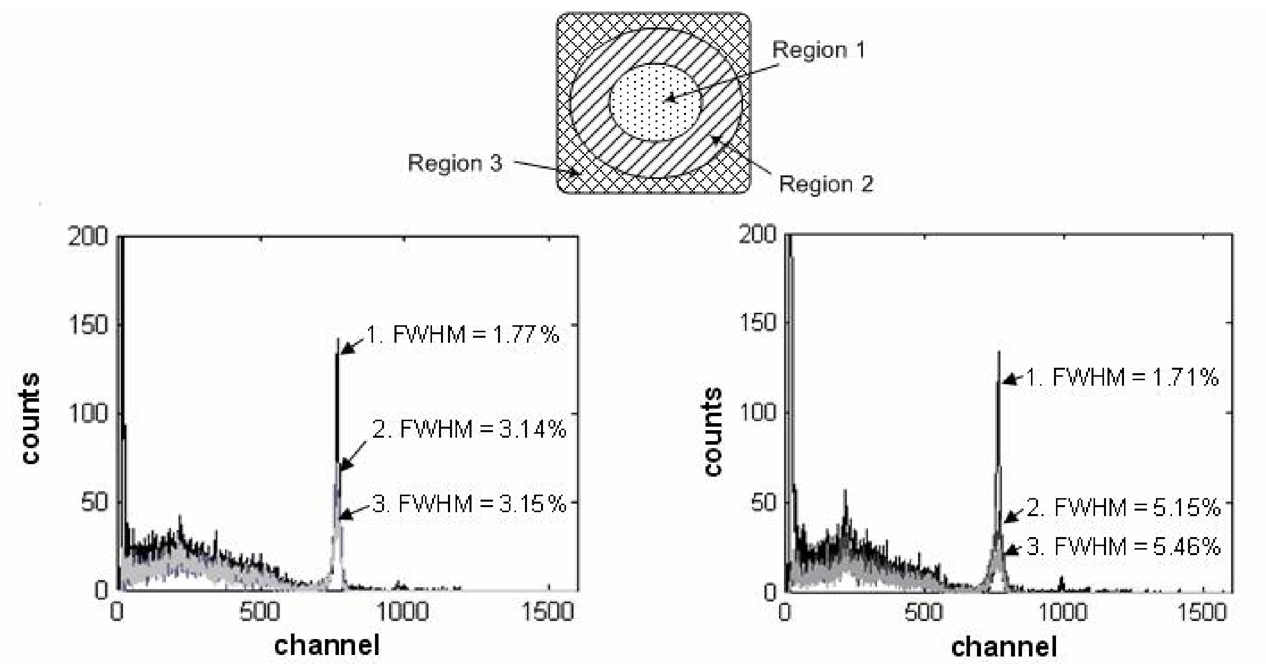
Figure 4. Energy spectrum using the depth sensing method with side B set as the anode (a), and resolution versus depth data for the same measurement (b).

3.1.2 CZT2-4-1

Measurements of the CZT2-4-1 detector were carried out using a negative noncollecting anode bias with respect to the collecting anode and the boundary electrode. Using the relative gain method, the best resolution was found to be 1.99%. Using depth sensing, however, a corrected resolution of 1.86% was achieved. Observing the resolution versus depth data for this biasing configuration, the trend was found to be nearly identical to that in Fig 3(b). After this set of measurements, the polarity of the detector was switched (as on the CZT2-4-2 detector) and a depth-corrected resolution of ~7% was observed. Again, observing the resolution versus depth data, the trend was nearly equivalent to that of Figure 4(b). Both detectors were found to have consistent behavior. A summary of the energy resolution results for both detectors is given in Table 1.

Detector	Anode side	% FWHM with depth sensing	% FWHM with relative gain
CZT2-4-2	A	1.75%	1.65%
	B	8.3%	6.8%
CZT2-4-1	A	1.86%	1.99%
	B	8.3%	7.0%

Table 1. Energy resolution data for 662 keV γ-rays for the case in which side A is biased as the anode and also the case where side B is biased as the anode.



(a) (b)

Figure 5. Radial spectra for the CZT2-4-2 detector (a) and the CZT2-4-1 detector (b) collected near the coplanar anodes, where regions 1 → 2 → 3 indicate increasing radial distance

3.2 Radial sensing results

The process of radial sensing has been discussed in previous publications[4, 9]. This technique allows us to obtain spectra as a function of radial position, providing additional information about the characteristics of the detector. The LabVIEW program used to process the depth sensing data is currently only configured to acquire the radial spectrum at one particular depth. A solitary depth near the coplanar anodes (depth index = 4) was chosen to acquire the radial spectrum data, since the variation in the induced signal as a function of radial position is most severe in this region of the detector. The radial spectra acquired for both detectors with side A biased as the anode are shown in Figure 5(a), (b). In each case we observe degrading energy resolution for increasing radial distances. This is consistent with previous findings, namely that the weighting potential asymmetry is more severe further from the center of the detector, resulting in degraded energy resolution for increasing radial distances.

The radial sensing data for the CZT2-4-1 detector shown in Figure 5(b) indicates the excellent energy resolution achieved in the center region of the detector (region 1) even for events occurring near the coplanar anodes. However, we observe a severe drop in performance for increasing radial distances. This effect, although present, is not quite as severe for the CZT2-4-2 detector shown in Figure 5(a). Both of these findings indicate that the degradation in resolution on the anode side displayed in Figure 3(b) is most likely caused by the weighting potential asymmetric effect. This is because if the degradation in resolution on the anode side was due to material effects, we would expect that the resolution versus radial position to remain fairly constant. That was not the case, however, and the trend observed is consistent with the asymmetric weighting potential effect found on other coplanar grid designs[4]. These findings attest that in terms of energy resolution, there is still potential for better performance with the introduction of an improved coplanar grid electrode design.

3.3 Measurement of $\mu_e\tau_e$ for the CZT2-4-2 detector

The measurement of the $\mu_e\tau_e$ product was carried out using the method described by He et al[10]. In this method, we measure the photopeak amplitudes N_1 and N_2 from events originating near the cathode surface for spectra collected at two different bias voltages V_1 and V_2. The $\mu_e\tau_e$ product is then solved using Equation (3)

$$\mu_e\tau_e = \frac{D^2}{\ln(N_1/N_2)}\left(\frac{1}{V_2}-\frac{1}{V_1}\right). \quad (3)$$

This measurement was carried out using an ^{241}Am γ-ray source that was exposed to the cathode side of the detector. In addition, ^{57}Co was used as a calibration to determine the 0-channel offset of the ADC. Measurements were acquired for -1000 V and -1400 V cathode bias. With side A biased as the anode (the 'good' side) the $\mu_e\tau_e$ product was found to be 1.012×10^{-2} cm^2/V, which is very high in comparison to traditional CdZnTe $\mu_e\tau_e$ values. With side B biased as the anode (the 'bad' side) the $\mu_e\tau_e$ was 7.92×10^{-3} cm^2/V. The difference in these values for opposite detector polarities is quite significant. These results are counterintuitive since one would not expect the $\mu_e\tau_e$ product to be directionally dependent to the electron movement. However, in the calculation of the electron mobility-lifetime product using equation (3), some underlying assumptions were made that could affect the measured value. These factors include the mean free path of ^{241}Am γ-rays in CdZnTe, which was set to be ~0.5 mm, and the way in which the photopeak centroid was calculated. The method for localizing the peak centroid value was accomplished by calculating the weighted average of the photopeak $\sum N_i H_i / \sum N_i$ over a standardized range of channels. The 'start' channel was the photopeak half maximum channel on the low energy side while the 'end' channel was the half maximum channel on the high energy side. Although this method provides an objective means for determining the peak centroid value, it may introduce systematic bias into the measurement.

4. CONCLUDING REMARKS

This paper highlighted the performance and characteristics of large-volume coplanar grid CdZnTe detectors using Yinnel Tech, Inc., crystals and BSI detector fabrication methods. The coplanar grid electrode design was accomplished using the software package Maxwell. Using this tool, we sought to achieve a balanced weighting potential profile amongst the coplanar anodes such that the difference of the weighting potential between the collecting anode and noncollecting anode was minimized. The best energy resolution achieved for the CZT2-4-1 detector was 1.86% FWHM for 662-keV γ-rays at room-temperature operation. An even better energy resolution was achieved with the CZT2-4-2 detector of 1.65%. The large $\mu_e\tau_e$ product measured for this detector is 1.012×10^{-2} cm^2/V when the better side is selected as the coplanar anode.

Some unexpected results will need further examination. One such result is the effect of severely degraded performance for opposite biasing polarities. That is, when the 'bad' side of the detector is biased as the anode, energy resolution values of ~7% are achieved which compares very poorly to the < 2% energy resolution achieved when the 'good' side is biased as the anode. The nearly linear trend of increasing resolution with increasing distance from the coplanar anodes while the 'bad' side was biased as the anode causes us to believe that the poor performance observed in this biasing configuration is due to a material bulk effect. These results were reproducible for both detectors, suggesting that these observations were not anomalous. Another unexpected result was the dependence of the measured $\mu_e\tau_e$ product on the drift direction of the electrons. Finally, the observation that the degradation in energy resolution near the anode surface (with the 'good' side of the detector biased as the anode) may be due to a non-ideal coplanar grid electrode design suggests that the spectroscopic performance of the detector may be further improved.

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