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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. γ-Ray spectra have been obtained from $11(x)\times 11(y)\times 20(z)$ voxels, each corresponding to $\sim 0.7\times 0.7\times 0.5$ 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.

Keywords: Gamma-ray spectrometers; High-energy particles

1. Introduction

γ-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-D 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-D γ-ray spectrometers fabricated from semiconductor crystals.

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2. System description

Each detector system [5] consists of a $10 \times 10 \times 10$ 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[1] 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 [6], 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 $0.7 \times 0.7 \times 0.5$ 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 and 1400 V, and the biases between the pixel anodes and the non-collecting grid were 50 and 30 V on the first and second detectors, respectively. The energy threshold for rejection of multiple-pixel events was ~ 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 ~ 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

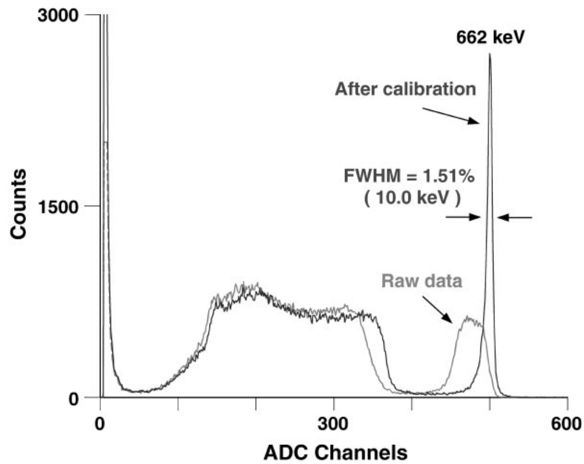

Fig. 1. Energy spectra of ^{137}Cs obtained from the central 9×9 pixels of the first detector for single-pixel events.

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

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. Three-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-D position sensing capability of the system, an experiment was conducted as illustrated in Fig. 2(a). In the first 10 h 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 h 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

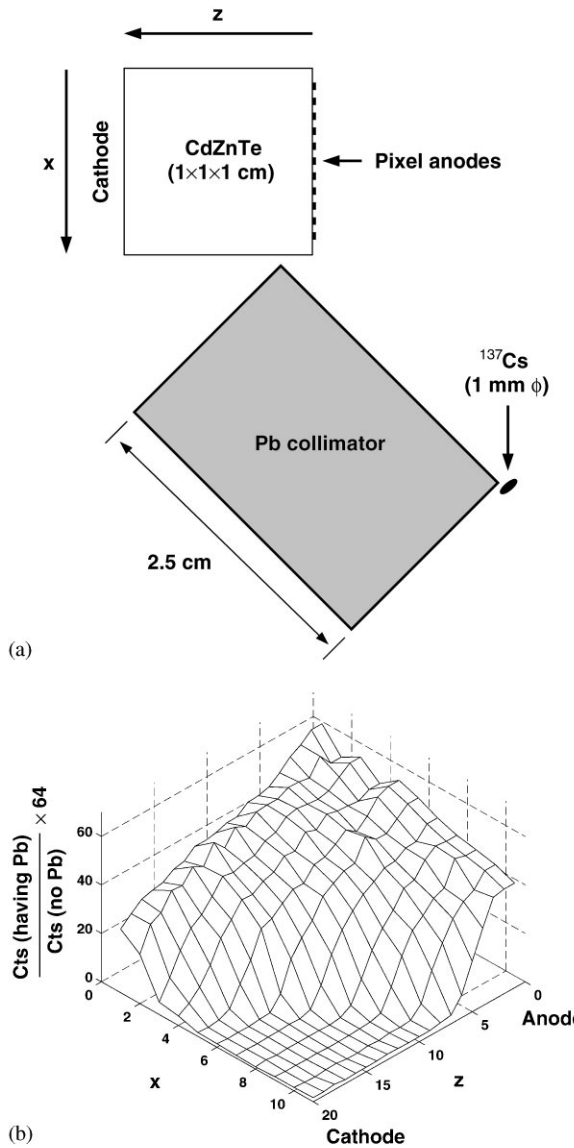

Fig. 2. Demonstration of 3-D position sensing of the device. (a) Top view of the experimental setup. (b) Ratio of the photopeak counts at 662 keV with detector partly shielded to the counts when detector was not shielded by a 2.5 cm thick Pb collimator.

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[2] 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 ~ 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.

[2] GEANT3, CERN, Geneva, Switzerland.

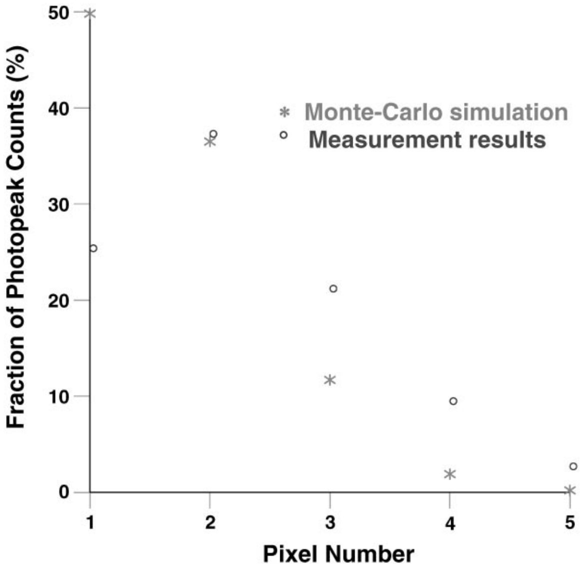

Fig. 3. The fraction of photopeak counts versus pixel number. The size of the electron clouds was not considered in simulation.

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 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.

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

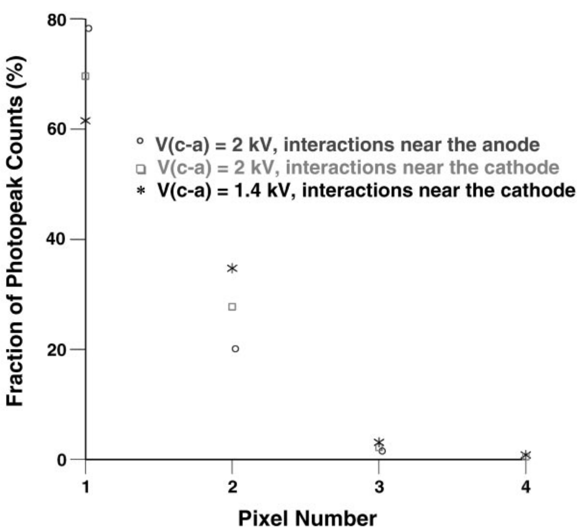

Fig. 5. The fraction of photopeak counts versus pixel number measured at 122 keV γ-ray energy.

The 3-D 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.

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References

[1] F.P. Doty et al., Nucl. Instr. and Meth. A 353 (1994) 356.
[2] H.H. Barrett et al., Phys. Rev. Lett. 75 (1) (1995) 156.
[3] Z. He et al., Nucl. Instr. and Meth. A 380 (1996) 228.
[4] Z. He et al., Nucl. Instr. and Meth. A 388 (1997) 180.
[5] Z. He et al., Nucl. Instr. and Meth. A 422 (1999) 173.
[6] C.M. Stahle et al., Proc. SPIE 3115 (1997) 90.