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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

Position-sensitive single carrier CdZnTe detectors

Z. He*, G.F. Knoll, D.K. Wehe, J. Miyamoto

Department of Nuclear Engineering and Radiological Sciences, University of Michigan, 1906 Cooley Building, Ann Arbor, MI 48109, USA

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Abstract

Single polarity charge sensing on room temperature semiconductor gamma-ray detectors can be achieved by using the coplanar electrode read-out technique. This mehod can eliminate the hole-trapping problem of the wide band gap semiconductors which are currently available. Our previous results on 5 mm cube CZT detectors confirmed [6] that the energy resolution can be dramatically improved compared with that obtained using the conventional read-out method. This paper explores the application of this technique to CdZnTe detectors of larger volume, namely 1 cm^3. In our previous work, we suggested a method to obtain γ-ray interaction depth and further progress is reported here. This technique can be used to correct for the electron trapping as a function of distance from the anode. The intrinsic position resolution has been analyzed and energy resolutions of less than 2% FWHM at 662 keV were obtained on both detectors tested. Finally, the factors which inhibit attaining the statistical energy resolution limit of CdZnTe detectors have been explored. These results will be of interest in the design of higher performance, portable and imaging-related, room-temperature semiconductor γ-ray detectors.

1. Introduction

Semiconductors with high atomic numbers and wide band gaps have long been desired for γ-ray detectors for their potential superior energy resolution, high stopping power and the ability to operate at room temperature. Although some progress has been made on crystal growth and electronic signal processing over the last two decades, and HgI_2, CdTe and CdZnTe detectors have been successfully employed in various applications, the widespread use of these detectors had been hindered by their charge-trapping problems. Because of this difficulty, the use of wide band gap semiconductors had been limited to thin detectors, typically with a thickness of about 2 mm.

In the fall of 1994, an innovative single polarity charge sensing method using coplanar grids was proposed by Luke [1] and a dramatic improvement in energy resolution was demonstrated on a cubic 5 mm CdZnTe detector. Luke's method is based on the principle of Frisch grids [2] employed in gas ion chambers, but uses parallel strip electrodes which are connected in an alternate manner to give two sets of inter-digital grid electrodes. Single polarity charge sensing is accomplished by reading out the difference signal between these two groups of electrodes.

When the relative gain between these two electrodes is set to be 1.0, the pulse amplitude read from the coplanar electrodes is only proportional to the number of electrons collected by the collecting electrode and the induced signal from the hole motion can be eliminated. In practice, electron trapping is still significant. From our measurements on two 1 cm thick CdZnTe detectors, about 5–10% of electrons are trapped within the bulk of the detector when electrons are drifting from the cathode side to the coplanar anodes. This means that the difference signal can still vary significantly depending on the location of γ-ray interaction between the cathode and anodes. In order to compensate for electron trapping, Luke [1] applied a relative gain between the two sets of electrodes before subtraction. The optimized relative gain depends upon the electron trapping characteristics of each individual detector. Luke demonstrated [3] an energy resolution of 2.4% FWHM at 662 keV on a 1 cm^3 CdZnTe detector in the fall of 1995. This relative gain compensation method assumes that the electron trapping is a linear function of the distance of γ-ray interaction from the coplanar electrodes. In practice, the electron trapping is an exponential function of distance; therefore, this method only works when the detector

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* Corresponding author. Tel.: 13137645285; fax: 13137634540; e-mail: hezhong@engin.umich.edu.

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thickness is much less than the electron drifting length $\lambda_e = \mu_e \cdot E \cdot \tau_e$, where μ_e and τ_e are mobility and lifetime of electrons and E is the intensity of the electric field.

For spectroscopic performance of CdZnTe detectors, we can assume that about 4.4 eV is needed to generate one electron–hole pair, thus the statistical limit on energy resolution at 662 keV should be 0.2% FWHM and 0.6% FWHM for a Fano factor of 0.1 and 1.0, respectively [4]. The best energy resolution demonstrated on 1 cm thick CdZnTe detector is 2.4% FWHM at 662 keV [3], which is still far worse than what could be achieved theoretically.

We proposed a method [6] to obtain depth sensing between the cathode and coplanar electrodes. As a result, a corrected pulse amplitude can be obtained using a measured parameter which is a monotonic function of the interaction depth. This method can, thus, correct for electron trapping for the non-linear case and allows us to see how the detector performance changes as a function of γ-ray interaction depth. This paper presents our latest progress on two 1 cm^3 CdZnTe detectors. The depth resolution which is achievable using this method is analyzed. Using the depth-sensing method, the energy spectra of γ-rays which deposit their energies closest to the cathode and coplanar electrode surfaces are shown. These two results show interesting characteristics of detector performance at the two extreme locations and indicate that some commerically available materials may already have sufficient quality to closely approach the theoretical statistical limit on energy resolution.

2. Position sensing of interaction depth

The charge induced on a conventional planar detector solely due to the electron motion is proportional to the drifting length of the electrons. This electron-induced signal can be measured by using a shaping amplifier with a shaping time constant which is long compared to the electron-drifting time, but short compared to the hole-drifting time. When this technique is applied on the cathode side, the induced charge on the cathode S_c increases roughly as a linear function of the distance D of γ-ray interaction location from the coplanar anodes. This can be expressed as $S_c \propto D \cdot E_\gamma$. On the other hand, the coplanar anode signal S_a is only proportional to γ-ray energy (this is only an approximation when the relative gain between the two sets of coplanar electrodes is set to 1.0), i.e., $S_a \propto E_\gamma$. As we suggested earlier [6], if induced signals from the cathode and the coplanar grid electrodes are both read out for each γ-ray event, the interaction depth can be estimated as $d = S_c/S_a \propto D$. When the relative gain between the coplanar electrodes is set to be 1.0 and the electron trapping is not linear, S_a decreases as the distance D of γ-ray interaction from the coplanar grids increases. The ratio parameter $d = S_c/S_a$ is still a monotonic function of γ-ray interaction depth between the cathode and the anodes. The greater the difference between the $\mu \cdot \tau$ products of electrons and holes, the more linear is this ratio as the function of interaction depth.

This method was demonstrated on a 5 mm^3 CdZnTe detector in our previous work [6], but was tested again using a 1 cm^3 CdZnTe detector. The experimental setup is illustrated in Fig. 1(a) and the distribution of the measured ratio parameter d is shown in Fig. 1(b), where the three peaks correspond to the three slits on the lead collimator. It is evident that the liniarity is quite good in the middle of the detector and a position resolution of about 1.1 mm FWHM was obtained without taking into account the finite width of collimator slits or the precise direction of the collimated γ-ray beams. Since the detector is sealed in a cylindrical aluminum housing, and the irradiation was from the side, the pointing direction of the collimator was not precisely known. The results

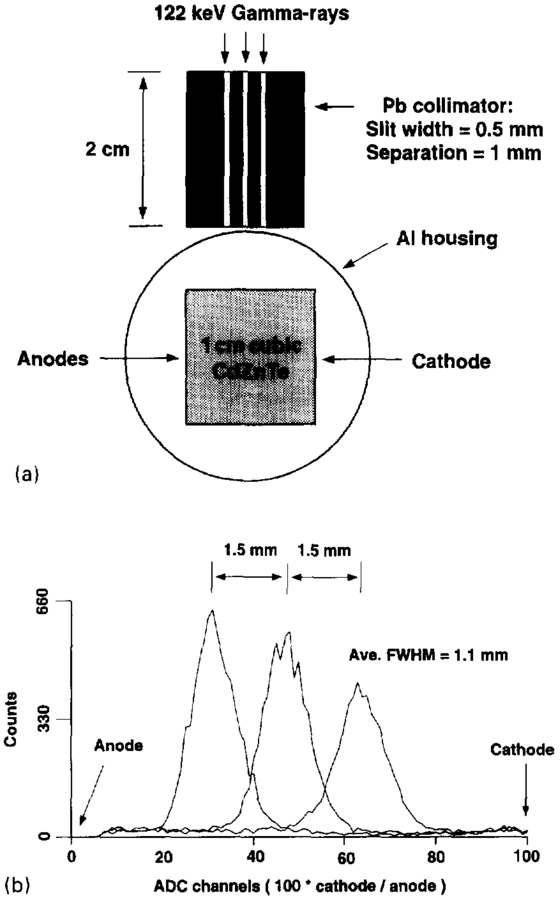

Fig. 1. Test results of the position-sensing technique at 122 keV: (a) top view of the experimental setup; (b) distribution of the recorded depth.

shown in Fig. 1 have confirmed that the γ-ray interaction depth can be estimated using this position-sensing technique. The photopeak amplitudes and energy resolutions can be obtained as a function of interaction depth. Therefore, this technique can correct for electron trapping even without applying the relative gain compensation on the coplanar electrode signal and should be able to correct for non-linear electron trapping between the cathode and anodes.

3. γ-Ray spectroscopy

Two 1 cm^3 CdZnTe detectors have been fabricated [7] and tested. The crystal used for the first (No. 1) detector was classified as "selected discriminator grade" while the second (No. 2) detector was classified as "spectrometer grade" [8]. The energy spectra at 662 keV from all events was obtained by selecting relative gains between the coplanar electrodes which minimize the FWHM of the photopeaks, and the results are shown in Figs. 2(a) and 3(a). When the measured interaction depth d was divided into 20 channels, each of which represents a thin slice of detector volume of about 0.5 mm thick, the energy spectra as a function of d were collected and are shown in Figs. 2(b) and 3(b). The results show that the best energy resolution of 1.5–1.6% FWHM was obtained using events from the cathode side and the energy resolution degraded gradually to about 5–6% FWHM for interaction locations close to the coplanar anodes. The experimental setup is summarized in Table 1. If the broadening of the photopeak obtained at the same interaction depth is caused by the variation of electron trapping along different electron paths, the poorest energy resolution

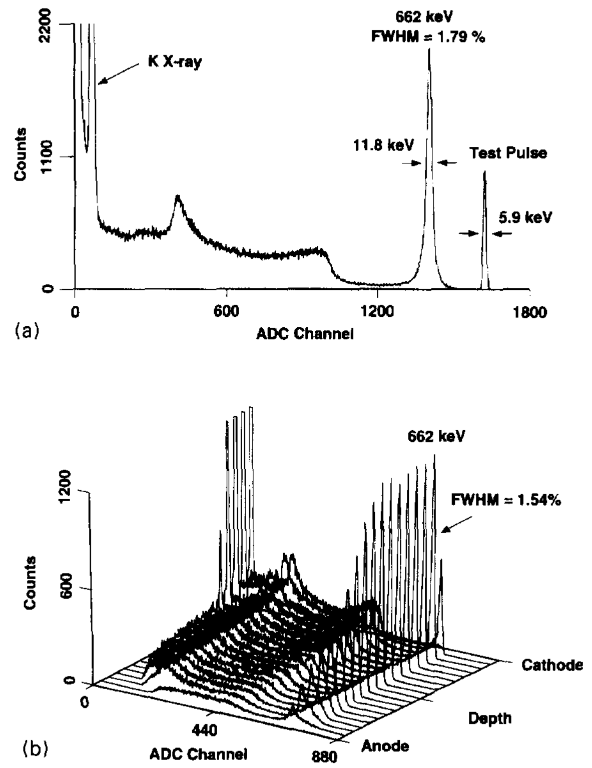

Fig. 2. Energy spectra at 662 keV from the first 1 cm^3 CdZnTe detector (No. 1); (a) energy spectrum of all events; (b) energy spectra as a function of the depth parameter.

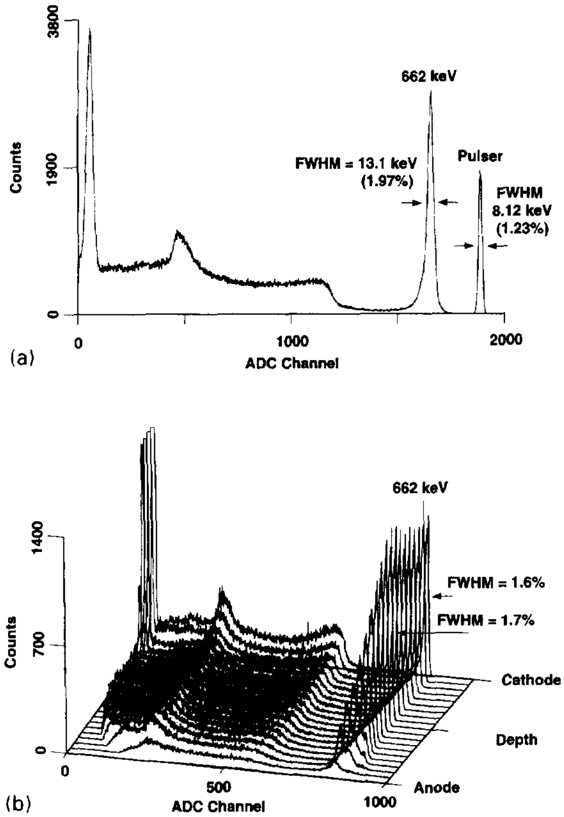

Fig. 3. Energy spectra of 662 keV from the second 1 cm cube CdZnTe detector (No. 2); (a) energy spectrum of all events; (b) energy spectra as a function of the depth parameter.

Table 1
Summary of experimental setup

Detector	No. 1	No. 2
V (cathode)	− 1400 V	− 2600 V
ΔV (coplanar)	+ 30	+ 40 V
Shaping Time (cathode)	2.0 μs	1.0 μs
Shaping Time (coplanar)	2 μs	0.5 μs
Room temperature	22°C	22°C

should come from the cathode side since the electrons travel the longest distance and are most influenced by trapping. The results shown in Figs. 2 and 3 indicate that the degradation in energy resolution towards coplanar anodes is not caused by electron trapping. This depth-sensing technique has provided an insight on how the detector performance changes as a function of depth and has helped us to understand how the coplanar electrode structure could affect the detector performance.

Comparing these results with those reported earlier [1,3,6], significant improvements on detector performance have been obtained. Except where otherwise noted, the experimental results shown in the following sections were obtained using the spectrometer grade detector (No. 2).

4. Position resolution

The depth parameter d for each γ-ray event is obtained by

$$d = \frac{S_c}{S_a}, \tag{1}$$

where S_c and S_a are cathode and coplanar anode signals, respectively. Since $S_c \approx S_a$ for γ-rays which deposit their energy near the surface of the cathode, the depth parameter d is in the range: $0 \le d \le 1.0$. In practice, for a given d, the variation of S_c and S_a is governed primarily by the noise and the inaccuracy of the pusle measurement caused by the read-out system (such as the non-symmetric effect of coplanar anodes). Thus, S_c and S_a can be approximately considered as non-correlated. The variance of d can be derived from error propagation:

$$\sigma^2(d) = \left(\frac{\sigma(S_c)}{S_a}\right)^2 + \left(\frac{S_c}{S_a}\right)^2 \cdot \left(\frac{\sigma(S_a)}{S_a}\right)^2. \tag{2}$$

Since FWHM = 2.35σ, σ in Eq. 2 can be replaced by the FWHM. At the cathode side, $S_c \approx S_a$, and Eq. 2 becomes

$$\mathrm{FWHM}(d) \approx \sqrt{\left(\frac{\mathrm{FWHM}(S_c)}{S_c}\right)^2 + \left(\frac{\mathrm{FWHM}(S_a)}{S_a}\right)^2}. \tag{3}$$

On the coplanar anode side, $S_c \ll S_a$, and Eq. (2) becomes:

$$\mathrm{FWHM}(d) \approx \frac{\mathrm{FWHM}(S_c)}{S_a}. \tag{4}$$

If the electronic noise is used to estimate FWHM(S_c) and FWHM(S_a), one can see that the position resolution at the cathode side is determined by the energy resolutions of both cathode and anode signals, whereas at the coplanar anode side, the position resolution should be limited by the electronic noise of the cathode signal divided by the pulse amplitude of the coplanar signal. The noise of cathode and coplanar anode signals were measured to be equivalent to about 4–8 keV FWHM. As an example, the estimated depth resolutions at both cathode and coplanar anode surfaces at several typical γ-ray energies are shown in Table 2.

Table 2
Predicted depth resolutions on a 1 cm thick CdZnTe detector for interactions near cathode and anode side.

γ-ray energy	Cathode side	Coplanar anode side
59.5 keV	1.5 mm	0.7 mm
122 keV	0.7 mm	0.3 mm
662 keV	0.1 mm	0.06 mm

While the photoelectric interaction dominates at γ-ray energies below about 250 keV, Compton scattering plays a major role at higher energies. Therefore, at higher energies, the measured depth parameter is the centroid of the multiple interaction locations. Thus, the measured position resolution includes the effect of Compton scattering and will be worse than that listed in Table 2.

5. Energy spectrum near coplanar anodes

With depth sensing capability, unusual detector performance at some special positions can be observed experimentally. For example, if γ-rays interact within close proximity of the coplanar anodes, the pulse amplitude of the difference signal obtained from the coplanar electrodes can be up to two times larger than when the γ-rays interact within the bulk of the detector. This surface phenomenon happens for interactions occurring within a depth less than the pitch of the coplanar electrodes [5]. This occurs because the holes generated by incident γ-rays within this depth may drift towards the non-collecting electrode instead of the cathode. In this case, the coplanar electrode read out is equivalent to that when both anode and cathode signals are read out on a conventional planar detector and then performs a subtraction between these two signals. Since the cathode and anode signals are mirror signals with the opposite polarity, the subtraction is equivalent to multiplying either of the signals by a factor of 2. This surface effect has been observed for the first time using the depth sensing method. Fig. 4 shows the distribution of interaction depths when 122 keV γ-rays are incident from the coplanar anode side. The exponential attenuation through the bulk of the detector material can be clearly seen. From previous analysis (Table 2), about 0.5 mm depth resolution should be achievable on a 1 cm thick CdZnTe detector. Therefore, we divided the measured depth parameter d into 20 channels as shown in Fig. 4 and the energy spectrum from γ-rays closest to the surface of coplanar anodes ($d = 1/20$) is shown in Fig. 5. The

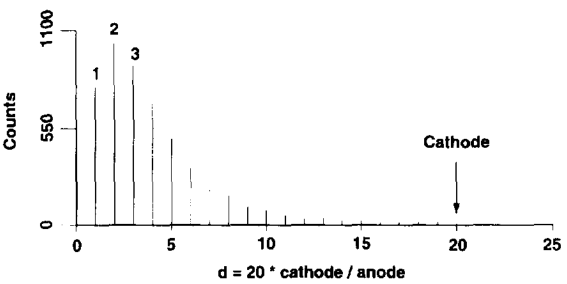

Fig. 4. Distribution of interaction depths when 122 keV γ-rays are incident from coplanar anode side.

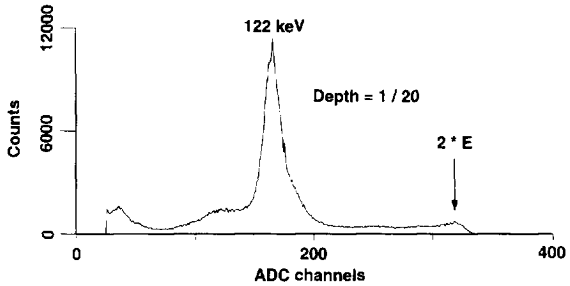

Fig. 5. Energy spectrum of ^{57}Co near coplanar anode surface.

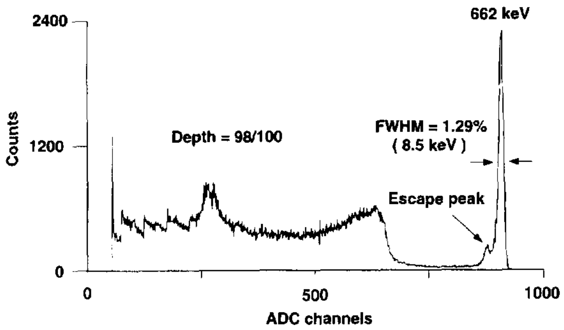

Fig. 6. Energy spectrum at 662 keV when γ-rays deposit energies near the surface of the cathode.

surface effect is evident in Fig. 5 and cannot be seen at other interaction depths.

6. Energy spectrum near cathode

The detector performance near the cathode surface can also be observed using the depth-sensing method. It has been noticed that the energy resolution at 662 keV improves when the interaction location is closer to the cathode surface. From our results shown in Table 2, the depth-sensing technique should have a precision of about 1% at 662 keV γ-ray energy. Therefore, we have divided the measured depth parameter d into 100 channels, each of which represents a thin slice of detector volume that is parallel to the cathode and anode surfaces. The energy spectrum of γ-rays which deposit their energies closest to the cathode surface is shown in Fig. 6. The Cd X-ray escape peak can be clearly seen which confirms that the events originate near the cathode surface. An energy resolution of 1.29% FWHM was obtained at 662 keV for this slice. Ensuring the ratio of the two integers from the ADC, S_c and S_a, is equal to a fraction $0 \le d \le 1$, leads to the artificial sawtooth shape at low energies.

We can assume that the measured FWHM of the signal S_m is made up of the electronic noise FWHM(S_e) and statistical fluctuation FWHM(S_s) in the number of charges generated, so

$$\mathrm{FWHM}(S_s) = \sqrt{\mathrm{FWHM}^2(S_m) - \mathrm{FWHM}^2(S_e)}. \qquad (5)$$

Since FWHM(S_m) and FWHM(S_e) are 1.29% and 1.23% (Fig. 3(a)), the estimated FWHM due to statistical fluctuation is about 0.4%. This is approaching the theoretical statistical limit. Since electrons travel all the way across the detector thickness in this case, the non-uniformity of the detector material on electron trapping should show the greatest effect on the events. However, our measurement results show that the best energy resolution is obtained from these events. This shows that the degradation of energy resolution towards the coplanar electrodes is caused by the detector system, not from the non-uniformity of the detector material. Thus, the energy resolution is currently being limited by our signal read-out system and electronic noise. By modifying the detector read-out technique and reducing the electronic noise, a significant improvement in energy resolution can be expected. This result also indicates that the quality of commercially available CdZnTe materials may allow us to approach the statistical limit on energy resolution much closer than we had previously thought.

7. Conclusions

A significant improvement in energy resolution has been obtained for two 1 cm^3 CdZnTe detectors. The depth-sensing technique has been demonstrated and applied to investigate the detector performance as a function of γ-ray interaction depth. This method is a powerful tool for investigating the cause of the difference between the current detector performance with that theoretically achievable on CdZnTe detectors. This technique should also be of interest for γ-ray imaging devices. An energy resolution of 1.29% FWHM at 662 keV was obtained from interactions near the cathode region of the detector, which leads to an estimated energy resolution of about 0.4% FWHM caused by statistical fluctuations. This indicates that the detector design should be improved to achieve better performance and excellent energy resolution should be achievable using currently available CdZnTe material.

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