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3-D Spatial Resolution of 350 μm Pitch Pixelated CdZnTe Detectors for Imaging Applications

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Abstract

We are currently investigating the feasibility of using highly pixelated Cadmium Zinc Telluride (CdZnTe) detectors for sub-500 μm resolution PET imaging applications. A 20 mm $\times$ 20 mm $\times$ 5 mm CdZnTe substrate was fabricated with 350 μm pitch pixels (250 μm anode pixels with 100 μm gap) and coplanar cathode. Charge sharing among the pixels of a 350 μm pitch detector was studied using collimated 122 keV and 511 keV gamma ray sources. For a 350 μm pitch CdZnTe detector, scatter plots of the charge signal of two neighboring pixels clearly show more charge

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sharing when the collimated beam hits the gap between adjacent pixels. Using collimated Co-57 and Ge-68 sources, we measured the count profiles and estimated the intrinsic spatial resolution of 350 μm pitch detector biased at -1000 V. Depth of interaction was analyzed based on two methods, i.e., cathode/anode ratio and electron drift time, in both 122 keV and 511 keV measurements. For single-pixel photopeak events, a linear correlation between cathode/anode ratio and electron drift time was shown, which would be useful for estimating the DOI information and preserving image resolution in CdZnTe PET imaging applications.

Index Terms

CdZnTe detectors; charge sharing; imaging applications; spatial resolution

I. Introduction

CADMIUM Zinc Telluride as a potential detector for medical imaging applications, such as Positron Emission Tomography (PET) and Single Photon Emission Computed Tomography (SPECT), has been widely investigated due to its room temperature operability, relatively-high atomic number, high energy resolution, and potentially high spatial resolution [1]–[3]. Using single polarity charge sensing configurations, for instance a pixelated detector, the energy resolution of CdZnTe detectors could be better than 1% FWHM at 662 keV, and the spatial resolution could be close to 1 mm [4]–[6]. Such kinds of CdZnTe detectors may allow one to improve image resolution and better reject scatter events for PET imaging applications.

We have previously demonstrated that a high-resolution PET insert device can be integrated into an existing microPET scanner to improve its image resolution to less than 1 mm FWHM using a Virtual-Pinhole PET approach [7], [8]. Our original prototype PET insert devices were built upon scintillator-based detector technology in order to facilitate the integration with existing PET scanners that employ scintillation detectors. With the advanced semiconductor processing techniques driven by consumer electronics, contacting CdZnTe substrates to produce highly pixelated detectors with sub-500 μm pitches has become easily achievable. In contrast, making scintillation crystal arrays with sub-500 μm crystal pitches is labor intensive and costly. As a result, semiconductor detectors may potentially offer higher intrinsic spatial resolution than scintillation detectors and be more suitable for high-resolution PET insert applications.

By making use of the small pixel effect [9], pixelated CdZnTe detector's energy resolution and spatial resolution have been shown to improve as the pixel size decreases. However, this tendency may not hold true when the pixel size becomes very small relative to the size of charge cloud created by the gamma ray interacting with the detector. Under this condition, there is charge sharing among multiple pixels that leads to large number of charge sharing events in the detector. Several key factors that can contribute to charge sharing include: the electron-hole cloud size, the diffusion of charge carriers, Compton scattering events, and characteristic X-rays [10]. Charge sharing in various types of geometries, such as pixelated and cross strip readout, has been studied extensively [1], [10]–[18]. Most studies of

pixelated CdZnTe detectors were focused on detectors with pixel size of 1 mm or larger. Several studies that employed CdZnTe detectors with 250 μm pixels were mainly for applications using lower energy photons [16]–[18].

In this work, CdZnTe detectors with 350 μm pixel pitch and 5 mm thick were fabricated and characterized using collimated Co-57 and Ge-68 sources. We studied the charge sharing characteristics and the intrinsic spatial resolution of pixelated CdZnTe detectors to evaluate the feasibility of using such kind of detectors for sub-500 μm resolution PET imaging applications. Furthermore, we studied the ratio of cathode and anode signal amplitude, as well as the electron drift time, in order to analyze the depth-of-interaction (DOI) of gamma ray interactions within the detector substrate. This 3-D positioning capability is critical for the proposed ultrahigh resolution PET imaging applications as it minimizes the parallax error in image reconstruction.

II. Materials and Methods

A. CdZnTe Detectors

A 20 mm $\times$ 20 mm $\times$ 5 mm modified high-pressure Bridgman (MHB) CdZnTe substrate from former Orbotech Medical Solutions (Israel) was polished and had anode and cathode contacts deposited in a class-100 clean room. The delivered CdZnTe substrate was first polished and etched with a 5%–95% Br-Methanol solution to improve both the electrical property and the adhesion of the contacts [19]. Following the etching, a standard photolithographic process and an electron beam evaporator were used to deposit pixel contacts. On the finished CdZnTe coplanar cathode surface, 125 nm thick Gold was deposited, which is high-work function material that can reduce leakage current and improve energy resolution. The anode surface is deposited with 100 nm Titanium, which has a relative low-work function and has been shown to provide the best energy resolution among four anode materials investigated: Indium, Titanium, Chromium and Gold [20].

One of the major challenges in using pixelated CdZnTe detectors is to read out thousands (or more) of channels of anode signals accurately and efficiently. Application-specific–integrated-circuit (ASIC) that has 2048 channels of preamplifiers and analog-to-digital converters (ADC) with 350 μm pitches is currently being developed at the University of Illinois at Urbana-Champaign for 511 keV gamma ray detection, but not yet available. As a result, we designed a special anode pattern that permits us to read out 9 pixels (3×3) of 350 μm pitches with discrete readout electronics in this study. The mask of the custom 9-pixel anode pattern is shown in Fig. 1(A). At the center of this 9-pixel pattern is 250 $\mu\text{m} \times$ 250 μm anode pixel with 100 μm gaps separating it from the 8 surrounding anode pixels of the same size. The 8 neighboring anode pixels are connected to eight circular readout pads that are 1.4 mm in diameter and 2.5 mm away. This layout allowed us to read out 9 anode signals using pogo pins and discrete components instead of custom ASIC. It is expected that the characteristics of the central anode pixel would be very similar to those of typical 350 μm pitch pixelated CdZnTe detectors.

To validate the above assumption, we simulated the weighting potentials and electric field of this 9-pixel pattern CdZnTe detector based on a solution of the 3-D Laplace equation [21].

We also simulated regular pixelated CdZnTe detectors using the infinite continuous anode structure. Fig. 1(C) and (D) shows the calculated weighting potential and electric field of the CdZnTe 9-pixel pattern detector, respectively. As shown in Fig. 1(C), the electric field in the CdZnTe with the special 9-pixel geometry differs from the uniform field in a CdZnTe with the infinite continuous structure only in the region that is less than one-tenth of the crystal thickness (5 mm) near the anode side. The weighting potential of the central 250 μm pixel is very similar to that of the infinite continuous geometry and shows small pixel effect. The weighting potential of the 8 peripheral pixels, such as anode A6, differs from that of the infinite continuous geometry due to the big readout pads that are connected to these pixels. However, the differences occur mainly in the regions that are connected to the readout pads and there is minimal difference in the regions surrounding the central anode pixel (A5). As a result, the central anode pixel in this special 9-pixel geometry is a good approximation of the 350 μm pitch pixelated CdZnTe detector that we intend to evaluate.

B. Experimental Setup and Data Acquisition System

The anode signals of the above CdZnTe detector were read out through 9 spring-loaded pogo pins. The pogo pins were arranged to form a 3×3 array spaced at 2.5 mm pitches. The central pin is in direct contact with anode A5 (central anode) while the other 8 pins read out the remaining anode signals through the large circular read out pads. All signals of anode and cathode were read out through low noise preamplifiers (A250, Amptek, Bedford, MA) and shaping circuits. Signals were subsequently digitized by one data acquisition (DAQ) system. The DAQ system employs 10 channels free running flash ADC with the maximal sampling rate of 500 MHz and 8-bit depth to capture the entire waveforms for offline analysis.

The CdZnTe detector and its readout boards are mounted inside a copper shielding box, as shown in Fig. 2(A), to minimize noise pickup. A 2-D translation stage is mounted next to the CdZnTe detector (also inside the copper box) to hold a radioactive source and a collimator in order to provide a collimated gamma ray beam for spatial resolution and charge sharing measurements. The minimal step size of the translation stage is 10 μm . The collimator was made of four 3.5 cm thick Tungsten blocks in a plane to create a square opening of $170 \mu\text{m} \times 170 \mu\text{m}$ on the top surface [Fig. 2(B)]. The gamma ray source was stuck above the square opening. The distance from the bottom of collimator to the CZT surface is 1.4 cm.

C. Charge Sharing and Intrinsic Spatial Resolution

Charge sharing between the central pixel and its neighboring pixels was measured using both Co-57 and Ge68 with the collimator shown in Fig. 2(B). To show charge sharing between adjacent anode pixels and to evaluate the intrinsic spatial resolution of 350 μm pitch pixelated CdZnTe detectors, we stepped the collimated Co-57 and Ge-68 sources across the central and its two neighboring anode pixels with a step size of 30 μm [11]. The effective gamma ray beam size was estimated to be around $270 \mu\text{m} \times 270 \mu\text{m}$ at the detector surface with the $170 \mu\text{m} \times 170 \mu\text{m}$ opening at the top of the tungsten collimator surface. This is the smallest dimension that our high-precision machine shop can make, given the type of material (tungsten alloy) and 3.5 cm block thickness. The experimental setup for the two sources was the same except that the energy threshold was 22.5 keV and 55 keV for the 122

keV and 511 keV gamma rays, respectively. The contribution of electronic noise was measured to be about 3 keV FWHM at a -1000 V cathode bias using a test pulse. We analyzed the photopeak events that involved single-pixel detection (charge collected by the central anode pixel only) and double-pixel detection (charge collected by the central pixel and one of the two neighboring anode pixels) in all collimator locations.

D. Depth of Interaction

Two approaches were used to analyze the DOI of detection events from the $350\text{ }\mu\text{m}$ pixelated CdZnTe detector. The first method is based on the ratio of cathode and anode signals. It is commonly assumed that the electron trapping is negligible when compared to hole trapping as charges move across the CdZnTe substrate toward anode and cathode. Under such condition, the anode signal amplitude would be independent of DOI of an event while the cathode signal amplitude depends linearly with DOI if the trapping of holes is fairly uniform throughout the substrate. As a result, the cathode/anode ratio would be a linear function of the DOI of an event and can be used as a “depth index” of an event. We used a collimated source (Co-57 or Ge-68) to acquire data when the gamma ray beam was centered at the anode A5. We plotted the anode and cathode signal as a function of cathode/anode ratio. A big ratio corresponds to events near the cathode surface, while a small ratio corresponds to events close to the anode surface.

The second method is based on electron drift time, which can be measured from the waveform samples acquired by the flash ADC DAQ system. We used the difference between the two time points when the cathode signal and the anode signal first started rising. For the single pixel photopeak events of 511 keV source, we also analyzed the correlation between these two approaches, i.e., cathode/anode ratio and electron drift time.

III. Results and Discussions

A. Charge Sharing

Fig. 3 shows scatter plots of charge signals from 2 neighboring anode pixels (A5 and A4) at different source locations as a collimated 122 keV gamma ray beam was stepped from one pixel to the other. Although we used a $30\text{ }\mu\text{m}$ step size to scan across the CdZnTe detectors, we only show five positions in Fig. 3 to illustrate the changes of charge sharing between the two pixels. From the scatter plots, we can clearly see that more charge sharing events occur when the collimated beam hits the gap between the two pixels (positioned at $300\text{ }\mu\text{m}$). With the effective collimated beam size of $270\text{ }\mu\text{m} \times 270\text{ }\mu\text{m}$, we could see both charge sharing events and single-pixel events in the scatter plots of position “ $150\text{ }\mu\text{m}$ ” and “ $450\text{ }\mu\text{m}$ ”. We have previously conducted similar measurements using a slit collimator of $80\text{ }\mu\text{m}$ in width and $650\text{ }\mu\text{m}$ in length [18]. The overall tendency of charge sharing pattern are the same, except that there was less mixture of the charge sharing events and single-pixel events when the collimated beam was located between the two anode pixels. However, since the gamma ray beam through the slit collimator reached regions too far away from the central anode pixel as the source was stepped across anodes A4 and A5, the results could not be used to adequately model the detector resolution. Therefore, results presented in this work is limited to those acquired using the square collimator.

Fig. 4(A) shows the energy spectrum of single-pixel events when the collimated 122 keV beam hits the center of anode A5 (position 540 μm). The energy resolution of single-pixel photopeak events is 9.6% FWHM (without correction for the noise contribution). Fig. 4(B) shows the energy spectrum of double-pixel events when the collimated 122 keV beam hits the gap between two pixels (position 300 μm). The energy resolution of double-pixel photopeak is 12% FWHM. It is worth noting that when the collimated 122 keV gamma ray beam is centered at the large readout pad of A4 (1.4 mm in diameter), energy resolution is 6.5% FWHM. This suggests that for finely pixelated CdZnTe detectors, such as 350 μm pitch detectors used in our experiments, the benefits from small pixels effect may start to diminish because the severe charge sharing among small pixels degrades the energy resolution [12]. This is particularly true for higher energy photons such as 511 keV gamma rays that produce large charge cloud that cannot be completely collected by 250 μm size anode pixels.

Fig. 5 shows the scatter plots of charge signal measured by anode A4 versus anode A5 using collimated 511 keV gamma ray beams. Results clearly illustrate that higher energy gamma rays (511 keV) produce more charge sharing events than lower energy gamma ray (122 keV) at all source locations. There are also more Compton scattering events with higher energy gamma rays when compared to those from the 122 keV gamma ray measurements. As a result, the photofraction of 511 keV gamma ray is much lower than that of 122 keV gamma ray in current measurement of 350 μm pixelated CdZnTe detector with 5 mm thickness.

When the collimated 511 keV gamma ray beam hits the central pixel A5, the single-pixel photopeak events show an energy resolution of 9.3% FWHM [Fig. 6(A)]. When the collimated 511 keV gamma ray beam hits the gap between two pixels, the double-pixel photopeak events show an energy resolution of 11.6% FWHM [Fig. 6(B)]. The electronic noise contribution was not subtracted in the energy resolution estimate.

B. Intrinsic Spatial Resolution

The intrinsic spatial resolution of the gamma ray detector is the dominant factor that limits the achievable image resolution of most PET scanners. The commonly accepted expression of PET image resolution, as proposed by Moses and Derenzo [22], consists of the quadratic sum of effective source dimension, acolinearity effect, and detector intrinsic spatial resolution. In our attempt to measure the detector intrinsic spatial resolution of 350 μm pitch pixelated CdZnTe detector, we scan across the detector surface with collimated gamma ray sources. Since the collimated beam has finite width, the detected count profiles are the results of gamma ray beam profile convoluted with detector intrinsic spatial resolution.

Fig. 7(A) and (B) shows the detected count profiles using collimated Co-57 and Ge-68 sources, respectively. The square dots are the count profiles of single-pixel photopeak events measured by central pixel A5 when collimated source was stepped across the anode A5. The triangle dots show the count profiles of double-pixel photopeak events measured by the central pixel A5 and its neighboring pixel A4 when the collimated source was stepped across the anodes and the gap between them. Results show that for a Co-57 source (122 keV), the FWHM of count profiles of single-pixel photopeak events and double-pixel photopeak events are 340 μm and 360 μm , respectively. For a Ge-68 source (511 keV), the FWHM of

count profiles of single-pixel photopeak events and double-pixel photopeak events are 410 μm and 520 μm , respectively. As expected, higher energy gamma rays cause greater uncertainty between the photoelectron origin and the final charge cloud distribution, which leads to wider count profiles for both single-pixel events and double-pixel events.

The count rate of single-pixel photopeak events reaches its peak at the center of the pixel A5. The count rate of double-pixel photopeak events should reach its peak at the center of the gap between adjacent pixels. However, Fig. 7 shows the peak distance between single-pixel profile and double-pixel profile in both 122 keV and 511 keV measurements are slightly wider than 175 μm . This could be potentially explained by the distorted field due to our asymmetric detector geometry (shown in Fig. 1). It should also be noted that the absolute count rate of the CdZnTe detector decreases when the gamma ray energy changes from 122 keV to 511 keV because the detection efficiency of 511 keV photon is much less than that of 122 keV photon within 350 μm pitch pixelated CdZnTe detectors of 5 mm thickness.

Table I summarizes the FWHM of count profiles when measured using a collimated Co-57 or a Ge-68 source. The values in the parenthesis are the FWHM of count profiles after the dimension of the collimated gamma ray beam is subtracted from the measured count profiles in Fig. 7. The effective collimated beam dimension was estimated to be around 270 $\mu\text{m} \times 270 \mu\text{m}$. It should be noted that while single-pixel photopeak events exhibit higher intrinsic spatial resolution, the double-pixel (or multi-pixel) charge sharing events may allow interpolation of event position between adjacent anode pixels. Therefore, these estimated FWHM represent the potentially achievable detector intrinsic spatial resolution for 350 μm pitch pixelated CdZnTe detectors, but not the theoretical resolution limit of such detectors.

Based on the total number of counts under the count profiles in Fig. 7, it is clear that the percentage of double-pixel charge sharing events (out of the total number of events) increases as gamma ray energy increases. This can be explained by the increased charge cloud dimension caused by higher energy gamma rays. In the case of a Co-57 source, the number of double-pixel charge sharing events is slightly higher than that of single-pixel photopeak events. In the case of Ge-68 source, the number of double-pixel charge sharing events is more than twice of that of single-pixel photopeak events. This suggests that charge sharing events among neighboring anode pixels are essential and must be included when using 350 μm pitch pixelated CdZnTe detectors for PET imaging applications.

C. Depth of Interaction

Fig. 8(A) and (B) shows the scatter plots of experimentally measured anode signal amplitudes versus the cathode/anode ratio and cathode signal amplitudes versus the cathode/anode ratio, respectively, when collimated 122 keV gamma rays were aimed at the central pixel A5. Fig. 8(C) shows the average signal amplitude of photopeak events for a given cathode/anode ratio. The corresponding scatter plots and average signal amplitude of photopeak events for 511 keV gamma rays are shown in Fig. 9.

At both 122 keV and 511 keV energy levels, the anode signal amplitude shows slight dependency on cathode/anode ratio rather than a constant for events at different DOI across

the 5 mm thick CdZnTe detector. This slight decrease in anode signal amplitude with increasing electron drift distance suggests that our 350 μm pitch pixelated CdZnTe detector is subject to electron trapping. In contrast, cathode signal amplitude is a strong function of cathode/anode ratio with good linearity [Figs. 8(B) and 9(B)], except at the regions very close to the anode or cathode surfaces. Compared to 122 keV photons, 511 keV photons have greater penetration and can interact with the CdZnTe detector substrate at a greater depth. These events are subject to more holes trapping, and hence smaller cathode/anode ratio.

It should be noted that there is virtually no single-pixel photopeak events that are originated near the cathode surface when 511 keV gamma rays are directed at the central anode pixel, as shown in Fig. 9. This can be explained by the lateral dispersion of charge cloud as electrons move from the cathode surface toward the anode surface. The further distance that electrons need to travel, the more time it takes and the wider the lateral dispersion of the electron cloud creates. If a gamma ray interacts with the CdZnTe substrate near the cathode surface, the electron cloud will disperse to a wider region when it reaches the anode surface. As a result, the total charge cannot be collected by a single anode pixel. Hence, this event will appear as a double (or multiple) pixel photopeak event. In contrast, when a gamma ray interacts with the CdZnTe substrate near the anode surface, the lateral dispersion of the electron cloud is limited. Hence, the entire charge can be collected by a single anode to form a single-pixel photopeak event.

It should also be noted that the use of cathode/anode ratio as a depth index cannot be applied universally to all types of events. For example, double-pixel (or multi-pixel) charge sharing events require one to read out multiple anode signals simultaneously in order to estimate the cathode/anode ratio correctly. Depending on the design of readout electronics, this parallel readout capability is not always available, particularly when the number of pixelated anodes becomes as large as a few thousands or a few tens of thousands per detector module. Similarly, if a gamma ray undergoes Compton scatter and results in 2 interactions in the CdZnTe substrate, the two separate charge depositions will be subject to different levels of hole trapping (assuming that their corresponding DOI are not the same, which should commonly be true). Even if one can identify these two interactions and read out their anode signals accurately, it is not possible to use the combined cathode signal to estimate the individual event's DOI using the cathode/anode ratio.

From the digitized waveform of both anode and cathode signals, we also estimated the electron drift time based on the rising edges of the cathode and anode waveforms. We analyzed the DOI of single-pixel photopeak events using electron drift time when the collimated 511 keV beam was centered at the central pixel A5. Fig. 10(A) shows scatter plots of anode signal amplitude versus electron drift time. Fig. 10(B) shows a good linear correlation between cathode/anode ratio and electron drift time for single-pixel photopeak events of 511 keV source. Based on electron drift time measured from individual anode signals, we can analyze the DOI locations for both single-pixel events and the double-pixel charge sharing events, as well as photopeak events and Compton scatter events, assuming that the charge drift time at particular depth will be independent on the amount of energy deposited. As a result, estimation of DOI using the electron drift time may be a more robust

approach than using the cathode/anode ratio. However, it is technically challenging if one needs to read out large number of anode pixels accurately not only for their total charge signals but also for timing information. Custom ASIC that can read out thousands of 350 μm pitch pixelated CdZnTe detector with both energy and timing information is, to the best of our knowledge, not yet in existence. However, if this type of ASIC becomes available, DOI estimation based on electron drift time will allow one to identify the 3-D locations of intra-crystal multiple Compton interactions, which has been one of the limiting factors for accurate event positioning in ultra-high resolution PET detectors.

By compensating the electron drift time, the timing resolution of CdZnTe detector could potentially be further improved using the depth sensing technique [23]. This would be very important for coincidence detection when CdZnTe detector is used for PET imaging application. Several algorithms based on the cathode signal fitting have been developed to improve the timing resolution of CdZnTe detectors [24], [25]. The accuracy of timing estimation based on cathode signal versus anode signal will require further investigation in order to optimize the timing performance of CdZnTe detector for PET image applications.

IV. Conclusion

We have studied three important factors that affect the 3-D spatial resolution of 350 μm pitch pixelated CdZnTe detector, including charge sharing, intrinsic spatial resolution measurements, and DOI analysis. The results suggest the following:

- 1) For 350 μm pitch pixelated CdZnTe detector, the number of double-pixel charge sharing events increases significantly when the gamma ray energy increases, from 122 keV to 511 keV. This can be explained by the larger charge cloud size and the higher probability of Compton scattering caused by higher energy gamma rays.
- 2) For 350 μm pitch pixelated CdZnTe detector, when irradiated by collimated 122 keV gamma rays, the measured single-pixel and double-pixel photopeak events show a count profile of 340 μm FWHM and 360 μm FWHM, respectively. For collimated 511 keV gamma rays, the count profiles of single-pixel and double-pixel charge sharing events were estimated to have a FWHM of 410 μm and 520 μm . When the gamma ray beam dimension is subtracted, the count profiles of single-pixel and double-pixel photopeak events at 511 keV (or 122 keV) energy were estimated to have a FWHM of 308 (or 207) μm and 444 (or 235) μm , respectively. These values represent a reasonable estimate of the intrinsic spatial resolution of 350 μm pitch pixelated CdZnTe detectors, despite that we do not have a reliable way to accurately measure of effective gamma ray beam dimension. In any case, it should be safe to assume that the intrinsic spatial resolution of 350 μm pitch pixelated CdZnTe detectors is no worse than 520 μm FWHM (the count profile's FWHM measured with a gamma ray beam of finite dimension without compensation for the beam width).
- 3) For single-pixel photopeak events, there is a linear correlation between the electron drift time and cathode/anode ratio for 511 keV gamma rays using 350

μm pitch pixelated CdZnTe detector. 3-D positioning based on electron drift time may be more robust than that based on cathode/anode ratio, but will require custom ASIC in order to read out both charge collection and timing information from individual anodes, and thus is technically more challenging.

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Fig. 1.

Custom design 9-Pixel-Pattern CdZnTe detector. (A) 9-pixel pattern mask. (B) Finished 20 mm $\times$ 20 mm $\times$ 5 mm CdZnTe detector. (C) Electric field over the central pixel (A5) and its right neighbor (A6). (D) Weighting potential of central pixel (iso-potential surface contours) and right neighbor pixel (grey shaped potential contours).

Fig. 2.
(A) Experimental setup with A250 preamplifiers and collimator inside a copper shielding box. (B) Custom designed collimator of four Tungsten blocks with 3.5 cm thickness. The middle square hole is $170\ \mu\text{m} \times 170\ \mu\text{m}$.

Fig. 3.

Charge sharing between two neighbor pixels, A5 and A4, in the 350 μm pitch pixelated CdZnTe detector measurements when collimated 122 keV beam hits different locations. The position of 300 μm corresponds to the gap between two pixels. The regions used to define double-pixel charge sharing photopeak events and single-pixel photopeak events are illustrated in the plots of “300 μm ” and “600 μm ”. In the drawing of 9-pixel anode pattern, the black dots represent the center of collimated 122 keV gamma-ray beam at the 5 locations where the data were acquired.

Fig. 4.

(A) Energy spectrum of single-pixel events, when collimated 122 keV beam hits the position of $540\ \mu\text{m}$, which is close to the center of anode A5. (B) Energy spectrum of double-pixel events when collimated 122 keV beam hits the position of $300\ \mu\text{m}$, which is between anode A5 and anode A4. The energy discrimination levels (LLD and ULD) shown in the figure were used in the integration of single-pixel photopeak events and double-pixel photopeak events in Fig. 7(A).

Fig. 5.

Charge sharing between two neighbor pixels, A5 and A4, in the 350 μm pitch pixelated CdZnTe detector measurements when collimated 511 keV beam hits different locations. The position of 300 μm corresponds to the gap between two pixels. In the drawing, the black dots represent the center of collimated 511 keV gamma-ray beam at the 5 locations where the data were acquired.

Fig. 6.

(A) Energy spectrum of single-pixel events, when collimated 511 keV beam hits the center of Anode A5. In order to increase the statistics, we selected four collimator positions (480 μm , 510 μm , 540 μm , and 570 μm) to create the energy spectrum of single-pixel. (B) Energy spectrum of double-pixel events when collimated 511 keV beam hits the gap between anode A5 and anode A4. In double-pixel energy spectrum plots, we selected four collimator positions (270 μm , 300 μm , 330 μm , and 360 μm). The energy discrimination levels (LLD and ULD) shown in the figure were used in the integration of single-pixel photopeak events and double-pixel photopeak events in Fig. 7(B).

Fig. 7.

Spatial resolution profiles of collimated Co-57 (A) and Ge-68 (B) beams scan across three 350 μm pitch pixels. The smooth curves are Gaussian fits of the measured data (dots).

Fig. 8.

(A) and (B) show the single-pixel signal amplitude of anode and cathode versus Cathode/Anode ratio, when collimated 122 keV beam hits central $350\ \mu\text{m}$ pitched pixel. (C) DOI effects for collimated 122 keV gamma ray beam measurements.

Fig. 9.

(A) and (B) show the single-pixel signal amplitude of anode and cathode versus Cathode/Anode ratio, when collimated 511 keV beam hits central $350\ \mu\text{m}$ pitched pixel. (C) DOI effects for collimated 511 keV gamma ray beam measurements.

Fig. 10.

Single-pixel events DOI analysis using collimated 511 keV beam centered at the central 350 μm pitched anode pixel. (A) Anode pulse height versus electron drift time. (B) Correlation between cathode/anode ratio and electron drift time for photopeak events, the straight red line is a linear fit to the data.

TABLE IIntrinsic Spatial Resolution of 350 μm Pitch Pixelated CdZnTe Detector

Source	FWHM of Single-Pixel Event profile in μm		FWHM of Double-Pixel Event profile in μm	
Co-57	340	(207)	360	(235)
Ge-68	410	(308)	520	(444)