3D Position Sensitive CdZnTe Spectrometer Performance Using Third Generation VAS/TAT Readout Electronics

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Abstract—Three-dimensional position-sensitive CdZnTe (CZT) gamma-ray spectrometers employing new VAS3.1/TAT3 ASIC readouts were developed and tested. Each spectrometer is a 1.5 × 1.5 × 1 cm³ CdZnTe crystal with 11 by 11 pixellated anodes wire-bonded to the readout electronics using an intermediate ceramic substrate with plate-through-via. The signals from the anode pixels and the cathode were all read out through these ASICs. The pixel position provides the lateral coordinates of the interaction, while the cathode to anode signal ratio and the electron drift time are used to obtain the interaction depth. Using the 3-D position information, the variation in weighting potential, electron trapping and material non-uniformity can be accounted for to the scale of the position resolution, ~ 1.27 mm × 1.27 mm × 0.2 mm. The new VAS3.1/TAT3 ASIC has less gain and baseline drift, lower cross-talk noise, more uniform thresholds, better linearity and better timing resolution than our previous VAS2/TAT2 system. For example, the 32 keV K X-ray from a ¹³⁷Cs source was observed for the first time. Two 3-D CZT spectrometers were tested and both achieved better than 1% FWHM energy resolution (at 662 keV, room temperature operation, with an uncollimated source) for single-pixel events. The experimental results for these two 3-D CZT spectrometer systems are presented and discussed.

I. INTRODUCTION

WIDE band gap semiconductor detector materials, such as CdTe, CdZnTe and HgI₂, have long been of interest because of the convenience of room temperature operation, high efficiency for gamma-ray detection and potential for good energy resolution. Among them, CdZnTe has gained particular interest. However, the performance degradation due to charge trapping limits its application using conventional planar electrodes when large sensitive volumes are needed. Single polarity charge sensing techniques, such as coplanar grids [1] or pixellated anodes [2], can overcome the severe hole trapping problem and greatly improved the energy resolution of large volume CdZnTe detectors. However, even with single polarity charge sensing techniques and methods to compensate for electron trapping, such as relative gain [1] and depth sensing [3], the variations in electron trapping and material non-uniformity can still degrade the energy resolution.

In 1998, we developed the first fully functional 3-D CZT spectrometer [4][5]. The 3-D position sensitivity of this CZT spectrometer using VA1 application specific integrated circuits (ASIC) chips enabled the correction for material non-uniformity and varying electron trapping. An energy resolution of 1.7% FWHM at 662 keV was achieved for single-pixel events from the whole bulk of a 1 cm³ 3-D CZT detector. However, this first-generation 3-D CZT spectrometer could only record the energy and 3D position information for single-pixel events.

After five years of effort and a fruitful collaboration between our group and Ideas ASA [6], in 2003 we introduced the 2nd-generation 3-D CZT system using the VAS2/TAT2 ASIC [7]. With the ability of sensing the electron drift time for each individual interaction, these 2nd-generation 3-D CZT systems can measure the energy and 3D position information for multiple-pixel events, as well as single-pixel events. Intelligent gamma-ray spectroscopy [8] and 4π Compton imaging [9] have been successfully implemented using these 2nd-generation 3-D CZT spectrometers.

Several problems were discovered in the 2nd-generation readout electronics. Firstly, the electronic noise was fairly high (~5-6 keV in different channels), limiting the energy resolution to 1.1% FWHM at 662 keV for single-pixel events. Secondly, some design flaws on the front-end board cause substantial cross-talk on the cathode induced by digital control signals. This leads to a high cathode triggering threshold (~100 keV). Thirdly, only one global threshold can be set for all the channels reading the signals from anode pixels. Because of the variations of the DC offsets in these channels, the global threshold has to be set above the highest threshold of all the channels, causing a fairly high triggering threshold for the anode pixels (~80 keV). Lastly, significant non-linearity was observed in the VAS2 (energy) channel, increasing the complexity in the calibration and degrading the energy resolution for multiple-pixel events. As a result, the best energy resolution achieved was 1.6% FWHM for two-pixel events and 2.1% FWHM for three-pixel events.

The 3rd-generation ASIC – VAS3.1/TAT3 has been designed to address the problems described above. This paper
briefly introduces the basic system configuration of the 3rd-generation 3-D CZT spectrometers. The experimental results from two detector systems are presented and discussed.

II. SYSTEM DESCRIPTION

A 3-D CZT spectrometer consists of a CdZnTe detector module with a ceramic substrate, an ASIC front-end board, and a controller (repeater) card (MCR3). The CdZnTe detector is wire-bonded to the ASIC inputs using an intermediate ceramic substrate with plate-through-via. The MCR3 repeater card is used to generate and send the readout clock signals to the ASIC and also convert the output of the ASIC to the voltage signal needed at the input of the data acquisition (DAQ) board. A PCI-6110 DAQ board from National Instruments is used as the A/D converter and as the controller interface between the DAQ program and the detector system.

A. Pixellated CdZnTe detector and front-end board

Both detectors were fabricated by eV-PRODUCTS [10] in 2001. Each has an 11×11 pixellated anode and a planar cathode on a 1.5 × 1.5 × 1.0 cm$^3$ CZT crystal. The pixel pitch is 1.27 mm. There is a common grid between pixel anodes biased at negative voltage to focus the electrons to the pixel anodes. The trace width of the grid electrode is 100 µm with a 200 µm gap between the grid and the pixel.

Four 33-channel VAS3.1/TAT3 chipsets are mounted on the front-end board to read out signals from 121 anode pixels and the cathode. The CZT crystal is mounted on a ceramic plate. The conducting traces on the two sides of the ceramic plate connect every pixel anode to a corresponding metal pad on the periphery of the plate. A short wire-bond connects each pad on the ceramic plate to the input of each ASIC channel on the front-end board, as shown in Fig. 1.

B. ASIC

The basic structure of the VAS3.1/TAT3 ASIC is nearly the same as the VAS2/TAT2 ASIC [7]. Several changes aiming to improve the system performance have been implemented in the VAS3.1/TAT3 ASIC. In the VAS2, because one channel (special channel) was used to read out the cathode signal (positive pulse) and the other channels (normal channels) were used to read out anode signals (negative pulse), an inverter was added after the shaper in each normal channel to make the anode signal polarity the same as the cathode polarity, so that all channels could employ a common design of peak-hold circuitry. However, the inverter is highly sensitive to temperature variation, causing a drifting of the baseline and the gain. This problem was solved with the use of two peak-hold circuits, one for anode signals and the other for the cathode signal, and the removal of the inverter. Other changes include adding a test channel with the peak hold turned off, using separate controls for the preamp feedback resistance for the special channel and the normal channels, and increasing the gain on TAT3 chips, which help to diagnose the system response and improve the system performance.

The VAS3.1 (version 3.1) ASIC chip is used to read out the induced charges on anode pixels and the cathode. The TAT3 (version 3) ASIC chip is used to trigger the system and read out the electron drift times. One VAS3.1 chip and one TAT3 chip form a chipset. The preamplifier output of each VAS3.1 channel is wire-bonded to the input of each TAT3 channel.

Each VAS3.1 chip has 33 independent channels, each consisting of a preamplifier, a shaping amplifier, a peak-hold and sample-hold circuitry. The first channel on each VAS3.1 chip has an opposite polarity to the other 32 channels, to read out the signal from the cathode. Fig. 2 shows the basic structure of a single VAS3.1/TAT3 channel.

Each TAT3 chip also has 33 channels, each channel having a fast shaper, a discriminator for triggering and a time-to-amplitude converter (TAC) for electron drift time sensing. A trigger mask can be set to disable those channels having high noise.

C. Depth sensing using C/A ratio and electron drift time

In the 3-D CZT spectrometer, the 2-D coordinates of interactions are determined from the individual location of the triggering pixels. For single-interaction events, because of the shape of the weighting potential, the cathode signal is proportional to both the deposited energy and the interaction
depth, while the anode signal is nearly proportional only to the deposited energy. Thus, the interaction depth can be derived from the cathode to anode signal ratio [3]. However, for multiple-interaction events, we cannot obtain the depth for each individual interaction using this ratio. Instead, electron drift times for each triggering pixel are individually recorded. Assuming nearly constant electron drift velocity inside the detector volume, the electron drift time can be used to obtain the depth for multiple-pixel events [7].

Fig. 3 illustrates the timing sequences of electron drift-time measurement for multiple-pixel events. When a gamma ray interacts in the detector and the electron clouds start to drift, a trigger is generated by the TAT3 special channel when the induced signal on the cathode crosses a threshold. This trigger starts the TAC in the TAT3 special channel and generates the system trigger. When an electron cloud approaches close to an anode pixel, the induced signal crosses a threshold, and triggers the corresponding TAT3 channel. This trigger starts the TAC in the TAT3 channel corresponding to that anode pixel. After a fixed delay following the system trigger, all channels are held by sample-hold circuits, and read out in serial mode through a multiplexer built into the chips. By using peak-hold in addition to sample-hold circuits on the VAS ASIC, the pulse amplitude of multiple-pixel events with different electron drift times (different peaking times) can be obtained correctly. The individual electron cloud drift times can be derived from the timing signal amplitudes generated by the TACs in the TAT3 channels.

**D. DAC thresholds**

In the 2nd generation system, the anode pixels had triggering thresholds ranging from 50 keV to 80 keV, with the spread caused by the variations of DC offsets and noise in each ASIC channel. However, only one global triggering threshold could be set for all the channels reading the anode pixels. As a result, the threshold needed to be set above the highest threshold among all channels (~80 keV). This problem has been solved in the new TAT3 ASIC. In addition to the global threshold, a 4-bit digital-to-analog converter (DAC) unit has been added to each TAT3 channel so that the threshold of each channel can be finely tuned to achieve more uniform and lower thresholds among all the channels.

**III. EXPERIMENTAL RESULTS**

Two 3-D CZT detector systems were assembled with the 3rd-generation readout electronics and tested. The first detector was biased at -2200 V on the cathode and the second at -1400 V. The anode pixels were DC-coupled to the ASIC inputs and thus all were at ground potential. The common grid electrode between the pixels was biased at a negative voltage to steer electrons drifting towards the anode pixels.

The whole system was operated at room temperature (~23°C). The detector was irradiated from the cathode side with uncollimated gamma-ray sources placed 5 cm away from the cathode. Data collected from a 137Cs gamma-ray source was used for the calibration. Spectra from a 241Am source were also collected for measuring the electron mobility-lifetime products and estimating the electronic noise.

**A. Electronic noise**

According to Ideal’s ASA’s test report, the electronic noise in the ASIC is ~3 keV. However, due to design limitation, the electronic noise of the ASIC cannot be directly measured after the ASIC has been wire-bonded to the detector. In order to estimate the overall electronic noise of the system, an uncollimated 241Am source was placed 5 cm away from the cathode. The 59.5 keV gamma rays from the 241Am source should all be stopped in a very thin layer on the cathode side. Thus, the collected anode signals should all come from interactions at almost the same depth, without extra broadening due to depth dependence. The energy resolution of the 241Am anode spectrum was measured to be ~4.8 keV FWHM. If we only consider the statistical fluctuation in the charge carrier creation and assume a Fano factor of 0.1, the electronic noise in the channels reading out the anode signal is estimated to be less than 4.5 keV FWHM after removing the photopeak broadening due to charge carrier generation from the observed overall energy resolution. Similarly, the electronic noise in the channel reading out the cathode signal was estimated to be ~7 keV FWHM.

**B. Results for 662 keV single-pixel events**

With the help of 3D position sensing, the material non-uniformity, the weighting potential variations and the electron trapping variations can be accommodated to the limit of the position resolution – estimated to be 1.27 mm × 1.27 mm × 0.2 mm. By implementing 3-D corrections, unprecedented energy resolution of 0.93% and 0.76% FWHM at 662 keV for single-pixel events have been achieved from the entire 2.25 cm³ volumes of the first and the second detector, respectively, as shown in Fig. 4(a)(b). As a result of the much lower thresholds than the previous systems, the 32 keV 137Cs K x-rays have been observed in both systems for the first time. The much smaller 32 keV photopeak in Fig. 4(b) is due to the higher thresholds in the second system.
Fig. 4. Energy spectra of single-pixel events from an uncollimated $^{137}$Cs source collected for 40 hours from all working pixels. (a) Detector 1 biased at -2200 V on the cathode. (b) Detector 2 biased at -1400 V on the cathode.

Fig. 5 shows the energy resolution (FWHM at 662 keV) distributions of the two detectors for single-pixel events. The two bad pixels in the two detectors are probably due to faulty wire-bonds. The first detector has 88 pixels that have better than 1% FWHM energy resolution, while the second detector has 116 pixels with better than 1% FWHM energy resolution.

C. Measurements of $(\mu \tau)_e$

The energy spectra of a $^{241}$Am source irradiating the cathode side were collected for each pixel under two different cathode biases (-1400 V and -2200 V for the first detector, -1400 V and -2000 V for the second detector). The electron mobility lifetime product can be estimated using [11]

$$\left(\mu \tau\right)_e = \frac{D^2}{\ln \left(H_{a1} / H_{a2}\right)} \left(\frac{1}{V_2} - \frac{1}{V_1}\right)$$

where $D$ is the detector thickness, $H_{a1}$ and $H_{a2}$ are the photopeak centroids under two different cathode biases - $V_1$ and $V_2$. The measured $(\mu \tau)_e$ for all the pixels are shown in

![Image](image-url)
Fig. 6. We can see that the mean \((\mu \tau)\) of the second detector is more than two times that of the first detector. This might be the reason why the second detector achieved much better energy resolution than the first.

D. Results for 662 keV two-pixel events

For two-pixel events, the depth of each interaction can be derived from the electron drift time for each pixel. After correction for timing-amplitude-walk, electron trapping and non-linearity for each signal, the true energy and 3-D position information can be obtained for each interaction.

An energy resolution of 1.23% FWHM at 662 keV has been achieved for two-pixel events collected from the entire volume of the second detector, as shown in Fig. 7. When a 662 keV gamma ray interacts twice inside the detector volume, the probability of depositing all of the 662 keV energy is much higher than only one interaction. This is evident by comparing Fig. 4(b) and Fig. 7 as the peak-to-Compton ratio increases from ~11 to ~20. This feature can be very useful in applications where the peak-to-total ratio determines the measurement sensitivity.

![Energy spectrum of two-pixel events from an uncollimated $^{137}$Cs source collected for 40 hours from the whole volume of detector 2.](image)

Fig. 7. Energy spectrum of two-pixel events from an uncollimated $^{137}$Cs source collected for 40 hours from the whole volume of detector 2.

Taking the second detector as an example, although an energy resolution of 0.76% FWHM at 662 keV has been achieved for single-pixel events, the energy resolution for two-pixel events was only 1.23% FWHM, worse than the conservatively estimated energy resolution based on the single-pixel resolution – $\sqrt{(0.76\%)^2 + (0.76\%)^2} = 1.07\%$ FWHM. Possible factors, such as charge sharing, poor depth resolution at low energy, and non-linearity, are still under investigation.

IV. SUMMARY AND CONCLUSION

With the help of the 3rd-generation ASIC – VAS3.1/TAT3, the performance of the 3-D CZT spectrometer has been significantly improved. The electronic noise is reduced to <4.5 keV from ~6 keV of the previous ASIC. The triggering thresholds of the anode pixels are lowered to ~30 keV. By implementing 3-D correction, unprecedented energy resolutions of 0.93% (6.16 keV) FWHM and 0.76% (5.03 keV) FWHM at 662 keV for single-pixel events have been achieved from the entire 2.25 cm$^3$ volumes of the two detectors, respectively. The energy resolutions for two-pixel events are 1.46% FWHM and 1.23% FWHM at 662 keV for the first and the second detector, respectively, worse than expected. The reasons for the energy degradation in two-pixel events are still under investigation.

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VI. REFERENCES

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