CZT Detectors Read Out with the RENA-2 ASIC

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Abstract—Multiple-site interactions initiated by Compton scattering are the primary interaction processes of gamma-rays in CZT in ~0.2 - several MeV range. Thus, exploiting gamma-rays as directional and spectral diagnostic probes requires detectors with 3-D resolution that resolve and measure individual interaction site's locations and energies. Desirable capabilities for Compton telescopes appear to be a spatial resolution of ~1 mm and an energy resolution of ~1 percent. Such capabilities are also important for coded mask imagers above 250 keV, where 3-D resolution can greatly improve the identification of a gamma-ray's initial interaction site, which is crucial for imaging. Significantly improved spectral resolution can be anticipated with CZT when multi-site interactions are resolved. This will allow each site's energy signals to be corrected for the site's specific signal loss characteristics, and the summed energies will then provide an accurate measure of the incident gamma-ray energy. We report on progress toward the development of 5 - 10 mm thick CZT detectors and electronics that are pursuing these objectives. Position sensing is provided by anode pixels with ~1 mm pitch for x-y positions and charge drift times for z-positions. Detectors are read out with the new RENA-2 ASIC. This chip contains preamplifiers, shaping amplifiers, threshold triggering, and peak detection for each of its 36 channels. To optimize energy resolution for various detector types and event rates, the RENA-2's peaking times and other parameters are adjustable. Each channel has a novel fast time stamp function that can record interaction times to ~10 nsec, allowing precise measurements of charge drift times and making PET imaging possible. The detector and ASIC designs are described and results are presented on tests of thresholding, energy resolution, and time resolution.

I. INTRODUCTION

CZT is an appealing detector material for hard X-ray and low energy gamma-ray imaging spectrometers. Due to its large average atomic number, Z ~50, photoelectric absorption is the dominant interaction below 250 keV, and its high density, 5.8 g/cm³, results in short interaction lengths, e.g., 1.2 mm for 100 keV X-rays. Photoelectron ranges are very short, e.g., 50 microns at 100 keV. Thus, few-mm thick CZT offers the potential for high efficiency detection and with sub-mm localization of X-rays below ~250 keV. Various groups have developed multi-electrode CZT detectors that achieve single-interaction localization accuracies from ~100 microns to ~2 mm at energies from ~10 - 150 keV. Such detectors can achieve good energy resolution, e.g., ~5% at 122 keV in large area formats [1], and excellent resolution, e.g., ~1 keV at 60 keV [2] is possible with small pixels and cooling to ~ -20°C.

Above ~150 keV, however, CZT imaging spectrometers must deal with significant difficulties which have impeded their development [3]. Multi-site gamma-ray interactions become significant, and above 250 keV Compton scattering dominates photoelectric absorption. Thus, at these energies most fully absorbed gamma-rays have multiple-site interactions, e.g., an initial Compton scattering followed by a photoelectric interaction. The average dispersion among sites is large, varying from 3 to 20 mm as the incident gamma-ray energy varies from 200 keV to 1 MeV. Identifying the initial interaction site is required for imaging, but the initial site is not necessarily the most energetic and the interaction sites usually are not symmetric around the initial site. Hence, identifying the initial site is challenging. However, our analysis [3] shown that 3-D readout coupled with a Compton kinematic analysis can identify the initial interaction more than 85% of the time for gamma-rays above 300 keV.

Good efficiency requires 5 - 10 mm thick detectors and the resulting long charge drift times can lead to significant electron trapping and degraded energy resolution. It becomes necessary to correct the anode signal of each interaction site for the signal loss due to electron trapping.

Due to the low hole mobility, which is only a few percent of that of electrons, hole trapping can reduce anode signals by an even greater amount than electron trapping. However, multiple anode designs with a small strong pixel effect [4], [5] can be used in spatially resolved detectors to virtually eliminate the deleterious effect of hole trapping.

Thus, the key difficulties that must be overcome if CZT detectors are to achieve their potential for high resolution imaging and spectroscopy above ~150 keV are (1) resolving multi-site events and identifying the initial site with high confidence, (2) correcting each site's signal for electron trapping, and (3) summing the corrected signals to obtain the true gamma-ray energy. The CZT Time Projection Detector, described below, is designed to achieve these capabilities.

II. CZT TIME PROJECTION DETECTOR (CZT-TPD)

Our group is developing CZT-TPDs for gamma-ray measurements in the ~100 keV to ~2 MeV range. Matteson et al. [3] presents a detailed description of the CZT-TPD and test results. Here we provide a summary.

The CZT-TPD is designed to obtain 3-D localization of each site of multi-site gamma-ray interactions with a spatial resolution of ~0.5 mm and energy resolution of ~1% FWHM at 662 keV after corrections for charge trapping. Fig. 1 shows the main features of the 1 cm² prototype CZT-TPD. A single cathode contact covers one face of the detector and an array of 80 anode pixels, each 200 microns in diameter, is on the opposite face in a 1 mm hexagonal pattern. Ideally, every electrode would be readout by a dedicated electronic chain. In the prototype, four anode electronic chains were available, one

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for a single anode called the central pixel, and three for its nearest neighbors, which were summed into three pairs.

At each site of a multi-site gamma-ray interaction, electrons and holes are produced, and they drift toward the anodes and cathode, respectively. A site's x-y position is given by the location of the anode, or set of neighboring anodes, that collects the electrons. The site's z-position is determined from the electron drift time to the anode(s), taking into account the electron mobility, \( \sim 10^3 \text{cm}^2/\text{V-s} \).

Drift time is measured as the delay from the onset of the cathode preamplifier output, which occurs immediately when a gamma-ray interacts, to the onset of the anode signal, which does not occur until a site's electrons drift to within \( \sim 400 \) microns of the anode. The delay is measured by a custom-built TAC (time-to-amplitude-converter) that uses the cathode preamplifier output as its start pulse and the anode preamplifier output as its stop pulse. Each of the four instrumented anodes has a TAC. The start and stop functions used threshold triggering at 30 keV.

Preamplifier signals were amplified and shaped in conventional electronics for energy analysis, and together with the TAC signals, they were pulse height analyzed to produce event-by-event data consisting of the cathode and 4 anode signal amplitudes and 4 TAC amplitudes.

To gain insight into the charge drift/trapping/induction processes, we modeled the CZT-TPD's electric fields and the anode and cathode weighting potentials. Next, we modeled the induced charge on the anode and cathode versus time by propagating the charges along the field lines and evaluating the induced charge on the anode and cathode versus time. Trapping and mobilities of electrons and holes were accounted for, and charge diffusion was ignored. Electron mobilities and trapping lifetimes of \( 10^3 \text{cm}^2/\text{V-s} \) and 3 microsec were assumed. Details are given in [3] and the results are shown in Fig. 2 for three interaction depths.

We performed such tests as follows. Flood illumination at 662 keV was used to produce gamma-ray interactions in the CZT-TPD. 662 keV gamma-ray interactions at 3 depths beneath the cathode, which correspond to the 3 (cathode-to-anode) delay values given. X-axis scale is 1 microsec/division. The cathode was biased at -1000 V. for a single anode called the central pixel, and three for its nearest neighbors, which were summed into three pairs.

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We performed such tests as follows. Flood illumination at 662 keV was used to produce gamma-ray interactions in the CZT-TPD and 662 keV single-site interactions were selected by triggering an oscilloscope on central pixel anode signals greater than 80% of 662 keV. This scheme allowed us to trigger on 662 keV energy losses that produced a reduced anode signals due increased electron trapping. Results are shown in Fig. 3 for single site gamma-ray interactions at three interaction depths that correspond closely to those of the calculations in Fig. 2. One can see that the TAC output is delayed by 250 nsec relative to the rise of the cathode and anode pulses. This is a feature of its design.

The agreement between the measurements and model results is excellent. One can clearly see the expected reduction in...
anode signal with increased drift time (larger TAC output). The model-predicted subtle curvature in the cathode signal, due to increasing numbers of electrons being trapped as they drift, is also seen. The anode pulse risetimes are greater than modeled, and the deviation is greatest for events with the greatest drift time. This trend is expected due to charge diffusion [6], which was not modeled. The measured drift time resolution was 25 and 60 nsec FWHM at 662 and 122 keV, respectively [3]. These correspond to z-axis position resolutions of 0.25 and 0.60 mm FWHM, respectively.

These tests confirmed the viability of the CZT-TPD concept. However, applying this technique to a useful detector size, e.g., 4 x 4 cm$^2$, requires ~1000 electronic channels, and, therefore, ASIC readout.

III. RENA-2 ASIC

A major objective of our program has been to read out the CZT-TPD with an ASIC chip that provides drift-time measurements as well as the usual energy information. NOVA R&D has developed such a chip, the 36-input RENA-2 (Readout Electronics For Nuclear Applications). UCSD worked closely with NOVA on the development and testing, and a consortium of other interested research groups and companies provided assistance as well. Tümer et al. [7] provide a comprehensive description of the RENA-2 and here we present a summary.

A block diagram of a single channel of the RENA-2 is shown in Fig. 4. This is a self-triggering, mixed signal ASIC chip with a low-noise, self-resetting charge sensitive preamplifiers at the input of each channel. The preamplifier is optimized for two input capacitances, 2 pF and 9 pF that are selectable channel-by-channel. Each channel's selectable parameters include dynamic range (= 9 fC and ≈54 fC, or 270 and 1620 keV in CZT), negative or positive input polarity to process signals from both anodes and cathodes with the same ASIC, preamplifier feedback capacitance and resistance, pole-zero, shaping time (0.4 to 40 microsec in 16 steps), and trigger threshold. The chip's numerous adjustable parameters allow it to obtain near-optimum performance for a wide range of event rates and detector types, e.g., Si, Ge, CZT, and HgI$_2$.

A programmable "hit-read" lookup table accommodates various readout schemes, e.g., sparse, generalized neighbor readout, and fully programmable for complex multi-electrode detectors. Each channels' pulse amplitude is captured by a peak detector, and the read out channels' peak detected levels are multiplexed to an off-chip pipelined ADC and converted into 14-bits at up to 3 M samples/s. A typical application might require 2 microsec of peaking followed by 3 microsec of hit-read processing to set up the readout of 6 channels, which would require and additional 2 microsec. Thus, the event would require 7 microsec to be captured and processed, and the maximum event rate would be ~140,000/sec. The control/readout architecture allows a single FPGA to control up to 8 RENA-2s, which operate as a single logical unit with 288 channels.

Some applications require accurate fast timing signals for coincident imaging such as positron emission tomography (PET) and Compton scatter detectors. The RENA-2 is designed to accommodate them by incorporating fast, low jitter shaping and a comparator circuit that produces a fast timing trigger for each channel. Another important function is the fast time stamp circuit of each channel. This utilizes FPGA-generated timing waveforms that are sampled by the fast trigger and then readout through the ADC to provide data on each channel's pulse arrival times with few-nsec accuracy.

Using the RENA-2 test board's built-in pulser, we measured the chip's noise versus simulated detector capacitance. The results are shown in Fig. 5. For the 9 pF FET the open input noise is 150 electrons rms, and for the 2 pF FET it is 140 e-rms. The noise slopes are 7.5 and 12.3 e-rms/pF, respectively. These results are close to expectations except the 2 pF noise floor was anticipated to be <100 e-rms. The discrepancy may be due to a layout problem in the test board that results in input charge being shunted away from the preamplifier, which will degrade the signal-to-noise. This problem is being corrected.

Integral linearity was measured with the pulser for many combinations of parameter values such as peaking time, gain, preamplifier feedback, etc. Fig. 6 shows typical results. In the upper panel a solid line connects peak centroids versus preamplifier amplitude. Non-linearities cannot be seen. The lower panel shows residuals from a linear fit to the data to have a smooth form of the deviations seen here occurs for all parameter settings. When the deviations are fit by a polynomial, the remaining residuals are seen to be only 0.02% rms.

This is excellent performance. It should enable the RENA-2 to provide readout of solid state detectors with <0.1%
energy resolution in Compton telescopes when multi-site energy depositions are summed to obtain the full gamma-ray energies.

IV. TEST RESULTS WITH CZT DETECTORS READ OUT WITH THE RENA-2

Fig. 7 shows the spectrum of an $^{241}$Am source obtained using one pixel of a 3 mm thick CZT detector with $1 \times 1$ mm$^2$ pixel pitch. The energy resolution is 3.5 keV FWHM at 60 keV. This result shows that the RENA-2 can obtain very good energy resolution.

We studied the capability to set very low trigger thresholds and simultaneously read out an anode and the cathode of a CZT pixel detector. Here $^{109}$Cd radiation at 22 and 88 keV illuminated the cathode above a single $2.5 \times 2.5$ mm$^2$ pixel in a 5 mm thick detector. Data were taken in the RENA-2’s highest gain setting, which allows the threshold to be controlled in ~1 keV steps. The anode threshold was set at 8 keV and when it triggered, the anode and cathode were read out. Results are shown in Fig. 8, where the anode versus cathode scatter plot clearly shows peaks at 22 and 88 keV in both the anode and cathode as well a peak at ~62 keV due to K X-ray escape after interactions at 88 keV. The cutoff due to the anode threshold can be seen. The figure's one dimensional spectra for the anode and cathode have the nominal form for $^{109}$Cd. The energy resolution is relatively broad, 8 keV FWHM, because the detector is distant from the ASIC (~20 cm leads) and in a moderately shielded, breadboard configuration. These results show that the RENA-2 can trigger at low thresholds while simultaneously reading out a detector's anode and cathode.

A novel and important feature of the RENA-2 is the fast time stamp for event timing. This replaces the TAC scheme used in the prototype CZT-TPD. The fast time stamp is derived from a fast shaping amplifier that feeds a threshold discriminator. When this triggers, two timing waveforms, VU and VV (see the lower right of Fig. 4), are sampled and held, and then read out through the same ADC as the energy signal of the slow shaper channel. The pair of digitized timing signals constitute the fast time stamp. VU and VV are Sin/Cos waveforms derived by analog smoothing and phase shifting of a digital approximation to a 1 MHz sine wave that is produced by the FPGA. Fig. 9 shows oscillograms of these three signals. It can be seen that the waveforms are not ideal sines and cosines, but since the distortion is due to gains and phase shift, is easily corrected when the data are analyzed. Note that for any fast trigger time within the 1 microsec period of VU and VV there will be a unique pair of (VU, VV) values from which the time-value is determined.

Test pulses were used to study the fast time stamp, first with pulses occurring at random phases of VU and VV. The results showed that the systematic uncertainty of the fast time stamp is <2 nsec rms, i.e., timing jitter was <2 nsec. Next, we tested the fast time stamp with a pulser that was synchronized to VU and VV. It was adjusted to issue test pulses at fixed delays of an integral number of 50 nsec steps. At each step a large number of pulses were processed and analyzed to determine the histogram of their time-values. The results are plotted in Fig. 10. Here the x- and y-axes represent normalized values of VU and VV. Each pulser setting's data are contained in one of the twenty histograms that are arranged around the circumference of a circle in the VU-VV plane, where one cycle of the circle corresponds to a change in time-value of 1000 nsec. Recalling that the data sets are in 50 nsec steps, one can see by inspection that histogram widths are <10 nsec. The fitted widths are written in the inner circle of numbers. Their average is 3.4 nsec rms or 7.9 nsec FWHM. These pulser tests were done without a detector connected to the RENA-2 channels, so the noise level is lower than with a
Further tests of the fast time stamp were performed with a pair of CZT detectors to measure the 511 keV pair coincidence time resolution. The setup is illustrated in Fig. 10. Two 12 x 12 x 2 mm$^3$ CZT detectors with planar electrodes were biased at 200 V and oriented edge-on to a 0.5 mm $^{22}$Na source that produces pairs of 511 keV gamma-rays following positron decay. Each detector's anode was connected to a RENA-2 input. The slow triggering threshold was set to 300 keV and the fast time stamp threshold was set to ~50 keV. Data were analyzed to determine each detector's time-value for each event. Candidate coincident events were defined as having time-values within 1000 nsec, and their pairs of time-values were plotted in the scatter plot shown in Fig. 11. The figure's axes span ± 600 nsec. Note the tight clustering of points along the diagonal that is the signature of coincident events. For these data the coincidence time resolution is 20 nsec FWHM. Subsequent work reduced systematic effects and the resolution improved to 15 nsec.

These results show that CZT detectors read out with the RENA-2 can achieve pair coincidence time resolution that is in the regime required for PET imaging. We expect that with further work we will achieve time resolution <10 nsec.

REFERENCES