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Continued Studies of Single-Sided Charge-Sharing CZT Strip Detectors

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***Abstract*— In this paper, we report progress in the study of thick single-sided charge-sharing cadmium zinc telluride (CZT) strip detector modules designed to perform gamma-ray spectroscopy and 3-D imaging. We report on continuing laboratory and simulation measurements of prototype detectors with 11×11 unit cells (15×15×7.5mm^3). We report preliminary measurements of the 3-D spatial resolution. Our studies are aimed at developing compact, efficient, detector modules for 0.05 to 1 MeV gamma measurements while minimizing the number and complexity of the electronic readout channels. This is particularly important in space-based coded aperture and Compton telescope instruments that require large area, large volume detector arrays. Such arrays will be required for the NASA's Black Hole Finder Probe (BHFP) and Advanced Compton Telescope (ACT). This design requires an anode pattern with contacts whose dimensions and spacing are roughly the size of the ionization charge cloud. The first prototype devices have 125μm anode contacts on 225μm pitch. Our studies conclude that finer pitch contacts will be required to improve imaging efficiency.**

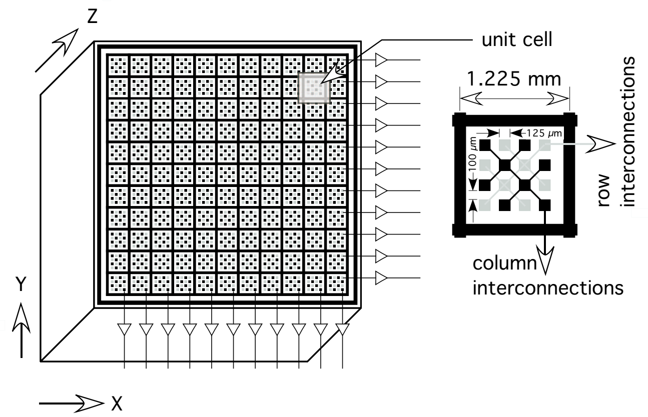

Fig. 1. Single-sided charge-sharing strip detector and dimensions of a unit cell showing interconnections.

I. Single-sided charge-sharing strip detectors

A. Detector concept and first prototype

FIGURE 1 shows the anode pattern of a charge-sharing CZT strip detector [1] with 11×11 unit cells. The pattern of a 1.225 mm square unit cell (expanded right) illustrates the pad interconnections. Each unit cell contains an array of closely packed anode contact pads in two groups (gray and black in this figure). The two groups are identically biased (0V) for electron charge collection but are interconnected in columns and rows in the layers of the carrier substrate. A non-collecting grid electrode surrounding each pixel, biased (-30V) between pixel pad and cathode, provides a signal that can be used for measuring the depth of interaction (the Z-coordinate). A single cathode contact (-1100V) on the opposite side is not shown. The principle of operation requires a sharing of charge between row and column anode contacts for each event. This is feasible when the pitch size of the anode pads is smaller than the lateral extent of the electron charge cloud reaching the anode surface. This approach takes advantage of the increasing capability of manufacturers to pattern and interconnect fine features.

The simplicity of the front-end electronics is the main advantage of this design. Polarities and shaping times are the same for both row and column channels. Also, the large area covered by the grid electrode should result in better depth resolution than was available from the individual strip column electrodes in our earlier single-sided strip detector design [2].

There are some disadvantages as well. Row and column signals must be added to measure the energy. This reduces the energy resolution by a factor related to the electronic noise. Capacitance effects due to the contact pad and interconnect structure also increase the noise. However, selecting the proper front-end electronics may minimize this effect. We also see that limited charge sharing due to the small size of the electron cloud, will for some events, result in a measurement of only X (row) or Y (column), not both, at least for the first prototype detectors, reduces the detection efficiency for imaging measurements. We measured 64% imaging efficiency at 122 keV with our first prototype detectors [3].

Photographs of the patterned CZT anode surface and prototype detector module assembly showing cathode surface can be seen in Figure 2.

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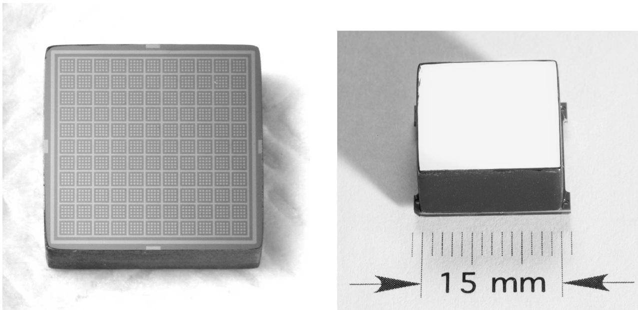

(a) (b)

Fig. 2. Patterned CZT anode surface (a); prototype detector module assembly showing cathode surface (b).

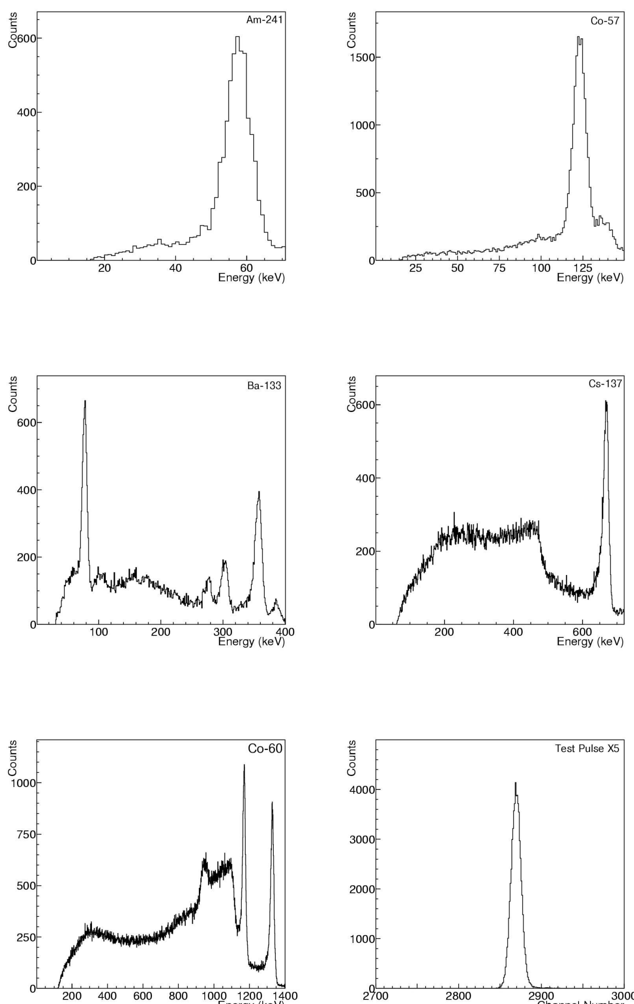

Fig. 3. Spectroscopic performance and test pulse response of a unit cell of first prototype detector.

B. Spectroscopy

Figure 3 shows the spectra from flood illumination of a prototype detector at room temperature in the energy range from 60 to 1333 keV. Energy resolution (FWHM) is 9.4, 10.1, 13.6, 19.5, 23.0 and 23.7 keV at 60, 122, 356, 662, 1173 and 1333 keV respectively. These single pixel spectra were constructed from the addition of maximum row and maximum column pulse heights (here we selected row 5 column 5 coincidence). The photopeaks are symmetric with no significant low energy tailing that would indicate a loss of signal to the non-collecting areas of the anode surface. The electronic noise is 5.7 keV FWHM per channel, or 8.0 keV FWHM for the combined row and column signals.

C. Depth measurement

We used the cathode-to-maximum anode signal ratio to compute depth of interaction, where maximum anode signal is the addition of maximum row and maximum column signals event by event. Either the grid or the cathode signal can be used to obtain the depth of interaction. For this demonstration we chose the cathode signal because the electronics noise width of the grid signal was too large for effective use at 122 keV. Using the grid signal has the advantage of keeping all signal contacts on the anode side but further work is needed to extend its operation to lower energies.

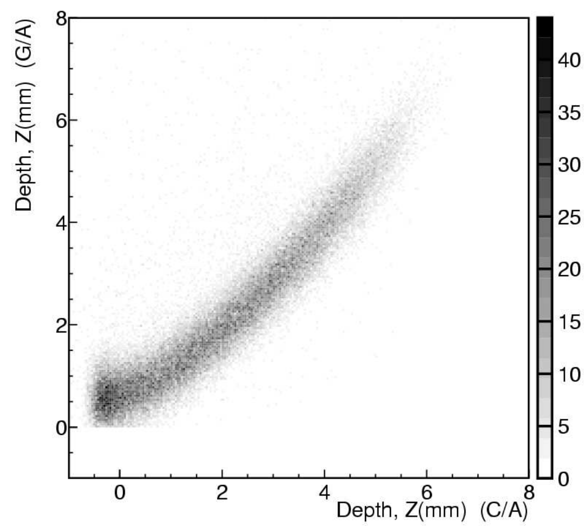

Fig. 4. Correlation of depth measurement using the cathode and grid signals for 662 keV photons.

Correlation of depth measurement using the cathode and grid signals for 662 keV from a ^{137}Cs source can be seen in Figure 4. The cut off at higher depth is due to the threshold value on the signals.

Figure 5 shows the measured distribution of interaction depths (Z) for 122 keV photons from a ^{57}Co source illuminating the entire cathode surface at normal incidence. The attenuation length, 2.16 ± 0.19 mm, determined from a fit to the data, compares well with the theoretical value, 2.01 mm.

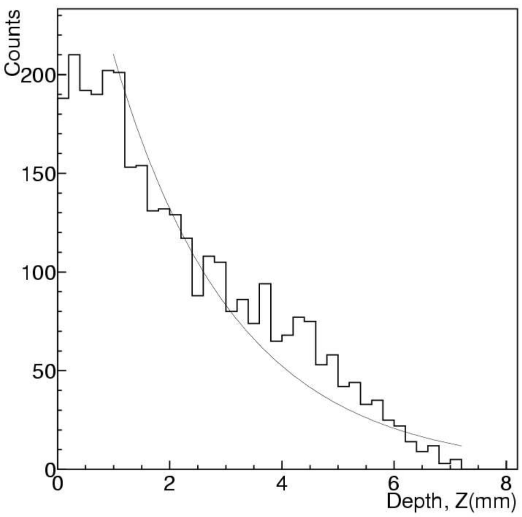

Fig. 5. Measurement of the attenuation length for 122 keV photons.

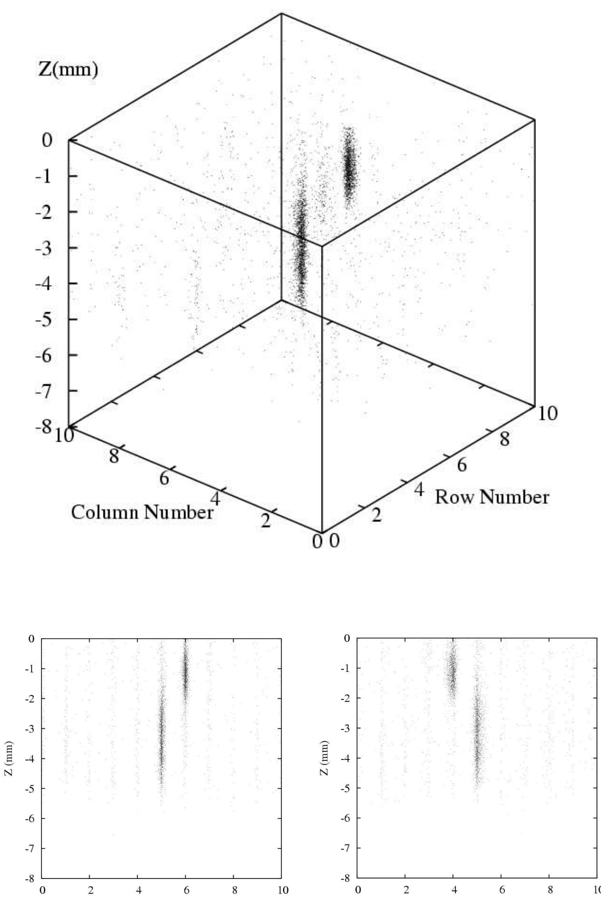

Fig. 6. 3-D event locations and projections on x-z and y-z plane. Cathode is at Z=0, sign of Z was inverted to facilitate the illustration.

D. 3-D imaging

To illustrate 3-D imaging capability of our current prototype detector, we have performed an experiment with 200μm beam spot of 122 keV photons incident at $\sim 30°$ from the Z-axis (Figure 6). The beam is directed so that it enters row 6 column 4 and crosses to row 5 column 5 as it passes through the 7.5 mm thickness of the detector. Spatial resolution is better than the unit cell pitch 1.225 mm, in the X and Y dimensions. Spatial resolution (1σ) in the Z dimension using the cathode signal is less than 1 mm. Using the grid electrode signal with 1μs shaping instead of the cathode signal, the spatial resolution (1σ) measured is about a factor of three worse.

II. SIMULATIONS

We performed GEANT (v4.6) simulations to determine the initial charge cloud radius and calculated the expected effects of diffusion and electrostatic repulsion of the charge as it drifts toward the anode.

A. Size of the charge cloud

The radius of the charge cloud reaching the anode for any interaction depends on the type of interaction (photoelectric or Compton), the energy deposit and the depth of interaction [4]. In order to register sufficient signal on both row and column channels, the extent of the electron charge distribution reaching the anode surface must be at least as large as the contact pad pitch, 225μm for our prototype devices. Our simulation results, however, show that, on average, 95% of the energy is concentrated within only a 100μm radius at 100 keV (Figure 7).

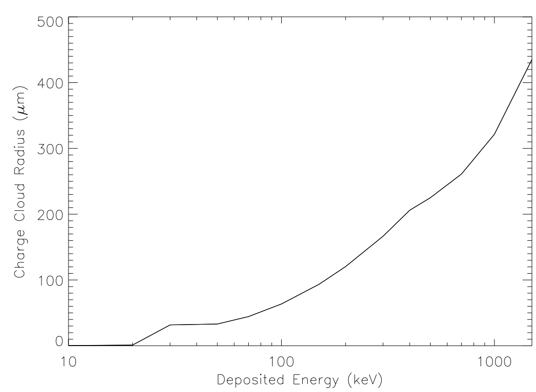

Fig. 7. GEANT (v4.6) simulated charge cloud radius.

B. Diffusion and electrostatic repulsion

Diffusion of the charge cloud as it moves toward the anode surface will increase the extent of the charge distribution. The diffusion coefficient is related to the mobility and the temperature through Einstein's relation so that, at room temperature, the diffusion coefficient for electrons in CZT is approximately $25cm^2/s$. The width of the distribution due to the diffusion must be added in quadrature with the width of the initial charge distribution to obtain the spread of the charge distribution. It is also seen that even for low ionization densities, electrostatic repulsion between the electrons plays a significant role for silicon detectors in the size of the cloud when it reaches the anode plane [5]. As the cloud expands as the square root of time under the effect of diffusion, it also expands as the cubic root of time with repulsion. It appears that repulsion may become the dominant effect at short times and that diffusion becomes more important when the cloud density decreases. The diffusion and repulsion processes are decoupled and their contributions to the cloud size add quadratically.

In addition to these effects, electrons will drift in the direction of the electric field. In a uniform electric field, all these effects are decoupled and the movement of the electrons is given by an expanding cloud that otherwise drift at a uniform speed.

Several groups have studied the charge spreading in semiconductor detectors. A study of the position resolution of stripixel detectors show that the pitch must be no greater than the size of the charge carrier cloud and that charge spreading improves the position resolution [6]. The spread has also been measured for germanium detectors [7]. There are also studies on CdTe [8], [9] and CdZnTe [4] detectors.

Considering these as well as our preliminary studies, we currently estimate, at 100 keV, 60μm FWHM for the initial size of the electron cloud, 60μm for diffusion and 120μm for electrostatic repulsion. This yields 145μm FWHM when all effects are added quadratically. This figure represents a reasonable target for the contact pad pitch in subsequent detector designs to improve imaging efficiency.

III. Conclusions

Our goal is to develop and demonstrate compact, efficient, high performance CZT strip detector modules for imaging and spectroscopy for 0.05 to 1 MeV gamma measurements and be ready to employ them in large area detector arrays when large volumes of suitable CZT material with uniform properties become available and affordable.

We have designed a new type CZT detector, the single-sided charge sharing strip detector, and fabricated the first prototypes for evaluation in the laboratory. These prototype devices feature 125μm anode contact pads on 225μm pitch and require signal charge to be shared among row and column pads in order to perform imaging measurements. The test results demonstrate good spectroscopic response even though the row and column signals must be summed to construct the spectra. We have also demonstrated 3-D imaging capabilities of our first prototype detectors.

We have developed Monte-Carlo simulation tools based on GEANT (v4.6) in part to help us understand the extent of the ionization and as an aid to guiding future detector design. Our simulations and measurements indicate that the lateral extent of the charge at the ionization site is 65% smaller than the contact pad pitch of our first prototype devices.

We will continue to use simulation tools to help us understanding the performance of our detectors. Future work includes extending simulation to include diffusion and repulsion effects imaging. We will pursue an improved design with smaller anode contact features to improve the imaging efficiency.

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