Performance and Simulation of CdZnTe Strip Detectors as Sub-millimeter Resolution Imaging Gamma Radiation Spectrometers

M. Mayer¹, D.V. Boykin¹, M.L. Cherry³, J.F. Courville², F.P. Doty⁴, A. Drake¹, T.G. Guzik³, L.A. Hamel², K. Larson¹, J.R. Macri¹, M.L. McConnell¹, J.M. Ryan¹, O. Tousignant²

¹ Space Science Center, University of New Hampshire, Durham, NH 03824 USA
² Department of Physics, University of Montreal, Montreal, H3C 3J7, Canada
³ Department of Physics and Astronomy, Louisiana State University, Baton Rouge, LA 70803 USA
⁴ DIGIRAD, San Diego, CA 92121-2410 USA

Abstract

We report γ-ray detection performance measurements and computer simulations of a sub-millimeter pitch CdZnTe strip detector. The detector is a prototype for γ-ray astronomy measurements in the range of 20–200 keV. The prototype is a 1.5 mm thick, 64 x 64 orthogonal stripe CdZnTe detector of 0.375 mm pitch in both dimensions, with approximately one square inch of sensitive area. Using discrete laboratory electronics to process signals from an 8 x 8 strip region of the prototype we measured good spectroscopic uniformity and sub-pitch (~0.2 mm) spatial resolution in both x and y dimensions. We present below measurements of the spatial uniformity, relative timing and pulse height of the anode and cathode signals, and the photon detection efficiency.

II. PROTOTYPE STRIP DETECTOR DESCRIPTION AND TEST SETUP

The prototype detector was manufactured by DIGIRAD. A pattern of 64 x 64 interdigitated and orthogonal contact stripes on each surface defines a 24 mm x 24 mm imaging area (5.76 cm²) on a 28 mm x 28 mm CdZnTe substrate that is 1.5 mm thick. The strip pitch is 0.375 mm with a 0.15 mm gap between strip contacts. See [11] for additional details.

Figure 1. Test setup (orthogonal stripe coincidence mode)

Figure 1 illustrates the laboratory setup for the prototype strip detector measurements. Independent ac-coupled signal channels for each of 8 consecutive stripes in each dimension define a 3 mm x 3 mm active test region of 64 "pixels," i.e.
1/64 of detector’s area. Amptek A225 preamp/shaper circuits and additional op amps provide fast (200 ns rise time) signals for level discrimination and coincidence logic and slow (2 μs) channels for pulse height measurements on each strip. All stripes on each detector surface are biased to assure a uniform electric field in the CdZnTe. The load resistance is 1 GΩ. Any x-y discriminator coincidence triggers the readout of 17 parameters for each event: 16 pulse heights and the relative arrival time of coincident anode and cathode discriminator trigger signals. The detector and test electronics are packaged so that the detector can be illuminated from either surface. The typical bias used for these measurements is 200 V. All measurements were performed at room temperature.

III. SIMULATION MODEL

The model is intended to be an end-to-end tool for simulating all detection and measurement processes from the photon interaction down to the electronic chain. The detector material (mobilities, trapping and detrapping coefficients), bias, and geometry (thickness, electrode pitch and gap) of the prototype detector are incorporated in the model. A GEANT module simulates the photon interaction locations, the energy deposit and the distribution of the ionization charge for incident photons of any given energy. A charge transport and signal generation module then computes the signal induced on any electrode by carriers drifting in the detector. The transport part of the simulation consists of an analytical solution of the continuity equations that provides the free electron and hole densities \( n_e(x,t) \) and \( n_h(x,t) \) in the detector in the presence of trapping and detrapping \[7, \[10], \[11\]. The relevant parameters for the simulations are given in table 1. The mobilities and trapping times are those reported by Luke \[12\] and are consistent with values found elsewhere in the literature. The detrapping times are estimates which, in view of our results, appear to be much too short.

<table>
<thead>
<tr>
<th>Simulation parameters</th>
<th>electrons</th>
<th>holes</th>
</tr>
</thead>
<tbody>
<tr>
<td>mobility ( \mu ) (cm²/V·s⁻¹)</td>
<td>1000</td>
<td>50</td>
</tr>
<tr>
<td>trapping time ( \tau_t )</td>
<td>3.6 μs</td>
<td>5 μs</td>
</tr>
<tr>
<td>detrapping time ( \tau_d )</td>
<td>170 ns</td>
<td>1.2 μs</td>
</tr>
</tbody>
</table>

The current through a given electrode \( j \) is obtained by integrating \( n(x,t) \epsilon \mu \mathbf{F}(x) \cdot \nabla \) throughout the detector volume, where \( \mathbf{F}(x) \) is the electric field in the detector and \( \nabla \) is the weighting field for the given electrode \( j \) \[7, \[10], \[11\]. That weighting field map is obtained by solving the Laplace equation in the detector, taken as an infinite slab of thickness \( L \), with the following surface boundary conditions: \( \Phi_s = 1 \) on the strip \( j \), \( \Phi_s = 0 \) on all other electrodes and everywhere on the opposite surface; the surface potential \( \Phi_s \) in the gap is taken to decrease linearly from 1 at the edge of the strip \( j \) to 0 at the edge of the neighboring strips. The solution is the weighting potential from which \( \Phi_{w_j}(x) \) is easily obtained. The weighting potential for the cathodes is \[13, \[14\]

\[
\Phi_{w_j}(x, y, z) = \frac{1}{L} \sum_{n=1}^{\infty} \sin \left( \frac{n \pi x}{L} \right) \int \phi_s(x') \exp \left( -\frac{n \pi (y - y')}{L} \right) dx'
\]

where \( x \) is the lateral coordinate perpendicular to the strip, \( y \) is the coordinate along the strip and \( z \) is the depth coordinate. The cathode strip \( j \) is at \( z = L \) and is centered at \( x = 0 \). The cathode weighting potential is of course independent of \( y \). The anode solution is obtained by replacing \( x \) by \( y \) and \( z \) by \( L - z \).

Figure 2 shows several simulated signals for a given anode at the output of the charge preamplifier for interactions occurring at \( z = 0.75 \) mm, i.e. at mid-depth in the detector, and at 5 different lateral positions \( (y) \) measured from the center of that specific anode.

For interactions occurring immediately below the readout anode \( (y=0) \) the induced charge asymptotically reaches 100% of the generated number of electron-hole pairs. From the three different rise times one clearly sees the different contributions from the fast moving electrons and slow holes; the much slower contribution from the detrapping holes is also observed. For interactions occurring half-way between two anodes, the signal is equally shared between both electrodes and the induced charge is then 50% on each anode. For gammas interacting under the next anode \( (y \geq 1 \) pitch), no carriers are collected on the readout anode because the model assumes no diffusion. The asymptotic induced charge is then
zero but, as long as carriers are drifting in the detector, there is some induced current through the anode, sometime positive, sometime negative, but giving rise to a zero net charge transfer. We have also observed this bipolar effect in the lab.

The model also simulates the charge signal processing of the fast and slow channels of the laboratory test electronics. The pulse heights, as measured by the ADC, and the relative timing of these processed signals can be histogrammed for comparison with the data.

IV. TEST AND SIMULATION RESULTS

A. Spectroscopy (anodes)

It has been demonstrated that signal charge for each detected event is shared by the triggering anode strip and, at most, one of its neighbors [1]. The charge transport and signal generation simulations support the observation that the event is mostly sensed by the two nearest electrodes on each plane. That effect is not a result of carrier diffusion but of induced current through various electrodes by carriers drifting in the detector. The magnitude of this effect depends on the electronics integration time.

Figure 3a shows the spectroscopic response of a single "pixel" of the prototype detector to flood illumination of photons from a $^{57}$Co source (122 and 136 keV). A "pixel" is the coordinate defined by the intersection of the coincidentally triggering anode and cathode stripes. To account for signal charge shared among neighboring stripes, the pulse height recorded for the triggering anode strip is summed with those of its two neighbors to compute the total energy of the event. Note that nearly all events reside in the photopeak or the fluorescence escape peak. The GEANT model also predicts nearly total energy deposit for the 122 and 136 keV photons of $^{57}$Co with a fraction of fluorescence escape events similar to that measured. Figure 3b is the sum of the anode histograms from all 64 "pixels". The limited broadening illustrates good uniformity of response across the 8 x 8 strip test region. Note that for these measurements individual amplifier channels were matched with a test pulse input and that no additional effort has been made to match photopeak pulse heights from the individual "pixels" before these histograms were computed.

Fig. 3a. 122 keV single "pixel" spectrum. FWHM 16 keV.

Fig. 3b. 122 keV sum spectrum of 64 "pixels." FWHM 36 keV.

Fig. 5a. Image produced by a 200 μm wide slit.

Fig. 5b. Image produced by a 100 μm wide slit. Note slit tilt relative to y-axis.

B. Imaging and spatial non-uniformity

Fig. 4a. Image of 170 μm diameter 122 keV beam.

Fig. 4b. Same as 4a but beam moved 150μm in -y direction.
Figures 4 and 5 are images obtained from the $8 \times 8$ strip ($3 \times 3$ mm$^2$) test region of the prototype using 122 keV photons. The upper and lower images in each case are formed from the same data set. In the upper images event location is assigned to the strip in each dimension recording the highest pulse height (0.375 mm pixels in each dimension). In the lower images event location is assigned based on a linear interpolation of the pulse heights recorded by neighboring stripes (two pixels per strip pitch, ~0.19 mm pixels in each dimension).

A gold aperture collimates a 170 μm diameter beam for the images shown in Fig. 4 a-b. Two tungsten foils were used to form the slits for the images shown in Fig. 5 a-b.

The lower images illustrate the advantage of recording the pulse heights of the triggering strip and its neighbors for each event. Half-pitch resolution (~190 μm) event location capability is demonstrated in both dimensions. Note in figure 4b that the beam spot was moved 150 μm (0.4 × strip pitch) in the -y direction from its position in figure 4a. This movement is more clearly seen in the finer resolution images. Note in Fig. 5b that the angle between the x-dimension stripes and the slit axis only becomes apparent in the finer resolution image.

The slit images also illustrate a non-uniform event location response. Such non-uniformities where neighboring pixels experience event rates that differ by as much as a factor of two across the imaging region are also seen with flood illumination. Sweeping collimator beam studies show that events can be mislocated by as much as 50% of a strip pitch (~190 μm). Our measurements indicate that events occurring between stripes are not lost but that the signal charge is preferentially collected by one of the neighboring stripes. In other words, the "reach" or effective widths of the individual stripes are not equal for this particular detector. This effect has been reported elsewhere [5].

Small bias differences between stripes may be responsible for some if not most of this non-uniformity.

Figure 6 shows the discriminator trigger rate of eight consecutive anode stripes for three settings of the differential bias, applied independently, to strip #8. Note that even a 1 volt change in the differential bias results in a trigger rate change of >30% and that the neighboring stripes register a complementary change. Issues related to materials and contacts must also be considered in future investigations of the causes of spatial non-uniformities.

C. Measurements of detection efficiency, sensitive depth vs. energy

Evidence of poor hole transport is obtained from measurements of the relative cathode and anode signals. Dramatic differences in the pulse height and discriminator trigger rate of cathode signals are measured in the laboratory when illuminating the detector from the cathode and anode sides with photons whose mean free path in CZT is less than the 1.5 mm detector thickness. Our measurements with photon sources from 22 keV to 122 keV indicate that as interactions occur closer to the anode, the signal detected on an individual cathode strip becomes so small that the cathode discriminator threshold (~15 keV equivalent) is not exceeded and the event is not registered. Anode pulse heights and trigger rates are relatively unaffected. Summing the individual cathode signals prior to discrimination helps to compensate for the charge sharing effect for interactions occurring in the region between electrodes. While the cathode trigger rate is improved by this summing technique, the cathode signals and trigger rate remain obviously smaller than those of the anode when illuminating from the anode side. The weak cathode signals measured for interactions far from the cathode plane is evidence of poor hole transport [12].

Based on the assumption that events occurring beyond a certain distance from the cathode do not generate cathode triggers and are therefore not detected with the required x-y coincidence, we measured the relative anode and cathode trigger rates and computed an effective thickness for coincident detection. The results over a range of energies are compared with the photon mean free path in figure 7.

Fig. 7. Effective detector thickness vs. photon energy. Illumination is from cathode side. The data points (squares) are labeled "individual discriminators" and "common disc. on sum" to distinguish between the methods for generating the cathode trigger. Circles show the simulation results.
We see that the strip detector has a limited effective thickness for coincident detection and thus its detection efficiency is less than one would expect from its thickness alone. In addition to summing cathode signals prior to discrimination the effective thickness increases if the readout electronics permit lower cathode thresholds. Other tests in the lab indicate the efficiency advantage of employing detectors fabricated with a coarser cathode pitch.

**D. Simulations of detection efficiency, sensitive depth vs. energy**

The results from the simulations for individual electrode signals are shown in figure 8.

Fig. 8: Simulated pulse heights on the fast and slow channels for anodes and cathodes for different interaction depths and lateral distances from the center of the readout electrode. The thick and narrow lines above each plot show one half of the electrode strip (from 0 to 112.5 µm) and the full gap (from 112.5 to 262.5 µm), respectively. The depth (z-coordinate) is measured from the anode plane.

The simulated pulse heights of the fast and slow signals for anodes and cathodes are shown as a function of two parameters. The first parameter is \( z \), the vertical distance from the anode plane. The second parameter is \( x (y) \), the lateral position perpendicular to the cathode (anode). The range in the lateral position shown in the figure extends from the center of the readout electrode \( y = 0 \) to the end of the gap before the next strip \( y = 262.5 \) µm). In all cases, the farther the interaction point is from the cathode plane, the smaller the amplitude. This effect is more apparent in the fast signals, especially the cathodes. The depth effect is less dramatic for the anodes particularly in the more sensitive region of the detector near the cathode surface. Events occurring directly below the center of the electrode have larger amplitudes from that electrode than events occurring in the region between electrodes. Note that the simulation predicts essentially linear charge sharing with the neighboring electrode for gammas interacting in the gap for both anodes and cathodes. The results at 60 and 122 keV are presented on Fig. 7, as effective detector thicknesses, along with the data.

As with the measurements (section IV.C) simulated efficiencies are obtained by counting the fraction of events for which the simulated fast signals are above a given threshold (15 keV equivalent for this simulation) for both the anodes and cathodes. The results at 60 and 122 keV are presented on Fig. 7, as effective detector thicknesses, along with the data.

The effect of summing signals from the two adjacent electrodes nearest to the interaction point can be simulated and the result is shown in Fig. 9. While the summing has little effect in the \( z \) direction, the effect in the lateral direction is striking. The summed signals show a much more uniform amplitude below the stripes and in the gap than before. As a consequence a smaller fraction of the events is rejected by the discrimination criterium and the efficiency is increased. Again, the resulting efficiencies from the simulated summed signals are shown in Fig. 7. Note that this simulation predicts a larger effective detector thickness than is measured in the lab. This indicates that hole transport properties for this detector are poorer than those assumed in our simulations.

Fig. 9: Simulated pulse heights on the fast and slow channels when summing signals from the two nearest stripes for anodes and cathodes for different interaction depths and lateral distances from the center of the readout electrode. The thick and narrow lines above each plot show one half of the electrode strip (from 0 to 112.5 µm) and the full gap (from 112.5 to 262.5 µm), respectively. The depth (z-coordinate) is measured from the anode plane.
E. Relative signal timing (anode/cathode)

Further evidence of poor hole transport is observed in measurements of the relative timing of the anode and cathode signals. A time-to-amplitude converter (TAC) was employed to measure the trigger time of the cathode signal relative to that of the anode. Figure 10 is a histogram of the TAC output for flood illumination events of the 8 x 8 strip test region with a 122 keV source. The cathode signals stop the TAC. The measured FWHM of 270 ns is consistent with the timing spread expected when using level discriminators for the timing of signals with ~ 200 ns rise times. The absence of late stop signals as would be expected for hole transport near the cathodes is more evidence that hole transport is poor and that electron transport dominates both the anode and cathode signals.

V. COMPARISON OF MEASUREMENTS AND SIMULATIONS

The model qualitatively predicts many of the observations and trends seen in the data: nearly all the energy is deposited in the detector at 122 keV, the signal on a given electrode is reduced and the signal is shared with the neighboring strip when the interaction occurs between electrodes, the cathode pulse heights decrease with increasing depth or distance from the cathode, and an efficiency advantage is realized when the signals on neighboring strips are summed prior to level discrimination. Quantitative comparison of the efficiency measurements and simulations is difficult because of the experimental uncertainties and because the results are dependent on a number of parameters that may not be accurately represented in the simulation. These parameters are the transfer function of the various elements of the electronic chains, the thresholds and the charge transport parameters (field profile, mobilities, trapping and detrapping times).

The simultaneous arrival of signals and their relative amplitudes indicate that electrons dominate signal formation on both anodes and cathodes. While this qualitatively agrees with the simulations, the observed cathode signals are still smaller than those predicted by the simulations. These discrepancies suggest that hole transport properties in our detector are even poorer than assumed and should be reexamined.

VI. CONCLUSIONS AND FUTURE WORK

Sub-pitch spatial resolution (~190 μm) in two dimensions and good energy resolution and spectral uniformity have been demonstrated with this prototype. The spatial response is, however, non-uniform as interactions can be mislocated by as much as 50% of a strip pitch (~190 μm). Small strip bias differences represent a likely source of this non-uniformity. We are considering alternate biasing schemes for future testing. Depth of interaction effects, particularly apparent for cathode signals, are exploited to compute an energy dependent sensitive thickness for the strip detector prototype in its present test configuration. The ability to set lower discriminator thresholds, particularly for the cathode stripes will improve the efficiency. Coarser cathode strip pitch and signal summing prior to level discrimination will also help. We will be conducting additional studies in this area.

A model that includes the photon interaction, carrier transport and the electronics has been developed that qualitatively reproduces the measurements, but it still does not provide satisfactory quantitative agreement. Further measurements of the CdZnTe transport properties might help resolve these discrepancies.

We are now measuring these transport properties in this detector in a series of dedicated Time-of-Flight experiments by scanning the anode and cathode planes with a collimated pulsed laser beam. Simultaneously recorded signals from many anode and cathode stripes will directly measure the electron and hole currents, and therefore impose stringent constraints on the mobilities, the trapping and detrapping coefficients and the field profile.

VII. ACKNOWLEDGMENTS

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VIII. REFERENCES


