

Further Studies on the Modified Two-Terminal Geometry for CdZnTe Detectors

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Abstract

This paper will report on additional studies undertaken on a novel electrode geometry, referred to as CAPture™ technology, wherein the cathode is extended up the sides of a planar CdZnTe detector. The initial presentation of this development focused on a single geometry, and a simple mechanism was proposed to explain the improved performance. In this presentation, we will describe the results of further electric field and charge transport modeling as applied to this detector configuration, and also compare the calculated performance with experimental results.

Keywords: CdZnTe, gamma ray detector, CAPture™ technology, charge transport, modified electric field.

1. Introduction

Compound semi-conductor, room-temperature, radiation detectors have been used for many years. Recently, CdZnTe has become the material of choice for many applications, including nuclear medical imaging, non-destructive testing and nuclear material safeguards and non-proliferation measurements.¹ However, CdZnTe, in common with all other materials that have been used, exhibits charge collection properties limit its use in spectroscopic applications. These problems arise from large differences in the mobility-lifetime product ($\mu\tau$) of electrons and holes in CdZnTe crystals. This results in an increase in the low energy tailing with increasing photon energy, due primarily to hole trapping at electrically active defect sites in the material. Various methods have been proposed to minimize this problem, including electronic correction methods, modification of the CdZnTe material properties and the fabrication of single carrier collection devices. However, all these methods have one or more undesirable properties in either fabrication or operation of the devices, with the net result that the availability and/or cost of the detectors is adversely affected.

We recently presented initial results on a novel device geometry, referred to as CAPture™ technology¹, which offers the possibility of fabricating medium volume (50 to 200 mm³) detectors exhibiting excellent energy resolution and good efficiency at a high fabrication yield and hence lower cost. Further, as was previously reported, these devices can be assembled into an array of discrete detectors, thereby offering the possibility of the production of large effective area devices from smaller, easier-to-produce, parts. These detectors are produced by allowing the cathode metallization to extend up the sides of the detector, whilst maintaining a full-area anode (Figure 1). In this geometry, the internal field is modified from that of the planar configuration, resulting in uniform charge measurement

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efficiency over a larger volume. The length of the cathode extension was chosen to allow for the optimum energy resolution and photopeak efficiency in the range 20 – 150 keV.

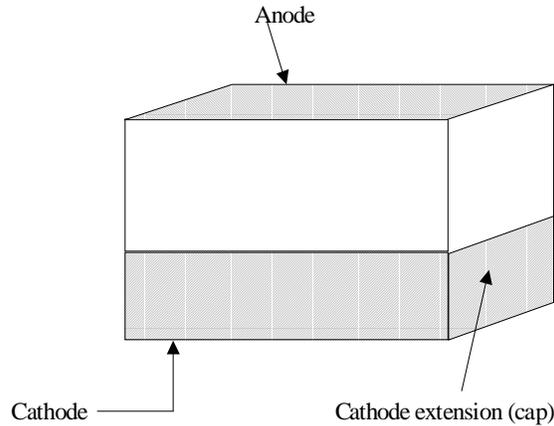


Figure 1. Schematic of the CAPture™ technology contact configuration

In this work, we will show that the modeled charge measurement efficiency of a CAPture™ technology detector is in good agreement with the measured performance.

2. Modeling

A two-dimensional (2-D) finite elements code was used to calculate the static electric field within a $4 \times 4 \times 2.5 \text{ mm}^3$ CAPture™ detector with a 1 mm cathode extension. In the calculations, the contacts were assumed to offer no resistance to charge flow into or out of the device. Consequently, the space charge under steady-state conditions was zero everywhere in the device. In practical devices, the potential barrier at the electrodes can give rise to space charge regions beneath the cathode, causing the bulk field to be lower than expected. In addition, the exposed surfaces of the device were assumed to have the same properties as the bulk material. This assumption is routinely violated in practical devices: The surfaces of CdZnTe detectors are usually found to have lower resistivity than the bulk material, which leads to distortion of the near-surface electric field.² Thus, the reader is advised that the calculations represent a somewhat ideal case that is useful for qualitative comparisons to experimental data. The charge measurement efficiency of the CAPture™ detector was calculated using the adjoint pulse mapping technique developed by Prettyman and implemented in ATLAS.^{3,4} This technique is based on Ramo's theorem, which is valid for quasi-stationary device operation. Namely, the excess free carriers created by radiation interactions do not significantly perturb the static field within the device. The free-carrier transport properties used in these calculations were $\mu_n=1000 \text{ cm}^2/\text{V-s}$, $\tau_n=5 \text{ }\mu\text{s}$ for electrons, and $\mu_p=50 \text{ cm}^2/\text{V-s}$, $\tau_p=500 \text{ ns}$ for holes. The lifetime of holes was selected such that the mobility-lifetime product was less than $5 \times 10^{-5} \text{ cm}^2/\text{V}$, which is the maximum experimentally derived value that we have observed for spectrometer-grade CdZnTe material. The free-carrier transport properties are similar to values reported in the literature.^{5,6} In the charge measurement experiments described in this paper, a linear amplifier was used with a peaking time of approximately $0.55 \text{ }\mu\text{s}$ (corresponding to a shaping time of $0.25\mu\text{s}$). As the peaking time is much shorter than the drift time for holes, ballistic deficit must be treated. This was carried out by imposing a cutoff time of $0.55 \text{ }\mu\text{s}$ in the adjoint calculation. This prevented charge, moving within the device after the peaking time, from contributing to the charge measurement efficiency. This simple model of ballistic deficit did not significantly affect electron measurement efficiency, since the transit time of electrons ($< 0.4\mu\text{s}$) was generally less than the peaking time. However, hole measurement efficiency was affected significantly in regions from which holes could not reach the cathode within the required time period.

Simulations of x-ray mapping experiments using charge measurement efficiency maps calculated for 150V and 400V biases are shown in Figs. 2a and 2b, respectively. The x-ray source was assumed to be well collimated and was swept along the side of the detector from the anode to the cathode. At each point, the depth-averaged charge measurement efficiency was calculated for both electrons and holes. For this purpose, the mean free path of the 59 keV x-rays used in the experiment was assumed to be $300 \text{ }\mu\text{m}$.

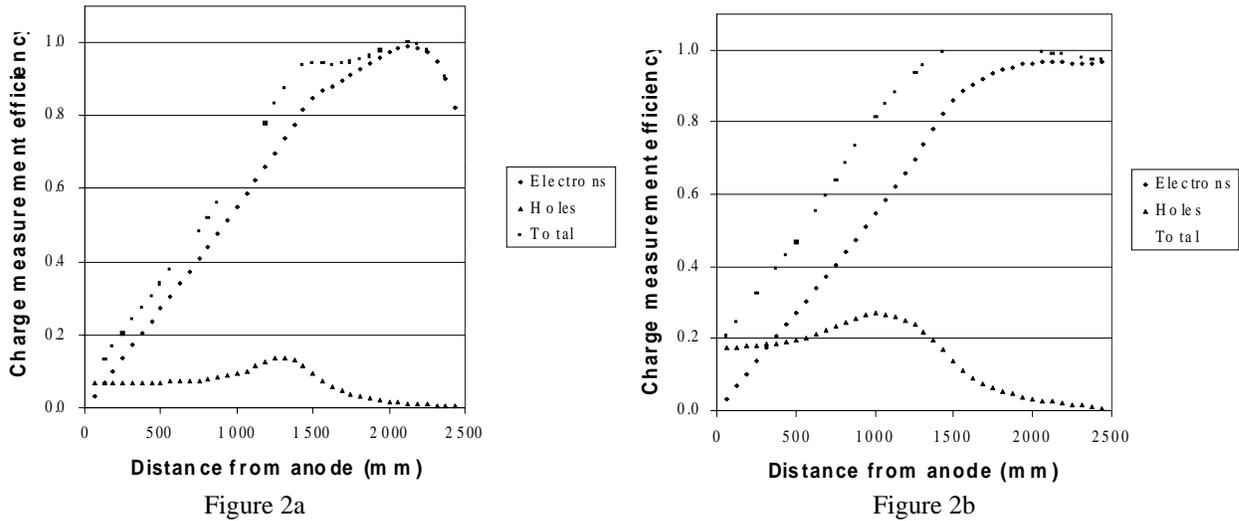


Figure 2. Calculated depth averaged components of the charge measurement efficiency for a $4 \times 4 \times 2.5 \text{ mm}^3$ CAPtUre™ detector with a 1 mm cathode extension. Two cases are shown: a) 150 V bias; b) 400 V bias.

The inclusion of holes in the calculation significantly changes the slope and intercept of the charge measurement efficiency profile in the extra-cathode extension (“cap”) region relative to what would be expected for an electron-only device. These changes can be observed experimentally. In the 400 V case, the holes cause an increase in the size of the uniform region within the cap, which is probably responsible for the observed good spectroscopic performance of CAPtUre™ detectors at high energy.

3. Results

In order to verify the CAPtUre™ device model results, we performed a series of x-ray scans. The unique feature of these scans, which were performed using an apparatus previously described⁷, is that the collimated x-ray photons irradiate a side of the device perpendicular to the cathode. This allows us to isolate electron and hole production to specific depths with respect to the cathode and anode. The scans were performed on CAPtUre™ devices with the same dimensions as used in the model. We employed a $100 \mu\text{m}$ diameter collimator with a $100 \mu\text{m}$ step size and utilized the 59.3 keV characteristic x-ray k_α peak generated by the tungsten anode of the x-ray tube. In particular, we measured the position of this peak on the MCA screen relative to the interaction position (distance from anode). Figure 3a shows the side scan configuration and Figure 3b a typical x-ray map for a $4 \times 4 \times 2.5 \text{ mm}^3$ CAPtUre™ device (400 V bias and $0.25 \mu\text{s}$ shaping time). The map shows that the induced charge in the cap region of the device is relatively uniform. At the end of the cap region, there is a rise in the induced charge as indicated by the higher peak channel numbers. Beyond this region, there is a gradual reduction in the induced charge. As the scan progresses even further from the cap region, we encounter a situation where we can no longer resolve the 59 keV peak with respect to the continuous spectrum produced by the x-ray tube. This limit is primarily a result of electronic noise produced by the motors used to move the sample and imposes a lower limit on the measurement of the induced charge using this technique. We find that the profile of the induced charge in the CAPtUre™ device is consistent with the models of the weighting potentials and internal electric fields. This step was performed using a fully 3-D, finite element program (COSMOS/M) and results are not shown here due to space constraints.

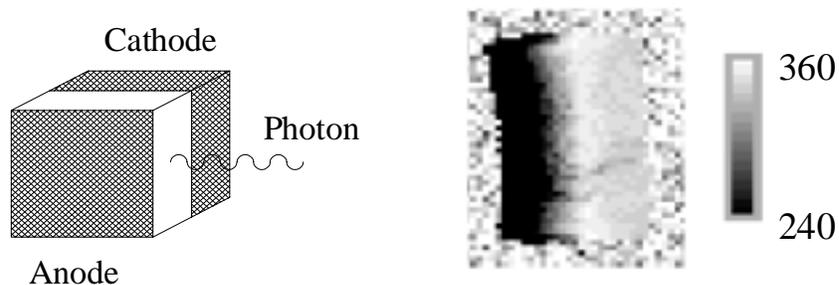


Figure 3. Schematic representation of x-ray side scan geometry and an x-ray response map for a sample $4 \times 4 \times 2.5 \text{ mm}^3$ CAPtUre™ detector

Next, we performed side x-ray scans on planar and CAPture™ devices with the same dimensions. These scans were performed at various bias voltages and shaping times. In order to present this data in a single plot, we generated profiles of the induced charge by averaging the peak channel data from six scan lines near the center of the device. These results are shown in Figure 4. The profiles from the planar device show a relatively linear reduction in the induced charge for a particular bias voltage. As noted above, we encounter a limit, dominated by the excess electronic noise, inherent to our measurement technique at channel number 140. The profiles for the CAPture™ device show relatively uniform and high induced charge distribution in the cap region, with a linear decline outside the cap similar to that seen in a planar device. The slight rise in the induced charge near the end of the cap is attributed to increased hole contribution, in good accordance with the model predictions. It is the region of relatively uniform induced charge that produces the improvement in resolution for a CAPture™ device, as the statistical variation in electron and hole production depth for specific photon energy does not result in significant changes in the induced charge. This is clearly not the case for a planar device or for electrons and holes produced outside the cap region of a CAPture™ device where the induced charge is strong function of interaction depth. Hence, in order to achieve optimal energy resolution with these devices, the cap height must be chosen to ensure that the majority of the photons of interest interact within the cap region.

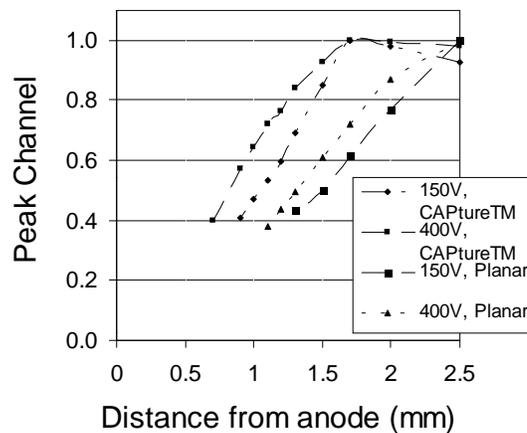


Figure 4. Peak position as a function of interaction depth for planar and CAPture™ detectors at 150 V and 400V bias

4. Conclusion

The measured performance of CdZnTe detectors produced using the modified two-terminal geometry referred to as CAPture™ technology has been shown to correspond to the predictions of the 2-D charge measurement efficiency model. The improvement in charge measurement efficiency, and hence energy resolution, is explained by the addition of a hole component of the signal, primarily in the cap region. The CAPture™ technology detectors show good uniformity of charge measurement efficiency across the detector, which again is in good agreement with the 3-D model.

Future work will include re-measuring the devices from this study in a new system, with significantly reduced electronic noise levels, to confirm that the charge measurement efficiency follows the model predictions for carriers generated close to the anode. We will use a modified x-ray generator, whereby the beam will be focussed on a variable target and the detector will be illuminated, through a fine collimator, by the characteristic x-rays generated by fluorescence. This will allow us to study the depth dependence of the carrier generation.

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