NE 204: Advanced Concepts in Radiation Detection and Measurement

Experiment 7: Charge Transport Properties in Pixellated CdZnTe Detectors

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Purpose

Wide band gap semiconductor detectors such as CdZnTe (CZT), mercuric iodide (HgI_2), or thallium bromide ($TlBr$) offer relatively high energy resolution with the convenience of room-temperature operation. However, the limited mean carrier lifetime τ and poor carrier mobility, particularly of the holes μ_h, result in degraded energy resolution compared to that intrinsically acheivable given the statistics of charge-carrier generation. The poor collection properties of the holes necessitate the implementation of "single-polarity" electrode configurations such as pixellating the anode, co-planar grid, and virtual Frisch grid schema. Each of these electrode configurations is designed to minimize the induced signal from positive carrier (i.e. hole) drift. In addition, the inclusion of a monolithic cathode with a weighting field that extends throughout the detector volume provides additional information that can be used to determine the position of gamma-ray interactions along the thickness of the detector; i.e. the depth of interaction. The depth information can be used to further compensate for trapping effects to improve system energy resolution, using depth-dependent energy calibration as introduced in lab 6. In this experiment, digital signal processing will be used to determine the achievable energy resolution in a small, pixellated CZT detector by measuring and compensating for trapping effects. The mobility-lifetime product, $\mu\tau$, of the carriers will be experimentally determined using the methods introduced in lab 6. Electron trapping compensation will be employed using depth information derived from comparison of correlated signals from the cathode and the anode.

Approach

A 1 cm^3 CZT crystal with a 3x3 pixellated anode fabricated by Mark Amman at LBNL will be used for this study. Specific details about the system can be found on the course website. As with all experiments dealing with the digital acquisition systems, the first step in the procedure will be to experimentally optimize the parameters of the trapezoidal filter for this system. The depth of interaction is to be determined either from the ratio of amplitudes of correlated cathode and anode signals, or from their time difference. Using the depth-of-interaction scheme, depth-dependent energy calibrations will be measured to compensate for electron trapping and improve the system energy resolution. Once the spectroscopic performance has been optimized and fully characterized, the charge collection properties of the detector will be probed. The spectral shift reflects the drift-length (λ)-dependent charge-loss in the detector. The drift length is expressed as $\lambda = \mu\tau E$ where $\mu\tau$ is the mobility-lifetime product and E is the electric field. Several different methods can be applied to experimentally determine the $\mu\tau$-product:

1. Measuring spectral positions of full-energy peaks from interactions gamma-ray interactions near the electrodes. This is accomplished by illumination of opposite electrodes with low-energy gamma-rays (e.g. ^{241}Am).

2. Measuring spectral positions of full-energy peaks vs. drift length by creating depth-dependent energy spectra.

3. Measuring spectral positions of full-energy peaks as a function of applied voltage.

Charge carrier loss due to mobility and trapping effects are given by the Hecht relation (1), which expresses the total obtainable charge Q as a function of the originally-generated charge eN and the position of the interaction in a detector of thickness d, normalized by the drift-length of the carriers, λ_e and λ_h:

$$Q = eN\left(\frac{\lambda_h}{d}\left(1 - e^{\frac{-x}{\lambda_h}}\right) + \frac{\lambda_e}{d}\left(1 - e^{\frac{x-d}{\lambda_e}}\right)\right) \tag{1}$$

Filter Optimization and Energy Calibration

Optimize the peaking and gap time of a trapezoidal filter for the cathode and central anode channels. Discuss the differences in the optimum filter parameters to those determined for HPGe. Perform an energy calibration for at least the cathode and central anode using standard check sources.

Required

- Optimize the peaking and gap time of a trapezoidal filter for both the cathode and the central anode.

- Perform an energy calibration for the same channels.

- Determine system energy resolution (without depth compensation).

Optional

- Analyze the individual components contributing to energy resolution. Determine the Fano factor and estimate the charge-loss component by conventional means.

Depth of Interaction

There are several ways that the depth of interaction can be determined by comparing correlated signals from the pixelated anode and monolithic cathode. The most straightforward method involves the ratio of the amplitude of the integrated charge signal, often termed the *cathode-anode ratio* or $\frac{C}{A}$ *ratio* method. Timing information from the signals can also be used for this determination. At least one of these methods must be implemented.

Required

- Implement a method for determining the depth-of-interaction from the cathode-to-anode amplitude ratio for the central anode pixel. Discuss the theoretical underpinnings for this approach, and the associated advantages and disadvantages.

Optional

- Implement a second method for determining the depth-of-interaction based on timing information from the cathode and anode signals. Compare the results from this method to the amplitude ratio method and quantify the differences.

Trapping-Compensated Spectral Response

Evaluate depth-dependent calibration techniques to compensate for the effects of electron trapping on the energy resolution of the system. For this analysis, focus only on single-site, non charge-shared events.

Required

- Using one of the depth-of-interaction determination methods developed above, plot energy spectra as a function of depth-of-interaction.
- Perform a depth-dependent energy calibration and apply the calibration to the data. Compare this trapping-compensated spectral performance to the non-compensated spectral performance from the filter optimization procedure.

Optional

- Extend the analysis to events that exhibit charge collection on multiple anode pixels.

Experimental Determination of Mobility-Lifetime Product, $\mu\tau$

Determine $\mu\tau$ values in this pixellated CZT detector by "conventional" means and compare this to one of several methods that are unique to detectors with depth sensitivity.

"Conventional" Approach - Photopeak Position vs. Applied Bias for Surface Interactions

Using the Hecht relation (1) it is possible to determine the mean drift length for electrons and holes by illuminating the detector from both sides and observing the spectral response as the applied bias is varied. Different values of applied bias yield different electric field strengths, which elucidate changes in drift velocity, depending on carrier mobility.

Required

- Measure and plot photopeak positions for different values of applied bias (e.g. 500 - 1000 V in 100 V steps) for both cathode and annode illumination with ^{241}Am.
- From your measurements, determine $\mu\tau$ of electrons and holes using equation 1. Be sure to document which electrodes you use for this analysis, and any simplifying assumptions you may make regarding the relationship between the electric field and applied bias.

- Discuss the advantages and limitations of this approach.

Depth-Dependent Approach - Photopeak Position vs. Drift Length with Interactions Throughout the Thickness of the Detector

Optional

- Using the same electrodes and assumptions made in the previous analysis, determine $\mu\tau$ of electrons and holes for interactions near the contacts from detector illumination with ^{137}Cs. Discuss the advantages and disadvantages of this approach.

Segmentation-Induced Charge Sharing and Charge Loss

Due to the segmentation of the anode into pixels it is possible that charges produced in the bulk detector volume are collected on multiple pixels. This phenomenon is described as "charge-sharing". In addition, it is also possible that charge is collected in regions between electrodes, resulting in a loss of signal due to the slow carrier motion in this region. This situation is undesirable is often termed "charge-loss". One method for compensating for charge loss is to provide a "steering-grid" on the pixelated anode side of the detector. This grid structure is laid down in the gaps between the pixels and is held at a potential slightly below 0V to provide a local electric field that "steers" electrons away from the inter-pixel gap regions as they approach the anode. Note that the detectors used in this lab **do not** have a steering grid, so charge loss problems are expected to be particularly pronounced.

Optional

- Develop an experimental procedure to quantitatively study charge sharing and charge loss effects for the pixellated anode.

- Determine the maximum charge loss and estimate the extent of the volume over which charge loss is observed.