NE 204: Advanced Concepts in Radiation Detection and Measurement

Experiment 6: Charge Transport Properties in HPGe

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Revised September 23, 2018

Purpose

A planar HPGe detector with orthogonal strip segmented electrodes is used to study charge transport properties in HPGe. Charge carrier transport influences the operation and performance of semiconductor detectors, impacting both energy and position determination. HPGe has excellent charge carrier properties in comparison with compound semiconductor radiation detectors. The goal of this experiment is to experimentally determine the mobility-lifetime ($\mu\tau$) product for holes and electrons in HPGe, and to study charge-sharing and charge-loss due to the segmentation of the contacts in the strip detector.

Approach

An HPGe detector with a double-sided strip segmented electrode structure fabricated by Mark Amman at LBNL will be used for this experiment. The segmentation is characterized by a strip pitch of 2 mm with a gap of 0.5 mm. The instrument is about 11 mm thick and has 37 strips plus a guard ring around each of the segmented electrodes. SIS3302 modules will be used to read out all 74 channels of the detector. The first critical component of the study includes the optimization of filter parameters, energy calibration, and characterization of energy resolution for each of the 74 readout channels. A digital time pick-off algorithm is to be implemented to determine the time of maximum induced current on each electrode, which serves as a proxy for the "arrival time" of the charge at that electrode due to the small pixel effect. This information is then used to determine the depth of the interaction along the axis orthogonal to the readout electrodes. Once the spectroscopic performance has been optimized and fully characterized, the charge collection properties of the detector will be probed, relying on the depth sensitivity of the segmented HPGe detector. Depth-dependent energy spectra can be created to quantify the change in the full-energy peak location in the spectrum as a function of depth, providing a way to improve the system energy resolution with a depth-dependent energy calibration. 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 for the trapezoidal filter implemented in the SIS3302 firmware using a procedure similar to that employed in lab 1. Note that the SIS3302 firmware does **not** allow tuning of the spectroscopic filter for individial channels. Repeat the optimization procedure with data from at least two strips (near center and nearer the edge) from each side of the detector to estimate optimal parameters for the entire system.

Required

- Optimize the peaking and gap time parameters for the trapezoidal filter developed in lab 1. Apply the optimum filter parameters to the one implemented in the SIS3302 firmware.
- Using standard gamma-ray check sources (^{241}Am, ^{133}Ba, ^{137}Cs), perform an energy calibration for each of the 74 channels.

Optional

- Perform the filter parameter optimization process in software for each of the 74 channels. Are the parameters constant for every strip strip location?
- Characterize the energy resolution performance of each of the 74 strips after energy calibration.

Gamma-Ray Event Determination

Determine the distribution of time intervals between the digitized signals from the electrodes. Use this information to experimentally determine a timing criterion for correlated signals.

Required

- Plot a histogram of the interval between the trigger times of signals recorded on all electrodes (sometimes referred to as a "time to next event" histogram), and explain any features in the distribution.
- From the plot, determine an inter-event timing interval for correlated signals. How does this value compare to the maximum charge collection time in the detector?
- Use the timing criteria and the calibrated energy depositions to reconstruct likely candidates for single-interaction events in the detector.

Determining Interaction Depth

Determine the location of gamma-ray interactions in the dimension along the length of the crystal (orthogonal to the two electrodes).

Required

- Derive a time pick-off scheme to extract the "T-50" time from the digital signals.
- Use the difference in T-50 times ($\Delta T50$) from correlated signals to determine the depth of interactions.
- Using standard gamma-ray check sources, compare the depth profile computed using the above method to the expected attenuation at various gamma-ray energies.

Depth-of-Interaction and Carrier Trapping Compensation

The information about the depth of individual gamma-ray interactions developed in the previous section is used to study and compensate for trapping effects in the detector.

Required

- Evaluate the spectral position of photopeaks (from single interactions) as a function of depth of interaction.
- Perform a depth-dependent energy calibration to compensate for depth-dependent charge loss in the detector.
- Quantify the improvement in spectral performance with and without the trapping-compensation technique.

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

Determine $\mu\tau$ values in double-sided strip HPGe detectors 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 detector contacts into strips it is possible that charges produced in the bulk detector volume are collected on multiple strips. 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". A great deal of effort goes into the design and semiconductor fabrication process to mitigate charge-loss for segmented-electrode detectors.

Optional

- Develop an experimental procedure to quantitatively study charge sharing and charge loss effects for both anode and cathode strips. For example, illuminate one side of the detector with an ^{241}Am source and select full-energy events from the electrodes on the same side as the source. Compare the recorded signal for these events to the total signal recorded on multiple strips on the opposite electrode.
- Determine the maximum charge loss and estimate the extent of the volume over which charge loss is observed.