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Charge-trap correction and radiation damage in orthogonal-strip planar germanium detectors

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ABSTRACT

A charge-carrier trap correction technique was developed for orthogonal strip planar germanium gamma-ray detectors. The trap corrector significantly improves the gamma-ray energy resolution of detectors with charge-carrier trapping from crystal-growth defects and radiation damage. Two orthogonal-strip planar germanium detectors were radiation damaged with 2-MeV neutron fluences of $\sim 8 \times 10^9$ n/cm^2. The radiation-damaged detectors were studied in the 60–80 K temperature range.

1. Introduction

Germanium detectors have been the best gamma-ray energy spectrometers over five decades. Their excellent energy resolution is due to good charge-carrier mobility and efficient charge-carrier collection at the detector contacts. Charge-carrier trapping causes position-dependent pulse-height deficits that degrade the gamma-ray energy resolution. In germanium, trapping sites can be formed during crystal growth both thermally and through contamination [1–3]. Nuclear collisions between energetic massive particles, such as protons and neutrons, and germanium nuclei create giant disordered regions in the germanium crystal [4,5]. In the depleted detector, these giant disordered regions develop a negative charge state making them preferential hole-trapping sites [6]. Radiation damage considerations are important in accelerator environments, near neutron sources, and on board satellites.

The detector geometry affects the degree to which a given amount of charge trapping degrades the energy resolution. For example, the charge signals from the center contact of a p-type (conventional electrode) coaxial detector are far more affected by hole trapping than electron trapping because holes generate the majority of the energy (charge) signal for most of the gamma-ray interactions. Segmentation of the detector contacts further modifies the shape of the signals and the manner in which trapping affects the signals. The charge carriers induce charge on the metallic contacts of the detector according to the basic physics of Green's reciprocation theorem [7]. The relevance of Green's theorem to semiconductor-detector signal induction is often described as the "weighting field" effect, the "near-field" effect, or "Ramo's theorem" [8–13]. The gamma-ray peak shape depends on multiple factors including Compton scattering, the electrostatics of charge induction, and the degree of charge-carrier trapping [14–16]. Charge-induction electrostatics have been recognized and used to correct some level of hole trapping in radiation-damaged coaxial germanium and segmented coaxial detectors resulting in improved gamma-ray peak shapes [17–20]. Building on this earlier work, we have developed a charge-carrier trap correction technique or "trap corrector" specifically for orthogonal-strip planar germanium detectors. A planar trap corrector provides a unique view of charge-carrier trapping because charge carriers drift in a single crystallographic direction, unlike a coaxial detector where charge drifts radially. The trap corrector thus provides insight on the distribution, extent, and variation of charge-carrier trapping throughout the germanium crystal. The gamma-ray peak shape improvements provided by our trap corrector are dramatic in detectors having significant trapping from grown crystal defects and radiation damage.

2. Trap corrector development

As shown in Fig. 1, the PHDS NPX-M mechanically-cooled planar strip detector system provides both spectral and spatial resolutions for nuclear physics research applications. For example, these detectors have been used for positron-annihilation spectroscopy applications [21] and implantation of beta-decay research [22]. For the work presented here, two NPX-M detector systems (referred

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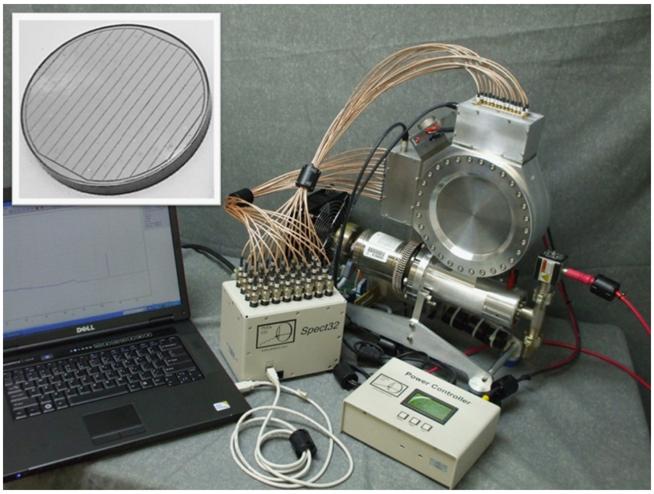

Fig. 1. The mechanically cooled NPX-M germanium detector system used to develop the trap corrector and study radiation damage in orthogonal-strip planar detectors.

to as NP3 and NP6) were used to develop the trap-correction technique and study radiation damage. Each of these NPX-M detector systems includes a 16 × 16 strip detector having 5-mm strip spacing with 0.25-mm width gaps. The detector contacts were fabricated using an amorphous-germanium process on 90-mm diameter, 10-mm thick germanium wafers. Each detector strip is connected to a charge-sensitive preamplifier. The outputs of the preamplifiers are processed by the SPECT32 readout system. The SPECT32 produces a slow ($T_P = 5\ \mu s$) gamma-ray energy and a 50% Constant Fraction Discriminator (CFD) arrival time for each gamma-ray interaction in the detector. The *x* channels are the DC-coupled channels 0–15 and the *y* channels are the AC-coupled channels 15–31. The USB 2.0 output of the SPECT32 streams data to a laptop PC to be processed by the Imager32 data-acquisition software application. The trap corrector was developed and implemented as part of the Imager32 application.

Before starting the trap-correction process, the 32 strip channels of the detector are individually calibrated using a known gamma-ray energy, usually the 662-keV gamma ray from ^{137}Cs. For the purpose of the trap corrector, the (*x*, *y*, *z*) location of each gamma ray interaction is estimated using the *x*-strip number (0–15), *y*-strip number (16–31), and the *z*-depth determined by a 50% CFD timing difference between the electron and hole collection in a manner described by [12]. In a typical 1-cm thick NPX-M detector, the 20-ns samples usually provide approximately 9 timing depths corresponding to thicknesses of approximately 1.1 mm each. The detector is effectively divided into 16 × 16 × 9 = 2304 volume elements or voxels, each having volume ~5 × 5 × 1.1 mm^3. In this manner, the (*x*, *y*, *z*) location and energy of each gamma-ray interaction are measured. The energy spectrum from each (*x*, *y*) pixel is a histogram of the average of the two energy values from the *x* and *y* strips. In the Imager32 software, the energy resolution of the entire detector is characterized by the sum of all (*x*, *y*) pixel spectra or the "pixel total" spectrum.

The trap corrector is most succinctly described as a spatially-dependent second-order energy calibration of the detector. To generate a trap-correction matrix, a gamma-ray energy spectrum is accumulated for each (*x*, *y*, *z*) voxel of the detector. In any (*x*, *y*) pixel, the gamma-ray peak centroid shifts as a function of depth (*z*) in accordance with the sign and severity of the charge-carrier trapping in that region of the crystal. The peak centroid of each (*x*, *y*, *z*) voxel spectrum is measured after accumulating sufficient statistics. The actual (correct) gamma-ray energy is then divided by the measured (shifted) peak centroid energy from each voxel spectrum to produce a correction factor for that voxel. The correction factors are very close to 1. After this 3D correction matrix is stored; it is used to correct all subsequently measured gamma-ray energies by multiplying each measured energy by the respective correction factor for that voxel. In this way, charge trapping is corrected in real time. This approach has the advantage of taking all position-dependent trapping effects into consideration regardless of their extent, sign, or variation throughout the volume of the detector. In the cases shown here, a ^{137}Cs source (~30 μCi) is counted from a distance of ~20 cm for 2 h to generate a 662-keV gamma-ray spectrum for each pixel and for each depth bin of each pixel.

The NP6 strip detector serves as an excellent example of the trap-correction technique because this detector was fabricated from a crystal grown with significant electron trapping. The NP6 detector was fabricated from a 90-mm diameter, 10-mm thick, p-type germanium wafer having a depletion bias of $V_{depl} = +650$ V and an operating bias $V_{op} = +800$ V. With this sign of bias, the electric field collects holes on *x*-channels 0–15 (the DC-coupled channels) and electrons on *y*-channels 16–31 (the AC-coupled channels). The ^{137}Cs spectrum from pixel (7, 24) is shown in Fig. 2. Pixel (7, 24) is near the center of the detector and is significantly degraded by electron trapping. Pixel (7, 24) has 662-keV FWHM = 3.7 keV and FWTM = 8.5 keV while pixel-total spectroscopy from the entire detector (all pixel spectra added together) is significantly better at FWHM = 2.7 keV and FWTM = 6.2 keV (see Table 1). The peaking time was 5 μs and the measured detector cold-plate temperature was 77.0 K.

The trap-corrector analysis provides a detailed breakdown of the 662-keV peak shape for an (*x*, *y*) pixel by depth. In the case of pixel (7, 24) of NP6, the depth-dependent trapping data follow a pattern reflecting predominant electron trapping as indicated in the left side of Fig. 3. Charge collected from depth-bin 9 requires electrons to traverse the longest distances, making it the most affected by electron trapping. The trap corrector measures and stores the centroids of the peaks for each depth of each pixel. Using the correction data, a subsequently corrected spectrum is shown in the right side of Fig. 3. The trap corrector improves the energy resolution of pixel (7, 24) significantly. The trap corrector produces this correction for every pixel of the detector according to the degree and sign of trapping measured in that pixel. 662-keV pixel-total spectroscopy from the whole detector improves from the uncorrected FWHM = 2.7 keV and FWTM = 6.2 keV to a corrected value of FWHM = 2.1 keV and FWTM = 4.6 keV.

Currently, this trap corrector does not account for multiple-site gamma-ray interactions due to Compton scattering within a pixel. The gamma-ray events used to create the trap correction matrix and the subsequently corrected gamma-ray events necessarily

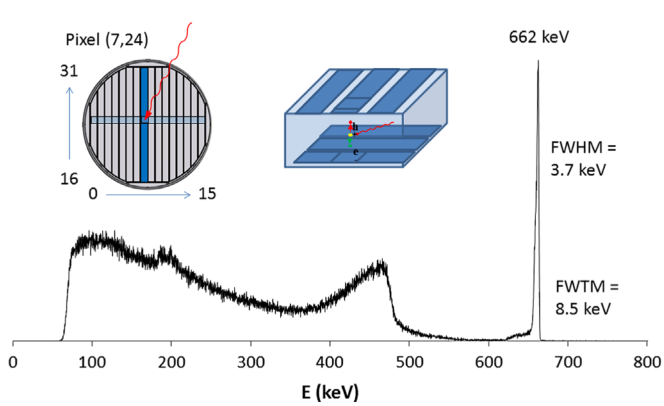

Fig. 2. The ^{137}Cs energy spectrum from pixel (7, 24) of the NP6 detector shows poor energy resolution caused by electron trapping.