CHARGE COLLECTION PHYSICS IN SEMICONDUCTOR DETECTORS

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Introduction

The NASA-funded IUCF-LBL collaboration to study the effects of radiation damage and the subsequent annealing of high-purity germanium detectors continues. Radiation damage considerations are extremely important in long duration germanium detector applications in space and in many accelerator experiments. Damaging radiation, such as high-energy protons and neutrons, create giant disordered regions in the germanium crystal lattice that predominantly trap a few percent of the holes produced by ionizing radiation.[1] The resolution of the detector degrades, as the hole-trapping results in a low-energy tail on gamma-ray peaks. During the last few years the scope of the program has broadened to include a general study of the collection of charge, both electrons and holes, as they move through the germanium lattice in undamaged, as well as radiation-damaged detectors. Various tools such as escape peaks from high-energy gamma rays, as well as analytical and Monte Carlo gamma-ray line-shape calculations, help provide understanding of many interesting charge collection properties. In addition to the research on germanium detectors, the radiation-damage effects of 200-MeV protons on room temperature CdZnTe detectors have also been evaluated.

Results and Conclusions

Extensive work was done with a radiation-damaged reverse-electrode (n-type) germanium coaxial detector where gamma-ray escape peaks were first used to characterize and understand the effects of radiation damage.[2,3] The detector is 67 mm in diameter, 68 mm long, with a 10-mm diameter hole extending to within 8 mm of the closed end. The detector was irradiated with 3.2×10^8 183-MeV n/cm^2 and subsequently underwent various temperature cycles, the most degrading of which was 3.5 days at 125 K with the bias off.[4] This combination of events degraded the resolution of the 1332-keV gamma-ray peak from a ^{60}Co source placed above the closed end of the detector from a detector contribution of FWHM=1.81 keV/FWTM=3.6 keV to 4.7 keV/22.2 keV with 3,800 counts/second between approximately 150 keV and 1400 keV, at an operating temperature of 83 K. The central conclusion of this work was that the effect of hole trapping on peak resolution depends strongly on whether the peak is a double escape, single escape, or full-energy peak. When high-energy gamma rays (E$\sim$2 MeV) produce electron-positron pairs, the back-to-back 511-keV photons, from the annihilation of the positron with a valence electron, are much more likely to escape from the detector without interacting if the the pair-production interaction occurs near the outer radius of the detector. Figure 1 shows the interaction-radii distributions of the three types of events that give peaks in a germanium detector as calculated using a Monte Carlo simulation. For this simulation 2615-keV gamma rays came from a point source 3 cm above the closed end of the detector. These distributions of the double escape pair-production events (a), single escape pair-production events (b), and first interaction of full-energy events (c) demonstrate a strong preference for escape events to occur at outer radii, especially double-escape events.

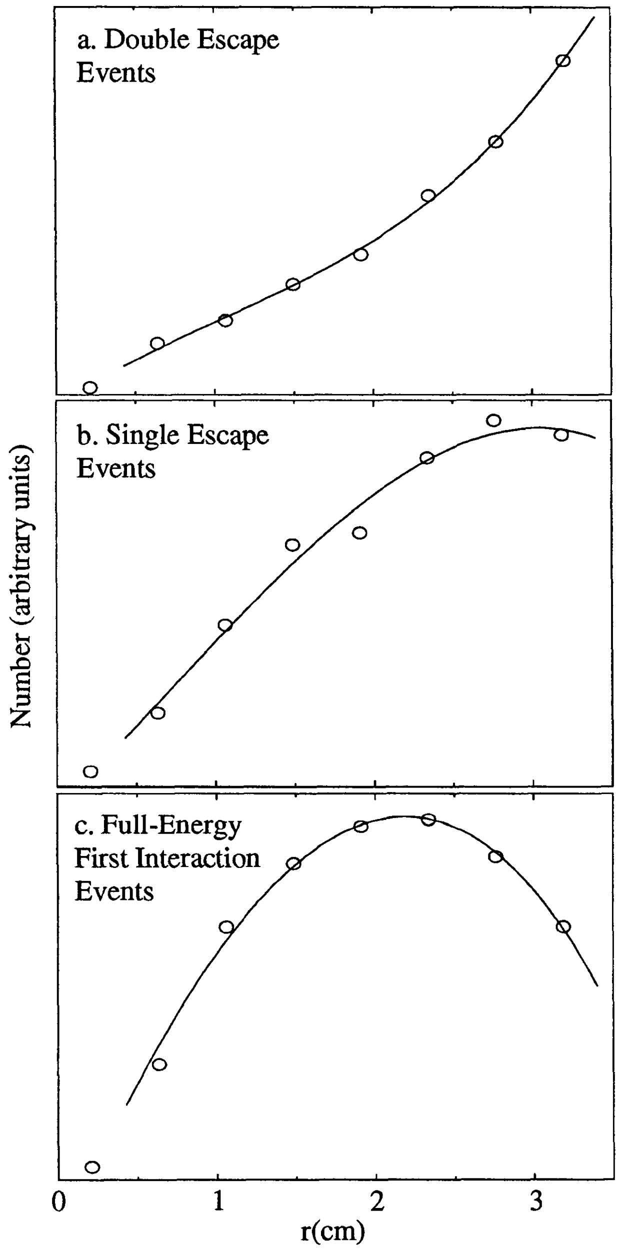

Figure 1. Monte Carlo distributions for 500,000 2615-keV gamma rays incident on a detector having the same dimensions as the actual detector. A total of 2,837 double-escape events (a) preferentially sample the outer radii of the detector, 5,593 single-escape events (b) also exhibit this behavior to a lesser degree. There were 43,719 full-energy events (c). The ratios of these numbers agree well with our experimental data. The cubic polynomial fits to the Monte Carlo results are used in our line-shape calculations.

For coaxial detector geometry, the signal amplitude induced per unit distance traversed by a charge carrier is largest near the inner electrode. For interactions occurring near the outer electrode, the corresponding holes induce only a small fraction of the total signal amplitude because they are relatively far from the inner electrode and they travel a short distance before reaching the outer electrode. In addition, the small contribution from the holes is affected little by hole trapping because the probability of a hole being trapped is proportional to the distance traveled before collection. Since escape-peak events preferentially occur near the outer radii of the detector, the double-escape-peak resolution should be better than the single-escape-peak resolution, which will be better than the full-energy peak resolution. Figure 2 shows a portion of the 6129-keV gamma-ray spectrum from the radiation-damaged detector and a nearly identical undamaged detector. The improvement of the double-escape-peak resolution over the single-escape-peak resolution and the improvement of the single-escape-peak resolution over the full-energy-peak resolution is quite dramatic. The damaged detector was operating at 87 K when these data were taken.

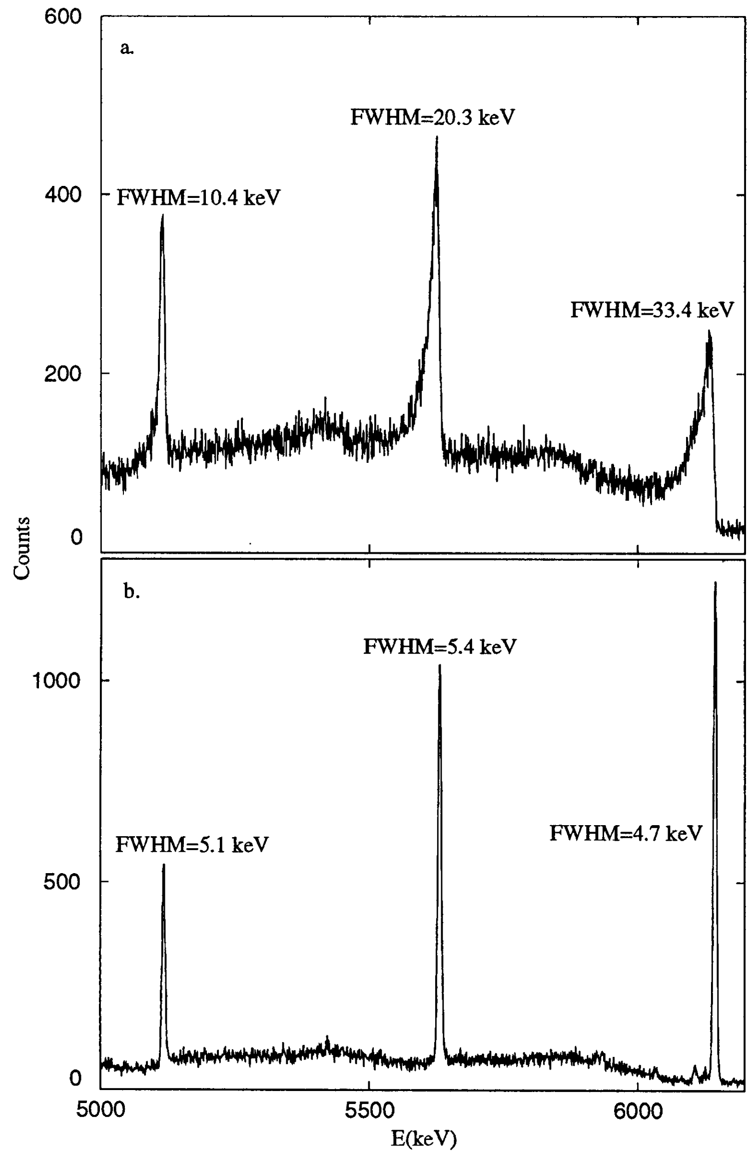

Figure 2. The 6129-keV gamma-ray peak along with its escape peaks from the decay of ^{16}N shows that the improvement of the escape-peak resolution over that of the full-energy-peak resolution is dramatic for the radiation-damaged detector (a). A spectrum obtained in the same configuration and counting time using a nearly identical but undamaged detector has much better resolved peaks (b). The peaks from the undamaged detector reflect a small amount of electron trapping and a Doppler shift that occurs in electron-positron annihilation.

The response of the undamaged detector is much different. However, the results are consistent with the geometric arguments used above combined with a small amount of electron trapping. The detector contribution for the 1332 keV spectrum was FWHM=1.68 keV/FWTM=3.12 keV. In the 6129-keV spectrum the full-energy peak has the best resolution followed by the double-escape peak and then the single-escape peak. These resolution differences reflect the small amount of electron trapping present in detector-grade germanium of even the highest quality. In detectors with reverse-electrode geometry, the resolution is degraded far more by electron trapping than by hole trapping.[5] The electron contribution to the signal is much larger than the hole contribution, on average, and the electron must travel much farther to be collected on the inner electrode. The double-escape events suffer the most trapping because they occur preferentially at the outer radii of the detector. Therefore, the resolution of the double-escape peak would be the worst of the three peaks if electron trapping were the only factor to consider. However, the single-escape peak has the worst resolution because of Doppler broadening of the energy of the annihilation quanta.[6] This is the same process that broadens annihilation-radiation peaks from positron sources. This effect is visible only in detectors having sufficiently good resolution. The double-escape peak is shifted down 660 eV relative to the full-energy peak, the single-escape peak is shifted down 280 eV relative to the full-energy peak. These shifts also reflect the electron trapping. A line-shape calculation for coaxial detectors using a uniform electron mean free path of λ_e=2500 cm (λ_h=10^7 cm) gives the correct 6129-keV resolution using the first full-energy interaction-radii distribution in Fig. 1. When the double- and single-escape-radii distributions are substituted, the peak energy shifts down in almost perfect quantitative agreement with the measured result. In addition to this calculation, the detector was also scanned radially with a beam of 1332-keV gamma rays to verify that electron trapping was more severe for events occurring at outer radii. As depicted in Fig. 3, a 10-μCi ^{60}Co source was placed over a 4-mm diameter hole in a 10-cm thick Pb brick, resulting in a line-of-sight 8-mm diameter beam spot on the detector, small enough to establish a peak-energy vs. position correlation clearly. The near face of the Pb collimator was held 5.2 cm over the detector by an arm attached to a translation table that facilitated reproducible positioning to an accuracy of better than 1 mm. Also shown is a plot of the energy of the 1332-keV peak as a function of collimator position. There is an $\sim$450 eV shift down in the peak energy as the collimator approaches the outer radius of the detector, consistent with electron trapping and our escape-peak observations. The same effects occurred to a lesser extent in a 49-mm diameter conventional-electrode (p-type) germanium coaxial detector to a lesser extent. The 1332-keV detector contribution of this detector was FWHM=1.57 keV. The detector showed an even smaller amount of hole trapping in the same ways the reverse-electrode detector showed electron trapping. All the same measurements and calculations done with the reverse-electrode detector were done with the conventional-electrode detector with similar results. Ballistic-deficit effects were eliminated as a possible cause of this shift by varying the amplifier peaking time from 2 μs to 24 μs; the magnitude of the shift was the same when the peaking time was 4 μs or greater. Our standard peaking time is 8 μs. These shifts in the escape-peak energy and the 1332-keV gamma-ray scans can serve as sensitive tests of small amounts of charge trapping.

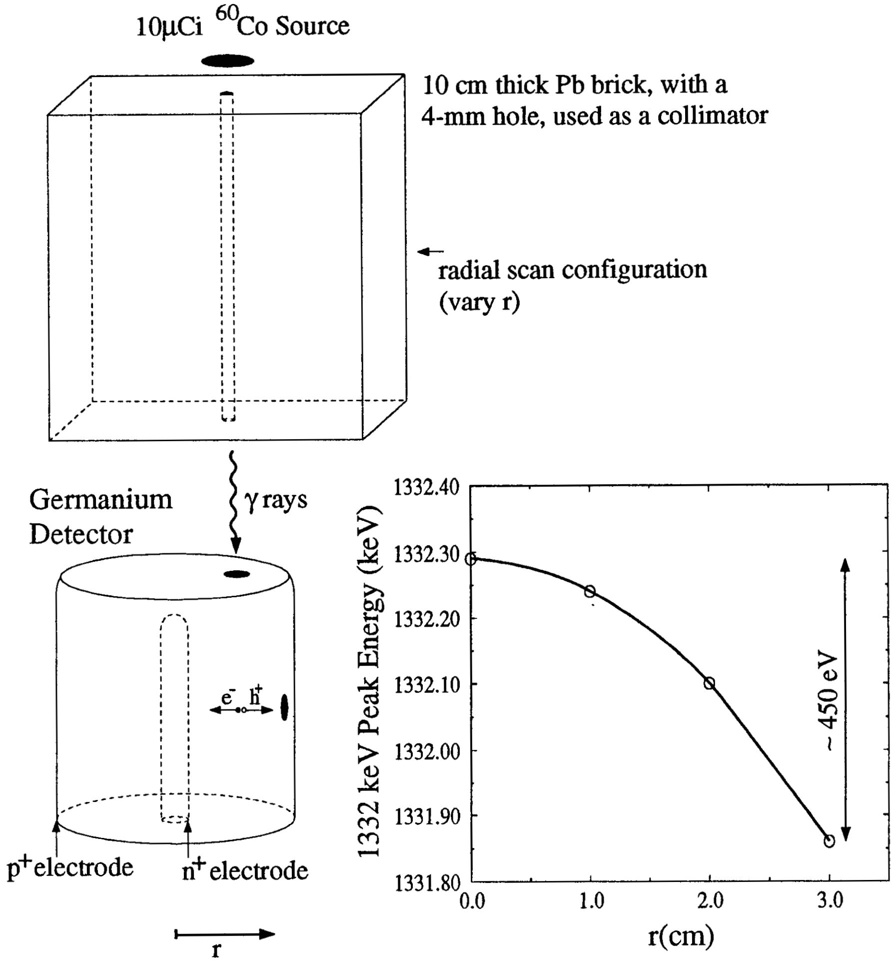

Figure 3. Configuration used to scan coaxial detectors. The Pb collimator was held by an arm attached to a translation table that facilitated repeatable positioning in the r direction. The 1332-keV peak shifts down in energy as the detector is scanned from the inner radius to the outer radius, indicative of electron trapping.

The 6129-keV spectra were obtained when the detectors were placed next to the holding tank for the IUCF 200-MeV cyclotron deionized water cooling system. Secondary neutrons produced when the beam strikes the cyclotron extraction elements react with the cooling water circulating in the cyclotron magnet excitation coils, producing ^{16}N via the $^{16}O(n,p)^{16}N$ reaction. The ^{16}N then beta decays with a 7-second half-life to an excited state of ^{16}O, which promptly decays to the ground state by emitting a 6129-keV gamma ray. A high-energy gamma-ray source is extremely useful for studies such as these. The highest-energy gamma ray normally available is the 2615-keV gamma ray from ^{208}Tl in the thorium decay chain. For the purpose of these studies and a handy source for detector calibration in general, an attempt is underway to make a predictable ^{16}N source. We propose to circulate water through or around a copper beam dump used to stop the high-energy proton beam from the cyclotron.

In addition to the work with germanium detectors, several CdZnTe-photon detectors were irradiated with 200-MeV protons to test their viability in space applications. Unfortunately, even the highest quality CdZnTe detectors have very poor hole mobility, the electron induces almost all of the signal. Therefore, they can only be used for low-energy gamma rays and x-rays. Relative to a material like detector-grade germanium, CdZnTe is extremely "dirty" so it was expected to be quite radiation resistant. The detectors were irradiated with 200-MeV protons in the radiation effects research area at IUCF.[7] As an example of the effect of radiation damage on the detector performance consider a 3-mm thick, 1-cm^2 area, planar CdZnTe detector. Before the irradiation the 122-keV peak from ^{57}Co had FWHM=3.6 keV. When damaged by a fluence of 5×10^9 p/cm^2 the 122-keV peak shifted down to 97 keV with FWHM=6.1 keV. The electronics were checked for stability with a pulser that remained at the same energy, with the same resolution, FWHM=2.8 keV, throughout the experiment. The explanation thus far is radiation-damage-induced electron trapping, an interesting contrast to the radiation-damaged-induced hole trapping that occurs in germanium detectors. Line-shape calculations predict that the electron mean free path $\lambda_e \sim 3$ cm decreased down to $\lambda_e \sim 0.4$ cm to allow for the huge peak shift observed. These surprising results indicate that radiation damages CdZnTe detectors much more easily than germanium detectors.

1. H.W. Kraner, C. Chaseman, K.W. Jones, Nucl. Instrum. and Methods **62**, 173 (1968).
2. R.H. Pehl, E.L. Hull, N.W. Madden, D.L. Friesel, IUCF Sci. and Tech. Rep. May 1994-April 1995, p. 124.
3. R.H. Pehl, E.L. Hull, N.W. Madden, J.S. Xing, D.L. Friesel, to be published in Nucl. Instrum. and Methods.
4. E.L. Hull, R.H. Pehl, IUCF Sci. and Tech. Rep. May 1992-April 1993, p. 143.
5. R.H. Pehl, Physics Today, **30**, 50 (1977).
6. I.K. MacKenzie, J.L. Campell, Nucl. Instrum. and Methods **101**, 149 (1972).
7. C.C. Foster, K.M. Murray, T.C. Rinkel, IUCF Sci. and Tech. Rep. May 1994-April 1995, p. 179.