Available online at www.sciencedirect.com
ScienceDirect
Nuclear Instruments and Methods in Physics Research A 586 (2008) 215–223
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A
www.elsevier.com/locate/nima

Incomplete charge collection in an HPGe double-sided strip detector

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Received 18 September 2007; received in revised form 2 December 2007; accepted 13 December 2007
Available online 7 January 2008

Abstract

For gamma-ray detection, high-purity germanium (HPGe) has long been the standard for energy resolution, and double-sided strip detectors (DSSDs) offer the possibility of sub-millimeter position resolution. Our HPGe DSSD is 81 mm in diameter, 11-mm thick, and has 3-mm strip pitch with a gap width of 500 μm. In this work, we focus on characterizing just the interactions that occur between collecting strips. Simulation and measurement results for our HPGe DSSD show that the gap between strips is the most position-sensitive region. But, spectra collected from events that occur in and near the gaps are complicated by: (1) incomplete charge-carrier collection, or charge loss; (2) signal variance introduced by charge-carrier cloud size, orientation, and lateral spreading; and (3) the difficulty of distinguishing single interactions from multiple close interactions. Using tightly, collimated beams of monoenergetic gamma rays, the measured energy spectra at the gap center show that incomplete charge collection is significant in our detector at 356 and 662 keV, resulting in degradation of the photopeak efficiency. Additionally, close interactions are identifiable in the spectra. Thus, close interactions must be identified on an event-by-event basis in order to precisely identify gap interaction position or make charge-loss corrections at these energies. Furthermore, spectral differences are observed between anode and cathode gaps, and a possible reason for this asymmetry is proposed.

PACS: 29.40.Wk

Keywords: Compton imaging; HPGe detector; Double-sided strip detector; Charge loss; Strip gap; Inter-strip position interpolation; Charge-carrier cloud

1. Introduction

For gamma-ray detection, germanium has long been the standard for energy resolution, and it has excellent detection efficiency. Double-sided strip detectors (DSSDs) provide the advantage of sub-millimeter position resolution. This is advantageous in gamma-ray imaging, which has shown to yield improved detection in complex radiation fields or if the radiation source is localized. For these reasons, high-purity germanium (HPGe) DSSDs are being researched for applications in astrophysics [1–3], nuclear physics [4], homeland security [5], medical imaging [6], and environmental remediation [7].

In astrophysics, the aim of the Advanced Compton Telescope (ACT) Project is particularly aggressive to allow imaging at 200 keV to 10 MeV with orders of magnitude improvement in sensitivity. The sensitivity is affected mainly by system energy resolution, position resolution, and detection efficiency. The background rejection methods employed are also very important, as data collected in astrophysical applications are background dominated. The background rejection methods also depend heavily upon position and energy resolution. Currently, the ACT is projected to have a sensitivity 10–50 times that of its predecessor, COMPTEL ($\sim 10^{-5}\,\gamma\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$), because its use of position-sensitive detectors with excellent spatial resolution aids in background rejection and reduces the uncertainty of the Compton-scattered photon angle dramatically [1]. Yet, it would benefit NASA's mission to be able to improve sensitivity by two more orders of magnitude.

Our research addresses the first of the primary technical challenges with use of HPGe DSSDs, as stated in the ACT

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doi:10.1016/j.nima.2007.12.013

report [1], "optimization of the electrode and guard ring geometries … and exploration of inter-strip interpolation to optimize position resolution". Both of these challenges focus around the detector gap, the most position-sensitive detector region. Use of the data obtained for interactions that occur in the vicinity of a gap are complicated by: (1) incomplete charge-carrier collection, or charge loss; (2) the signal variance introduced by charge-carrier cloud size, orientation, and lateral spreading; and (3) the difficulty of distinguishing single interactions from multiple close interactions. As a whole, they decrease efficiency, introduce unwanted background counts, degrade energy resolution, and result in increased position uncertainty using current interpolation methods, reducing the sensitivity of the resulting image.

This work characterizes incomplete charge collection in the UM HPGe DSSD at gamma-ray energies where Compton scattering is dominant, exploring its underlying causes. Section 2 presents background on the UM detector and previous charge-loss measurements on similar detectors, Section 3 describes our simulation, Section 4 explains experimental and simulation results, and Section 5 gives conclusions.

2. Background

2.1. The UM HPGe DSSD

The UM double-sided strip detector was fabricated by Ethan Hull and Dick Pehl at PHDs Co. [8]. The detector is 11.2-mm thick, 81.3 mm in diameter and its strips are fabricated with amorphous-Ge (a-Ge) contact technology [9,10]. The 23×23 orthogonal strips have a pitch of 3 mm, and the gap in between strips is 500 μm; so the gap-to-strip width ratio is 1/6. The active part of the crystal is surrounded by a guard ring.

The detector employs a P-type crystal with reported impurity concentration of $\sim 4.5 \times 10^9\,\text{cm}^{-3}$. The capacitance between strips is 27 pF, and preamplifier JFET input capacitance is 10 pF. The detector is fully depleted at −320 V, depleting from the anode side to the cathode side. The detector is biased to −700 V on the cathode side, and it is operated at a temperature of 92 K. It has a low energy threshold of ~40 keV due to its aluminum housing. Energy resolution on a single strip was measured to a range from 1 to 2 keV at 60 keV and 2 to 3 keV at 662 keV. Charge sharing in this detector was described elsewhere [11].

2.2. Charge loss associated with interactions occurring between strips

Charge loss in HPGe strip detectors with a-Ge contacts has been identified by others. Amman and Luke [12] measured charge loss in a 500 μm gap, reporting a maximum of ~5% loss at 60 keV. They demonstrated reduction in charge loss through biasing a field-shaping strip in between two collecting strips with a potential of opposite sign, forcing charge to the collecting strips. Introducing this opposite bias on field-shaping strips on each side of a collecting strip resulted in improved photopeak efficiency, reduced background, and minor improvement in energy resolution at 60 and 662 keV, but degraded the position resolution of the detector by forcing all charge carriers to collecting strips.

Coburn et al. [13] studied charge loss on cathode and anode sides by measuring coincident pulse heights on nearest neighbor strips. Their detector was uniformly irradiated by gamma rays with varying energies. At 60 and 122 keV, nearest neighbor coincidences were found to constitute about 15% of all events, where 25% was expected based upon the gap-to-strip width ratio. Charge loss was measured as the photopeak shift of those pulses with nearest neighbor coincidences. At 60 keV, they found ~6% loss in the photopeak channel number on the anode side and ~1% loss on the cathode side of their detector. But at 662 keV, the photopeak shift was much less significant on the anode side than the cathode side. Since the fractional charge loss was lessened for carriers formed deeper in the detector, they concluded that there was a dead region of high charge loss near the anode surface. Furthermore, they suggested that: (1) a correction has to be made based upon the charge collected by all relevant cathode and anode strips based upon depth interpolation, and (2) the gap-to-strip width ratio has to be minimized to reduce the percentage of nearest neighbor events.

Based upon numerical simulation, Amrose et al. [14] suggested that incomplete charge collection might result from surface conductivities higher than measured in the amorphous layer of their HPGe DSSD. The measured conductivities of their detector were $10^{-16}\,\Omega^{-1}$ at the surface and $10^{-12}\,\Omega^{-1}\,\text{cm}^{-1}$ in the bulk. They showed that if the surface conductivity were increased by a factor of 100, the field in the gap would be similar to the field along the strips, allowing charge to become stuck in the gap.

3. Simulated signals for interactions between strips

The UM HPGe detector code models detector response through the drifting of individual charge clouds in 3D. The modeling of surface electric fields, which appear to significantly affect charge loss for gap interactions, is discussed as well.

3.1. Simulated charge clouds for interactions in a gap

Signals induced from interactions in HPGe strip detector gaps are sensitive to the size and orientation of charge-carrier clouds. Since gap interaction measurements are performed using collimated Ba-133 and Cs-137 sources, GEANT4 [15] was used to determine energy deposition positions in germanium for photoelectrons with 356 keV (Ba-133) and 662 keV (Cs-137). The 3D interaction positions and the energy deposited at these positions were used as the input for the detector simulation.