Inter-electrode charge collection in high-purity germanium detectors with amorphous semiconductor contacts

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Abstract

High-purity germanium (HPGe) radiation detectors with segmented signal readout electrodes combine excellent energy resolution with fine spatial resolution, opening exciting possibilities in radiation imaging applications. Segmenting the electrodes provides the ability to determine the positions of radiation interactions in the detector, but it also brings potential challenges that can inhibit performance. A challenge unique to segmented electrode detectors is collection of charge carriers to the gap between adjacent electrodes rather than to the electrodes themselves, which gives a deficit in the summed energy. While amorphous semiconductor electrical contacts have enabled a simplified fabrication process capable of fine electrode segmentation, the amorphous semiconductor passivation layer between electrodes is prone to inter-electrode charge collection. This article presents a study of the impact of fabrication process parameters on the energy deficit due to inter-electrode charge collection for double-sided strip detectors. Eight double-sided strip HPGe detectors were fabricated with amorphous germanium (a-Ge) and amorphous silicon (a-Si) contacts formed by sputter deposition. Each detector was evaluated for inter-electrode charge collection performance, using as a metric the deficit in the summed signal of two adjacent electrodes. It is demonstrated that both a-Ge and a-Si contacts can be produced with nearly non-existent inter-electrode charge collection when the appropriate combination of sputter gas hydrogen content and gas pressure are selected.

Keywords: Gamma-ray detectors, high-purity germanium, amorphous semiconductor contacts, segmented radiation detectors, detectors for imaging

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25 1. Introduction

26 High-purity germanium (HPGe) detectors have provided the gold standard in energy resolution for
27 gamma-ray detection applications for many decades [1]. Gamma-ray detectors that combine this excellent
28 energy resolution with position sensitivity for radiation interactions open up exciting possibilities in
29 imaging, where some benefit is gained by imaging a radiation source either through increased signal-to-
30 background ratio or better knowledge of the source distribution. This combination lends itself particularly
31 well to gamma-ray Compton imaging [2], where the incident photon direction is determined without the
32 limitations of a collimator. The Nuclear Compton Telescope (NCT) [3], Gamma-Ray Imager/Polarimeter
33 for Solar Flares (GRIPS) [4], and SmartPET [5] systems are examples of HPGe detectors utilizing position
34 sensitivity for Compton imaging. Other applications in nuclear safeguards [6], medical imaging [7], and
35 basic science [8] [9] also take advantage of the simultaneous high energy resolution and imaging properties
36 of segmented HPGe detectors.

37 Although existing fabrication processes are well established for simple HPGe-based spectrometers,
38 fabrication processes for segmented electrode detectors could benefit from further development. The
39 electrodes must be electrically separated and the inter-electrode region properties must be considered. One
40 of the key challenges is creating the surface region between electrodes in a way that provides high
41 resistance between electrodes, resists collection of charge carriers to the inter-electrode region, and is stable
42 over time. A typical solution involving conventional, impurity-based contacts includes an etching or
43 cutting step to eliminate the low-resistivity material between electrodes. For ion-implanted contacts,
44 standard lithographic and etching processes can be successfully used [10] [11] [12]. However, the thicker
45 Li-diffused contact poses a greater challenge because it is not conducive to standard etch processes. Saw-
46 cutting has been used to segment the Li-diffused contact [13] [14]. Alternatively, the Li may be evaporated
47 through a shadow mask and subsequently diffused in a limited area [15]. Both of these methods are limited
48 in electrode spacing by virtue of the technique used, and have a lower limit of about 1 mm for the gap
49 between electrodes [15]. For all processes just described, when material is removed by chemical etching,
50 saw-cutting, or other methods, the resulting bare crystalline-germanium surface can be vulnerable to
51 environmental exposure. Depending on the detector application, additional processing steps may be
52 required in order to protect or passivate the inter-electrode surfaces.

53 Amorphous semiconductor contacts are a promising alternative for the manufacture of segmented HPGe
54 detectors because they enable a greatly simplified fabrication process. Amorphous germanium (a-Ge) and
55 amorphous silicon (a-Si) have been shown to form suitable electron-blocking and hole-blocking contacts
56 [16] [17] as well as surface passivation [18]. It is possible to coat the entire outer surface of a HPGe crystal
57 with an amorphous semiconductor layer, deposit metal electrodes in the desired configuration, and have a
58 fully passivated segmented detector. No additional processing steps are required to modify the region
59 between electrodes. Amorphous semiconductor contacts have been used to create position-sensitive
60 detectors for x-ray and gamma-ray imaging [16] [19] [20] [21] [22], applied to Li-drifted Si detectors [23]
61 [24], shown to be appropriate for thin entrance window applications [16] [25], used to create very fine
62 contact segmentation [9], and enabled unique detector configurations such as field shaping [21] [22] and
63 proximity electrode signal readout [26] [27]. HPGe detectors with amorphous semiconductor contacts have
64 been successfully used or are being developed for a wide variety of application areas including space
65 science [3] [28] [29] [30] [31] [32] [4], material science [9], nuclear and particle physics [8] [33] [34]
66 medical imaging [7] [35], nuclear nonproliferation and homeland security [6] [36] [37] [38], and
67 environmental remediation [39].

68 Amorphous semiconductor contacts can bring additional challenges in detector fabrication. Since they
69 behave much like metal-semiconductor contacts, they have inherently higher leakage current than that from
70 the standard impurity-based contacts. Furthermore, the leakage current may also increase with time if the
71 detector is kept at room temperature. Fortunately, these performance issues can be managed by selecting
72 appropriate material (a-Ge or a-Si) and sputter deposition parameters [40] [41].

A potential pitfall specific to segmented detectors in general is the collection of charge carriers directly to the gap between electrodes. This process is illustrated in Figure 1 by the white dashed line. Since the charge does not reach close proximity to either electrode within a typical measurement time, there will be less induced charge on the electrodes in comparison to a completely collected event (such as that shown in black). Consequently, the measured energy will be smaller than that deposited in the detector by the gamma ray.

Figure 1. Schematic illustration of inter-electrode charge collection. Two possibilities are illustrated. In one (black lines), the charge splits, is fully collected by the electrodes, and leads to the correct measure of the gamma-ray energy. In the other (white dashed line), the charge is collected to the gap between the two electrodes.

Charge collection to the gap has been studied on a variety of segmented HPGe detectors. For example, a detector with impurity-based contacts exhibited good performance on the B-implanted contact, but the Li-diffused contact showed a significant deficit [42]. Another study on a detector with an a-Ge contact but with the inter-strip passivation layer removed by plasma etching showed no charge loss [43]. Other studies of detectors with a-Ge inter-strip passivation tended to show a significant energy sum deficit [22] [44] [45]. It has, however, been shown that the a-Ge deposition parameters can affect this behavior [21].

This article presents the results of a study of the impact of the fabrication process on inter-electrode charge collection for HPGe detectors with a-Ge and a-Si contacts. It is demonstrated that detectors with contacts formed using a certain range of parameters show a severe energy sum deficit similar to previously published results for a-Ge contacts, but selecting an appropriate range of sputter pressure and sputter gas hydrogen content forms contacts with significantly lower deficit. An optimized fabrication process is presented for HPGe strip detectors that yields both long-term stability and favorable inter-electrode charge collection properties.

2. Experimental methods

2.1 Detector fabrication

In order to investigate the effect of the fabrication process on inter-electrode charge collection, we fabricated a series of double-sided strip HPGe detectors with a-Ge and a-Si electrical contacts and surface passivation. A basic methodology similar to that used for studying leakage current [41] was used, where all aspects of the fabrication and testing process were kept constant except for the fabrication of the bottom contact. Two crystal samples were cut from a p-type HPGe slice purchased from ORTEC [46], with a net ionized impurity concentration of $7 \times 10^9 \text{ cm}^{-3}$. Each sample was cut using a diamond-grit saw to obtain a rectangular prism, shown in Figure 2, with a square cross-section and two handles at the bottom surface. These handles remain undepleted during detector operation and create an insensitive surface that can be used for handling during detector fabrication and mounting in the test cryostat. Both samples measure 18 mm on a side for the square cross-section, and have thicknesses of 13 mm and 7 mm respectively. After

108 cutting the samples to the desired geometry, the flat faces were lapped and then all surfaces were
109 chemically polished.

110
111 **Figure 2. HPGe crystal geometry used for making double-sided strip detectors in this study.**

112 Both HPGe crystal samples were used in multiple fabrication runs to produce double-sided strip detectors
113 with electrical contacts formed under varying conditions. For each fabrication run, the crystal was first
114 submerged in 1% HF to remove any previously existing Al electrodes, then etched for 1 minute in 4:1
115 HNO₃:HF to remove any previous amorphous layers and to clean the surface. The crystal was then loaded
116 into an RF sputter deposition system and the top contact and side surface passivation were formed by
117 sputtering a-Ge in an Ar/7% H₂ gas mixture at 15 mTorr pressure. This recipe was previously shown to
118 provide good hole blocking and to be stable with time at room temperature [41]. Next, the bottom contact
119 was formed by sputtering either a-Ge or a-Si under varying conditions. The electrodes were formed by
120 thermally evaporating Al on the top and bottom surfaces to form a guard ring and five strip electrodes. The
121 guard ring was abnormally wide in order to minimize any effects caused by surface channels [47] [48].
122 Each strip electrode was 10 mm in length and 0.5 mm wide, with a 0.5 mm gap between strips. Most of the
123 electrode area consisted of 50 nm of Al, but a small pad of 500 nm thickness was added at the end of each
124 electrode to facilitate wire bonding. The detector was then mounted into a metal frame by clamping onto
125 the handles. Electrical connections to all electrodes were completed by wire-bonding from the detector
126 electrodes to circuit boards attached to the metal frame. A photograph of a completed detector is shown in
127 Figure 3.

128
129 **Figure 3. Photograph of a completed and mounted detector.**

2.2 Measurement procedure

When the fabrication run was completed, the detector was loaded into a cryostat and the chamber was evacuated using a turbomolecular pump. When the pressure dropped to an acceptable level ($\sim 10^{-6}$ Torr), an ion pump was activated and the turbopump was disconnected to minimize the microphonic noise from pump vibration. Liquid nitrogen was then added to cool the detector to 78 K.

A positive bias V_d was applied to the top electrodes up to a maximum of a few hundred volts above full depletion. If the measured leakage current of all electrodes was measured to be <10 pA, the detector was tested with a radiation source using the configuration shown in Figure 4. A low-energy gamma-ray source (typically Am-241) was used to illuminate the top surface of the detector, creating electron-hole pairs almost entirely within 1 mm of the top surface. In this configuration, the electrons generated by each gamma interaction are immediately collected by the top electrodes and therefore are not observed to a significant level by the bottom strips. The generated holes drift across the detector thickness due to the applied electric field and generate the majority of the induced charge signal seen by the bottom electrodes. In order to read out these signals, two adjacent strips on the bottom surface were connected to ac-coupled preamplifiers. All other bottom electrodes were connected directly to ground potential.

Figure 4. Illustration of detector readout scheme and measurement setup.

The preamplifier output waveforms were digitized using SIS3302 digitizers from Struck Innovative Systems [49]. A radiation event was recorded when at least one of the two readout channels surpassed the threshold of about 10 keV. When this condition was met, a 20- μ s waveform for both channels was recorded at 100 MHz sampling frequency and 16-bit resolution. A pre-trigger delay was used so that the time of trigger was approximately halfway through the waveform sample.

2.3 Data analysis

The waveforms were analyzed using a digital trapezoidal filter [50]. For the first detector analyzed, extensive optimization was performed to select the proper peaking time, gap time, and pole-zero correction factor. In subsequent measurements, the same optimized parameters were used without repeating the optimization measurements. Pulser events were used to fit the exponential decay of the preamplifier in order to find the best correction for each channel. An optimized peaking time of 9 μ s and gap time of 150 ns were determined based on 60-keV events from an Am-241 source.

The pulse height for each channel was taken as the maximum of the trapezoidal filter waveform if the channel was over threshold. If the channel was not over threshold, its pulse height was taken as the trapezoidal filter value at the same time where its neighbor reached its maximum value. An energy calibration and cross-talk correction were applied for each new measurement. A cross-talk correction factor was determined by mapping the pulse height in one channel as a function of the pulse height in the

164 other channel. Each channel was corrected by subtracting the pulse height of the other channel multiplied
 165 by the correction factor so that both channels had events in the zero-energy peak independent of the pulse
 166 height of the other channel. After this, all pulse height values were scaled so that the full-energy peak was
 167 at the radioactive source energy.

168 The final analysis was performed using a plot of the sum of the energy of two adjacent strips versus the
 169 energy of one of those strips. A plot of this type would have events spanning a horizontal line at the full
 170 gamma-ray energy for a detector where there is no charge collected to the inter-strip-electrode surface,
 171 while a detector with inter-strip collection would show a dip near the center of the plot. The results section
 172 will compare plots of this type for several double-sided strip detectors, focusing primarily on the magnitude
 173 of the deficit of summed energy near the center of the plot.

174 Electrostatic calculations were conducted to determine what should be expected from the experiment.
 175 The Shockley-Ramo theorem describes the charge induction efficiency of electrodes as a function of
 176 position of the charge by introducing a weighting potential [51] [52]. A model of the detector was created
 177 in the Maxwell simulation package [53], and the weighting potentials were calculated for two adjacent
 178 strips. The weighting potentials for the two strips, when evaluated at the surface, give an estimate for the
 179 pulse height of events collected directly to that surface. Figure 5 shows the weighting potentials V_w for two
 180 strips evaluated at the surface as well as the sum of the two potentials. The sum reaches a minimum of 0.84
 181 in the center of the gap between strips, indicating that a detector with this geometry where charge carriers
 182 are collected directly to the gap center would experience a 16% deficit in the energy sum for the two
 183 adjacent strips.

184
 185 **Figure 5.** Calculated weighting potential V_w for a HPGe detector of the geometry shown in Figure 3 evaluated at the
 186 detector surface for two adjacent strips (red and blue curves) as well as the sum of the two (green curve).

187 3. Results

188 Measurements were taken on double-sided strip detectors with a-Ge bottom contacts formed under
 189 varying conditions. A detector with an a-Ge bottom contact sputtered in 15 mTorr pure Ar displays a
 190 severe energy sum deficit for shared events, matching almost exactly the prediction from simulation where
 191 the holes are collected directly to the surface. This is shown in the charge sharing plot of Figure 6. The
 192 vertical axis in this plot is the energy sum of the two adjacent strips, while the horizontal axis is the energy
 193 from one of those strips (note the different scales). A bold, horizontal line is drawn at the gamma-ray
 194 source energy of 59.54 keV. A thin, black curve displays the weighting potential sum from Figure 5. Since
 195 plots of this type are not conducive to showing multiple data sets, a compressed view of the data is
 196 produced where a series of vertical slices are taken of the two-dimensional histogram. Each vertical slice is
 197 fit with a Gaussian function and the mean of that fit is displayed with a black circle. Overall the conclusion
 198 from Figure 6 is that a-Ge sputtered in pure Ar produces significant charge collection to the inter-electrode
 199 surface, which matches that reported previously [21][22].

Figure 6. Charge sharing plot for a detector with a large energy sum deficit. The data were acquired for holes collected to the bottom contact, which was a-Ge sputtered in 15 mTorr Ar.

Several double-sided strip detectors were fabricated with a-Ge contacts sputtered in an Ar/7% H₂ mixture at varying pressure. Figure 7 displays the mean vertical slice fit values of three data sets for detectors sputtered in 7 mTorr, 11 mTorr, and 15 mTorr pressures. Directly comparing the 15 mTorr Ar/7% H₂ recipe to the 15 mTorr Ar recipe from Figure 6 reveals the critical importance of hydrogen content in eliminating the charge sharing deficit. None of the H₂ mixture detectors had as large a deficit as the detector with an a-Ge sputtered in pure Ar, but sputter pressure is clearly an important parameter. While the 15 mTorr Ar/7% H₂ recipe had almost no deficit, progressively lower sputter pressure resulted in progressively greater deficit. A previous study along this line identified the importance of H₂ in the sputter gas, but the influence of sputter pressure was not investigated [21].

Figure 7. A comparison of the charge sharing deficit for a-Ge contacts sputtered in Ar/7% H₂ at varying pressure. Markers indicate data from three detectors and the black curve is the calculated weighting potential from Fig. 5.

A detector was also fabricated with an a-Si bottom contact sputtered in 7 mTorr Ar/7% H₂. Figure 8 shows the charge sharing plot for this detector. Almost no charge sharing deficit is observed. The lower deficit is accompanied by a reduction in the fraction of events that are shared significantly between the two strips. Based on this result and the results from our previous leakage current study [41], it is clear that a desirable segmented electrode detector configuration consists of the hole-blocking contacts formed with a-Ge sputtered in 15 mTorr Ar/7% H₂ and the electron-blocking contacts formed with a-Si sputtered in 7 mTorr Ar/7% H₂. Such a detector would have low leakage current, be stable with room temperature storage, and would have little charge collection to inter-electrode surfaces.

Figure 8. Charge sharing plot for a detector with an a-Si bottom contact sputtered in 7 mTorr Ar/7% H₂.

Since the a-Ge contact sputtered in 15 mTorr Ar/7% H₂ showed very little charge deficit and was previously shown to be stable with storage at room temperature and a good hole blocking contact [41], it was investigated more thoroughly. The data reproducibility was first assessed by taking six identical data sets over the period of about a week. In all cases, the charge sharing deficit was not significantly larger than the inherent detector energy resolution. A slight reduction in energy sum deficit was noticed when the detector had been biased for many hours, compared with the same detector when it was recently biased.

The process run reproducibility was assessed by making two detectors with identical fabrication process parameters using the same crystal. A third detector was also fabricated using identical fabrication process parameters, but using a different HPGc crystal. No significant differences were observed; all had an energy sum deficit on the order of the detector energy resolution.

One detector was tested with varying bias to determine if the inter-electrode charge collection was significantly affected by the strength of the electric field at the contact. For a detector that fully depleted at 600 V, data sets were acquired at 1000 V, 1500 V, and 1900 V. No significant differences were observed. Taking advantage of the bipolar blocking nature of a-Ge contacts [16], the detector bias polarity was reversed so that the same bottom contact was collecting electrons instead of holes. Data sets were acquired at -1000 V, -1400 V, and -1700 V, but no significant differences were observed.

All detectors previously described had their metal electrodes formed by thermal evaporation through a shadow mask. However, photolithography grants additional flexibility in the patterns that can be formed and the feature size that can be achieved. We tested multiple detectors to observe any effect that the different processing steps associated with photolithography might have on inter-electrode charge collection. First, a detector with an a-Ge bottom contact sputtered in 15 mTorr Ar/7% H₂ was tested normally. It was then removed from the cryostat and baked at 90^o C for 30 minutes to simulate the bake process used during photolithography. The detector was loaded in the cryostat and re-tested. After this, the crystal was reprocessed using the same fabrication process parameters, but the electrodes were formed with photolithography. This involves not only the bake step, but additional chemical exposure and handling. No significant differences were observed; in all three cases, the energy sum deficit was small.

An important concern for double-sided strip detectors, especially when used in large instruments with multiple detectors, is long-term stability. For example, the detector might be required to perform adequately after storage in a dry box for many months. To test the stability of the inter-electrode charge collection performance, two detectors were re-tested after long-term storage in a nitrogen-purged box at room temperature. One detector had an a-Ge contact sputtered in 15 mTorr Ar and the other had an a-Ge contact sputtered in 15 mTorr Ar/7% H₂. Although the two detectors were vastly different in their initial performance, no significant change was observed after storage in a nitrogen-purged box for more than two months.

4. Conclusions

Charge collection to the gap between electrodes is a challenging issue encountered with segmented electrode HPGe detectors. This article has presented the results of a study of the impact of the fabrication process on inter-electrode charge collection. It was demonstrated that a-Ge contacts sputtered in pure Ar allowed charge carrier collection directly to the inter-electrode surface, resulting in the worst energy sum deficit possible for the given geometry. However, including 7% H₂ in the sputter gas dramatically improves performance. Even with the added hydrogen, sputter pressure remains an important parameter. Higher sputter pressure results in more desirable charge collection as evidenced by a lower energy sum deficit. An almost non-existent deficit is achieved at a 15 mTorr sputter pressure. Both a-Ge contacts sputtered in 15 mTorr Ar/7% H₂ and a-Si contacts sputtered in 7 mTorr Ar/7% H₂ had a very low energy sum deficit. The low deficit for the optimized a-Ge process was also shown to be highly reproducible across time, multiple fabrication runs, and varying detector bias.

Acknowledgments

This work was supported by the U.S. Department of Energy, Office of Science, under contract number DE-AC02-05CH11231.

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