Proximity Electrode Signal Readout of High-Purity Ge Detectors

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***Abstract*—Proximity electrode signal readout of semiconductor-based radiation detectors is accomplished by measuring the charge induced on electrodes positioned close, but not electrically connected, to the detector material. This technology can be applied to high-purity Ge (HPGe) to create a position sensitive gamma-ray detector. The proximity readout technique offers the advantages of simplified detector fabrication, expanded electrode geometry options, and greatly improved position resolution through simple signal interpolation. We have produced small, HPGe prototype detectors that utilize strip proximity electrodes for gamma-ray interaction energy and position measurement. With these detectors we have collected event data sets under a variety of detector and source conditions. With this data we have explored energy and position reconstruction methods and have demonstrated sub-strip-pitch position determination. In this paper, we summarize the results of our investigation.**

***Index Terms*—Gamma-ray detectors, high-purity germanium, radiation detectors, semiconductor radiation detectors.**

I. Introduction

SEMICONDUCTOR-BASED radiation detectors are routinely used for the detection, imaging, and spectroscopy of x-rays, gamma rays, and charged particles for applications in the areas of nuclear and medical physics, astrophysics, environmental remediation, nuclear nonproliferation, and homeland security. Detectors used solely for determining the presence, intensity, and energy of a radiation source can be relatively simple, and typically consist of a single piece of semiconductor onto which two electrodes have been fabricated. These electrodes are used for bias voltage application and signal readout. Well established and reliable technologies exist for manufacturing such detectors. An example of this type of detector is the high-purity Ge (HPGe), coaxial gamma-ray detector that is widely used for high resolution gamma-ray spectroscopy [1].

In contrast to the simple, single element spectroscopy detectors, detectors used for imaging and particle tracking are more complex in that they typically must also measure the location of the radiation interaction in addition to the deposited energy. In such detectors, the position measurement is often achieved by dividing or segmenting the electrodes into many strips or pixels and then reading out the signals from all of the electrode segments. Fine electrode segmentation is commonly done on thin wafer Si devices that are manufactured using high process temperatures but is problematic for many of the standard semiconductor detector technologies. This includes HPGe and lithium-drifted Si (Si(Li)) based detectors. The lack of a good passivating oxide on Ge and the process temperature limit of Si(Li), which precludes the use of a thermal oxide, means that isolation between electrode segments cannot simply be achieved through a native oxide as is done for a conventional Si device. Additionally, Li diffusion is the basis for one of the standard electrodes on these detectors, and Li readily diffuses in Ge at room temperature and thereby limits the granularity of the electrode segmentation to no better than about 1 mm. Detector electrodes based on amorphous-semiconductor layers have in part been able to address these limitations, but the technology still requires additional development in order to minimize leakage current, reduce sensitivity to temperature cycling, and improve robustness [2].

In addition to the challenges of fabricating a position-sensitive detector are the difficulties of connecting to and reading out the signals from all of the electrodes on such a detector. The electrical connection to the detector can be done through techniques such as spring-loaded pins, wire bonding, or bump bonding. The pin approach is limited to coarse electrode segmentation and can damage the fragile detector electrodes. Wire bonding is commonly used but is not appropriate for densely packed structures such as finely pixelated detectors and must be carefully done when directly bonding to the active areas of the detectors (as is typically the case for HPGe detectors). Bump bonding in which an intermediate board with electrical interconnection traces is bonded to the detector through soft metal bumps is a technology that has been used for finely pixelated detectors. This approach however is not straightforward for detectors that must be cryogenically cooled such as those based on HPGe. Differential thermal contraction between the detector and bonded board can lead to bond failure and detector damage.

Signal readout is also a challenge since the position accuracy of a detector is normally given by the spacing between the electrodes. As such, to achieve a better position resolution, a greater number of electrodes and, consequently, channels of readout electronics are required. High channel densities are costly, have high power requirements, and can be difficult to design and manufacture (particularly with cryogenic detectors such as HPGe where the detector must be contained within a vacuum enclosure).

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The proximity electrode signal readout technology can potentially overcome the problems just described. With this technology, the signal readout is accomplished by measuring the charge induced on electrodes positioned close, but not electrically connected, to the semiconductor detector material. These electrodes can be fabricated on a circuit board that is positioned a small distance from the detector surface onto which charge is collected (proximity surface). The electrode complexity is then no longer a problem associated with detector fabrication, but is one that is easily dealt with using well established and inexpensive circuit board manufacturing processes. When compared to conventional, position sensitive detectors, this approach significantly simplifies the electrodes that are formed on the detector, which are still necessary for bias voltage application and charge removal.

The proximity readout technique offers the advantages of simplified detector fabrication, expanded electrode geometry options, and improved position detection through signal interpolation. The options for electrode geometries are greater because the electrodes no longer need to be placed on a single plane. For example, a multilayer circuit board can be used to create an orthogonal strip electrode configuration that is implemented using only one side of the detector for signal readout. The substantial benefit of improved position detection is made possible by the fact that the charge is not fully collected to any one proximity electrode. Instead, the charge from a radiation interaction event is collected to the detector surface and induces a net charge on the proximity electrodes in an amount determined by the electrode geometry and position relative to the radiation-generated charge. Since multiple electrodes will have non-zero integrated signals, simple interpolation (or other similar calculations) can be used to achieve position resolution much finer than the electrode spacing. This interpolation can be based on simple ratios of measured pulse heights and is in contrast to the more complex techniques that are required with conventional detectors such as the measurement of fast transient signals combined with pulse shape analysis.

Proximity electrode charge sensing is an established technique in that it has been utilized in gas detectors [3], [4] and for edge compensation in CdZnTe coplanar-grid detectors [5]. It has also been applied previously for the readout of semiconductor-based radiation detectors [6], [7]. In the work by Kurz *et al.* [6], proximity electrode readout was implemented on HPGe detectors of a unique configuration. In these detectors, the depletion of free charge carriers was achieved through the use of an external electric field, and periodic charge restoration was required in order to maintain the depleted region. More recently, Luke *et al.* [7] demonstrated that position-sensitive readout of conventionally depleted Si(Li)-based detectors and background rejection in HPGe-based detectors were both possible with the proximity readout technology. Our current study aims to demonstrate position sensitive readout of conventionally depleted HPGe detectors, investigate methods of position and energy reconstruction, and explore the performance potential of the method. To this end, we have fabricated, tested, and analyzed data from small, HPGe-based, proximity readout strip detectors. In this paper, we summarize the results of our study. Specifically, we first describe the detectors and our signal acquisition system. Then the position and energy reconstruction methods employed to analyze the event data from the detectors are presented. Following this, example measurements demonstrating sub-strip-pitch position determination and energy spectroscopy are shown. Finally, we outline our plans for future work in this area.

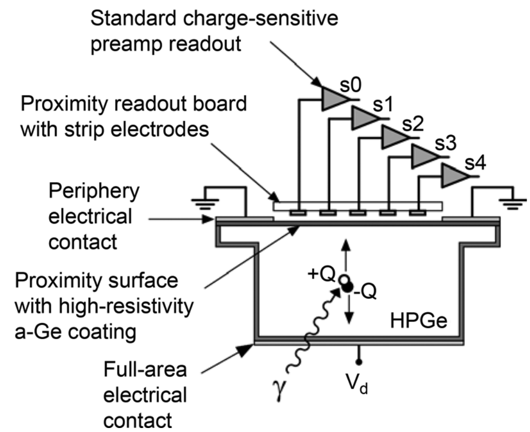

Fig. 1. Schematic cross-sectional diagram of the HPGe-based proximity electrode readout detector. The readout electrodes consist of five strips oriented perpendicular to the cross-sectional plane. Not shown is a thin Kapton sheet used to set the distance between the strips and the proximity surface.

II. HPGE PROXIMITY ELECTRODE READOUT DETECTORS

A schematic, cross-sectional diagram of the proximity electrode readout detectors that were fabricated for our study is shown in Fig. 1. The HPGe crystals used for the detectors were cut to produce an active volume approximately 10 mm thick and $18 \times 18\ \mathrm{mm}^2$ in area. The geometry includes two wing regions that remain undepleted during operation and facilitate handling during detector processing and attachment of the detector to its test holder. The on-detector electrodes (used for bias voltage application and charge removal) consist of two periphery strip electrodes on the proximity readout side of the detector and a full-area electrode on the opposing detector side. An amorphous Ge (a-Ge) layer coated with Al was used to produce these electrodes [2]. The region between the two on-detector strips is referred to as the proximity surface. This surface and the detector sides were also coated with a-Ge. Positioned just above the proximity surface is the proximity readout board containing the five readout strips. The strips are approximately 0.76 mm wide with a center-to-center pitch of 2 mm. The board is clamped to the detector with an intervening Kapton film that sets the spacing between the proximity strips and the proximity surface at approximately 75 $\mu\mathrm{m}$.

The a-Ge coating on the proximity surface is critical to the proper functioning of the detector. Charge is generated by gamma-ray interaction events in the detector volume, then is collected to this surface and is sensed by the proximity strip electrodes, which are positioned just above the surface. For charge to be effectively induced on the proximity electrodes, the a-Ge must be transparent to the field of the radiation-generated charge but still conductive enough that the collected charge (and detector leakage current) efficiently drains to the on-detector periphery strip electrodes. A sheet resistivity on the order of 10^9 ohm/square is desirable for a typical low-leakage current detector [7]. Based on current-voltage measurements made between the on-detector strips, the proximity surfaces of our detectors had a sheet resistance on the order of 10^{11} ohm/square. To see that this resistance is acceptable, note that the detector leakage is low at about 10 pA. This current multiplied by the characteristic surface resistance then gives us a rough estimate of 1 V for the change in surface potential due to the leakage. Consequently, the resultant field distortion at the surface should be a few orders of magnitude smaller than the field in the bulk of the detector. However, the characteristic charge dissipation time at the proximity surface will be larger than desired ($\sim$ 1 s assuming a detector capacitance of $\sim$ 10 pF) and will limit the count rate capability of this particular detector.

The measurements were done with the detector housed in a vacuum cryostat and at a detector temperature of about 85 K. The signals from the proximity strip electrodes were read out with standard charge sensitive preamplifiers that operate at room temperature. These signals were then digitized and saved with either a multichannel digital oscilloscope or processed and saved using XIA Pixie-4 digital spectrometers. The gain of each signal readout channel was matched by injecting an identical amount of charge into the input of each preamplifier and then adjusting the variable gain settings of the Pixie-4 electronics so that the resultant pulse heights obtained from each channel were identical. The Pixie-4 system was capable of saving both digitized signals and processed signal event data. The event data of interest for the work presented in this paper consisted of extracted pulse height and event time from all five channels that were recorded anytime any one of the channels surpassed a preset threshold level. With the detector exposed to a gamma radiation source (for example, collimated Am-241), such event data were acquired and stored for later offline processing. This data processing is described in the following section.

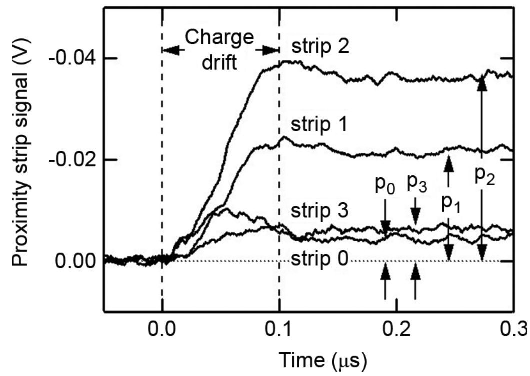

Fig. 2. Induced charge signals measured from a detector of the type shown in Fig. 1 The signals result from the collection of charge generated by a single gamma ray emitted by a Cs-137 source. The signal from strip 4 is not shown.

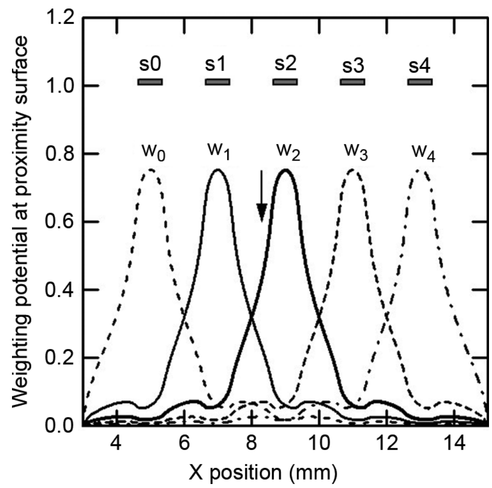

Fig. 3. Proximity strip weighting potentials calculated for the geometry shown in Fig. 1 and described in the text. The potentials have been calculated for a line along the proximity surface that is perpendicular to the strips. The arrow indicates the reconstructed location of the event shown in Fig. 2.

III. Position and Energy Reconstruction

As an illustration of the information obtained with a proximity detector, we plot in Fig. 2 the induced charge signals acquired as the result of a single gamma-ray interaction. In this plot, the gamma-ray interaction occurs at a time of zero, and the induced charge signals on the proximity strips develop as a result of the drift, separation, and collection of the generated electrons and holes. The generated electrons are collected to the full-area anode ($V_d = +2000$ V for this measurement) and the holes to the proximity surface. Since the holes persist for some time at the proximity surface, standard pulse processing methods can be used to extract the signal pulse heights.

For the event shown in Fig. 2, we see that strip 2 has the largest signal followed by strip 1 then strip 3. This indicates that the event occurred between strips 1 and 2 but closer to 2 than to 1. This example illustrates the potential of this detection technique in achieving sub-strip-pitch position localization by simply utilizing the pulse height information.

As we have seen with the proximity readout technique, the generated charge is not fully collected to any one strip, but rather induces charge on several strips. As a result, the deposited energy is not directly measured but must be reconstructed from the pulse height information measured by multiple strips. Furthermore, to obtain event position data finer than the strip spacing, interpolation or other data processing must be applied. The relative magnitudes of the measured pulse heights are dictated by the location of the collected holes at the proximity surface. The concept of an electrode weighting potential is useful for visualizing and calculating the charge induced on a proximity strip [8], [9]. A weighting potential for an electrode is a mathematical construct that allows one to determine the amount of charge induced on the electrode by a charge exterior to the electrode. The weighting potential of an electrode is the electrostatic potential calculated with the electrode at unity potential, all other electrodes at ground potential, and all space charge removed. The induced charge on the electrode resulting from a nearby point charge is simply the charge, in the opposite polarity, on the point charge multiplied by the weighting potential value at the point charge location. The weighting potentials for all five strips of the detector in Fig. 1, calculated at the proximity surface, are shown in Fig. 3. Each weighting potential is peaked under its corresponding strip.

Different position and energy reconstruction approaches are possible with the proximity electrode technique. Two methods will be described in this paper. In one of the simplest methods, we rely on the calculated weighting potentials. These potentials are determined using electrostatic modeling software and require accurate knowledge of the detector geometry. The event reconstruction procedure for this simple method is outlined below, and the event shown in Fig. 2 is used as an example.

First, the two adjacent strips with the largest pulse heights are identified. For the example, this would be strips 1 and 2 with corresponding pulse heights of p_1 and p_2. Following this, the location, x, of the interaction is determined by solving the following equation:

$$\frac{w_j}{w_k}(x) = \frac{p_j}{p_k} . \tag{1}$$

In this equation, w_j and p_j are the weighting potential and pulse height of the strip with the largest pulse height, and w_k and p_k are the weighting potential and pulse height of the strip with the second largest pulse height. In the example from Fig. 2, j and k are 2 and 1, respectively, and a numerical solution to (1), based on the weighting potentials of Fig. 3, leads to a position of approximately 8.3 mm. Finally, the event energy, E, is calculated from

$$E = \frac{p_j}{w_j(x)} C_j , \tag{2}$$

where C_j is the conversion factor for strip j that converts from pulse height to energy.

The simple method just described requires accurate knowledge of the electrodes and detector geometry, and assumes that the charge is point like and is completely collected to either the proximity surface or the full-area contact.

The second reconstruction method is analogous to the first in that it is based on weighting potentials, but instead of calculating these from a geometry that is not perfectly known, we extract them from a measurement. Since, in this case, these extracted potentials will likely depend on more than just the electrostatics of the detector, we will refer to them as pseudo weighting potentials and denote them by $\tilde{w}_j$, where j signifies the j-th strip. In analogy to the simple reconstruction method, we locate the interaction using the pseudo weighting potential ratios and then, with the location known, calculate the energy using the pseudo weighting potential of the strip with the largest pulse height.

The measurement used to determine $\tilde{w}_j/\tilde{w}_k$ and then $\tilde{w}_j$ is the acquisition of pulse height data when the detector is uniformly illuminated with a mono-energetic source. A large event data set is acquired and then searched for all events in which the largest pulse height occurs on the j-th strip and the next largest on the neighboring k-th strip. These events will all be positioned somewhere between the midpoint between the two strips and directly beneath the j-th strip, and the distribution would be spatially uniform. The pulse height ratio p_j/p_k for all of these events is then calculated and histogrammed, thereby generating an event distribution $H(r)$, where $r \equiv p_j/p_k$. Assuming noiseless data and identical strip geometries, this distribution will be non-zero from $r = 1$ to $r = r_m$, where

$$r_m \equiv \frac{\tilde{w}_j}{\tilde{w}_k}\left(x = \frac{d}{2}\right) . \tag{3}$$

Here, it has been defined that the midpoint between strips j and k is at $x = 0$ and that strip j is centered at $x = d/2$, where d is the strip pitch. The event distribution can as well be written as a function of x and would be constant since the detector was uniformly illuminated. Equating the number of events over equivalent regions in the two distributions, we obtain

$$\int_0^x H_o dx = \int_1^r H(r) dr, \tag{4}$$

where H_o is the constant number of events per unit distance in the position histogram. The total number of events in the histograms is

$$N = H_o \frac{d}{2} = \int_1^{r_m} H(r) dr . \tag{5}$$

Using (5) to eliminate H_o in (4), we obtain

$$x = \frac{d}{2N} \int_1^r H(r) dr . \tag{6}$$

From the flood illumination measurement, N and $H(r)$ are known, and d is known from the strip geometry. Replacing the r in the upper limit of the integral with $\tilde{w}_j/\tilde{w}_k$ gives us an equation through which we can numerically determine $\tilde{w}_j/\tilde{w}_k$ as a function of x. With this information, we can determine the location of any event from an unknown source (within the region $0 \leq x \leq d/2$) using the analogous expression to (1):

$$\frac{\tilde{w}_j}{\tilde{w}_k}(x) = \frac{p_j}{p_k} . \tag{7}$$

With the event locations from the unknown source determined, we now need to extract $\tilde{w}_j$ from the flood illumination measurement so that the event energies from the unknown source can be calculated. To do this, we generate a pulse height histogram from all flood illumination events whose positions lie within a small window about the location x. Since the source used in the measurement is mono-energetic, the generated histogram will contain a single peak. The pulse height corresponding to this peak location is related to $\tilde{w}_j$ through a relationship analogous to (2):

$$\tilde{w}_j(x) = \frac{p_j}{E} C_j , \tag{8}$$

where E is the known energy of the flood illumination source gamma rays, C_j is the conversion factor used in (2), and p_j is obtained from the peak location in the generated pulse height histogram. This process is then repeated for all values of x between 0 and $d/2$ to obtain $\tilde{w}_j(x)$. With both the event location

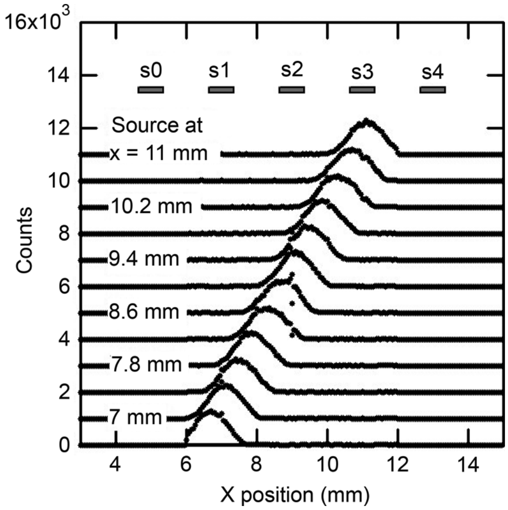

Fig. 4. Gamma-ray interaction site position histograms obtained from a detector of the type shown in Fig. 1. For the measurement, a collimated Am-241 source was scanned perpendicular to the proximity strips. Event positions were then reconstructed and histogrammed for equally spaced (0.4 mm step size) source locations along the scan. The individual histograms are plotted and offset vertically from each other in the graph for clarity.

and strip pseudo weighting potential known, the energy of an event from any unknown source is given by

$$E = \frac{p_j}{\tilde{w}_j(x)} C_j \ . \qquad (9)$$

IV. Measurements

To demonstrate sub-strip-pitch event localization, a detector of the type shown in Fig. 1 was scanned with a collimated Am-241 source. The collimation consisted of two W apertures: one with a 1 mm diameter hole and 10 mm thickness adjacent to the source, and the other with a 0.5 mm diameter hole and 5 mm thickness 22 mm from the source. The source to detector distance was 76 mm. The source was scanned along the full area contact in a direction perpendicular to the strips. A step size of 0.2 mm between each source location was used. At each location, pulse heights from all five strips for each gamma-ray interaction event were acquired and saved using the Pixie-4 electronics. These data sets were then processed in order to reconstruct interaction position and deposited energy using the pseudo weighting potential method described in the previous section. To generate the pseudo weighting potentials and their ratios ($\tilde{w}_j$ and $\tilde{w}_j/\tilde{w}_k$), the events from all source locations in the scan were combined and used. Since the scan step size was small relative to the source collimation, this combined data set sufficiently replicates a flood illumination measurement. The pseudo weighting potential ratios were determined from (6) using the combined data set, then the events from individual source positions were spatially reconstructed using (7). The results from this reconstruction are shown in Fig. 4. The figure shows event position histograms obtained at various source locations. The detected event distribution at each source location is comparable to what would be expected from the source collimation, and its location closely matches that of the source itself. The accuracy to which this method can determine the source location is clearly much better than the strip pitch of 2 mm.

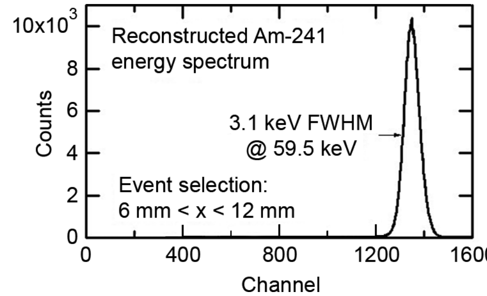

Fig. 5. Am-241 energy spectrum reconstructed from pulse height data acquired with a detector of the type shown in Fig. 1. Only gamma-ray events whose reconstructed location fell between 6 and 12 mm were included in the spectrum. Figs. 3 and 4 provide an indication as to where this region falls relative to the proximity strips.

Continuing further with the pseudo weighting potential method, the energy of the scan data was reconstructed. In Fig. 5 we show a reconstructed energy spectrum generated by selecting all events whose reconstructed positions fell between 6 and 12 mm. The single channel electronic noise for the measurement was about 1.5 keV FWHM. Since the procedure for reconstructing the energy makes use of the signals from multiple channels, it is expected that the electronic noise contribution to the photopeak width will be greater than 1.5 keV. The photopeak width of 3.1 keV FWHM will also include a contribution from any non-uniformity in the proximity strip and proximity surface geometries. Little effort was made to control these non-uniformities in the current detectors.

V. Future Plans

In this paper we have demonstrated the proximity electrode signal readout method on HPGe-based gamma-ray detectors. Gamma-ray interaction site localization with accuracy much better than the readout electrode strip pitch was shown as well as the accurate reconstruction of the deposited energy. This demonstration is the first step in exploring the potential of the technology. In future work, we plan to refine the technique so that its full potential and applicability can be assessed. An important aspect of this will be optimizing the electrical characteristics of the proximity surface and controlling the uniformity of the proximity electrode and proximity surface geometries. Furthermore, position readout in three dimensions is a requirement of many applications, yet the small detectors used in the current study were only for one dimensional position measurement. In the future, we will address this need by developing three dimensional position readout methods for the proximity technique. Once developed, the optimized fabrication processes and three dimensional readout method will be applied to produce large area HPGe proximity readout detectors.

Another important aspect of the proximity electrode signal readout technique is the position and energy reconstruction method. Two methods were described in this paper, but many others are possible and will be explored as part of our future work.

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