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Three-Dimensional Position-Sensitive Germanium Detectors

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1. Executive Summary

A critical need within DOE is the ability to characterize radioactive contamination. Simultaneous high-resolution gamma-ray imaging and spectroscopy is a powerful technique for the in-situ, passive, and non-destructive characterization of equipment and building structures containing such contamination. Instruments based on germanium (Ge) position-sensitive detectors have the potential to achieve a combined imaging and spectroscopy performance level far superior to that of today's commercial instruments. The gamma-ray imaging technique employed in such an instrument allows the characterization to be done at a distance from the contaminated objects and can accurately acquire the spatially dependent gamma-ray emission information in a single measurement. Consequently, the device can more efficiently discriminate between contaminated and non-contaminated areas of heterogeneous objects while at the same time reducing worker exposure. Furthermore the advanced spectroscopic capabilities of this instrument enables isotopic identification of the radioactive contaminants, increases instrument sensitivity through a reduced background, improves image resolution of buried contaminants, and allows gamma gauging to be done. Each of these characteristics ultimately leads to a more complete and accurate characterization than is feasible with current baseline technologies. The success of this technology however relies on the ability to effectively produce large-area, efficient Ge detectors and associated electronics that measure both position and energy as accurately as possible in the simplest manner possible. This presents several challenges, including producing the detectors, minimizing performance degradation effects, and effectively dealing with the complexity of the gamma-ray interaction events and the detected signals. To meet these challenges, the objectives of this project were to first gain an understanding of the basic physics leading to image formation and spectroscopy in a Ge-based instrument, and the mechanisms that can degrade system performance. Then based on this research, devise and demonstrate techniques to overcome these degradation effects. In this project, we developed further the fabrication processes required to produce the position-sensitive detectors needed for imaging applications. Several detectors were produced, and a new technique for extracting the depth of gamma-ray interaction within the detector was demonstrated. This then leads to a detector with better spatial resolution since the location of the gamma-ray interaction events within the detector are measured in all three dimensions rather than only two as is conventionally done. The technique will eventually lead to improved image resolution in a complete imaging system. Furthermore, with these detectors, techniques were devised and demonstrated in order to overcome energy resolution degradation effects caused by the electrical contact segmentation on the detectors. These techniques then enhance detection sensitivity and specificity. Finally, innovative readout electronics capable of dealing effectively with the complex signals generated from the detectors were prototyped. The work that remains to be done includes demonstrating the technologies we

developed in a full imaging system, producing an optimized instrument for field studies, and transferring the technologies to an industrial partner.

2. Research Objectives

Critical to the DOE effort to deactivate and decommission the weapons complex facilities is the characterization of contaminated equipment and building structures. This characterization includes the isotopic identification of radioactive contaminants and the spatial mapping of these deposits. The penetrating nature of the gamma rays emitted by the radioactive contaminants provides a means to accomplish this task in a passive, non-destructive and non-intrusive manner. Through conventional gamma-ray spectroscopy, the radioactive isotopes in the contaminants can be identified by their characteristic gamma-ray signatures and the amount of each isotope by the intensity of the signature emission. With the addition of gamma-ray imaging, the spatial distributions of the isotopes can simultaneously be obtained. The ability to image radioactive contaminants can reduce waste as well as help ensure the adequate protection of workers and the environment. For example, if equipment and building materials have been subjected to radionuclide contamination, the entire structure must be treated as radioactive waste during demolition. However, only partial removal may be necessary if the contamination can be accurately located and identified. Hand-held survey instrumentation operated in the near vicinity of the contaminated objects is a common method to accomplish this task. This method necessitates long data acquisition times, direct close access, and considerable worker exposure, as well as leads to imprecise information. In contrast, imaging devices operated at a distance from the contaminated objects can accurately acquire the spatially dependent gamma-ray emission information in a single measurement. Consequently, the devices can more efficiently discriminate between contaminated and non-contaminated areas of heterogeneous objects while at the same time reducing worker exposure.

The potential of gamma-ray imaging for environmental remediation has been recognized as evidenced by the development and testing of several systems within the DOE Deactivation and Decommissioning Focus Area (D&D) [1-3]. The viability of these systems has been demonstrated, however they all have fundamental performance limitations as a result of the detector technology utilized in the instruments. The detectors of these and other commercial instruments [4] are scintillator based and as a result provide only poor or no spectroscopic information on the gamma-ray emission. This is because of the inherent inefficiencies in the conversion of the incident gamma ray into visible light in the scintillator and the subsequent electrical signal generation in the photomuliplier or photodiode stage [5]. This lack of or minimal spectroscopic capability is a serious limitation of the imaging technologies for several reasons. First, the spectroscopic information is required for isotopic identification of the radioactive contaminants. Without this information, additional characterization with a separate non-imaging instrument may be necessary if the nature of the contaminants is not known from process knowledge. Furthermore, if multiple contaminants are known to exist, it is not possible to separately determine the amount and distribution of each contaminant if the instrument does not have good spectroscopic capabilities. A second benefit of spectroscopic information is that it can be used to greatly improve the sensitivity of an instrument. For example, an imaging instrument with no spectroscopic capabilities simply counts the number of detected gamma rays within the sensitive energy range of the instrument. This may be a wide range such as 0.1 MeV to 2 MeV. Background gamma rays from naturally occurring radiation and from scattered gamma rays will be present over this entire energy range and will tend to obscure the actual gamma-ray counts of interest. If instead the energy of each gamma ray was measured, then only gamma rays that fall within a narrow energy window of interest (for example, 2 keV in width) could be used to form an image. A narrower window means that fewer background counts will be included while at the same time the signal counts remain unchanged. The signal-to-background ratio is increased thereby improving the ability of the instrument to detect radioactive contaminants above the background. With all other characteristics equal, a detector technology with better energy resolution allows narrower energy windows to be selected and therefore should have greater sensitivity. This ability to select small energy windows of interest also improves the image resolution for contaminants that lie within an object or structure [6]. The material between the contaminants and the imaging instrument will cause some of the emitted gamma rays to scatter off the material and into the instrument. This scattering makes the gamma-ray source appear more diffuse and less well defined. However, these scattered gamma rays are reduced in energy as compared to the unscattered ones. Selecting only the gamma rays within a narrow energy window about the energy of interest will remove the image broadening gamma rays from the image and thereby produce a clearer image. A final benefit of spectroscopy is that it allows gamma gauging to be done [7]. Radioactive contaminants contained within an object may emit gamma rays at several distinct energies. Each of these energies will be attenuated differently by the material between the contaminant and the imaging detector. By comparing the relative number of counts at each energy to the well-known ratios that the contaminant emits, it is possible to determine the nature of the

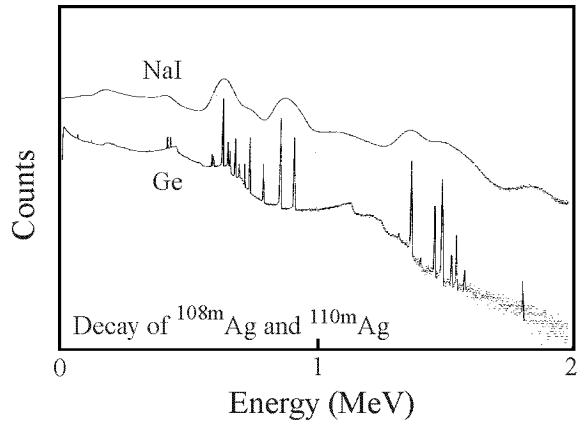

Figure 1. Comparison of a gamma-ray spectrum acquired with a NaI scintillator-based spectrometer (top) to that acquired with a Ge-based spectrometer (bottom). The gamma rays resulted from the decay of ^{108m}Ag and ^{110m}Ag. This figure has been adapted from reference [8].

intervening material. Information such as the thickness or average atomic number of the intervening material can be determined.

From the above discussion, it is clear that a gamma-ray imaging technology that provides accurate spectroscopic information as well as image data can greatly improve the radioactive contamination characterization process. Semiconductor-based-detector technologies are far superior to the presently utilized scintillator technologies in terms of spectroscopic performance and are therefore an appropriate choice for a high-performance imaging instrument. For gamma-ray imaging applications, position-sensitive, cryogenically-cooled, germanium (Ge) detectors provide several advantages over other semiconductor detectors. These include (1) the commercial availability of large detector volumes, (2) the ability to fully deplete thick detector layers, (3) the relative high atomic number of Ge for efficient stopping of gamma rays, (4) the excellent energy resolution achieved, and (5) the potentially high spatial resolution. A comparison of the spectroscopic capabilities of Ge to that of the NaI scintillator is shown in Figure 1 [8]. The superior performance of the Ge detector is evident by the resolution of many closely spaced peaks in the spectrum obtained with the Ge detector, whereas these peaks are unresolved by the NaI detector. As a result of the excellent energy resolution of Ge detectors, nearly all gamma-ray spectroscopy that involves complex energy spectra is done with these detectors.

Our research efforts were directed towards the imaging technology with the greatest promise to meet the DOE deactivation and decommission needs -- those based on Ge detectors. The primary objective of our program was to develop the technologies necessary to readily produce large-area Ge gamma-ray detectors with combined imaging and spectroscopy capabilities superior to that of presently available technologies.

3. Methods and Results

In this section, we describe the challenges faced in developing the Ge detector technologies, present the innovative techniques we developed to overcome these challenges, and summarize the results from our research. To facilitate this presentation, some additional background concerning gamma-ray imaging and Ge detectors is required and is therefore given in the following paragraphs.

3.1 Background

A number of methods are presently exploited to perform gamma-ray imaging. One of the simplest is direct imaging with a single-element omni-directional gamma-ray detector as shown in Figure 2a. This method works by restricting the region viewed by the detector during the measurement with a single-hole collimator or by simply placing a partially shielded detector in close proximity to the object of interest. An image is obtained by making many measurements while moving the detector/collimator combination between each measurement. This technique is equivalent to the DOE D&D baseline technology of a manual survey. The technique is prohibitively slow for image acquisition and consequently is not a good choice for the characterization of large amounts of contaminated material.

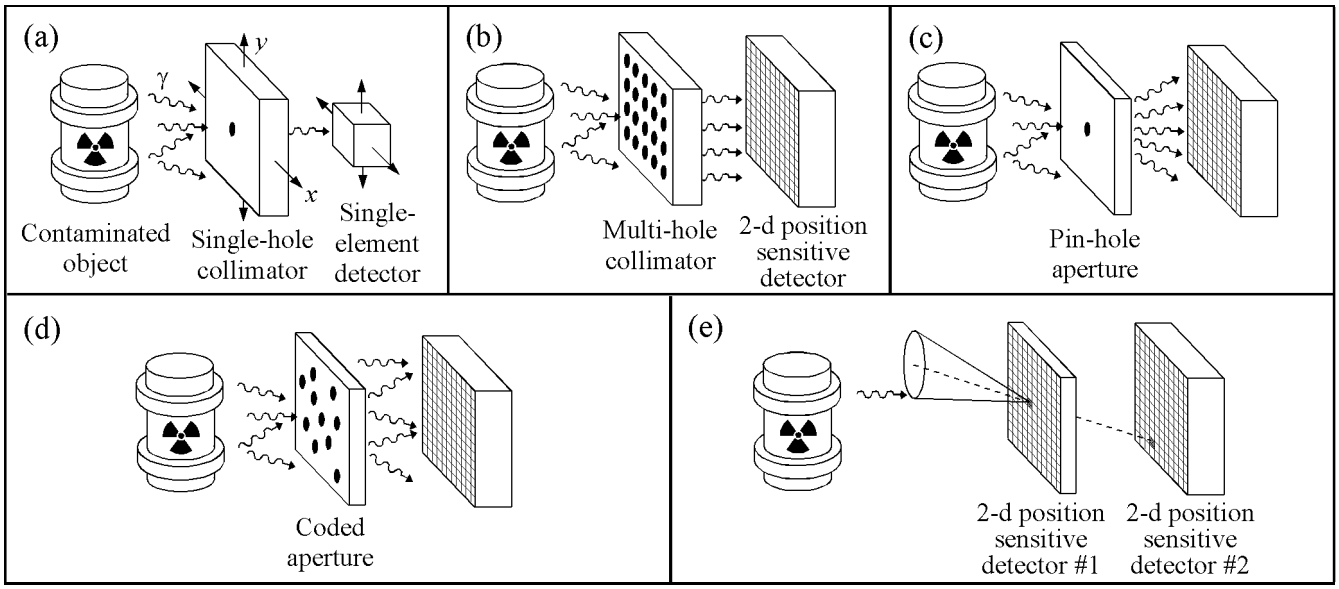

Figure 2. Gamma-ray imaging techniques. **(a)** Direct imaging with a single-element omni-directional gamma-ray detector. The detector/collimator must be scanned over the object in order to obtain an image. **(b)** Direct imaging with a 2-d position-sensitive detector and a multi-hole collimator. **(c)** Pin-hole gamma-ray camera formed with a pin-hole aperture and a 2-d position-sensitive detector. **(d)** Coded-aperture imaging with a 2-d position-sensitive detector. **(e)** Gamma ray image formation with a Compton camera.

Imaging methods that are more time efficient rely on position-sensitive detectors. With these detectors the lateral location (x and y positions) of each gamma-ray interaction event within the detector is measured. These position-sensitive detectors are utilized in various imaging schemes. One is direct imaging with a multi-hole collimator as shown in Figure 2b. In this scheme, the collimator acts to ensure that each region of the detector views a small region of the object to be characterized, thereby acquiring spatial information. For a single exposure, this direct imaging method is unfortunately limited to areas that are of the size of the detector. A simple method to image objects larger than the detector area without moving the detector and acquiring multiple images is the pin-hole camera illustrated in Figure 2c. The field of view of the pin-hole camera is proportional to the object to pin-hole distance and can be made large allowing large areas to be characterized with single exposures. However a disadvantage of the pin-hole camera is that for good image quality the pin hole is small by design, resulting in an imaging scheme that is inherently inefficient. A similar but typically more efficient scheme is the coded-aperture imaging method (Figure 2d). Like the pin-hole technique, this technique relies on an absorbing plate to restrict the view of the object from the detector, but instead of a single hole, a known multi-hole pattern is fabricated into the absorbing plate thereby increasing the measurement efficiency. The image formed is more complex than that of the pin-hole camera, but nonetheless the real-space image can be extracted using standard algorithms [9-11].

The above imaging techniques require the use of mechanical collimators or apertures. Above a gamma-ray energy of a few hundred keV, the high atomic number materials used for the collimators and apertures are not effective absorbers of the gamma rays. As a result, the performance of the imaging techniques just described degrades. An alternative imaging technique of electronic collimation is applicable to higher energy gamma rays. The imaging device in this technique is referred to as a Compton camera and one implementation is illustrated in Figure 2e [12]. In the Compton camera of Figure 2e, two position-sensitive gamma-ray detectors are used. The gamma rays that contribute to the image are Compton scattered (scattered off an electron) in the first detector and then subsequently absorbed in the second detector. Based on the known physics of Compton scattering, the measured energy deposited in each detector, and the measured interaction location in each detector, the original direction of the incoming gamma ray can be restricted to a cone of directions. Each detected

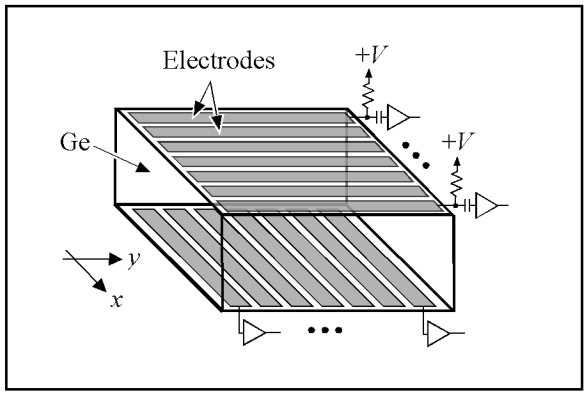

Figure 3. One possible implementation of an orthogonal-strip position-sensitive detector.

gamma ray from a source will result in a cone of allowed incoming directions. The intersection of these cones spatially locates the radiation source. The useful energy range of this technique extends over the range where Compton scattering is a significant mechanism of energy loss in the detector, from about 100 keV to beyond 10 MeV [12].

The imaging method of choice depends on the needs of the application. For environmental remediation activities, a large or adjustable field of view and efficient detection are desired. The logical choices are then coded-aperture or Compton imaging with the simpler coded-aperture technique being preferred when high-energy gamma rays are not of interest.

In addition to the importance in selecting the optimal imaging method, the selection of the detector technology plays a crucial role in dictating the success of gamma-ray image characterization of contaminated equipment and structures. As discussed in the previous section, Ge-based detectors have several advantages including that of excellent spectroscopic resolution. A simple single-element Ge gamma-ray detector consists of a block of high-purity Ge material in which electrical n- and p-type contacts (electrodes) have been fabricated on opposite sides of the block. The detector is operated by applying to the electrodes a reverse bias that is sufficiently large to fully deplete the detector volume of free charge carriers. When a gamma ray interacts in the depleted detector volume, electron-hole pairs are created whose number is directly proportional to the energy deposited by the gamma ray. Under the influence of the field applied to the detector, these carriers drift and separate. The holes drift to the negatively biased (p-type) contact and the electrons to the positively biased (n-type) contact. During the charge drift process, charge is induced on the electrodes of the detector as a result of the charge separation within the detector. This induced charge is measured with a charge-sensitive preamplifier connected to one of the electrodes. Upon complete collection of the charge carriers, the accumulated charge in the charge-sensitive preamplifier is directly proportional to the number of electron-hole pairs originally created by the gamma ray and consequently serves as a measurement of the gamma-ray energy.

To perform gamma-ray imaging using the coded aperture or Compton techniques, the spatial locations of the gamma-ray interactions within the detector must also be measured. Position detection in a Ge gamma-ray detector can be achieved by segmenting (dividing into a number of pieces) one or both of the electrodes on the detector and measuring the induced charge signal on each of these contact segments. The segment on which a net charge signal is measured for a particular interaction event indicates the lateral location of the event. A seemingly straightforward method to implement two-dimensional sensing is to segment one of the electrodes in both the x and y directions thereby forming an array of pixel electrodes. To locate the gamma-ray event, the induced charge is measured on each of the pixel electrodes. For an $N \times N$ array of pixels, N^2 sets of pulse processing electronics (charge-sensitive preamplifier and subsequent pulse-shaping circuitry) are required. For large pixel arrays this can be a prohibitively large quantity of electronic channels and is a disadvantage of this segmentation method.

A segmentation method requiring fewer channels of pulse-processing electronics is the orthogonal-strip geometry shown in Figure 3 [13-15]. In this method, both electrodes are segmented into strips such that the strips on one detector side are orthogonal to the strips on the opposing detector surface. The top electrode strips of the detector shown in Figure 3 are used to locate the interaction event in the x direction while those of the bottom surface locate the event in the y direction. The number of channels of electronics required for an $N \times N$ array of distinct detectable positions is only $2N$. Spectroscopic measurements can be made with this configuration by using spectroscopic grade pulse-processing electronics for each strip on one side of the detector. The gamma-ray energy is then extracted from the charge signal induced on the strip from this detector side that collects the drifting carriers.

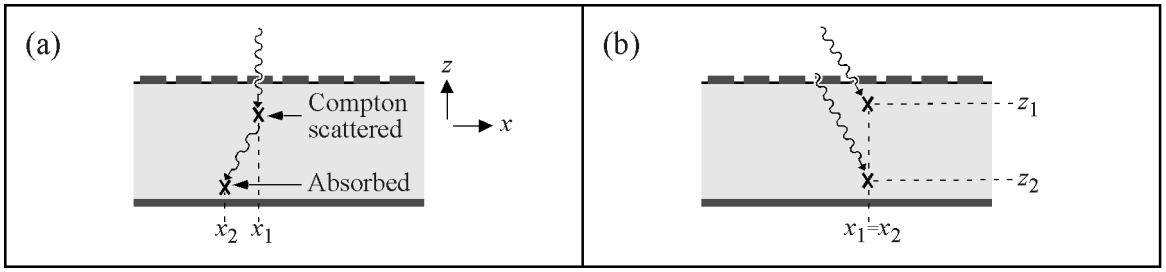

Figure 4. Schematic illustration of two effects that cause image degradation in gamma-ray imaging cameras. **(a)** Compton scattered gamma rays, which deposit energy at multiple points within the detector thereby producing multiple detected positions of interaction for a single incident gamma ray. **(b)** Depth-of-interaction broadening or parallax resulting from the lateral detected position (x and y) being determined at a different depth z within the detector for each gamma ray. For the case shown, the two gamma rays have the same detected position even though they entered the detector at two different positions.

3.2 Challenges and Techniques

Our research efforts are directed towards the imaging technology with the greatest promise to meet the D&D needs -- those based on orthogonal-strip Ge detectors. The success of this technology relies on the ability to effectively produce large-area, efficient Ge detectors and associated electronics that measure both position and energy as accurately as possible in the simplest manner possible. There are several challenges that this need presents. The first is the production of the detectors themselves. Simple, single-element Ge detectors have been widely used in spectroscopy applications for decades. However, Ge detectors with the position sensitivity required for imaging applications have not been widely used primarily because of the difficulties in fabricating such detectors. Progress in the development of these detectors has however been made over the years [13,16-26]. In particular, the amorphous-semiconductor contact technology developed by our group has the potential to satisfy the needs of imaging applications [24-26]. Through the detector development effort within our lab including the work accomplished in this project (described below), we have demonstrated that we will be able to meet this detector fabrication challenge.

Another challenge is dealing with the complexity of the gamma-ray interaction events and detected signals. For example, the spatial resolution and image quality obtained with the Ge detectors are dependent on more than simply the physical electrode segmentation of the detector. The physics of the gamma-ray interaction can also limit the spatial resolving power of the detector. The main interaction mechanisms involve the partial or complete transfer of the gamma-ray energy to electron energy in the detector. The lateral location of these interaction events is the position data acquired with a conventional two-dimensional position-sensitive detector. These interaction events however take place at random depths (z position) within the detector. This random depth of interaction combined with possible multiple interaction events for a single gamma ray lead to an interaction position uncertainty. Two possible situations where this occurs are shown in Figure 4. The first, Figure 4a, is the case of a Compton scattered gamma ray. Here the gamma ray first interacts at location x_1 by scattering off an electron and leaving behind a fraction of its energy. The remaining gamma-ray energy is then photoelectrically absorbed at a different location x_2. In the conventional position-sensitive detector, the locations x_1 and x_2 are determined, but which of these two positions corresponds to the location that the gamma ray entered the detector is unknown. The event then must be thrown out thereby reducing the detector efficiency or some average position must be used which will ultimately degrade the spatial resolution of the detector. This can be a serious problem since Compton scattering is often the predominant reaction mechanism for gamma-ray energies typical of radioactive isotopes. The other problem illustrated in Figure 4b is that of depth-of-interaction broadening or parallax. Because of the difference in the depth of interaction between the two gamma rays shown, the position of interaction determined by the detector will be the same for both gamma rays even though they entered the detector at different positions. This effect leads to a loss in the spatial resolution of the detector for imaging techniques where the incoming radiation is not perpendicular to the detector surface, such as that found in pin-hole, coded-

aperture, and Compton cameras described previously. The combination of the need for a thick detector to stop the energetic gamma rays and the deeply penetrating nature of this radiation, potentially leads to a substantial depth-of-interaction broadening.

The image degradation effects from Compton scattering and parallax can be greatly reduced with a position-sensitive detector in which not only is the lateral position of the interaction event determined but also the depth of the interaction within the detector measured. For the Compton scattering problem, a measurement of the deposited energy and interaction depth for each position an individual gamma ray interacts allows one to determine the most probable location of the first interaction. This results from the strong tendency for an energetic gamma ray to be forward scattered in a Compton event [27]. Therefore, of the measured positions, the one most probable to be the first is the one closest to the detector surface exposed to the gamma rays. The position of this interaction, in three dimensions, would be used for imaging purposes. The second problem of parallax broadening is also reduced through a depth-of-interaction measurement. For example, in the case of the pin-hole camera, the angle of incidence between the detector and the gamma ray is known once the interaction event is located in three dimensions since all the gamma rays pass through the pin hole. A simple geometric calculation can then be used to determine the location at which each gamma ray entered the detector thereby eliminating parallax. The coded aperture and Compton camera techniques will also derive a similar performance benefit from the more accurate measurement of the interaction location. As part of our project, we have demonstrated a technique to measure the depth of gamma-ray interaction within an orthogonal-strip detector thereby producing a three-dimensional position-sensitive detector (results presented later in this section). The remaining task in this area is then to implement this technique on a fully functional imaging instrument.

The complexity of the gamma-ray interaction events and detected signals also presents a challenge for the electronics development. A single gamma ray can interact multiple times in the detector. For such an event, induced charge signals will be generated on multiple strip electrodes on each side of the detector. Furthermore, even if the gamma ray deposits its entire energy at only one location, the generated charge can actually be collected by more than one strip electrode on each side of the detector. This results from the finite size of the generated charge cloud and the outward diffusion of the cloud during the collection process. If the detection electronics were capable of only extracting a single position and energy for each gamma ray that interacts within the detector, the events just described would either be thrown out or inaccurately characterized. Since these complex interactions can occur frequently, the performance of an imaging system based on these simple electronics could be substantially degraded. Consequently, to achieve the best performance, the electronics must be sophisticated enough to extract, for a single gamma ray, the three-dimensional location of each interaction site and the energy deposited at each site. A further complication that the electronics must deal with is that of transient charge signals on the electrodes. As the gamma-generated charge cloud is collected to a particular strip electrode, the nearby electrodes will develop an induced charge signal as a result of the close proximity of the drifting charge. These signals are transients in that no charge is physically collected to the electrodes and the signals eventually return to zero. However, simple peak-detection pulse-processing electronics may produce a non-zero energy value for these transients. Since these anomalous energy values will be summed with the real energy values in order to get the total energy of the gamma ray, the gamma-ray energy will be inaccurately measured. If this leads to a significant degradation of the energy resolution, it will be necessary to include transient rejection circuitry in the signal processing electronics. All of the physical effects just described lead to the challenge of developing a complex electronics readout system with the competing field-portability requirements of compactness and low power consumption. There is therefore a need to assess the significance of each of these performance degradation mechanisms and then, based on this assessment, design the simplest possible detector/electronics system that despite the simplicity will still acquire the gamma-ray information to the accuracy level required for the application.

3.3 Results

In the remainder of this section, we summarize the results from our research project. The overall objective of our work has been to develop the basic technologies necessary to make a Ge-detector-based imaging instrument viable for field use. In this three-year project, we have focussed on the most immediate and fundamental challenges: detector fabrication, detector performance improvement, and electronics development. Our success in each of these areas is described below.

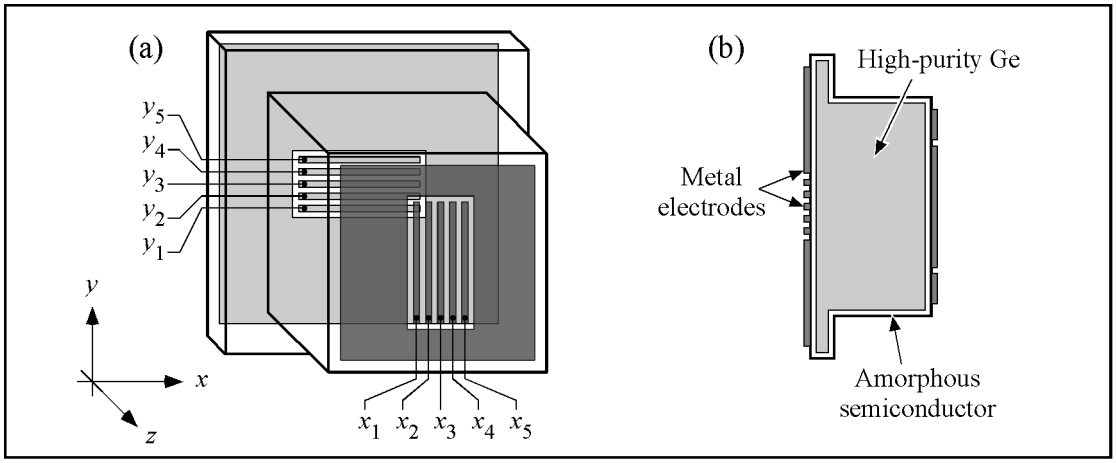

Figure 5. (a) Geometry of the prototype Ge detectors used for fabrication process development and detector performance studies. **(b)** Cross-sectional schematic diagram of the prototype detectors showing the structure of the amorphous-semiconductor contact.

3.3.1 Detector Fabrication Process Development

Key to the success of gamma-ray imaging with Ge detectors is the development and use of cost-effective, robust detector fabrication processes. The production of the finely segmented detectors required for imaging applications has been an impediment in the past to the development of full imaging systems based on these detectors. The LBNL-developed amorphous-semiconductor contact technology can potentially fulfill the needs in this area. Through this project, this fabrication technology has been further refined for the specific requirements of imaging applications [25,26]. The basic structure of a prototype orthogonal-strip detector made using amorphous-semiconductor contacts is illustrated in Figure 5. In such a detector, the electrical contacts to the bulk single-crystal Ge are made through an RF sputtered amorphous semiconductor (normally Ge or silicon (Si)) layer deposited onto the bulk Ge. These contacts allow for the application of the high voltages necessary to fully collect the electrons and holes generated by gamma-ray interaction events within the bulk Ge and for the measurement of the electrical signals produced by this charge collection. These electrical signals form the basis for the determination of each gamma ray's energy and interaction location thereby allowing spectroscopy and imaging to be performed. The amorphous-semiconductor contacts typically consist of a high-resistivity amorphous-semiconductor layer that covers much of the detector surface. On top of this layer is deposited a metal electrode layer to which an electrical connection can be made. The physical contact area is defined by this low-resistivity metallization. To produce a detector capable of imaging, the metal layer is segmented (divided into a number of pieces) and an electrical connection is made to each segment. For high spatial resolution, these electrodes will be finely spaced. A challenge is then electrically connecting each of these finely spaced electrodes to the measurement electronics. Through this project, we have accomplished this task by developing a metallization/wire bonding process that allows us to make contact to these closely spaced (< 1 mm) electrodes on Ge detectors without damaging the detector. We have also worked to reduce the number of processing steps required to produce a detector. This high-yield process has now been successfully used to produce a number of detectors. An example of a prototype amorphous-semiconductor-contact detector used for our fabrication and detector performance studies is shown in Figure 6a, and an example of the larger detectors we are developing for imaging studies is shown in Figure 6b.

The amorphous-semiconductor contact technology offers several advantages over the conventional processes used to produce Ge detectors. First, the contact is thin in contrast to the commonly used lithium-diffused contact. Second, the amorphous film acts as a passivant of the Ge crystal surface [28]. Therefore, the contact formation process automatically leads to a passivated detector, which is important for ensuring long-term performance stability. Third, since the physical contact electrodes are defined by the metallization, finely spaced contacts can be made simply by patterning the metallization through standard

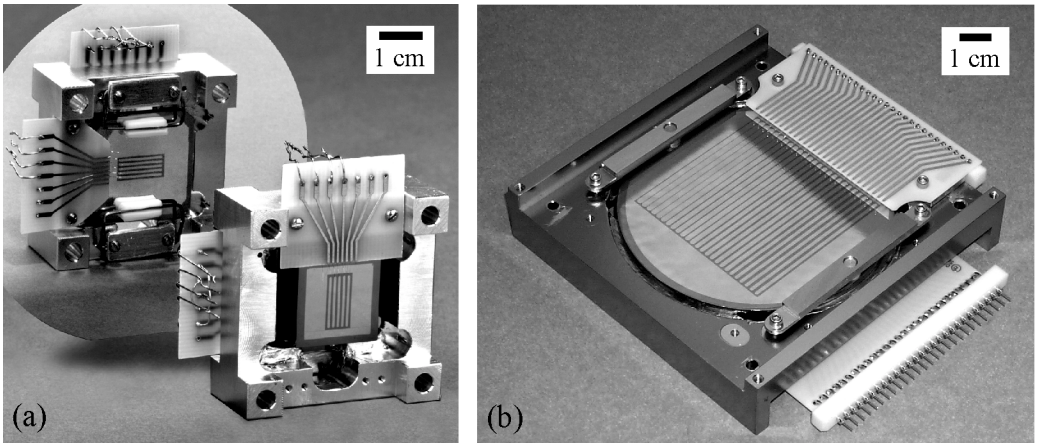

Figure 6. (a) Prototype 5×5 orthogonal-strip Ge detector. The detector has an active volume of 0.5 cm×0.5 cm×1 cm. **(b)** Large-area 25×25 orthogonal-strip Ge detector. The detector has an active volume of 5 cm×5 cm×1 cm.

processing methods. Finally, the amorphous-semiconductor contact can block the injection of both types of charge carriers. The same contact can therefore operate with low leakage current under either bias polarity. This is in contrast to conventional doped or metal barrier contacts which block injection under only one bias polarity [29,30]. As will be demonstrated in the following section, this bipolar blocking nature of the amorphous-semiconductor contact enables the simple implementation of inter-strip biasing schemes. The bipolar blocking property also allows the entire detector to be produced with a single contact technology, thereby simplifying detector fabrication.

Most of the important features of the amorphous-semiconductor contact structure that lead to its advantages are dictated by specific properties of the amorphous-semiconductor to bulk Ge interface and of the amorphous-semiconductor layer itself. In particular, both a large electrical barrier to charge carrier injection and a specific film resistivity are necessary. As part of this project, we have systematically studied the injection barrier properties of amorphous Ge and amorphous Si films deposited under various conditions onto bulk Ge. From this work, we know that amorphous Ge sputtered in pure argon produces a contact that works nearly equally well as a barrier for hole and electron injection and can therefore be used for either a positively or negatively biased electrical connection. Also, if necessary, a greater hole barrier to injection can be obtained (with a correspondingly reduced electron injection barrier) from amorphous Ge sputtered in a hydrogen-argon mixture. Likewise, a greater electron barrier is obtained from Si sputtered in pure argon. Similar to the barrier properties, the resistivity of the amorphous films depends on the type of film (either Ge or Si) and the amount of hydrogen incorporated into the film as dictated by the sputter gas mixture and the residual gases in the sputter chamber. An increase in resistivity by orders of magnitude is obtained by incorporating hydrogen into the films. This allows us to adjust the resistivity such that we achieve low inter-electrode leakage while still maintaining efficient charge collection through the film. We have used this ability to our advantage to improve the performance of our detectors as discussed in the following section.

3.3.2 Detector Performance Improvement

A primary goal in the development of the detector and signal readout technology is to measure as accurately as possible the location of and energy deposited by each gamma-ray interaction event within the detector. The ultimate performance of the gamma camera will be dictated by the quality of these measurements. The orthogonal-strip detectors we have produced for this project work well for conventional two-dimensional position measurement (lateral dimensions of x and y) [31]. However, if only this position measurement were made, there remains a large uncertainty in the interaction location since it could have taken place anywhere throughout the depth of the detector (typically 1 cm in size). This uncertainty will lead to a loss of image resolution. To mitigate this problem, we have developed a method to measure the depth of the gamma-ray interaction (z position) thereby producing a three-dimensional position-sensitive detector [26,31]. The technique, as depicted in Figure 7,

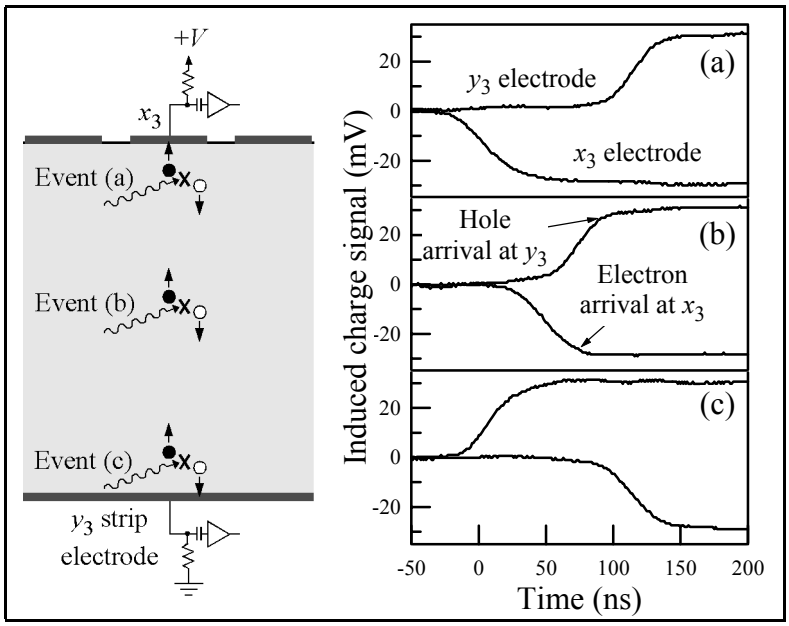

Figure 7. Diagram and measured induced charge signals from a detector of the type shown in Figure 5 illustrating a method to measure the depth at which a gamma ray interacts within the detector. The three events shown are for separate gamma rays interacting near **(a)** electrode x_3, **(b)** the center of the detector, and **(c)** electrode y_3.

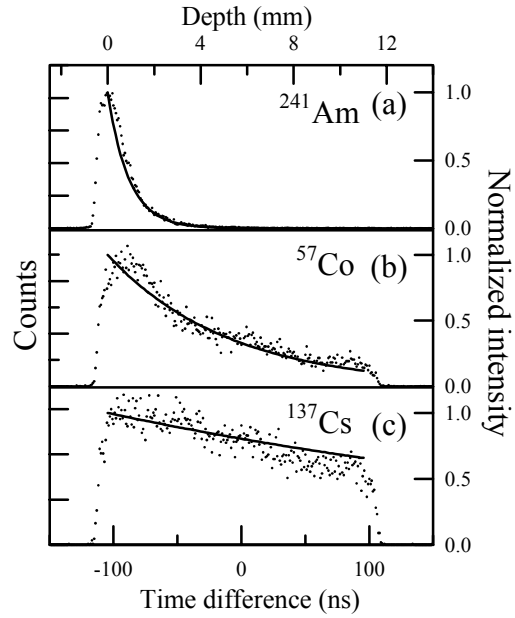

Figure 8. Time spectra acquired with a detector of the type shown in Figure 5. A separate spectrum (dots) was measured for each of the following gamma-ray sources placed in front of the detector: **(a)** ^{241}Am, 59.5 keV, **(b)** ^{57}Co, 122 keV, and **(c)** ^{137}Cs, 662 keV. For comparison, the expected exponential decay in the intensity of the gamma rays (solid lines) is superimposed on top of the measured spectra.

relies on measuring the time difference between the electron arrival at the *x* strips and the hole arrival at the *y* strips. For example, if the electron arrival occurs much sooner than the hole arrival, the interaction must have taken place near the *x* strips (Figure 7a), whereas if the opposite is true, the event must have occurred near the *y* strips (Figure 7c). As a result of the small-electrode effect [32-34], the charge arrival at a strip electrode is marked by the rapid rise in the induced charge signal on that electrode. Consequently, the separate arrival times of the electrons and holes can be readily extracted and the time difference used as a measure of the depth of gamma-ray interaction. An illustration of this method is given in Figure 8 where time spectra acquired with a prototype detector are shown. In the figure, a time difference near -100 ns corresponds to an interaction event near the side of the detector illuminated with the gamma rays. At the opposite extreme, a difference of 100 ns corresponds to an event occurring the furthest distance within the detector from the source. As expected, the lower energy gamma rays predominantly produced events near the entrance side of the detector (Figure 8a), whereas the higher energy gamma rays led to a more uniform distribution of the events with depth (Figure 8c). Each of these distributions agrees well with the theoretical distributions based on gamma-ray absorption shown as solid lines in the figure. This shows that an accurate depth of interaction measurement can be made. Our plan is to utilize this depth of interaction measurement in our imaging systems to improve spatial resolution.

The position sensitivity of our detectors relies on finely dividing into a number of strips the normally full-area electrodes of a conventional planar detector. This act of segmenting the electrodes can lead to degraded detector energy resolution and efficiency. One of the primary physical causes of the degraded performance is the existence of weak lateral electric field regions between adjacent strip electrode segments. A weak inter-electrode field, for example, can allow collection of charge

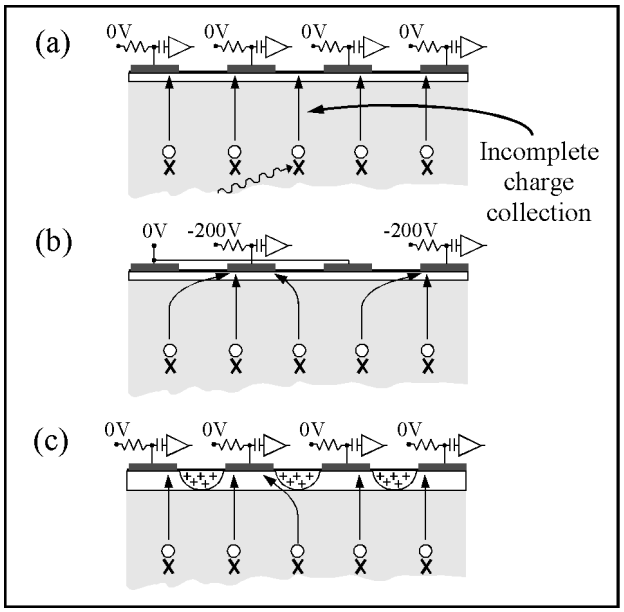

Figure 9. Schematic diagrams of the charge collection from several gamma-ray interaction events within an orthogonal-strip detector. **(a)** A weak inter-electrode field can lead to incomplete charge collection for certain events. **(b)** The charge collection can be improved through inter-electrode biasing or **(c)** through a high-resistivity inter-electrode surface film that accumulates charge.

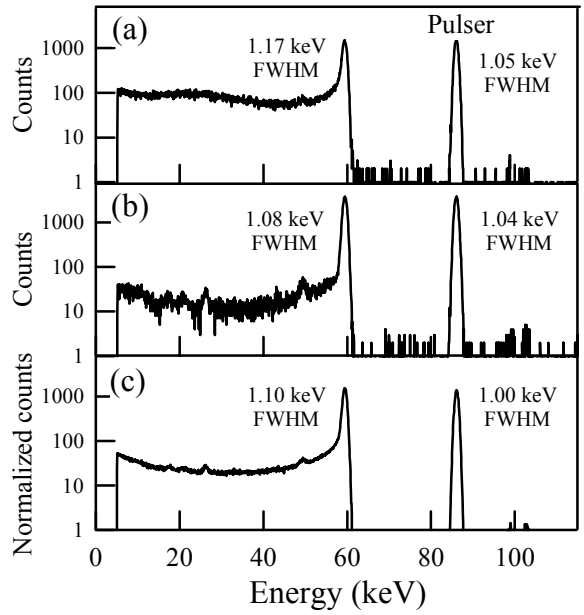

Figure 10. ^{241}Am pulse-height spectra acquired from a single strip of detector of the type shown in Figure 5. The configuration of the detector used for the measurements corresponds to the diagrams of Figure 9. **(a)** No field shaping. **(b)** Field shaping used to improve performance. **(c)** High-resistivity contact layer used to improve performance.

to the detector surface between electrodes as opposed to the electrodes themselves as shown in Figure 9a. This incomplete charge collection results in an inaccurate measurement of the gamma-ray energy. One method to reduce this problem is to reduce the gap between the electrodes. This has the associated disadvantage of increasing the electronic noise due to an increase in inter-electrode capacitance. As part of this project, we have developed two other methods to overcome the charge collection problem [26]. In the first, a potential difference is introduced between adjacent electrodes. This is accomplished by using only every other electrode for signal readout. These charge-sensing electrodes are each connected to a separate readout channel. The remaining strip electrodes are then interconnected to act as field-shaping electrodes. Through the application of an appropriate bias between the field electrodes and the sensing electrodes, the weak lateral electric field at the detector surface can be eliminated, thereby enabling complete charge collection to the sensing electrodes (Figure 9b). Such a detection scheme can be easily implemented with our detectors because of the bipolar blocking nature of the contacts. In contrast, a detector produced with conventional contacts would require the more complex process of producing alternate p^+ and n^+ electrodes on each side of the detector in order to allow inter-electrode biasing. The spectroscopy results achieved using the field-shaping technique with one of our small prototype detectors is shown in Figure 10b. This can be compared to the spectrum of Figure 10a that was measured using the same detector except without the benefit of field shaping. In comparing the two spectra, it is clear that the application of the sensing-electrode bias substantially increased the counts in the photopeak by allowing the charge from events within the inter-electrode regions and beneath the nearby field electrodes to be fully collected. The background counts were also reduced as a result of a decrease in the number of events with incomplete charge collection. Additionally, the application of the sensing-electrode bias did not measurably increase the electronic noise as the pulser widths indicate, and the energy resolution at 59.5 keV improved slightly.

The basic idea behind our second approach to improve charge collection is to inhibit the charge collection to the inter-electrode surface by modifying the properties of the amorphous-semiconductor film on this surface. Specifically, if the film is

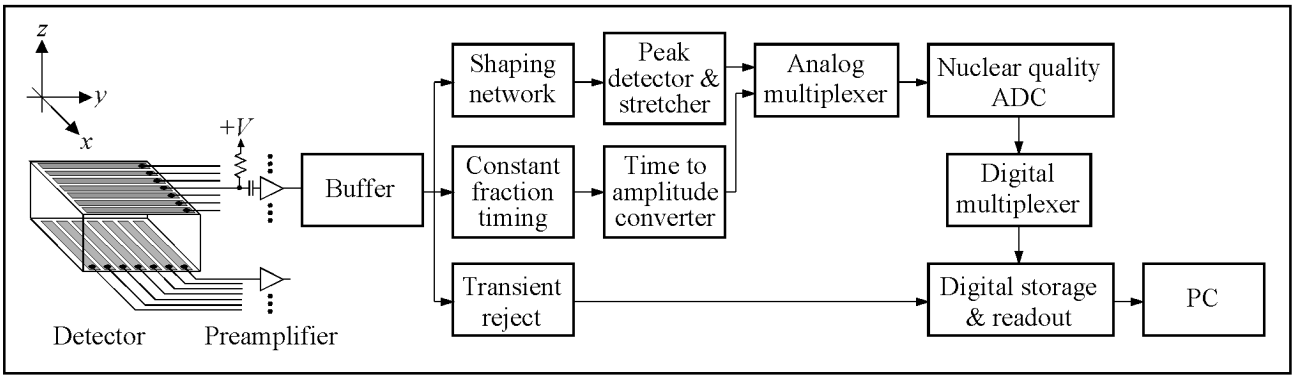

Figure 11. Block diagram of the readout electronics being developed for research studies.

high enough in resistivity, a sufficient amount of charge could be collected to and accumulated within the film to prevent subsequent charge collection to the surface. This is schematically illustrated in Figure 9c. Using the knowledge gained during our amorphous-semiconductor film study, we produced prototype detectors with much higher resistivity amorphous-Ge layers by sputtering the Ge in an argon-hydrogen mixture instead of pure argon. The improved spectroscopic performance of the detector (over that of Figure 10a) is demonstrated in Figure 10c. The spectrum of Figure 10c has a reduced background and a slightly better energy resolution than that obtained from the detector with a lower resistivity contact layer. Both improvements lead to a detector with better performance.

3.3.3 Electronics Development

We learned a great deal during this project concerning the physics of the position-sensitive detectors. This knowledge was then directly applied to the development of innovative readout electronics. As a first step in this process, we designed and fabricated prototype research electronics that would allow us to extract as much information as is reasonably possible from each gamma-ray event. Our plan is to then use this unique measurement system for further studies of depth-of-interaction measurement, charge sharing, transient rejection, and detection uniformity. The information from these studies will then enable us to optimize the readout electronics for a future field-deployable instrument.

A block diagram of the research electronics system is shown in Figure 11. The design is such that when a gamma ray interacts possibly multiple times in the detector, the induced charge signal on each strip electrode will be measured with a separate preamplifier. These signals, after buffering, will each be processed to obtain three separate pieces of information. The *Shaping Network* and *Peak Detector & Stretcher* circuits allow for the extraction of the pulse height, thereby giving the energy deposited by the gamma ray. The *Constant Fraction Timing* and *Time to Amplitude Converter* circuits provide a measurement of the time at which the charge was collected by the strip. This can then be used to determine the depth of the interaction within the detector as described in Section 3.3.2. Finally, the *Transient Reject* circuit determines if the signal returns to zero after a short time delay from the signal start. If the signal returned to zero during the delay, no charge was actually collected to the strip. If this occurs, the energy extracted by the *Shaping Network* and *Peak Detector & Stretcher* circuits would not be used for spectroscopic purposes. These three pieces of information from each strip electrode will then be converted to digital information and transferred in real-time to a PC for processing.

For each gamma ray that interacts within the detector, this readout system will determine the 3-dimensional location of each interaction site and the energy deposited at each site. Charge sharing between adjacent electrodes as described previously in Section 3.2 can be correctly handled since the readout system processes the signals from all the strip electrodes. The system will also address the transient problem described in Section 3.2 since it differentiates between real charge collection events and transient signal events. The present status of this effort is that each circuit block has been designed, fabricated, and tested. Integration into a complete set of measurement electronics is now underway.

3.3.4 Additional Hardware Development

We have successfully developed other hardware as part of this project. The Ge detectors for this project must be operated at cryogenic temperatures. The general-purpose cryostats previously available to us are not sufficient for the testing of these large, multi-channel, position-sensitive detectors. For this reason, we have designed, fabricated, and tested a research cryostat specifically for the evaluation of these detectors. The cryostat is designed to accommodate an 8 cm diameter detector with 50 readout channels. Other features of the cryostat include easy detector access and mounting, and rapid thermal cycling. In collaboration with a separate project, we have also developed an automated gamma-ray scanning system for the evaluation of the detectors. With such a system, a finely collimated gamma-ray source can be scanned over the detector surface while the response of the detector is measured. This allows us to determine the position-dependence of charge collection, depth of interaction measurement, detection efficiency, or any other detector performance characteristic. Such measurements provide vital information on the physics of the detectors that can then be used to improve detector and electronics designs.

4. Relevance, Impact, and Technology Transfer

a. How does this new scientific knowledge focus on critical DOE environmental management problems?

As described in Section 2, this project directly addressed the DOE need for advanced instrumentation to characterize equipment and structures contaminated with radionuclides. Through this project, innovative detector technologies, detection techniques, and electronics have been developed that will form the basis for a high-performance gamma-ray imaging instrument that will achieve a combined imaging and spectroscopy performance level far superior to that of today's commercial instruments.

b. How will the new scientific knowledge that is generated by this project improve technologies and cleanup approaches to significantly reduce future costs, schedules, and risks and meet DOE compliance requirements?

As described in Section 2, when implemented in a field-deployable instrument, the technologies developed through this project will provide a faster more accurate in-situ characterization of radioactive contaminants. The gamma-ray imaging technique employed in such an instrument allows the characterization to be done at a distance from the contaminated objects and can accurately acquire the spatially dependent gamma-ray emission information in a single measurement. Consequently, the device can more efficiently discriminate between contaminated and non-contaminated areas of heterogeneous objects while at the same time reducing worker exposure. Furthermore the advanced spectroscopic capabilities of this instrument enables isotopic identification of the radioactive contaminants, increases instrument sensitivity through a reduced background, improves image resolution of buried contaminants, and allows gamma gauging to be done. Each of these characteristics ultimately leads to a more complete and accurate characterization than is feasible with current baseline technologies.

c. To what extent does the new scientific knowledge bridge the gap between broad fundamental research that has wide-ranging applications and the timeliness to meet needs-driven applied technology development?

Our research has focussed on understanding the basic physics leading to image formation and spectroscopy in a Ge-based gamma-ray imaging instrument, and the mechanisms that can degrade system performance. Then based on this research, we have devised and demonstrated techniques to overcome these degradation effects. The issues studied in our work are those most critical for the next stage of applied technology development where our developed techniques would be integrated into a complete gamma-ray imaging instrument. More details concerning these issues are given in Section 3.2.

d. What is the project's impact on individuals, laboratories, departments, and institutions? Will results be used? If so, how will they be used, by whom, and when?

This project has developed some of the underlying technologies for an advanced gamma-ray imaging instrument. For this work to directly impact DOE's cleanup effort, the technologies must be integrated into a complete instrument. This project has been one component of our overall program to develop gamma-ray imaging instruments based on Ge-detectors. Several projects are involved in this program. These include NASA-funded projects for gamma-ray astronomy applications, a NIH SBIR funded project for medical imaging applications, and a DOE Office of Defense Nuclear Nonproliferation funded project for arms control, counter proliferation, and safeguards applications. Each of these individual projects benefits from the research accomplishments of this DOE EMSP funded project. The results of the EMSP project will de directly used by these projects (and hopefully an additional DOE EM project) in the development of gamma-ray imaging instruments for their respective applications. Furthermore, our findings have been presented at technical conferences and published in the most appropriate journals for this field of research and as a result will benefit other researchers in this area.

e. Are larger scale trials warranted? What difference has the project made? Now that the project is complete, what new capacity, equipment, or expertise has been developed?

After the integration of the technologies into a complete gamma-ray imaging instrument, field testing will be warranted. The difference that this project has made is that it addressed several challenges facing the development of a Ge-based gamma-ray imaging instrument. The results of the project then simplify the subsequent instrument development. The new knowledge that this project has produced is described in Section 3.3.

f. How has the scientific capabilities of collaborating scientists been improved?

This project has required gaining an understanding of the basic physics of a Ge-based instrument and the mechanisms that degrade system performance, as well as the applied development of detector, cryostat, and electronic system components. In each area, the expertise of collaborating scientists has been improved. Issues critical to the performance of a Ge-based imaging instrument and methods to improve performance have identified and disseminated. Detector fabrication, cryostat design, and electronics design capabilities have all been enhanced.

g. How has this research advanced our understanding in the area?

See the answer to question f as well as the information in Section 3.3.

h. What additional scientific or other hurdles must be overcome before the results of this project can be successfully applied to DOE Environmental Management problems?

The technologies produced through this project must be integrated into a complete imaging instrument appropriate for field studies before they can be applied to DOE problems. This entails the development of imaging and cryostat hardware, readout electronics, and data processing software.

i. Have any other government agencies or private enterprises expressed interest in the project?

As indicated in the answer to question d, there is substantial interest in the results from this project.

5. Project Productivity

The primary goal that was originally proposed for this program was to develop Ge-based gamma-ray detectors capable of measuring gamma-ray interaction locations within the detectors in three dimensions as well as making accurate measurements of the gamma-ray energies. This goal encompassed the adaptation of fabrication processes in order to produce the detectors, the development of detection techniques that allowed for the accurate extraction of three-dimensional position and energy information, the development of research electronics for detector testing, and the detailed evaluation of the detectors and

associated detection techniques. As the discussion of Section 3.3 demonstrates, this goal was clearly achieved in this project. The early success in the project allowed us to take on the more ambitious goal of working towards a field instrument that would incorporate our innovative technologies.

6. Personnel Supported

Name	Title	Project Activity
Mark Amman	Scientist	Principle Investigator, basic detector studies, detector and cryostat development
Paul Luke	Scientist	Co-Principle Investigator, basic detector studies, detector and cryostat development
Morgan Burks	Scientist	Electronics development
Norman Madden	Electronics Engineer	Electronics development
Lorenzo Fabris	Electronics Engineer	Electronics development
Vincent Riot	Electronics Engineer	Electronics development
Cheryl Weldon	Electronics Technician	Electronics fabrication
Derek Yegian	Mechanical Engineer	Cryostat mechanical design
Eric Johnson	Mechanical Technician	Mechanical parts fabrication

7. Publications

"Position-Sensitive Germanium Detectors for Gamma-Ray Imaging and Spectroscopy," M. Amman and P.N. Luke, Proceedings of the SPIE **4141**, 144 (2000).

"Three-Dimensional Position Sensing and Field Shaping in Orthogonal-Strip Germanium Gamma-Ray Detectors," M. Amman and P. N. Luke, Nucl. Instr. Meth. A **452**, 155 (2000).

"Germanium Orthogonal Strip Detectors with Amorphous-Semiconductor Contacts," P. N. Luke, M. Amman, B. F. Phlips, W. N. Johnson, and R. A. Kroeger, IEEE Trans. Nucl. Sci. **47**, 1360 (2000).

8. Interactions

Poster presented at the 2001 IEEE Nuclear Science Symposium, "A Germanium Gamma-Ray Imager with 3-D Position Sensitivity," M. T. Burks, M. Amman, S. E. Boggs, E. L. Hull, P. N. Luke, N. W. Madden, V. J. Riot, and K. P. Ziock, San Diego, CA, November 4-10, 2001.

Invited talk presented at the Hard X-Ray and Gamma-Ray Detector Physics Conference of the 2000 Annual Meeting of the SPIE, "Position-Sensitive Germanium Detectors for Gamma-Ray Imaging and Spectroscopy," M. Amman and P.N. Luke, San Diego, CA, July 30 – August 4, 2000.

Talk and poster presented at the 2000 EMSP National Workshop, "The Development of Germanium Detectors for Gamma-Ray Imaging and Spectroscopy," M. Amman, P. N. Luke, and M. T. Burks, Atlanta, GA, April 25-27, 2000.

Talk presented at the 1999 IEEE Nuclear Science Symposium, "Germanium Orthogonal Strip Detectors with Amorphous-Semiconductor Contacts," P. N. Luke, M. Amman, B. F. Phlips, W. N. Johnson, and R. A. Kroeger, Seattle, WA, October 23-30, 1999.

Talk and poster presented at the 1998 EMSP Deactivation and Decommissioning Workshop, "Three-Dimensional Position-Sensitive Germanium Detectors," M. Amman and P. N. Luke, Savannah River Site, November 17-18, 1998.

Poster presented at the 1998 IEEE Nuclear Science Symposium, "Amorphous-Ge and Amorphous-Si Contacts on Ge Detectors," P. N. Luke, M. Amman, J. S. Lee, and J. T. Walton, Toronto, Canada, November 8-14, 1998.

9. Transitions

This project has been one component of our overall program to develop gamma-ray imaging instruments based on Ge-detectors. Several projects are involved in this program. These include NASA-funded projects for gamma-ray astronomy applications, a NIH SBIR funded project for medical imaging applications, and a DOE Office of Defense Nuclear Nonproliferation funded project for arms control, counter proliferation, safeguards applications. Each of these individual projects benefits from the research accomplishments of this DOE EMSP funded project. The results of the EMSP project will de directly used by these projects (and hopefully an additional DOE EM project) in the development of gamma-ray imaging instruments for their respective applications.

10. Patents

None.

11. Future Work

The work that remains to be done includes demonstrating the technologies we developed in a full imaging system, producing an optimized instrument for field studies, and transferring the technologies to an industrial partner.

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