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"Three-Dimensional Position-Sensitive Germanium Detectors"

DOE Need and Research Objective

A critical component of the DOE decontamination and decommissioning effort is the characterization of radioactively contaminated equipment and structures. Gamma-ray spectroscopy and imaging with germanium (Ge) based detectors are powerful techniques that allow for the quick and accurate in-situ identification, spatial mapping, and quantification of radioactive contaminants. However, the image resolution obtained with a Ge detector can be limited by the accuracy to which the gamma-ray interaction events are spatially detected within the detector itself. Our primary objective is to develop the technologies necessary to produce Ge gamma-ray detectors with enhanced accuracy in locating gamma-ray interaction events thereby resulting in improved image resolution. Our approach is to locate the gamma-ray interaction events within the detector in all three dimensions rather than just two. Additionally, we will base the detectors on LBNL fabrication technologies and work to develop the simplest possible detector geometries and signal-readout electrode structures in order to reduce the system complexity and difficulties in fabrication. The technologies developed as a result of this research will form the basis for the design and construction of future high-performance gamma-ray imaging systems. These instruments will greatly facilitate DOE's radioactive materials characterization process.

Research Progress and Implications

This section summarizes the work from the initial 17 months of our three-year project. During this period, we have concentrated our efforts on three separate task areas: detector fabrication development, orthogonal-strip detector fabrication and testing, and detector modeling. The progress made in each area and the importance of the work is given below.

Key to the success of gamma-ray imaging with Ge detectors is the development and use of cost-effective, robust detector fabrication processes. Such processes have been developed previously at LBNL and, through this project, are being further refined for the specific needs of this application. In our detectors, 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 an 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. 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 electrical connecting each of these finely spaced electrodes to the measurement electronics. 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. This high-yield process has now been successfully used on a number of detectors.

Achieving specific properties in the amorphous contact layer is also crucial to the proper performance of the detector. In particular, both a large electrical barrier to charge carrier injection and a specific film resistivity are necessary. 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. Similarly, a greater electron barrier is obtained from Si sputtered in pure argon. 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. We are presently working to understand the effect that this film resistivity has on the detector performance and will eventually optimize the film based on this newly gained understanding.

With the aid of the above fabrication process development, we have produced small prototype Ge detectors. The objectives of this task have been to test and refine the fabrication processes, study the physics of charge collection and signal formation in highly segmented Ge detectors, and investigate depth-of-interaction sensing. An orthogonal-strip type geometry was chosen for these detectors because of its simplicity. In this geometry the electrodes on one side of a planar detector are segmented into a set of linear strips. On the opposing detector surface is another set of strips that run perpendicular to the first set. The location of a gamma-ray interaction event within such a detector is determined by measuring the induced charge signals from each strip of both sets of electrodes. For a simple gamma-ray interaction event, a single strip on one side of the detector will collect the generated holes and a single strip from the opposing detector surface will collect the electrons. Therefore for such an event, only one strip on each side of the detector will produce a net charge signal thereby localizing the interaction event in two dimensions. To locate the interaction event more precisely, we desire to also determine the depth at which the gamma ray has interacted within the detector thereby producing a three-dimensional position-sensitive detector. We have accomplished this by measuring the difference between the arrival time of the holes at a strip on one side of the detector and the arrival time of the electrons at a strip on the opposing detector side. The eventual use of this technique for gamma-ray imaging should allow for the more accurate spatial mapping of radioactive contaminants. This work has been summarized in reference 1 given below.

In addition to high position sensitivity, it is also important that the detector be efficient and have excellent energy resolution. From tests with an orthogonal-strip detector, we see evidence of a loss of energy resolution and photopeak efficiency for gamma rays interacting in the region between two adjacent strips. Based on these measurements and modeling results, it appears that this is caused by slow charge collection in a weak field region between adjacent strips. This loss of efficiency would degrade detector performance. One method to solve this poor charge collection problem is to increase the field between adjacent strips. This can be accomplished by using only every other strip for signal measurement. The remaining strips are used as field-shaping electrodes to which a voltage can be applied thereby increasing the field between adjacent strips and improving the charge collection to the signal measurement strips. We have successfully used this technique to improve the photopeak efficiency and energy resolution of our orthogonal-strip detector (see reference 1). However, from preliminary measurements, it also appears that this charge collection problem can be substantially reduced without the field-shaping electrodes simply by using an optimized amorphous semiconductor contact layer. We are presently investigating this method.

The spectroscopy and imaging performance of the Ge detectors depends on the detector and electrode geometry and the readout electronics configuration. Numerical modeling is an efficient means to optimize the detector and readout electronics design for the best possible system performance. We are presently modeling the response of orthogonal-strip detectors in order to refine the detector design and to allow us to design the most effective readout electronics. These calculations combined with our measurements will be used to determine the best method to electronically extract the gamma-ray interaction position from the measured induced charge signals.

Planned Activities

In the short term we plan to continue the investigation with small orthogonal-strip detectors concentrating on improving energy resolution, photopeak efficiency, and position sensitivity. We will also continue the development of a specialized cryostat and electronics for the more thorough measurements required to accomplish the detector development tasks.

In both the short term and long term our efforts will continue to be directed at refinements in the fabrication processes. The development and use of modeling tools to better understand the physics of our detectors and to optimize their performance will also continue throughout the project.

Once a good understanding has been gained from modeling and measurements made with small detectors, we will design, fabricate, and test larger area detectors more suitable for imaging applications.

Information Access

1. "Three-Dimensional Position Sensing and Field Shaping in Orthogonal-Strip Germanium Gamma-Ray Detectors," M. Amman and P. N. Luke, Nucl. Instr. and Meth. A, accepted for publication.

2. "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., submitted for publication.