SEGMENTATION OF THE OUTER CONTACT ON P-TYPE COAXIAL GERMANIUM DETECTORS

Ethan Hull [1], Harry Miley [2], Richard Pehl [1], Craig Aalseth [2], and Todd Hossbach[2]

PHDs [1] and Pacific Northwest National Laboratory[2]

Sponsored by National Nuclear Security Administration
Office of Nonproliferation Research and Engineering
Office of Defense Nuclear Nonproliferation

Contract Nos. DE-AC05-RLO1830[1] and DE-FG-02-05ER84157[2]

ABSTRACT

Arrays of segmented germanium detectors are needed for low-level gamma-ray counting facilities. Applications of such user facilities include characterization of low-level radioactive samples and the search for rare events like neutrinoless double-beta decay. Coaxial germanium detectors having segmented outer contacts can provide the next level of sensitivity improvement for these low-background measurements. The segmented contact allows advanced pulse-shape analysis measurements that decrease the measured background. Currently, such detectors are very expensive and available only after relatively long lead times. Advances in segmentation technology will reduce fabrication costs and improve availability of these detectors for the low-level counting community.

For similar reasons, segmentation research also extends to applications of interest to the nuclear explosion monitoring community. Large segmented p-type coaxial detectors could serve as the gamma-ray spectrometers on instruments such as the Radionuclide Aerosol Sampler/Analyzer (RASA). These detectors will provide a more sensitive, lower background, measurement than currently available with unsegmented p-type coaxial detectors. In addition to more sensitive spectroscopy, the position resolution within a segmented germanium detector can be used to determine the impinging direction of incident gamma rays. This directional sensitivity can be used to futher reduce background by separating the directions of interest from directions contibuting only to background. Furthermore, the directional sensitivity can help locate an intense source of gamma rays at a distance.

The conventional contacts used to fabricate germanium detectors are boron-implanted p+ and the lithium-diffused n+ contacts. Boron-implanted contacts are thin (~1000 Å) and can be segmented. Lithium-diffused contacts are thick (~ 0.5 mm) and very difficult to segment. For pulse-shape analysis using a coaxial detector, the outer detector contact must be segmented. Consequently, the outer contact must be a segmented boron-implanted p+ contact forcing the bulk detector material to be n-type germanium. Because of electron trapping limitations, n-type germanium detectors of sufficient quality for large-diameter coaxial detectors are far more difficult and expensive to produce than p-type germanium. This project shall research alternatives to the thick lithium n+ contact to allow the use of p-type germanium as the material for segmented coaxial detectors. Amorphous germanium contacts pose a possible solution. Amorphous contacts are being researched as an alternative to lithium-diffused contacts. The thin (~1000 Å), easily segmented, amorphous germanium contact naturally lends itself to fine segmentation of the n+ contact.

OBJECTIVES

Funding for this program has only just begun. This paper is a brief on the work to be done and the motivation for that work.

Germanium detector arrays are needed for low-level counting facilities. The practical applications of such user facilities include characterization of low-level radioactive samples. In addition, the same detector arrays can also perform important fundamental physics measurements including the search for rare events like neutrinoless double-beta decay (Miley et al. 1991, Miley et al. 1990, Majorance Collaboration White Paper, 2003). Coaxial germanium detectors having segmented outer contacts will provide the next level of sensitivity improvement in low-background measurements. The segmented outer contact allows performance of advanced pulse-shape analysis measurements. These techniques can be used to discriminate between multiple Compton-scattered gamma-ray events and single-point beta-decay events. Recently, such techniques have been demonstrated with Clover detectors at Los Alamos National Laboratory and confirming simulations done at Pacific Northwest National Laboratory, Lawrence Berkely National Laboratory, and Oak Ridge National Laboratory. Because of their complexity, the segmented coaxial detectors are expensive and available only after relatively long lead times. Improved detector segmentation techniques would be both important and timely. Such technological advances will reduce fabrication costs and improve availability of these detectors for the low-level counting community. These highly sensitive detectors are also useful for nuclear explosion monitoring in systems such as the RASA.

Currently, the fabrication of a segmented coaxial germanium detector requires an n-type germanium crystal for the detector. Depleting a coaxial detector with a reasonable bias voltage requires the rectifying (p^+n or n^+p) junction to be at the outside diameter of the detector. For an accurately segmented coaxial detector, the outer contact must be segmented. The n-type (reverse-electrode) germanium coaxial detectors are needed because the boron-implanted (p+) outer contact is the more conveniently segmented conventional contact. However, p-type (conventional-electrode) coaxial detectors are more desirable for a number of reasons. P-type coaxial detectors are significantly less expensive and have better gamma-ray energy resolution than n-type coaxial detectors. Fundamentally, this is due to the presence of electron-trapping sites found in even the best detector-quality germanium. A small percentage of the electrons arising from gamma-ray interactions in the detector are trapped before reaching the electron-collecting contact. The charge is trapped for a sufficient duration that it is not included in the processed signal for that event. The resulting pulse-height deficits cause broadening of gamma-ray peaks. The magnitude of energy-resolution degradation from electron trapping is strongly dependent on the geometry of the detector. In detectors of coaxial geometry, the charge carriers collected on the inner contact are responsible for inducing most of the total signal from gamma-ray interactions occurring in most of the volume of the detector. In n-type coaxial detectors, electrons are collected on the inner contact. Consequently, the gamma-ray energy resolution of n-type coaxial detectors is degraded by even small amounts of electron trapping. On the other hand, the spectroscopy of p-type detectors of coaxial geometry relies more heavily on the collection of holes on the inner contact. As a result, electron trapping causes much less resolution degradation in a p-type coaxial detector than in an n-type coaxial detector. This allows a greater percentage of grown detector-grade germanium crystals to be used in the fabrication of p-type coaxial detectors having excellent energy resolution. The lesser importance of electron trapping also allows fabrication of larger-diameter p-type coaxial detectors. Thus fewer detectors are needed to make an array of a given total volume. It is important to note that electron trapping is still relatively poorly understood and difficult to control in the growth of detector-quality germanium. Any large-scale low-level counting facility employing segmented coaxial detectors would benefit greatly, both technically and financially, from the use of p-type coaxial detectors. These segmented detectors will also be quite useful as ultrasensitive gamma-ray detectors for nuclear explosion monitoring.

Currently, the segmentation of the required outer Li-diffused n+ contact of a p-type coaxial detector is a nontrivial operation. The outer contact of a p-type coaxial detector is conventionally made using a rather thick (as much as ~ 1-mm thick) lithium-diffused layer as the hole-injection barrier. Thick lithium-diffused contacts are very rugged and reliable but require rather drastic techniques for segmentation. The current state-of-the-art involves cutting through the lithium-diffused layer with a saw to segment the contact. Although it can work, such detector fabrication techniques are expensive, time-consuming, and mechanically cumbersome. In the event that a saw-cut lithium contact does not successfully function, successive fabrication attempts may prove very difficult. Accommodating the saw-cut grooves during the subsequent fabrication attempts may be sufficiently complicated to compel regrinding the crystal diameter or even starting over again with a new crystal. In addition, such saw cuts can cause charge-collection and surface-channel problems in the vicinity of the grooves between the segments. Grooves often result in effectively "dead" germanium near the grooves. The initial saw cuts and electronically dead germanium consume valuable germanium detector volume, resulting in a decrease in sensitivity.

Suffice it to say that better outer coaxial contacts must be researched to replace the conventional saw-cut segmented thick lithium-contact. This must be accomplished to make segmented p-type coaxial detectors viable. In this age of photolithographic techniques capable of fabricating millions of transistors on a square inch, we believe that more elegant contacting and segmentation solutions can be found for germanium detectors. There are other contact technologies with the potential to provide hole-injection barriers that are more easily segmented than thick lithium-n+ contacts. This study seeks to determine the best solution for producing segmented hole-injection barrier contacts on p-type germanium detectors.

We will investigate alternative techniques for making segmented hole-injection barrier contacts in lieu of conventional thick lithium-diffused n+ contacts. Amorphous germanium contacts represent one possible alternative. We will fabricate many small planar detectors (~ 4-mm thick, ~30-mm diameter) having a boron-implanted p+ contact as the electron-injection barrier and segmented amorphous germanium contacts as the hole-injection contacts. Amorphous germanium contact technology naturally lends itself to the simple fabrication of finely segmented germanium detectors (Luke et al. 1992, Hull et al. 2002, Hull et al. 2003). Our commercial research facility in Livermore, California, is specifically designed to fabricate and test many germanium detectors in rapid succession. We will study the rectification and segmentation of amorphous germanium contacts with a focus on the hole-injection barrier. Fabrication parameters will be optimized to make reliable segmented amorphous germanium contacts having the largest possible hole-injection barrier height. Our fabrication techniques will then be demonstrated by fabricating a segmented p-type pseudocoaxial detector. The detector will serve to demonstrate the viability of this approach for making segmented p-type coaxial detectors.

Segmented planar germanium detector technology is our specialty. We believe that the best way to approach the fabrication of segmented coaxial detectors is to first understand the fabrication processes for planar detectors. With the fundamental physics and technology well in hand, the technology can be extended to accommodate the nonplanar geometry issues arising in coaxial detector fabrication. We are familiar with the complexities of cooling, connecting, and instrumenting germanium detectors systems having many detector segments on a single wafer of germanium. This program will benefit our planar germanium detector efforts as well as provide coaxial detector technology for nuclear explosion monitoring.

RESEARCH ACCOMPLISHED

This project will establish the viability of fabricating p-type coaxial detectors with segmented outer contacts. The outer contact of a p-type coaxial detector must prevent the injection of holes into the detector. The commonly used hole-injection barrier is a thick lithium-diffused n+ contact. Lithium-diffused contacts are extremely rugged and reliable but they are thick and difficult to segment. This difficulty makes them unsuitable for the fabrication of segmented p-type coaxial detectors. This study will evaluate the viability of amorphous germanium contacts as replacements for thick lithium-diffused contacts.

One of the central points to be addressed is the rectification ability of the amorphous germanium contact. The contact must function as the outer contact of a large-diameter p-type coaxial detector. This means the contact must prevent hole injection into the detector. The most important property of a detector contact is its ability to prevent charge injection while maintaining a high electric field throughout the volume of the detector. In large coaxial detectors, it is not uncommon to have electric fields of ~ 3000 V/cm. The high electric field is important for good charge collection over long distances (~ 4 cm). The hole-injection barrier formed by the amorphous germanium contact must be demonstrated to be consistently capable of suppressing hole injection to the extent needed in large-diameter coaxial detectors. At common operating temperatures (~ 85 K), hole injection from the amorphous germanium contact should not cause more than a few tens of picoamperes of leakage current while withstanding electric fields on the order of 3000 V/cm. In addition, the contact must be sufficiently rugged to withstand temperature cycles between liquid-nitrogen temperature and room temperature. Excessive leakage current is undesirable because it causes electronic noise in the detector.

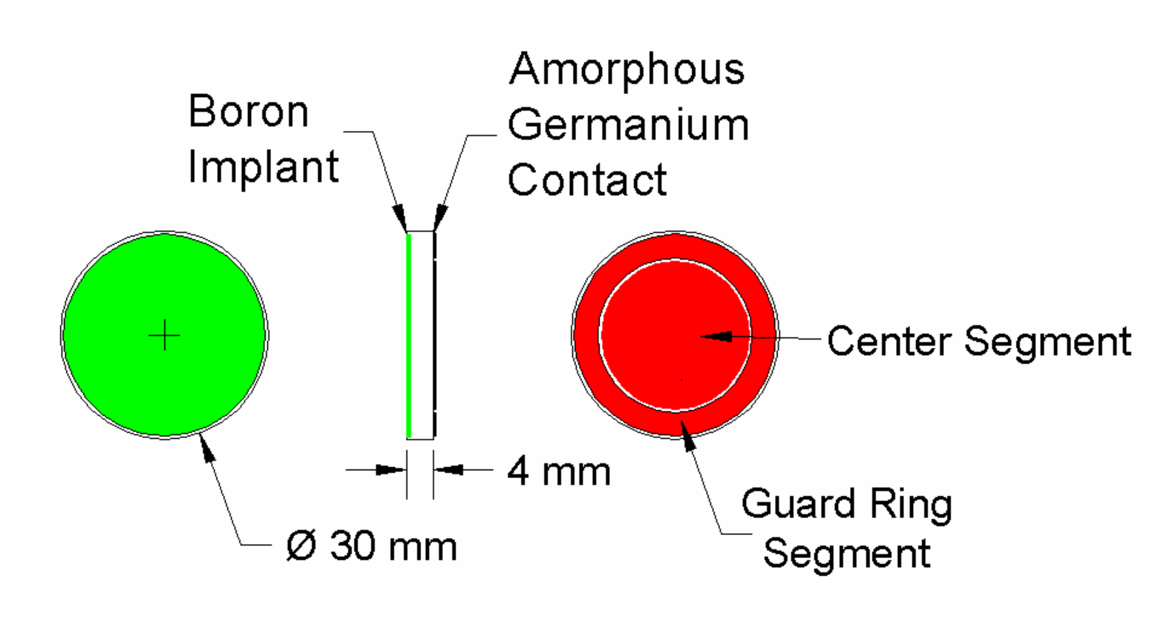

Figure 1. A drawing shows the test detector structure. One side of the detector is a boron-implanted p+ contact while the other side is a segmented amorphous germanium contact. The amorphous germanium contact is divided into center and guard-ring segments.

Small p-type planar test detectors will serve as the basis for studying the rectification properties of the contacts. Many such detectors will be fabricated and tested in rapid succession to find the best detector fabrication parameters and techniques. Making many detectors provides meaningful statistics and makes trends in performance easily visible. Our detector research system at PHDs is set up for the fabrication and testing of several detectors each day. The p-type test detectors will be 4-mm thick and approximately 30 mm in diameter. Figure 1 shows a diagram of one of the test detectors. One side of the detector will be boron implanted to form a p+ electron-injection barrier. The boron implant will be done by a local area implantation shop, Core Systems in Sunnyvale, CA. We will then sputter-deposit an amorphous germanium layer on the other side of the detector, providing the hole-injection barrier. Finally, a layer of aluminum will be evaporated over the amorphous germanium. A shadow-mask ring will be placed on the amorphous germanium side during the aluminum evaporation to provide electrically separate center and guard-ring segments of the detector. When finished, the detectors will look like the drawing in Figure 1.

After the detectors are fabricated, they will be placed in one of our test cryostats, cooled, and tested. Negative-bias voltage will be applied to the boron-implanted contact. The center and guard-ring segments of the amorphous germanium contact will be grounded separately through charge-sensitive preamplifiers. The preamplifiers provide separate leakage-current measurements from the center and guard-ring contacts. The leakage current will be measured as a function of bias voltage. These measurements, known as I(V) measurements, serve as an indication of the success of the fabrication process.

This detector contact structure has been chosen to facilitate the study of the hole-injection barrier formed by the amorphous germanium contact. The boron-implanted contact forms a well-understood, very large electron-injection barrier having a height of the entire germanium band gap, 0.7 eV. The amorphous germanium contact forms either a hole- or electron-injection barrier of approximately half the height of the crystalline-germanium band gap (Hansen and Haller, 1977). Because the boron-implanted electron-injection barrier is so much larger than the amorphous germanium hole-injection barrier, hole injection from the amorphous germanium contact will dominate the leakage current of the detector. Figure 2 shows band diagrams of two different detector structures. On the left side of the figure is a standard p^+-p-n^+ structure. On the right side of the figure is our innovative p^+-p-αGe structure. The standard p-n^+ junction forms a hole-injection barrier height equal to the germanium band gap, 0.7 eV. Our proposed structure uses an amorphous contact to form the hole-injection barrier. The amorphous germanium barrier height is somewhat smaller than the barrier formed by a p-n junction. The actual height of the amorphous germanium hole-injection barrier can be adjusted by changing fabrication parameters during the sputter deposition process. However, the specific relationship between the sputter-deposition parameters and the height of the hole-injection barrier is not quantitatively known. Understanding this relationship is a central goal of this project. This will facilitate fabrication of the largest possible amorphous-germanium hole-injection barrier for segmented outer contacts of p-type coaxial detectors.

The amorphous-germanium hole-injection barrier height will be measured as a function of fabrication parameters. To measure the barrier height, the I(V) of detectors will be measured as a function of operating temperature. The detector I(V) will be measured in the 83^{o}K to 120^{o}K temperature range. The test cryostat will be outfitted with a variable-temperature stage of the style described in (Pehl et al., 1989). By applying power to a zener diode on the variable-temperature detector stage of the cryostat, the temperature of the detectors can be set and held constant at any temperature between 83^{o}K and 423^{o}K. As described below, making these I(V,T) (leakage current as a function of voltage and temperature) measurements gives us the hole-injection barrier height formed by the amorphous germanium contact. After the barrier height has been determined for a particular set of detectors, the contacts will be etched off and the same set of germanium wafers will be made into new detectors. This is another advantage of the amorphous germanium contact. Along with ease of fabrication and segmentation, the contact may be easily refabricated, if necessary, with minimal loss of germanium volume. If the contact does not function the first time, the process can be repeated with only the loss of a few tens of microns of germanium during etching.

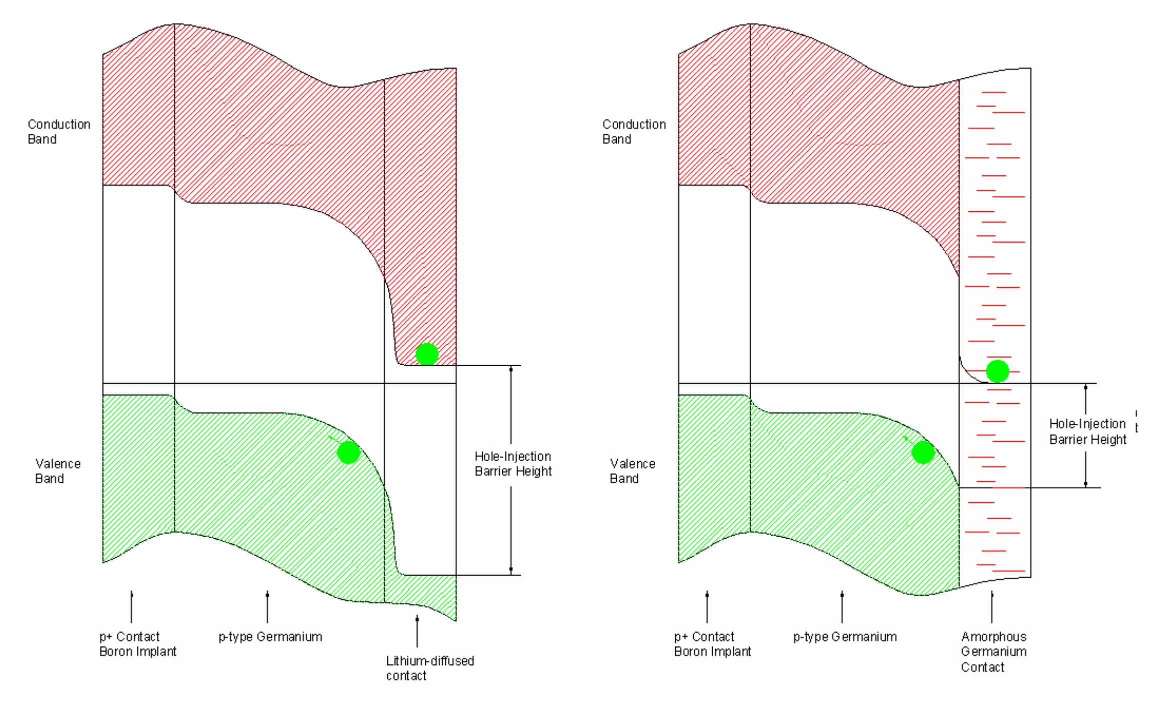

Figure 2. The left-hand energy band diagram shows the standard p+-p-n+ electrode structure used in most commercially available germanium detectors. The right-hand diagram shows our proposed innovative electrode structure that relies on the amorphous germanium contact to provide a hole-injection barrier.

The amorphous contact has recently been understood in terms of a long existent amorphous-crystalline heterojunction model (Hull 2004) (Dohler and Brodsky, 1984). A barrier height and a Fermi-level density of states N_f characterize the reverse-biased properties of the amorphous-crystalline heterojunction. The leakage-current density follows the expression:

$$j = j_{\infty} \exp(-\{\varphi - [(\varepsilon_0 \varepsilon_{Ge}/N_F)^{1/2}(V+V_{depl})/d]\}/k_B T). \tag{1}$$

The expression is for a fully depleted planar detector of thickness d. The applied voltage is V and the depletion voltage is V_{depl}. The matrix element j_{∞} is taken to be a constant determined by experiment.

Like a Schottky barrier, the amount of leakage current thermionically ionized over the amorphous-germanium hole barrier is proportional to $\exp(-\varphi/k_B T)$. The barrier height, φ, is of paramount importance. Increasing the barrier height from .35 eV to .40 eV reduces the amount of thermionically emitted leakage current by a factor of ~ 2000 at 80 K. In fact, our calculations predict that a hole-injection barrier ~.42 eV is sufficiently high that thermionic emission over the barrier is no longer the dominant source of leakage current. As the hole-injection barrier height increases toward ~.42 eV, the dominant source of leakage current becomes thermal generation in the bulk germanium rather than the contact. Thermal excitations generate free electron-hole pairs from generation-recombination sites at the mid-band-gap position throughout the bulk germanium (Pehl et al., 1973). If the hole-injection barrier height can be increased to .42 eV or greater, there will be effectively no measurable difference between the rectifying properties of an amorphous-germanium hole barrier and lithium-diffused n+ contact!

The density-of-states (N_f) term in the leakage-current expression determines the amount of electric-field dependent barrier lowering. In typical cases, the electric field lowers the barrier enough to increase the thermionically emitted leakage current over the barrier by a factor of ~ 2 from 100 V/cm to 3000 V/cm. Although the original barrier height is a much more important term, it would also be advantageous to also maximize the density of states to decrease the electric-field dependent barrier lowering.

The matrix element j_{∞} is a constant to be determined by measurement. This matrix element differs somewhat from the temperature dependent A^*T^2 matrix element for Schottky barriers. The parameter A^* is the Richardson constant. The temperature dependence of the Schottky matrix element arises from calculable transition probabilities from extended states in the metal contact to extended states in the crystalline material. The comparable matrix element for the amorphous-crystalline heterojunction is not readily calculable because it involves transitions from localized states on the amorphous side of the junction to extended states on the crystalline side of the junction. Experimentally, j_{∞} does indeed appear to be a constant with respect to temperature. It will be interesting to understand the fabrication parameters affecting j_{∞}. If possible, j_{∞} will be minimized to lower the leakage current.

The contact parameters N_f, φ, and j_{∞} will be determined by fitting the I(V,T) curves to our expression for leakage-current density. Together, these three parameters fully characterize the rectifying electronic properties of the amorphous germanium contact. By making many detectors under different sputter-deposition conditions, we will understand the relationship between fabrication parameters and the contact parameters.

In the past, we have made detectors that rely on amorphous germanium contacts for both hole- and electron-injection barriers. We usually deposit identical contacts on both sides of the germanium wafer. If the same contact is made on both sides of a detector, a symmetric barrier is formed. This would be comparable to mirroring the amorphous-germanium contact in Figure 2 onto both sides of the crystalline piece of p-type germanium. When a bias voltage is applied to such a detector, the contact at the higher potential will rectify as a hole-injection barrier while the other side forms an electron-injection barrier after full depletion of the carriers in the bulk. In such a situation, the sum of the hole-and electron-injection barriers is equal to the band gap, .7 eV. A large hole-injection barrier, say .42 eV, would result in a small electron-injection barrier, .28 eV. A relatively large amount of electron-injection current would result. For the purpose of making our strip detectors, we usually want both hole- and electron-injection barriers to be approximately the same size, ~ .35 eV. The work proposed here is different. Here we need to maximize the barrier for just one sign of charge injection - hole injection. An improved understanding of the parameters affecting the type and height of the charge-injection barrier formed by the amorphous germanium contact will be of great practical importance in the fabrication of segmented contacts for p-type coaxial detectors. In addition, such an understanding stands on its own as an interesting piece of semiconductor physics.

CONCLUSIONS AND RECOMMENDATIONS

After many different fabrication parameters have been studied with the planar test detectors, we will choose the best method and make a more elaborate detector to evaluate the optimum fabrication technique for a coaxial-like detector. The detector will have 8 segments. It will be called MJ1. Figure 3 shows a drawing of MJ1. This detector will be a small p-type pseudocoaxial detector. It will be approximately 4 cm in diameter and 2 cm thick. The crystal will be ground into a right cylinder with one end having a rounded edge as shown in the drawing. The electron-injection barrier will be a small boron implanted spot in the middle of the larger flat surface of the detector. The outer diameter and rounded top of the detector is the sputtered amorphous-germanium hole-injection barrier contact. The amorphous germanium contact will be segmented into eight elements or pixels.

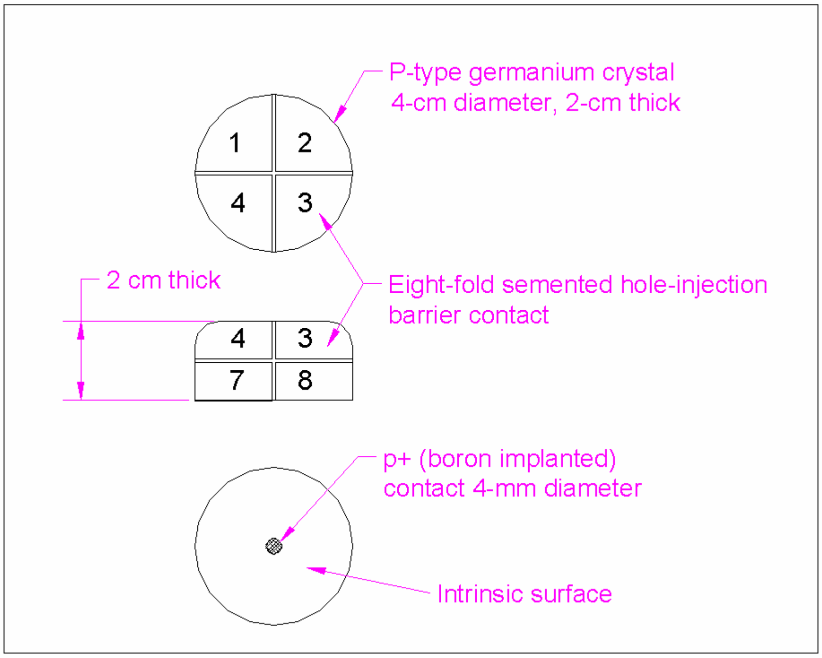

Figure 3. A technical drawing shows the segmented p-type pseudocoaxial detector (MJ1) having a segmented outer hole-injection barrier contact. Successful development of this detector is a key step in the establishment of amorphous germanium contacts as viable hole-injection barriers on p-type coaxial detectors.

Once the detector is functioning it will serve as a demonstration of the viability of the amorphous germanium contact for the hole-injection barrier on a segmented p-type coaxial detector. The detector performance will be evaluated. Later in the project, larger more sensitive segmented p-type coaxial detectors will be fabricated for low background highly sensitive gamma-ray detectors. These detectors will be ideal candidates for nuclear explosion monitoring systems such as the RASA.

REFERENCES*:*

Miley, H, S., R. J. Arthur, R. L. Brodzinski, W. K Hensley, J. H. Reeves, and F. T. Avignone (1991), Low Background Detectors for Exotic Physics Experiments, *Proceedings of the 4th International Workshop on Low Temperature Particle Detectors*.

Miley, H. S., F. T. Avignone, R. L. Brodzinski, J. I. Collar, and J. H. Reeves (1990), Suggestive Evidence for the 2-Neutrino Double-Beta Decay of Ge- 76. *Physical Review Letters* 65: (25), 3092-95.

Majorana Collaboration White Paper, The Majorana Zero-Neutrino Double-Beta Decay Experiment, LA-UR-2003-7709 and P. N. NL-14420. November 3, 2003, http://majorana. pnl. gov/MajoranaWhitePaper. pdf

Luke P. N., C. P. Cork, N. W. Madden, C. S. Rossington, M F. Wesela (1992), Amorphous Ge bipolar blocking contacts on Ge detectors, *IE. E. E Trans. Nucl. Sci.* 39(4), 590

Hull E. L., M. T. Burks, C. P. Cork, W. Craig, D. Eckels, L. Fabris, A. Lavietes, P N. Luke (With Madden, R. H. Pehl, K. P. Ziock) (2002), A germanium orthogonal strip detector system for gamma-ray imaging, AIP Conference Proceedings, *Unattended Radiation sensor systems for remote application*, 632**,** Washington, DC, 118.

Hull E. L. (2003). Germanium Detectors for Gamma-Ray Imaging, In *Radiation Detection Technologies Program, R & D Portfolio*, Eds. Spears DP and Alonzo GM, Albuquerque, NM, Dec 9-11, 22.

Hansen W. L., E. E. Haller (1977). Amorphous germanium as an electron or hole blocking contact on high-purity germanium detectors, *IE. E. E Trans. Nucl. Sci.* 24: (1) (1977), 61.

Pehl R. H., N. W. Madden, D. F. Malone, C. P. Cork, D. A. Landis, J. S. Xing, D. L. Friesel 1989). A variable temperature cryostat that produces in situ cleanup of germanium detector surfaces. *IE. E. E Trans. Nucl. Sci.* 36(1), 190-193.

Hull E. L., R. H. Pehl (Accepted for publication September 13, 2004). Amorphous germanium contacts on germanium detectors, *Nucl. Instr. and Meth.*

Döhler G. H. and M. H. Brodsky (1974). Amorphous-crystalline heterojunctions, in *Tetrahedrally Bonded Amorphous Semiconductors*, in American Institute of Physics, Eds. Brodsky, Kirkpatrick, and Weaire, New York (1974), 351-356.

Pehl R. H., E. E. Haller, and R. C. Cordi (1973). Operational Characteristics of Germanium Detectors at Higher Temperatures, *IE. E. E Trans. Nucl. Sci.,* 20, 494.

Döhler G. H. and M. H. Brodsky (1974). Amorphous-crystalline heterojunctions, in *Tetrahedrally Bonded Amorphous Semiconductors*, Eds. Brodsky M. H., Kirkpatrick S, Weaire D, NY, 351-356.

Hansen W. L., E. E. Haller (1977). Amorphous germanium as an electron or hole blocking contact on high-purity germanium detectors, IE. E. E *Trans. Nucl. Sci.* 24: (1), 61.

Hull E. L. (2003). Germanium Detectors for Gamma-Ray Imaging, In *Radiation Detection Technologies Program, R & D Portfolio*, Spears D. P. and Alonzo G. M., Eds, 22.

Hull E. L., M. T. Burks, C. P. Cork, W. Craig. D. Eckels, L. Fabris, A. Lavietes, P. N. Luke, N. W. Madden, R. H. Pehl, K. P. Ziock (2002). A germanium orthogonal strip detector system for gamma-ray imaging, AIP Conference Proceedings, 632**,** *Unattended Radiation Sensor Systems for Remote Application,* 118.

Hull E. L., R. H. Pehl (Accepted for publication September 13, 2004). Amorphous germanium contacts on germanium detectors, *Nucl. Instr. and Meth.*

Luke P. N., C. P. Cork, N. W. Madden, C. S. Rossington, M. F. Wesela (1992). Amorphous0 Ge bipolar blocking contacts on Ge detectors, IE. E. E *Trans. Nucl. Sci.* 39: (4), 590.

Majorana Collaboration White Paper, The Majorana Zero-Neutrino Double-Beta Decay Experiment, LA-UR-2003-7709 and P. N. NL-14420. November 3, 2003, http://majorana. pnl. gov/MajoranaWhitePaper. pdf

Miley, H. S., R. J., Arthur, R. L. Brodzinski, W. K. Hensley, J. H. Reeves, and F. T. Avignone (1991). Low Background Detectors for Exotic Physics Experiments, in *Proceedings of the 4th International Workshop on Low Temperature Particle Detectors.*

Miley, H. S., F. T. Avignone, R. L. Brodzinski, J. I. Collar, and J. H. Reeves (1990). Suggestive Evidence for the 2-Neutrino Double-Beta Decay of Ge- 76. *Phys. Rev. Let*. 65: (25), 3092-95.

Pehl R. H., E. E. Haller, and R. C. Cordi, Operational Characteristics of Germanium Detectors at higher Temperatures, *IE. E. E*

Pehl R. H., N. Madden, D. Malone, C. Cork, D. Landis, J. Xing, D. Friesel (1989), A variable temperature cryostat that produces in situ cleanup of germanium detector surfaces, *IE. E. E Trans. Nucl. Sci*. 36: (1), 190-193.