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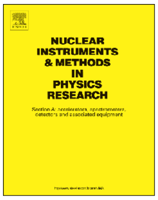

Leakage current in high-purity germanium detectors with amorphous semiconductor contacts

Q. Looker[a,b,*], M. Amman[a], K. Vetter[a,b]

[a] Ernest Orlando Lawrence Berkeley National Laboratory, University of California, Berkeley, California 94720, USA
[b] Department of Nuclear Engineering, University of California, Berkeley, California 94720, USA

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ABSTRACT

Amorphous semiconductor electrical contacts on high-purity Ge radiation detectors have become a valuable technology because they are simple to fabricate, result in thin dead layers, block both electron and hole injection, and can readily be finely segmented as needed for applications requiring imaging or particle tracking. Though significant numbers of detectors have been successfully produced for a variety of applications using the amorphous semiconductor contact technology, there remains a need to better understand the dependence of performance characteristics, particularly leakage current, on the fabrication process parameters so that the performance can be better optimized. To this end, we have performed a systematic study of leakage current on RF-sputter-deposited amorphous-Ge (a-Ge) and amorphous-Si (a-Si) contacts as a function of process and operational parameters including sputter gas pressure and composition, number of detector temperature cycles, and time spent at room temperature. The study focused primarily on the current resulting from electron injection at the contact. Significant findings from the study include that a-Si produces lower electron injection than a-Ge, the time the detector spends at room temperature rather than the number of temperature cycles experienced by the detector is the primary factor associated with leakage current change when the detector is warmed, and the time stability of the a-Ge contact depends on the sputter gas pressure with a higher pressure producing more stable characteristics.

1. Introduction

For decades, radiation detectors based on high-purity Ge (HPGe) have been the preeminent technology for gamma-ray spectroscopy when excellent energy resolution and good efficiency are required [1–4]. Detectors of this type that are used solely for spectroscopy can be simple in design and typically consist of a single piece of HPGe onto which two electrical contacts have been fabricated. These contacts are used for bias voltage application and signal readout, and must block charge carrier injection so that low leakage current is achieved and associated electronic noise is reduced. Well established and reliable processes exist for manufacturing such contacts. The industry standard utilizes B implantation to form a p^+, electron-blocking contact, while Li diffusion is used to form a thick and robust n^+, hole-blocking contact. The success of this technology has enabled its use for a wide spectrum of tasks ranging from those of basic science to the highly applied activities found in industry.

More complex than the simple spectrometer detectors are those that, in addition to measuring energy, also determine the positions of the radiation interaction events in the detector. These position-sensitive HPGe detectors are needed for applications requiring imaging or particle tracking in addition to excellent spectroscopy. In such detectors, the position measurement is often achieved by dividing or segmenting the electrical contacts into many strips or pixels and then reading out the signals from each of the contact segments. The conventional B implanted contact can be readily segmented [5–8]. However, the Li-diffused contact presents a challenge for segmentation as a result of its thickness and significant diffusion of Li at room temperature [9,10]. Practically, the segmentation of the Li contact is limited to a granularity of no better than about 1 mm [7]. Modern applications are demanding increasingly fine position resolution, meaning smaller contact structures, thereby limiting the applicability of Li-diffused contacts. Although thin n^+ contacts have been developed using P implantation [11,12], they are difficult to produce and are less robust than either B-implanted or Li-diffused contacts.

The amorphous semiconductor electrical contact has emerged as an important technology capable of providing finely segmented contacts on HPGe detectors with both electron blocking and hole blocking properties, and is thereby capable of replacing both the B implanted contact and the problematic Li diffused contact. The

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[*] Corresponding author at: Ernest Orlando Lawrence Berkeley National Laboratory, University of California, Berkeley, California 94720, USA.
Tel.: +1 510 495 2186.
E-mail address: qlooker@lbl.gov (Q. Looker).

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technology allows a simple fabrication process where the HPGe crystal is first coated with a high resistivity thin film of an amorphous semiconductor such as amorphous Ge (a-Ge) or amorphous Si (a-Si). This is then followed by depositing a patterned layer of metal, typically Al, on top of the amorphous film. The amorphous film dictates the charge blocking behavior of the contact and the metal defines the physical area of the contacts. Since the metal can be patterned using standard photolithographic processes, very fine contact segmentation can be achieved.

Amorphous Ge contacts were first experimentally investigated on crystalline Ge by Grigorovici et al. [13] and then later applied to Si radiation detectors by England et al. [14]. The use of the contacts on HPGe detectors was first demonstrated by Hansen and Haller in 1977 [15]. Hansen et al. also showed that a-Ge could be used to passivate the HPGe surfaces not covered with the electrical contacts and thereby control the charge state of these surfaces and make them less susceptible to change as a result of environmental exposure [16]. Over the years since the initial work on a-Ge, amorphous semiconductor contacts have been used to create position-sensitive detectors for x-ray and gamma-ray imaging [17–21], applied to Li-drifted Si detectors [22,23], shown to be appropriate for thin entrance window applications [17,24], used to create very fine contact segmentation [25], and enabled unique detector configurations such as field shaping [20,21] and proximity electrode signal readout [26,27]. HPGe detectors with amorphous semiconductor contacts have been successfully used or are being developed for a wide variety of application areas including space science [28–34], material science [25], nuclear and particle physics [35–37] medical imaging [38,39], nuclear nonproliferation and homeland security [40–43], and environmental remediation [44].

Despite the success of the amorphous semiconductor contact, additional work is needed in order to better understand the relationship between the process parameters used when fabricating the contact and the performance characteristics of the detector. With this understanding, better optimized electrical contacts can be produced. Earlier work of this nature revealed that undesirable charge collection to the detector surfaces between segmented contacts on HPGe detectors could be reduced by adjusting the properties of the amorphous semiconductor layer [20] and that a-Si produces a better electron blocking contact than that obtained with a-Ge [45,46]. In the work presented in this article, we have measured the bulk injected leakage current as a function of deposition parameters for RF-sputtered a-Ge and a-Si contacts. Our measurements have focused on the leakage current resultant from electron injection at negatively biased contacts. However, through a simple model of the contact, we argue that the results also provide useful information regarding the hole injection at positively biased contacts. Since our study focused on the impact of detector fabrication process parameters on detector performance, we first provide extensive details on the detector fabrication, detector testing, and data analysis. Following this, we present the results from our study and then end with a section summarizing the conclusions that can be drawn from our work.

2. Experimental methods

2.1. Detector fabrication

We fabricated a large set of small test detectors in order to examine the effect of altering amorphous film deposition parameters and identify critical factors determining performance and reliability. Multiple HPGe crystals from different sources were used, including material grown at LBNL several decades ago, ORTEC [47] material obtained more than a decade ago, and recently purchased ORTEC material. In this article, detectors made from these materials will be referred to as LBNL1, ORTEC1, and ORTEC2, respectively. All of these materials were p-type with approximate impurity concentrations of 9×10^9, 1.8×10^{10}, and 7×10^9 cm^{-3}, respectively. Several detector crystals were cut from a slice out of the three different boules. The main body of each detector crystal consisted of a square contact area measuring 18 mm on a side and a thickness perpendicular to the contact faces of about 10 mm (see Fig. 1). In addition to this active volume of the detector crystal were thin extensions (handles) protruding from the bottom side of the crystal. The geometry of the crystal and contacts is such that, during operation as a detector, the depletion region within the crystal never extends significantly into the handles. Since the handles remain undepleted, surface damage to the handles will not introduce leakage current. Consequently, the handles simplify detector fabrication and mounting during testing by providing an area of the crystal that can be handled without negatively affecting the detector performance.

To convert an HPGe crystal into a test detector for our study, the crystal was first cut to the shape shown in Fig. 1 using a diamond saw. Each of the exposed surfaces of the cut crystal was then lapped in order to remove any blade marks left by the cutting operation. The surface damage introduced by these mechanical processes was then removed by etching the crystal in a 4:1 nitric to hydrofluoric acid mixture. Following this surface polish etch, the crystal was again etched briefly in fresh 4:1 etchant, quenched in deionized water, rinsed in methanol, and blown dry with nitrogen in order to prepare the surfaces for the electrical contact depositions. During this etch and all subsequent processing steps, only the crystal handles were used to hold and manipulate the crystal. The crystal was then immediately loaded into an RF diode sputtering system. The first of two sputter depositions consisted of coating the top contact face and the sides of the crystal with a-Ge. The deposition was done with the crystal offset from the sputter target center and with rotation to ensure adequate coating of the crystal sides. The recipe used for this contact was approximately the same for all detectors and consisted of depositing the a-Ge with a 15 mTorr pressure of Ar with 7% H_2 gas mixture at a power of 300 W. This produced a film thickness on the top face of about 300 nm. The sputter target used was 8 in. in diameter and composed of 99.999% purity Ge obtained from American Elements

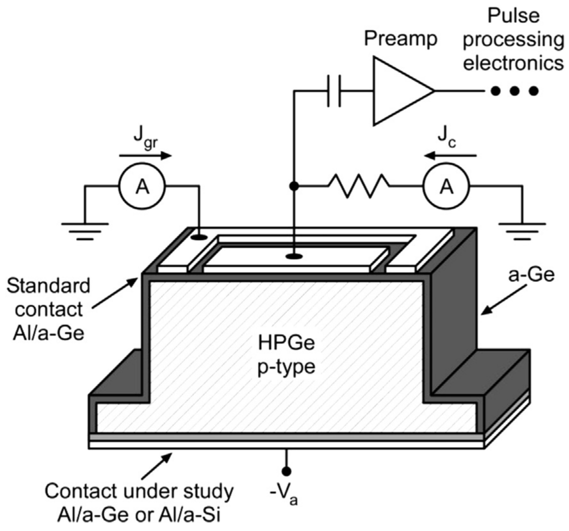

Fig. 1. Schematic cross-sectional drawing showing the geometry of the HPGe detector and the measurement circuit. The top electrical contact was produced using the same process for all detectors whereas the bottom contact varied from detector to detector and was the contact being studied. The top contact had the Al layer patterned into separate center and guard ring electrodes. The Al layer on the bottom covered the entire contact surface.