Ameliorating neutron damage in orthogonal-strip planar germanium detectors

E.G. Jackson^{*1}, E.L. Hull², C.J. Lister¹, R.H. Pehl²

¹*Department of Physics and Applied Physics, University of Massachusetts Lowell, Lowell, MA 01854*

²*PHDS Company, 3011 Amherst Road, Knoxville, TN 37921*

Abstract

The segmentation of the electrodes of germanium detectors facilitates gamma-ray imaging and tracking. Replacing the traditional n-type lithium drifted contact is a key to finer segmentation. Amorphous-germanium is a promising alternative contact technology, and large, highly segmented detectors have been fabricated. One factor in adopting any new detector technology is its robustness in hostile environments. Therefore, to explore the effects of neutron damage on position sensitive amorphous-contact germanium gamma-ray detectors and investigate methods for mitigation and repair of damage, two detectors were intentionally exposed to a non-uniform neutron fluence of greater than $4(1) \times 10^9$ n/cm² produced in the ${}^7\text{Li}(p, n){}^7\text{Be}$ reaction at the UMass Lowell Van-de-Graaff accelerator. Post-irradiation tests were made on the counters by varying the electric field, the charge deposition rate, the operating temperature, and utilizing various annealing cycles in order to ascertain the robustness of their performance after irradiation.

Keywords: gamma-ray detectors, X- and gamma-ray spectroscopy, germanium, radiation damage by neutrons, trapping, charge carriers in bulk matter

1. Introduction

Germanium detectors have proven to be the optimum gamma-ray spectrometers for five decades mainly because of their excellent energy resolution. This superior resolution,

^{*}Corresponding author.

12 even in very large crystals, is due to the small band-gap, uniformly high charge-carrier
13 mobility with little charge loss, and good charge collection at the electrodes. Segmenta-
14 tion of the electrodes has opened the way for germanium counters in which the positions
15 of charge creation can be localized at the 1 mm level, facilitating imaging and track-
16 ing. To achieve this degree of spatial resolution and maintain good charge collection the
17 electrodes need to be highly segmented, at the 5-10 mm pitch level, with very small inter-
18 strip gaps of <0.5 mm. This level of segmentation is difficult to achieve with traditional
19 high-temperature lithium-diffused n+ electrodes [1]. In early segmented planar counters,
20 a continuous lithium electrode was established and then segmented by saw-cutting. Later
21 counters used thin lithium deposition with segmentation achieved by masking. Either
22 way, the mobility of lithium prevented the reduction of inter-strip gaps below 1 mm.
23 Thus, to achieve excellent position resolution and retain energy resolution performance,
24 new electrode technologies are essential. This paper discusses germanium detectors with
25 highly segmented amorphous germanium contacts.

26 One of the challenges to any new gamma-ray detector technology is the robustness
27 to damaging radiation, particularly neutrons. In traditional-contact germanium detec-
28 tors, both co-axial and planar, the damage effects have been carefully studied [2, 3] and
29 techniques have evolved to mitigate neutron damage, particularly for n-type coaxial ger-
30 manium counters. In this current work the issue under investigation is the robustness
31 of position sensitive amorphous-contact planar germanium counters to neutron damage
32 and post-damage procedures to restore position and energy resolution. In this study we
33 have investigated detectors fabricated from p-type material. However, for planar “LEPS”
34 detectors, the charge collection of holes and electrons is symmetric, so the differences be-
35 tween annealing p-type and n-type planar detectors is expected to be much less than the
36 differences between p-type and n-type coaxial detectors.

37 Mitigating the effects of neutron damage is important to the continuing development
38 of germanium detectors as they are frequently employed in research settings involving
39 energetic (fast) neutrons, for example at accelerator facilities and on satellites. In these

40 settings, prolonged exposure to neutrons will damage the lattice structure of the germa-
41 nium crystals, creating hole trapping sites that result in a degradation of charge collection
42 and energy resolution, which must be remedied for the continued use of the detector. On-
43 line electronic signal manipulation and software methods of mitigating this damage are
44 useful in situations where removal of the detector from the experimental environment is
45 inconvenient (i.e. during accelerator runs) or impossible (i.e. deployment in space).

46 Eventually the accumulated neutron damage becomes too severe for these in-situ
47 methods and it becomes necessary to anneal the crystal to physically remove some of the
48 charge trapping sites. In-cryostat annealing has been proven to be reliable in traditional
49 coaxial n-type germanium detectors. The lithium and boron contacts on these detectors
50 have been verified to be robust enough to withstand repeated annealing cycles with no
51 loss of resolution and only a small reduction of efficiency.

52 This research was aimed at quantifying the level of neutron damage that can be
53 accommodated by position sensitive amorphous germanium contact detectors and as-
54 certaining at what point signal manipulation can no longer restore position and energy
55 performance. To this end we irradiated the detector with a non-uniform fluence of neu-
56 trons with the fluence highest in the center of the crystal. In this way, the damage can be
57 explored as a function of position. It is known that the degree of charge trapping centers
58 can be diminished by filling them with charge, so rendering them less effective. We have
59 studied this effect and its time constants. Beyond that, we have started to explore the
60 issues surrounding the high-temperature annealing of these p-type, amorphous-contact
61 detectors.

62 **2. Effects of neutron damage**

63 Germanium detectors, through normal operation, are damaged by fast neutrons. The
64 radiation damage in these detectors is in the form of disordered regions in the crystal
65 lattice caused by elastic and inelastic scattering of the neutrons. Atoms in the crystal
66 are displaced from their normal sites and relocate in interstitial positions, leaving behind

vacancies in the lattice [3]. These defects are not static and accumulate into larger disordered regions which form charge trapping centers. This dynamic behavior rapidly increases with temperature. The effect that these trapping centers have on the collected charge depends on the location of the interaction in relation to the electrodes collecting the charge. For example, if a photon interaction occurs near the electron-collecting contact, the holes have to traverse the entire thickness of the detector to before being collected and are therefore at greater risk of being trapped.

3. The detectors

Three orthogonal-strip planar detectors were investigated in this work. The crystals were all p-type, high-purity germanium wafers which were 10 mm thick and 90 mm in diameter fabricated by PHDS Company of Knoxville, TN [4]. Both the segmented detector contacts were fabricated by amorphous germanium deposition in a manner discussed in [5, 6, 7]. Each detector had 16 strip contacts on each side with 5 mm pitch and 0.25 mm inter-strip separation [Figure 1, left]. The electrodes on either side of the wafers were arranged orthogonally such that their intersection created pixels 5 x 5 mm square. To maximize the active area of the circular wafer, the electrodes were not all of equal length. Contacts near the edge of the wafer were shorter and, as a result, there were a total of 232 active pixels in each detector. The three detectors used in this work are referred to by their manufacture number: NP3, NP6, and NP7. The detectors had impurity concentrations of $3.9 \times 10^9/\text{cm}^3$, $1.1 \times 10^{10}/\text{cm}^3$, and $6.0 \times 10^9/\text{cm}^3$, respectively.

The detectors were mounted in all metal-sealed circular cryostats, 32 mm behind thin (3 mm) aluminum front and back windows. The system had a small ion pump to maintain vacuum and was connected to a Stirling-cycle mechanical cooler which allowed the operating temperature of the detector to be adjusted over a wide range from 50 K to 150 K. Signals collected with SPECT32 readout system and Imager32 data acquisition software [8] [Figure 1, right].

Figure 1: (left) The planar germanium crystal used in the NPX-M detectors. Easily visible are the individual strips and guard ring. (right) The entire NPX-M system including mechanical cooler, digital electronics and data acquisition [4].

93 4. The neutron irradiation experiment

94 Neutrons for these damage studies were produced using the ${}^7\text{Li}(p, n){}^7\text{Be}$ reaction
 95 with a beam of 3.7-MeV protons from the UMass Lowell 5.5-MV Van-de-Graaff acceler-
 96 ator. The experimental setup is shown in figure 2. For a thin target at zero degrees, this
 97 reaction produces neutrons of 2.0 MeV. The lithium targets were evaporated onto a tan-
 98 talum backing in-situ in the target cone of the beam line while under vacuum. The target
 99 cone is the terminal end of the beam line where the beam line diameter tapers from 10
 100 cm to 2.5 cm. The target cone also houses the lithium oven for target preparation. The
 101 detectors were mounted directly downstream of the water-cooled tantalum beam dump
 102 with the front face of the germanium crystal ~ 71 mm behind the target. The detectors
 103 were maintained at 77 K for this irradiation. The AC-coupled (electron-collecting) elec-
 104 trode of the detector was placed closest to the target. However, the neutron irradiation
 105 was quite uniform through the crystal thickness; taking the interaction cross-section for
 106 2.0 MeV neutrons in germanium as 3.3 barns [9] their mean free path is 6 cm, so the
 107 intensity is only reduced by 15% passing through the 10 mm thickness of the crystal. In
 108 practice, this can be seen as an advantage of planar wafer counters in real experiments,
 109 as compared to large coaxial detectors, as most neutrons pass through the device without

any interaction at all.

Figure 2: (left) The experimental setup at the UMass Lowell 5.5-MV Van-de-Graaff accelerator. The (yellow) arrow shows the path of the protons on the main beam line. The dashed (red) circle encloses the NPX-M crystal and target cone with mounted ^7Li target (color online). (right) A close-up of the detectors position relative to the target.

The irradiation was split into several runs as the goal was to induce considerable damage without reaching the point where the detector ceased to function. After each run the resolution and line shape of the detector was checked to ascertain the onset of measurable damage. The flux was incrementally increased by changing the proton beam intensity and the target thickness. The neutron fluence seen by the detectors was calculated after each run by assaying the target in a calibrated germanium counting station. ^7Be is ideal for this type of assay as it emits a 477.6-keV gamma ray in 10.44(4)% of the decays and has a convenient half-life of 53.22(6) days [9]. Fresh targets on clean backings were evaporated before each run. On average, beam currents were between 10 and 15 μA . The ^7Li target had a thickness of $\sim 250 \mu\text{g}/\text{cm}^2$. This was sufficiently thin that the neutrons were almost mono-energetic. Restricting the beam intensity to $\sim 10 \mu\text{A}$ meant the damage was induced over a period of about two hours, so it could be monitored to reach a point of critical damage before total destruction of the detector. The measured ^7Be activity was equal to the integrated fluence of the neutrons. The

⁷Be assay was corroborated with two other counting methods. The planar detectors themselves were used to count the relative ⁷Be activity after each irradiation and a NE213 liquid scintillator was mounted 4 m downstream of the target to count neutrons. The non-isotropic nature of the neutron emission in the center-of-mass frame was also taken into account by using methods found in [9]. In addition, the distance of each pixel from the target was calculated and accounted for as central pixels were considerably closer to the neutron source than peripheral pixels. The combination of angular distribution in the center of mass, the center-of-mass to laboratory boost, and the change of solid angle of the pixels produced a variation of neutron fluence across the counter with the fluence at the edges of the detector 25% less than the fluence in the center of the counter. In all, the NP3 detector was irradiated with a maximum fluence of $6.1(1.0) \times 10^9$ n/cm² in 122 minutes and NP6 was irradiated to a maximum fluence of $4.1(1.0) \times 10^9$ n/cm² in 240 minutes. These numbers are slightly (15%) lower than in an earlier report [8], due to a more exact reappraisal of the detector position during irradiation, and represents the calculated fluence at the front face of the actual germanium wafer. The counter NP7 was not exposed to neutrons and was retained as a benchmark for subsequent comparative tests.

5. Spatial visualization of neutron interaction and damage

Pulse height spectra were produced for each of the 32 strips using a sealed ¹³⁷Cs source. In addition, energy spectra for each of the 232 pixels were produced by taking the average of both charges (electrons and holes) as collected by the two strips that define each pixel. Events with exactly one strip firing on each side of the detector were most clear-cut and easy to analyze. Because a pixel location was defined by two intersecting strips, pixel spectra could only be visualized when both sides of the detector were functioning. These pixel spectra always have better resolution than the two contributing strips.

Beyond the strip-level interaction location, the 2D interaction point could be improved

using the pulse on a strip and the induced signals from neighboring strips. An interaction in the center of a strip induces similar signals on its neighbors whereas edge interactions induce very asymmetric pulse heights. The time difference between the electron and hole signals was used to calculate the depth of the interaction. The time difference was collected into 24 bins through the 10 mm thickness of the detector. In total, the crystal was divided into nearly 451000 sub-pixels (voxels).

6. Results of neutron damage

After irradiation, an extensive series of tests were made on the counters. These mainly involved the response to 662 keV photons from ^{137}Cs sources. Figure 3 shows the effect the neutron fluence incident on a germanium detector. This 2D image was created by histogramming interactions with full energy deposition in a single pixel. An average was taken of the charge collected on both sides of the detector and events were histogrammed if they fell within a chosen energy window (here 662 ± 5 keV). Gamma-ray events affected by significant charge trapping (deficit) were outside this energy range and were therefore not included in the image. It was clear that the initial influence of neutron damage was the loss of good events in the center of the counter, mainly caused by the degraded collection of holes.

Figure 3: A germanium detector before (left) and after (right) exposure to a neutron fluence of $6.1(1.0) \times 10^9$ n/cm². These spectra were not corrected to ameliorate damage and dark areas (blue) show a deficit of collected charge (color online).

169 7. A software method for trap-correction

170 A software trap corrector has been developed [8]. The operating principle was to
171 locate the depth of the leading interaction in each pixel and empirically correct for charge
172 loss as a function of depth. This was achieved by use of a position- and depth-dependent
173 lookup table derived from data collected from a single-line source; a trap-correction
174 matrix.

175 After irradiation, the signals could be corrected for charge trapping by applying the
176 corresponding correction to each event. This had the effect of shifting the deficient
177 energies up to their correct energy value, canceling any distortions in the spectra from
178 neutron damage or any other trapping mechanism. This correction was made in real time
179 allowing the end user to make critical decisions during data collection without needing
180 to stop and process the data.

181 Figure 4 demonstrates the effects of the trap-correction on the centroid position and
182 resolution. With the trap-correction applied, the degraded peak was greatly improved.
183 The corrected peak (solid line) showed great improvement in both measures of resolution:
184 full-width-at-half-maximum (FWHM) and full-width-at-tenth-maximum (FWTM).

Figure 4: Pixel (24,7) in detector NP3 after neutron irradiation without trap-correction (dotted line) and with trap-correction (solid line). The trap-correction significantly improved resolution.

185 There are limits to the amount of charge trapping that can be corrected for using
186 this method. There must be significantly good charge collection such that there is still
187 a distinct full-energy peak that can be located for gain-matching in order to generate a
188 correction for that voxel.

189 **8. Effects of increased bias voltage: NP3**

190 One effective intermediate step to mitigate the effects of neutron damage was increas-
191 ing the electric field in the detector. The bias voltage establishes the electric field that
192 drifts the electrons and holes to their respective electrodes for collection. As described
193 by [10], the hole traps can be considered as potential wells with depths proportional to
194 the cross section of the trap. With a stronger electric field, the charge carriers experience
195 a larger force and are less likely to be trapped as the effective capture cross section is
196 reduced [8].

197 Before any temperature cycling was attempted with NP3, the bias voltage applied
198 to the crystal was increased to investigate this effect. Figure 5 shows the 2D histograms
199 of events within the same event selection criterion used previously. Starting from the
200 recommended full-depletion bias (+500 V) the voltage was increased in increments of 50
201 V. Only a modest increase to +650 V was needed to nearly eliminate the void in the
202 center due to poor collection of holes.

Figure 5: Data from NP3 illustrating the advantage of operating with increased bias after neutron damage. This data was collected before any temperature cycling. Lighter areas (green) show regions of high 662 keV charge collection efficiency, dark areas (blue) show low charge collection efficiency (color online).

9. Annealing cycles: low-temperature

Neutron damage sites are variable in position and strength depending on the temperature of the crystal. The operation of detectors at temperatures below that of LN_2 slows the formation of trapping centers, thereby increasing tolerance to damage, while elevation of temperature can be used to drive out trapping centers. This latter process is usually called annealing. Annealing is an established, if not completely understood, method for repairing lattice defects in germanium crystals. It can occur at room-temperature but is rapidly accelerated at elevated temperatures. Typically germanium is annealed at ~ 373 K and can be used to almost totally remove all neutron-induced trapping centers. Ex-

212 tensive work done in the 1970s identified temperature ranges and responses to annealing
 213 cycles for both n-type and p-type germanium detectors [2, 3, 9, 10, 11, and references
 214 therein].

215 In this work we were careful to maintain low (~ 77 K) temperatures during all post-
 216 damage initial tests. However, once voltage tests were complete, the detectors were
 217 both “room-temperature” (296 K) cycled. Detector NP6 was at room-temperature for
 218 21 days and NP3 was at this temperature for 10 days. Figure 6 shows the effects of a
 219 room-temperature cycle on the 2D charge-collecting map for NP6. Prior to cycling (left),
 220 the center portion of the crystal showed a diffuse area of increased charge trapping as
 221 demonstrated by a lack of events with equal charge collection on each set of contacts.
 222 After the cycle to room-temperature (right), the detector showed a larger and much more
 223 clearly defined area of charge-trapping. This was consistent with a germanium detectors
 224 response to the temperature cycle presented in [2] which reported severe hole-trapping
 225 with a detector annealed at 200 K for 15 hrs.

Figure 6: Detector NP6 before (left) and after (right) a temperature cycle up to 296 K. The hole trap variability due to the room-temperature thermal cycle is shown in the sharp delineation of the center area containing increased hole trapping of incident 662 keV gamma-rays.

226 After the NP3 detector was cycled to room-temperature it lost functionality, devel-
 227 oping a very large leakage current (discussed in section 12 below). Interestingly, the
 228 AC-coupled (electron-collecting) side of the detector remained operational with reason-

able resolution but the DC-coupled side showed no observable signals due to high leakage
current even at very low electric fields.

10. Post-annealing effects of increased bias voltage: NP6

In figure 7, we show data from neutron-damaged detector NP6 with various applied
biases after the cycle to room-temperature. The normal depletion voltage for this crystal
was +800 V. Using the 2D map of charge collection it was clear that as the bias was
increased, the donut-shaped damage pattern due to incomplete hole collection was sig-
nificantly reduced. With this detector, the bias could be increased to +1100 V, a nearly
40% increase above the recommended voltage.

Figure 7: Data from NP6 illustrating the advantage of operating with increased bias after neutron damage. Lighter areas (green) show regions of high 662 keV charge collection efficiency, dark areas (blue) show low charge collection efficiency (color online).

238 11. Correlation of neutron flux and detector performance

239 Figure 8 shows the distribution of the neutron fluence across one middle strip (strip
240 24) on the DC (hole-collecting) side of the NP6 detector. The maximum fluence, $4.1(1.0)$
241 $\times 10^9$ n/cm², was deposited in the center pixels. The fluence dropped to 75% on the
242 outer most pixels. For pixels at the edge of the detector, 0-3 and 12-15, the resolution
243 remained good and could be measured to less than 1 keV. Somewhat surprisingly, where
244 the neutron damage was worst and the peak was shifted by hundreds of keV, pixels 5-10,
245 a clear photopeak was still evident and the centroid could be determined to 2 keV. Only
246 in pixels 4 and 11, in the transition region, was the centroid difficult to determine. A
247 plausible explanation for the sudden onset of poor charge-collection was that the damage
248 had become sufficiently bad that the central region of the counter was no longer fully
249 depleted. This would be especially deleterious for the hole-collection. This would also
250 be consistent with the beneficial effect of increasing the bias voltage. From figure 8 we
251 can conclude that the fluence seen by pixels 4 and 11 was approximately 3×10^9 n/cm²,
252 which corresponds to the neutron flux level required to trigger this effect in these wafers.

Figure 8: The correlation of high incident neutron fluence and the poor performance of the center pixels within strip 24, on the DC (hole-collecting) side of NP6. Peak centroids are shown as blue diamonds and neutron flux is shown as green triangles (color online).

12. Annealing cycles: high-temperature

To fully eliminate the hole trapping from the neutron damage, high-temperature annealing was studied. Amorphous-contact detectors have not been previously annealed. The annealing process in normal n-type detectors is usually done at 100-110 C (373-383 K) for 2-4 days. Lower temperature annealing for a longer time has a similar effect. Slow heating has the additional benefit of keeping outgassing rates low and cryostat vacuum good. For the counters in this study, the strategy was to start with long, lower-temperature cycles at 70 C and become more aggressive with experience. We heated NP6 from 273 K to 345 K, using an internal power resistor, over a period of 2 days as dictated by the outgassing rate. The internal vacuum during outgassing and annealing was inferred from the current drawn by the internal ion pump to be $\sim 10^{-3}$ to 10^{-4} Torr. The NP6 detector was then annealed for 3 days before re-cooling.

After cessation of heating and cooling to room-temperature, the mechanical cooler was restarted and signals investigated. It was found that even this conservative annealing

267 procedure was too aggressive and the detector did not recover sufficiently to ascertain if
 268 the neutron damage trapping effects were reduced. The NP6 detector showed very high
 269 leakage current with reasonable signals (FWHM ~ 6 keV) for the AC-side of the counter,
 270 but saturation of the DC preamplifiers, so no signals could be observed. The leakage
 271 current through each strip was < 1 nA when the detector was functional, even at a full
 272 bias of 600 V. After the annealing cycle this current was > 20 nA, even when the bias
 273 voltage was 100 V, leading to the saturation of the DC preamplifiers. Such a dramatic
 274 change could arise from failure of the rectifying contacts or from surface contamination
 275 of the crystal creating a low-resistance surface by-pass route.

276 **13. Effects of source strength**

277 It is empirically well known that the performance of neutron-damaged detectors can
 278 be improved by flooding the detector with charge (for example by placing strong gamma
 279 sources close to the counter) until trapping centers get dynamically “loaded” and have
 280 a reduced capacity for signal degradation. Similar studies were undertaken in [10] with
 281 bias voltage transient effects on resolution and capacitance. We have tried to quantify
 282 these effects for our NPX detectors.

283 A $30 \mu\text{Ci } ^{137}\text{Cs}$ source was placed 13.6 cm from the center of a wafer on the DC
 284 (hole-collecting) side. At this distance, a count rate of approximately 5×10^3 counts
 285 per second was recorded in the central strips. Despite the source strength, this rate is
 286 quite modest as the detector is thin: 10 mm of HPGe transmits nearly 67% of 662 keV
 287 gamma-rays [12], compared to 13% transmission for a 7 cm thick co-axial detector.

288 The source was then moved to ~ 3.5 cm from the germanium wafer and the resolution
 289 was recorded for the following 120 minutes. With the source at 3.5 cm, the center strip
 290 count rate was approximately 4×10^4 counts/sec. In figure 9 (top), we see that as
 291 the count rate increases by a factor of 10, the resolution improved from approximately
 292 4.5 keV to 3.9 keV (FWHM) for NP6. The FWTM showed even greater improvement
 293 measuring approximately 12.3 keV at time zero and improving to nearly 9.7 keV in 120

minutes.

The reverse procedure was then followed starting with the source 3.5 cm from the germanium wafer, allowing the count rate to stabilize, and then moving the source to 13.6 cm. In figure 9 (bottom), we found the opposite behavior as the resolution for NP6 began at 3.9 keV and degraded to nearly 5 keV (FWHM) over 120 minutes. The FWTM behaved similarly starting at 9.7 keV and degraded to 12.7 keV.

Figure 9: Resolution vs. time after a 30 μCi ^{137}Cs source was moved from ~ 13.6 cm to ~ 3.5 cm (top) and ~ 3.5 cm to ~ 13.6 cm (bottom) from the face of the detector. The FWHM is shown with solid data points, FWTM with open data points.

Data from these saturation studies were fit to an exponential curve and the time

301 constants of the saturation or emptying of the traps were extracted. For trap emptying,
 302 NP3 and NP6 had very consistent characteristics with a 12(1) min time constant for both
 303 FWHM and FWTM. For trap saturation, the situation was more complicated with the
 304 FWTM saturating with a constant of 18(2) min and the FWHM continuing to improve
 305 with a time constant of 30(3) min. The NP7 counter was also tested in the same way and
 306 showed that these saturation and emptying effects were completely absent. Therefore,
 307 these effects are related only to neutron-damaged detectors.

308 **14. Applications and conclusion**

309 Large segmented planar germanium detector technology is still in its infancy, but has
 310 huge potential both for academic research and many practical applications, especially
 311 in gamma ray imaging. One promising academic application is “superheavy” element
 312 spectroscopy. Here, the production cross-sections for the nuclei of interest are tiny, but
 313 the production reactions generate huge backgrounds of both gamma rays and neutrons.
 314 Current arrays of large coaxial detectors cannot survive this hostile environment, so “in-
 315 beam” spectroscopy is not possible. It appears that segmented planar technologies may
 316 provide a solution. The x-rays and gamma rays from superheavy elements are low in
 317 energy (100-500 keV), while the gamma backgrounds are much higher (~ 1000 keV), so
 318 a thin detector is advantageous. The high degree of segmentation and short charge drift
 319 distances allow a single crystal to count at gamma rates approaching 1 MHz. In this work
 320 we have examined the effects of neutrons on this type of counter. The thin geometry is
 321 advantageous here too, as most energetic neutrons are transmitted without interaction.
 322 Consequently, the tolerance to neutrons is quite good. However, improving this response,
 323 especially the ability to withstand high temperature annealing is critical.

324 In this work two double-sided amorphous-germanium strip detectors were intention-
 325 ally exposed to a neutron fluence in excess of $4(1) \times 10^9$ n/cm² to investigate the effects
 326 of neutron damage on their charge collection abilities. Various methods of mitigat-
 327 ing the damage, including a software trap-correction algorithm, over-biasing, and low-

328 temperature annealing were investigated before more drastic repair methods were needed.
329 The point at which the neutron damage became so severe that photopeaks became hard
330 to locate has a sudden onset and was most likely due to a loss of full depletion in that
331 area of the crystal. In this work we could quantify this fluence as $>3 \times 10^9$ n/cm², as the
332 irradiation was non-uniform across the counters. Neither detector survived the annealing
333 cycles. Prior to the neutron-damage studies, room-temperature cycling was performed
334 routinely, with NP7 being cycled more than a dozen times. Post irradiation, NP6 sur-
335 vived room-temperature cycling but failed after a high-temperature anneal. NP3 failed
336 after a single post-irradiation room-temperature cycle. While it was clear that there
337 was improvement in the performance of the damaged detectors with the trap-correction
338 software and over-biasing, full in-cryostat high-temperature annealing remains a work in
339 progress.

340 After these tests, both detectors were returned to PHDS and analyzed. The outcome
341 was different for the two detectors. The NP6 detector that was annealed at an elevated
342 temperature was found to be heavily damaged and has not recovered. NP3, the detec-
343 tor that failed the room-temp cycle, appeared to have had a contamination problem.
344 This detector is now functional. Our research into high-temperature annealing is con-
345 tinuing with PHDS as in-cryostat annealing is essential for many applications, especially
346 superheavy element research.

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