NEUTRON RADIATION DAMAGE ON A PLANAR SEGMENTED GERMANIUM DETECTOR*

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The resistance of a prototype planar electrically segmented p-type high-purity germanium (HPGe) detector to neutron damage and subsequent annealing procedures was investigated. The detector possesses 4 segment contacts made of laser-diffused Sb. To test its neutron resistance, the detector was subjected to a fast-neutron flux generated by the $^7\mathrm{Li}(p,n)^7\mathrm{Be}$ reaction. The detector underwent irradiation, annealing, and repeated irradiation to simulate prolonged operational conditions. Our study reveals the gradual deterioration in resolution and efficiency as neutron fluence increases. The detector's recovery after annealing was successfully demonstrated. The results highlight the importance of understanding neutron damage effects on p-type HPGe detectors. Further experiments and investigations are necessary to fully characterize this type of detector and understand all effects.

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1. Introduction

Since their inception, high-purity germanium detectors (HPGe) stood out for gamma-ray spectroscopy applications due to their excellent energy resolution, representing a major improvement over scintillators for gamma-ray detection. Germanium crystals utilized in the detector production are commercially available with a doping concentration of less than 2×10^{-4} ppb, and doping material will determine the type of germanium crystal, n-type

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if it has an excess of electron donor impurities and p-type if it has an excess of electron acceptor impurities [1]. In gamma-ray spectroscopy applications, HPGe often operates in high neutron radiation environments which are known to damage their structure creating charge traps and worsening the detector energy resolution. Once damaged, the detector's resolution can be recovered using annealing procedures.

The new generation of gamma-ray detector arrays, such as AGATA [2] and GRETA [3], relies on precisely identifying radiation interaction position within the crystal and, for this reason, make use of electrically segmented germanium detectors. This requires the creation of contacts which allow stable operation and do not alter the germanium crystal properties even when subjected to annealing procedures [4]. Currently, the detectors present in most spectrometers are n-type HPGe, with external boron implanted $p+$ segment contacts, and lithium diffused $n+$ central contacts [5]. This type of detector presents some limitations, the junction of the Li in Ge produces a very thin junction of the order of millimetres; it is not stable under annealing treatments, with a loss of active volume increasing over time [6], and prevents thin segments [5]. Moreover, the outer $p+$ contacts collect hole signals which are more prone to neutron damage, which degrade segments resolution, crucial for modern spectrometers to perform tracking algorithms. A working p-type detector, with thin outer $n+$ contacts, could significantly diminish the maintenance cost of large detector arrays, as electron-generated signals are more resistant to neutron damage than hole-generated ones [7], meaning they operate longer before needing an annealing procedure.

A prototype planar electrically segmented p-type HPGe detector was produced at the Laboratori Nazionali di Legnaro (LNL) under the Next Generation Germanium Gamma detector project (N3G). The prototype was produced with pulsed laser diffused Sb $n+$ contacts [4]. The tested prototype

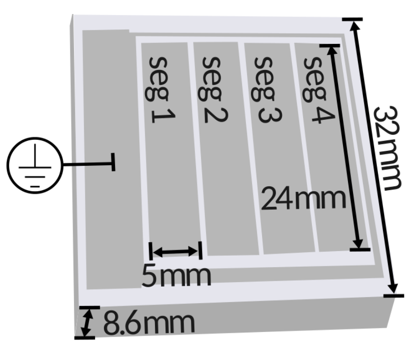

Fig. 1. Graphical representation of the frontal part of the detector. The segments are represented by the darker areas which are surrounded by a grounded contact called the guard ring.

is divided into 4 such segments plus a common $p+$ contact made with pulsed laser diffused Al. It is assembled in a planar geometry having a square front of 32×32 mm with a thickness of 8.6 mm and the segments are arranged as shown in figure 1. In this work, the prototype is subjected to a controlled fast-neutron flux to investigate its resistance to neutron damage and annealing procedure. The neutrons were produced in the CN accelerator at the Legnaro laboratories using the $^{7}\mathrm{Li}(p,n)^{7}\mathrm{Be}$ reaction, with a beam energy of 4 MeV and 380 nA beam current. The objective was to observe the worsening of its resolution and quantify it as a function of the neutron fluence.

2. Experimental details

The experimental procedure to test the detector's resistance to neutron damage consisted of several steps. First, the detector was characterized to determine its resolution and efficiency values, operational bias voltages, and leakage current. The second step was to irradiate the detector with neutrons to determine if a worsening of its resolution was observable and create an experimental procedure to measure it. The third step was to perform an annealing procedure and check if the detector returned to its initial operation condition. The last step was to slowly irradiate the detector again, carefully monitoring the neutron fluence.

To characterize the detector, the energy resolution and efficiency were tested for multiple operational voltages. The HPGe crystal and its cold preamplifier electronics (including the Field Effect Transistors) were mounted into a cryostat to be kept at liquid nitrogen temperatures for signal integrity, while the warm preamplifier electronics were mounted outside the detector encapsulation. The experimental setup for the characterization was composed of the assembled detector, the ^{241}Am and ^{60}Co radioactive sources, low- and high-voltage power supplies for the electronics and to polarize the detector to its operational bias, and an AGATA digitizer. The initial procedure consisted of acquiring source runs for 10 minutes for different bias voltages and observing the resolution and efficiency of the detector triggering on the segments. The source was centred 9.5 cm away from the target with the detector segments facing it. The predicted total depletion of the detector would be achieved for a bias voltage of 400 V. However, it was not possible to operate at such a high voltage without damaging the detector due to the high leakage current (> 50 nA). After discarding problems related to the temperature and crystal impurities, the most likely hypothesis for the leakage current is that small surface defects may have arisen from the multiple mounting and dismounting cycles of the crystal into the cryostat in which the probing pads for the signals might deform or scratch the surface of the contact. Further investigations are being performed to investigate it and improvements in the mounting procedure are being developed. The signal probes were composed of a gold tip contacting indium cylinders with 2 mm diameter and 1 mm height. Figure 2 (a) and 2 (b) shows the energy resolution and counts of the 59.5 keV gamma-ray peak of the ^{241}Am as a function of the operational voltage, respectively. The energy resolution for the operational bias voltages stayed around 1.0 and 1.2 keV for the ^{241}Am gamma-ray peak. It is possible to observe a worsening in the resolution after 250 V due to the increase in the current passing through the detector as can be observed in figure 2 (c). The same procedure was applied for the 1332.5 keV ^{60}Co peak, where the resolution stayed below 2.0 keV for all segments. As the efficiency of this high-energy peak was very low, it was decided to rely mainly on the ^{241}Am data. The common contact was also tested and characterized reaching, a resolution of 6–7 keV for the 59.5 keV ^{241}Am peak. The reasons for such a bad resolution are under investigation, although it is already known that this contact is very sensitive to external noises and vibrations. Another part of this problem might be linked also to the incomplete depletion of the detector, as it was not operating at 400 V.

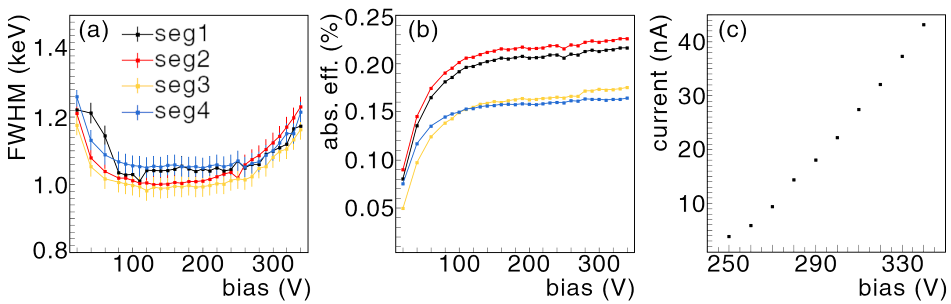

Fig. 2. (a) Detector energy resolution for the 59.5 keV gamma-ray peak of the ^{241}Am. (b) The same for the efficiency. (c) Current in the detector as a function of the applied bias voltage. This setup is sensitive only to values above 1 nA.

After its characterization, an experiment to damage the detector with neutrons was performed. A proton beam of 380 nA with 4 MeV energy hit a 100 μm ^{7}Li target to produce a ^{7}Li$(p,n)^7$Be reaction, where the exiting fast neutron is used to irradiate the detector the centre of which is positioned 9.5 cm away 30° from the beam line. The neutron fluence was monitored by measuring the activation of the target using a coaxial HPGe detector positioned 1 m away and 90° from the beam line. The counting of neutrons is only possible because the produced ^{7}Be decays beta with a lifetime of $\approx$ 53 days towards an excited state of the ^{7}Li that emits a 477.6 keV gamma ray. The experimental procedure consisted of setting an operational bias of 80 V to the detector and irradiating it with neutrons for a variable time interval that started at 20 minutes and ended at 2 hours. After each irradiation, a 5-minute run using ^{241}Am was taken to obtain its resolution and efficiency. After less than four hours of total neutron irradiation time, equivalent to $\approx 4 \times 10^9$ neutrons/cm^2, the detector was no longer able to produce gamma-ray spectra for the adopted operational bias. This result indicates that too much neutron damage was inflicted on the detector, preventing us from quantifying and observing the gradual change in the neutron flux. The lessons learnt from this first irradiation experiment were used to refine the irradiation procedure.

After the irradiation, an annealing procedure was performed to recover the detector back to working conditions. The annealing consisted of keeping the crystal at ≈ 110°C for 7 days. After such a procedure, the detector was again characterized using the ^{241}Am source and the results can be observed in figure 3. This time, the leakage current sharply increased for voltages above 170 V and, to keep all other parameters under control, we limited our tests to lower voltages. The higher efficiency of segments 3 and 4 was observed only during this measurement and it was discovered to be related to the mounting pressure of signal probes on the segments. In an attempt to overcome this issue, the probing pads were changed to indium cylinders with 4 mm diameter and 4 mm height and this efficiency difference was no longer observed in the following irradiation run.

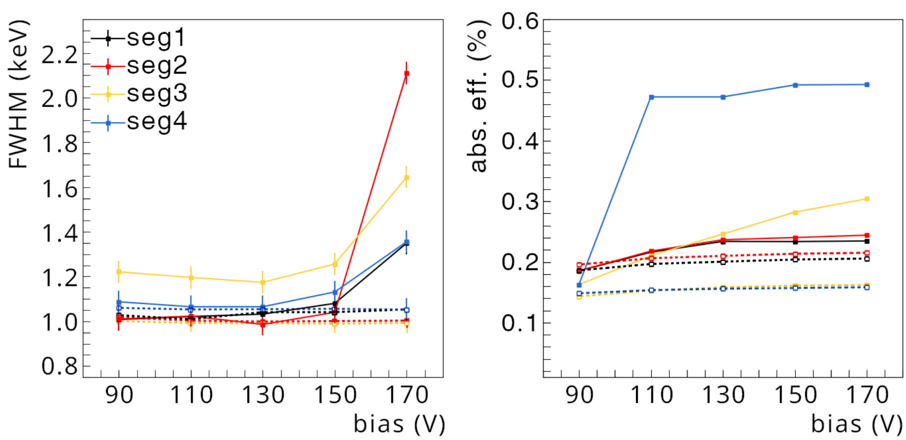

Fig. 3. Detector energy resolution and efficiency for different operational voltages after the annealing procedure for the 59.5 keV gamma-ray peak of the ^{241}Am. The dashed lines correspond to the data taken before the irradiation.

A second irradiation experiment was performed to irradiate the detector with neutrons. The same setup was exploited with the significant addition of a CLYC7 scintillator detector [8] to count the neutrons during the irradiation, adding a cross-check layer to the target activation measurement. The CLYC7 was positioned 2 m away at a 30° angle from the beam line. The experimental procedure was also refined proceeding with 20-minute irradiation runs and 5-minute source acquisition runs for 3 different operational biases. This procedure was kept until a quick worsening in the resolution and efficiency was noted, then it was changed to 2-minute irradiation runs, followed by 5-minute source runs. Figure 4 shows the experimental results, where it is possible to observe the gradual change in resolution and efficiency for the segments. The neutron fluence shown in the picture was obtained with the CLYC7 data, which is in complete agreement with the target activation measurement. The experiment indicates a slow deterioration of the detector resolution and efficiency until reaching a threshold, occurring at $\approx 3 \times 10^9$ neutrons/cm^2. After this point, the worsening in resolution and efficiency are drastic.

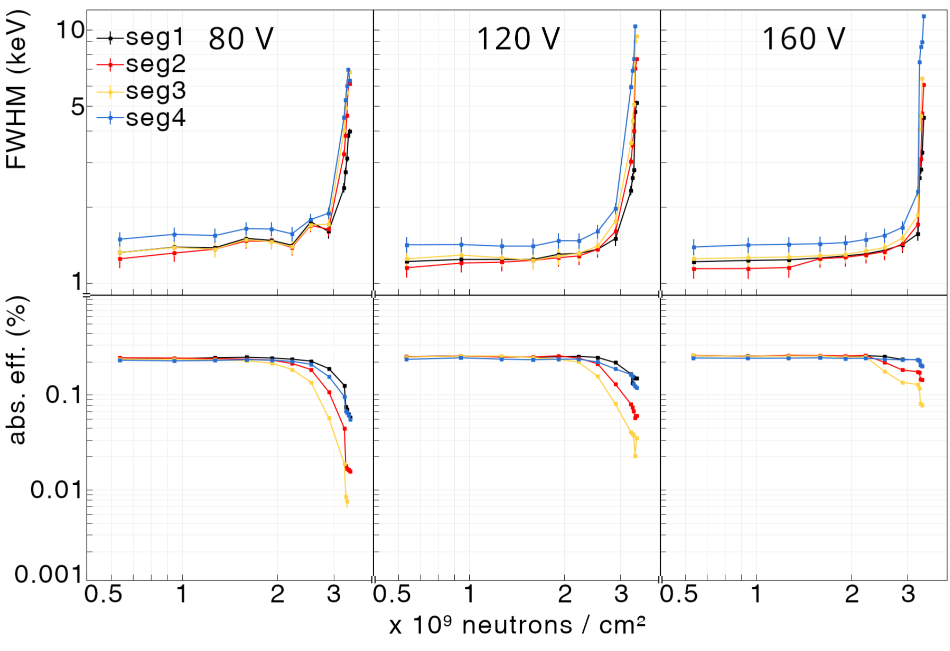

Fig. 4. Deterioration of the resolution and efficiency for the ^{241}Am 59.5 keV gamma-ray peak of the segments for different voltages as a function of neutron fluence.

3. Conclusion

The detector was irradiated with fast neutrons with doses of several 10^9 neutrons/cm^2. It was possible to observe a worsening resolution and efficiency caused by the neutron damage but the detector was successfully recovered after standard annealing procedures. A threshold effect was observed, meaning that after a certain fluence of neutrons, the resolution and efficiency deteriorate at a much faster rate. Improvements in the mounting procedure of the HPGe crystal into the cryostat are being evaluated to minimize problems related to the pad's mounting pressure. Several effects regarding the common contact of the prototype detector are currently under investigation and further experiments will be necessary to characterize and test it for its neutron damage resistance.

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