Application of GRAS Tool to study performance degradation of HPGe detector due to radiation damage

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Abstract:

When subjected to high energy particles, HPGe detectors degrade due to irradiation resulting in error in the output. Semiconductor detectors are generally used in areas where high level of accuracy is involved like nuclear security and space missions. Geant4 is an open source object-oriented simulation toolkit that offers a wide set of electromagnetic and hadronic physics models. GRAS is a Geant4 based tool that provides a general space radiation analysis for 3D geometry models. GRAS allows the definition of a multi-volume 3D geometry and incident particle source. Then, using the Geant4 toolkit it simulates radiation transport through the geometry of detector, treating electromagnetic and nuclear interactions. High energy neutrons have a major role in irradiation of semiconductor detectors and degradation due to these neutrons is considered. Total ionizing dose (TID) and Non-ionizing energy loss (NIEL) dose are calculated to study performance degradation in HPGe detectors.

1. Introduction

Excellent energy resolution makes high purity germanium (HPGe) detectors prime candidates for gamma-ray spectroscopy in fields like nuclear security or space missions. As a drawback for HPGe detector applications in nuclear security, radiation damage seems to limit their use in long term since the bombardment of subatomic particles degrades their energy resolution extensively. Radiation damage results in resolution loss, reduced timing quality as well as performance variability as function of time and temperature. The performance degradation analysis has been done using GRAS tool. GRAS [1] is a Geant4-based tool that provides a general radiation analysis for 3D geometry models. More specifically, GRAS allows the definition of a multi-volume 3D geometry and incident particle source. Then, using the Geant4 toolkit, it simulates radiation transport through the geometry, treating electromagnetic and nuclear interactions.

In spite of the seemingly complex interactions of radiation with matter, with the various dependencies of the interactions on the properties of the incident particle and target materials, in the end there are two essential consequences as far as effects on semiconductor devices are concerned: ionization [2] (generation of electron/hole pairs) and displacement damage [3] (dislodging atoms from their normal lattice sites). In general, particles passing through semiconductor materials deposit a portion of their energy into ionization and the remainder into atomic displacements.

HPGe detectors when used in the areas of nuclear security are generally damaged by high energy neutrons. For high energy neutron irradiation, the primary mechanisms for device degradation are attributed to atomic displacement damage, even though there can be considerable ionization associated with neutron interactions.

2.1 Displacement damage dose

A calculation of absorbed dose requires a specification of the radiation field at the point of interest, the knowledge of the cross-sections for interactions and a calculation of the energy of the recoiling atoms that lead to energy loss in the target volume [4]. It is assumed here that the range of the recoiling atoms is small compared to the dimensions of the target of interest. In the case of a monoenergetic beam of particles, the radiation field is characterized by the flux density, i.e. the number of particles per unit area per unit time. The integral of the flux over time gives the fluence, with units of particles per unit time. The integral over all angles of the product of the differential cross-sections for displacement and the resulting recoil energy of the target atom gives the energy loss. When this is multiplied by the atomic density, a quantity called the nonionizing energy loss (NIEL) is obtained. For elastic interactions the NIEL [5] can be calculated using,

$$NIEL = \frac{N}{A}\int L[T(\Theta)]\,T(\Theta)[\frac{d\sigma(\Theta)}{d\Omega}]d\Omega$$

where N is Avogadro's number, A is the atomic mass, $L[T(\Theta)]$ is the Lindhard Partition factor, which gives the fraction of transferred energy that is nonionizing, $T(\Theta)$ is the transferred energy due to an incident particle scattered through an angle Θ in the center of mass system, and $\frac{d\sigma(\Theta)}{d\Omega}$ is the differential cross-section for elastic scattering for particles scattered into a solid angle increment $d\Omega$. The integral has a lower limit, that is the scattering angle for which the recoil energy equals the threshold for displacement. For most semiconductors the displacement threshold energy ranges from ~ 5 < E_{th} < ~ 25 eV. Maximum energy transfer occurs for Θ = 180^{0}.

2.2 Ionization effects

An electron in the valence band is excited across the bandgap into a conduction band state, either as a direct result of interaction with an energetic charged particle or as the result of the decay of a plasmon excitation (the collective oscillation of a large number of valence-band electrons). Very rapidly (on the order of a picosecond), the excited electron in the conduction band and the hole left behind in the valence band lose their excess kinetic energy through lattice scattering and are "thermalized" in energy, falling to the vicinity of the conduction and valence-band edges, respectively. If an electric field is present, there will be net charge separation and, therefore, an electric current. These radiation-induced photocurrents can be a major problem in semiconductor junction regions. In ehp generation, a fraction of the kinetic energy of the incident particle is lost to ehp creation. The mean energy, needed to ionize a material is dependent on the bandgap of the target material. The number of ehps generated for a given dose is thus strongly dependent on mean energy as well as the material density.

3. Method

Simulations have been done online on SPENVIS, a WWW interface [6] to models the effects of sub-atomic particles on various geometries of particular density. GRAS has been designed to enable an easy implementation of the analysis of many radiation environment effects. The simulation is entirely driven via user interface (UI) scripting commands (interactively and via macro files). This includes the selection of the geometry model, the physics, the insertion of analysis modules, and for each module the definition of the relevant parameters, such as the volumes in which the analysis has to be performed, or the units for the result printout. The user can select the input format for the geometry model via UI commands. The present standard format is the geometry description markup language (GDML).

The shape of the HPGe detector model defined is given in Fig. 1. The top view is given in Fig. 2. An isotropic, spherical, monoenergetic neutron source of 3 mm diameter and energy, 15 MeV is simulated by keeping the detector at a distance of 50 mm from the source shown in Fig 3. The number of neutrons used in simulation is 10000 s^{-1}.

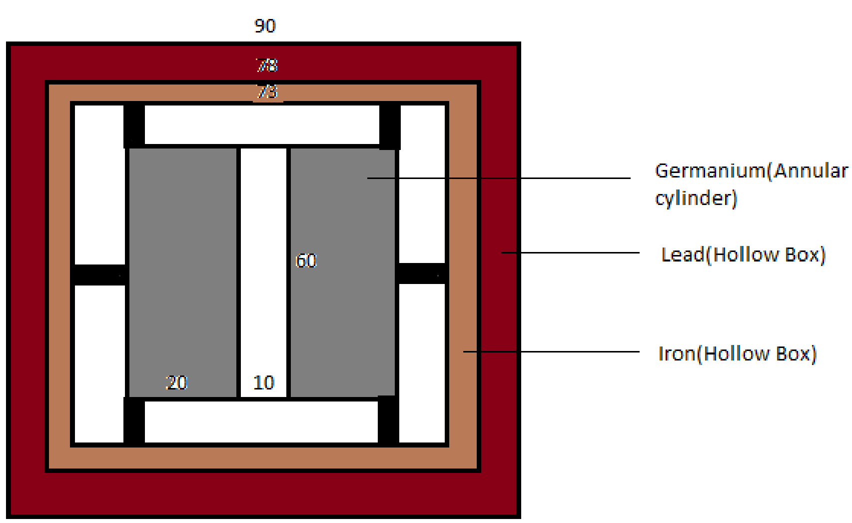

Fig. 1 Geometry of HPGe detector (Dimensions are in mm)

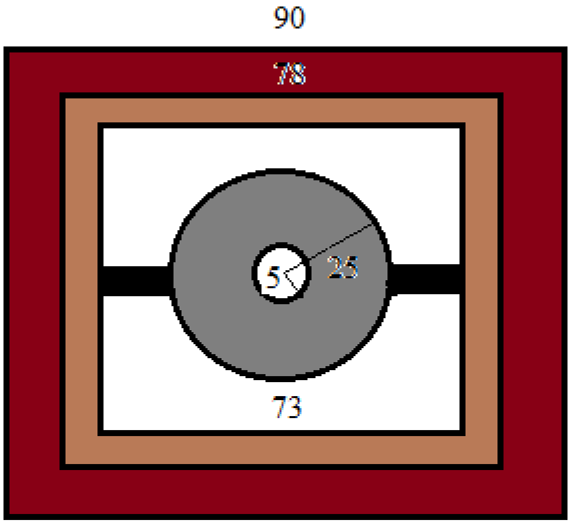

Fig 2. Top View of HPGe detector (Dimensions are in mm)

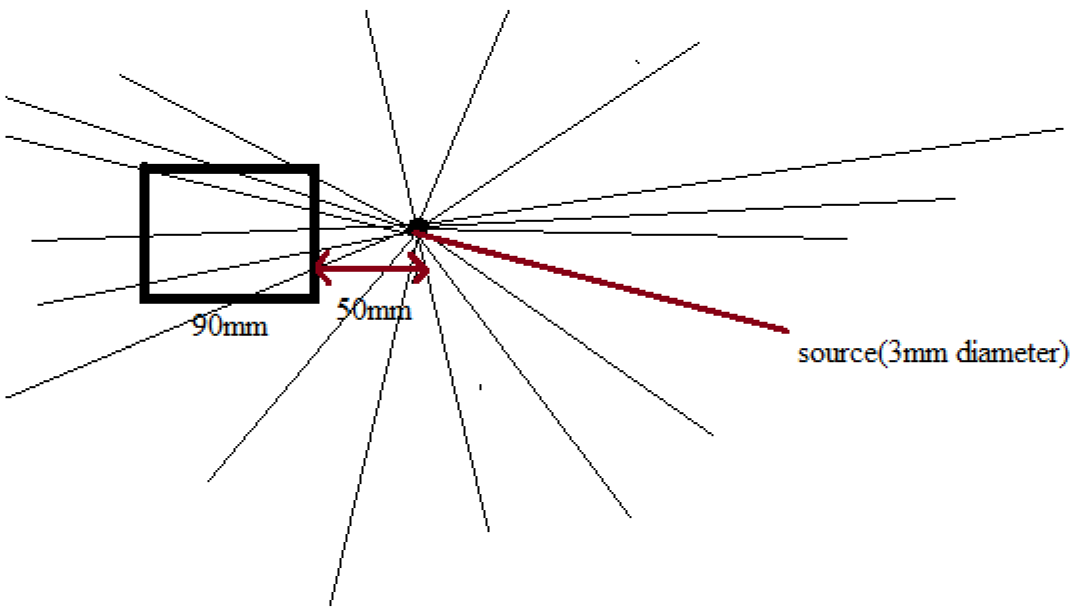

Fig 3. The simulation setup

4. Result

Non-ionizing energy loss (NIEL) and Total ionizing dose (TID) is calculated across the annular germanium cylinder defined in the detector geometry.

NIEL= $\boldsymbol{4.069\times10^{-3}\ MeVcm^2/g}$

TID = $\boldsymbol{3.001\times10^{-11}\ rad}$

5. Conclusion

A simple application of GRAS is shown to determine irradiation damage to HPGe detector. Results can be more accurate if we simulate the correct geometry of the detector. The geometry defined should resemble the actual design of the detector as far as possible. Incident particle interacts to form secondary particles can be taken into account. The parameters like equivalent dose and energy deposited at each layer can also be calculated. The radiation damage study of HPGe detectors is crucial because they are used by security agencies to identify radionuclides from their passive gamma ray emissions. For high energy neutron irradiation, the primary mechanisms for device degradation are attributed to atomic displacement damage, even though there can be considerable ionization associated with neutron interactions.

6. References

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