Comparative Study of Radiation damage in Si, Ge and Diamond used as Detector

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Introduction

Semiconductor materials are widely used in High Energy Physics (HEP) experiments for high precision tracking and vertexing. The typical choices are Ge, Si and Diamond. The properties like high signal to noise ratio, low material budget, fast response, radiation hardness make them more suitable detector materials over other possibilities for HEP experiments. In this paper I will present a comparison of radiation damage for Ge, Si and Diamond using simulation package FLUKA.

Radiation damage

There are two categories of radiation damage, namely, surface damage and bulk damage.

Bulk damage

Bulk damage happens in the bulk of a detector due to non-ionizing energy loss (NIEL). In the NIEL mechanism, particle loses energy by nuclear interactions e.g recoil of nucleus and bremsstrahlung. If it transfers enough energy to remove an atom from its site, it creates a vacancy and a displaced atom (interstitial). If a displaced atom has large enough energy, it can further create clusters of vacancies and interstitials (Frankel pairs).

Recoil energy of atom

In the case of elastic scattering between incident particles and lattice sites in the detector, a minimum kinetic energy (E_{min}) in the incident particles is necessary to impart the threshold displacement energies of 20 eV, 25 eV and 43.6 eV in the cases of Ge, Si and Diamond respectively. E_{min} is calculated by considering the two body elastic collision as given by Eq.(1) [2].

$$E_{min} = \frac{1}{2}\left[E_{rec} + \sqrt{E_{rec}^2 + 4m_p^2 + 2E_{rec}M_{atom} + \frac{2E_{rec}m_p^2}{M_{atom}}}\right] - m_p \quad (1)$$

Here, E_{min} represents minimum energy in the incident particles that can recoil a crystal atom by E_{rec}. M_{atom} and m_p refer to the masses of crystal atom and individual incident particles respectively. Here the energy and mass are in units of eV and eV/c^2 respectively. Table 1 shows the calculated value of E_{min} in different materials for different particles.

TABLE I: E_{min} of incident particles in eV

Particles	Silicon	Germanium	Diamond
Electron	255915	457390	199668
Muon	1560	3212	1176
Pion	1184	2434	896
Kaon	344	695	269
Proton	187	371	153
Neutron	187	370	153

Simulation details and results

The simulation to estimate the number of vacancies and interstitials in Ge, Si and Diamond was done in FLUKA employing USRBIN card for different energies of incident Pion and Proton. To cover the other aspects of transport and physics, the PART-THRES, MULSOPT, and FLUKAFIX cards available in FLUKA are used. In FLUKA, bulk damage is characterized by two quantities Displacement per atom (DPA) and Non-Ionizing Energy Loss (NIEL). The simulation uses a fixed dimension of $1 \times 1 \times 0.03\ cm^3$ for Ge, Si and Diamond detectors to compare the number of Frankel pairs produced per primary incident

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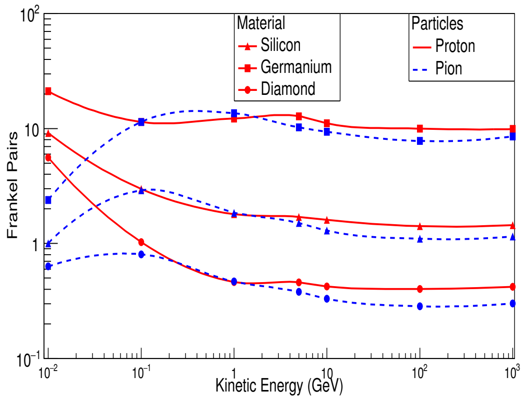

FIG. 1: Frankel pairs in Ge, Si and Diamond are plotted with kinetic energy of incident primary particle

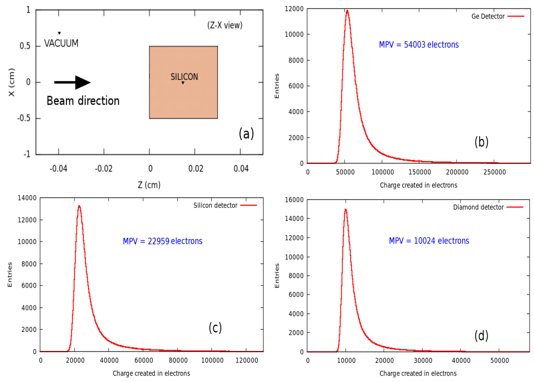

FIG. 2: (a) Geometry used in simulation for the comparison of charge for MIP in 300 μm thick (b) Ge , (c) Si and (d) Diamond sensors

particles at different energies. The Displacement Per Atom (DPA) is defined as

$$DPA = \frac{1}{\rho} \sum_i N_i N_F^i \qquad (2)$$

where N_i, N_i^F and ρ are particles per interaction channel i, Frankel pairs per channel i and density of material in atoms/cm^3 respectively. So the number of Frankel pairs is given by DPA $\times$ ρ, which are plotted on y axis of Fig 1. The Frankel pairs created inside the three materials deceases as kinetic energy of the incident particles increases.

Surface damage

Surface damage is due to the ionizing energy losses, when a charge particle passes through a semiconductor material, creating e-h pairs (simulated number of e-h pairs shown in Fig. 2). In the case of Si and Ge, some charges created in the oxide layer on the surface are not collected, leading to build up of charge in the oxide layer which works as a trapping center. Ionizing energy loss is responsible for the degradation of oxide layer. The surface damage is characterized in terms of total ionizing radiation Dose (Gy)(1 Gy= 1 Joule/Kg), this is long term effect on sensors and readout chips and calculated over an integrated period of 10 years for estimated fluence of particles. In the case of Diamond we have no oxide layer and we have Ohmic contact so the problem does not arise. The charge created by a Minimum Ionizing Particle (MIP) in 300 μm thick Ge, Si and Diamond sensors is calculated from the energy loss distributions by dividing it with mean energy of electron-hole pair creation energies.

Conclusion

The material with comparatively lesser number of Frankel will be a more suitable material for high energy and high luminosity experiments (as Frankel pairs increases signal to noise ratio decreases). The comparison shows that diamond has the least number of Frankel pairs per primary particle. Since there is no surface damage in Diamond, it comes out to be the most suitable material for radiation hard detector applications.

References

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[2] "Study of radiation effects on prototypes of the PANDA Micro Vertex Detector", Ilaria Balossino, *et al.*, pages 36-37, *Anno Accademico* (2012-2013)