EFFECT OF THE HEAVY IONS TO THE SILICON DETECTORS

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Silicon particle detectors are used in several applications such as accelerators in high energy physics, space, nuclear physics experiments and medicine. Thereby, it is crucially important to understand the effects of various particles with different energies on performance of silicon detectors. In this study, it has been focused on recoil heavy ions ($Z \geqslant 3$) produced by 50 to 500 MeV protons in silicon. In order to investigate the effects of the recoil heavy ions on silicon, it has been simulated some physical quantities such as variety, ranges, linear energy transfers (LET) and non-ionizing energy loss (NIEL) of the recoil heavy ions through GEANT4 (Geometry And Tracking) [1], FLUKA (FLUktuierende KAskade) [2] and SRIM [3] Monte Carlo tools.

Key words: LET, NIEL, Ion, Silicon, GEANT4, FLUKA, SRIM.

1. INTRODUCTION

When a charged particle (proton, heavy ion, alpha particle, recoils of nuclear interactions between proton or neutron and atoms of material) passes through a device and losses its energy by ionizing processes, if the charge accumulation resulting from holes and electrons released in electronic devices, circuits or systems by a single high LET particle is bigger than a critical charge, Single Event Effect (SEE) can occur and the electrical performance of the device or circuit may be affected. Effects on a semiconductor due to SEE can be destructive or nondestructive. While destructive effects result in catastrophic failure of device, nondestructive effects cause loss of data or control of electronic systems [4, 5].

The other energy loss mechanism is due to atomic displacements in a material. Energy loss by non-ionizing process is called NIEL. It has been claimed that NIEL results in the changes of electrical properties of semiconductor devices or electronic components. It is also a negative factor for the lifetime of electronic components or other devices [5].

In this work, atomic and energy spectrums of the recoils heavy ions from Z=3 to 15 as a result of interactions between 50 to 500 MeV protons and silicon have been investigated by using GEANT4 and FLUKA tools. LET of the recoil heavy ions have been simulated by using GEANT4 and SRIM tools and also NIEL spectrums of the recoil heavy ions have been obtained by using GEANT4 tool.

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2. SIMULATION AND RESULTS

2.1. PHYSICS

When protons traverse a material, they interact through atomic Coulomb interactions, and nuclear elastic/inelastic reactions. At energies below about 10 MeV, Coulomb interactions become dominate and the production of displaced atoms from their lattice sites can occur. At energies above 30 to 50 MeV, the nuclear interactions start to dominate. Then, the recoil heavy ions can be produced [6].

A simulation needs various physics models depending on types of interactions between particle and material. Physics list should contain electromagnetic physics, hadronic elastic and inelastic physics for proton energies studied here. `QGSP_BIC_EMY` reference physics list has been used in GEANT4 simulations. When `QGSP_BIC_EMY` is activated in a simulation, it defines hadronic models for nucleons (Quark Gluon String Pre-compound), inelastic models for ions (Binary Ion Cascade, BIC), and electromagnetic models for all particles (ElectroMagnetic Y, EMY) [7]. FLUKA covers a large class of physics models depending on the purpose to be used. Hadron-nucleon interaction models in FLUKA are based on resonance production and decay below a few GeV, while it is based on Dual Parton model for larger scales. Also, these two models are used in hadron-nucleus interactions. In case of elastic scattering, useful cross sections including nucleon-nucleon, nucleon-nucleus interactions are available in FLUKA. BME (Boltzmann Master Equation) is being used bellow 0.125 GeV per nucleon for nucleus-nucleus interactions [2].

2.2. ATOMIC AND ENERGY SPECTRUMS OF RECOIL HEAVY IONS

Distributions of the recoil heavy ions have been simulated, which are produced by protons with 50, 100, 200, and 500 MeV in silicon. We have used GEANT4 and FLUKA tools containing physics models mentioned above. Figure 1 shows histograms of the respective contributions from each nucleus for these proton energies. Some differences in numbers of some recoil heavy ions were observed in GEANT4 and FLUKA simulations as shown in Figure 1. For instance, it has been found that in FLUKA simulation, the number of magnesium recoils produced by 50, 100, 200 MeV protons are more than about 44%, 55% and 52% according to GEANT4 simulations, respectively. However, for 500 MeV protons, it has been observed that the number of magnesium recoils in GEANT4 simulation is more than about 67% compared to FLUKA simulation. Variety of the recoil heavy ions produced by interactions between proton and silicon in GEANT4 and FLUKA simulations were found to be consistent with the literature [8].

Energy transfers to the recoil heavy ions have been simulated for the incident proton energies of 50, 100, 200, and 500 MeV by using GEANT4 and FLUKA tools.

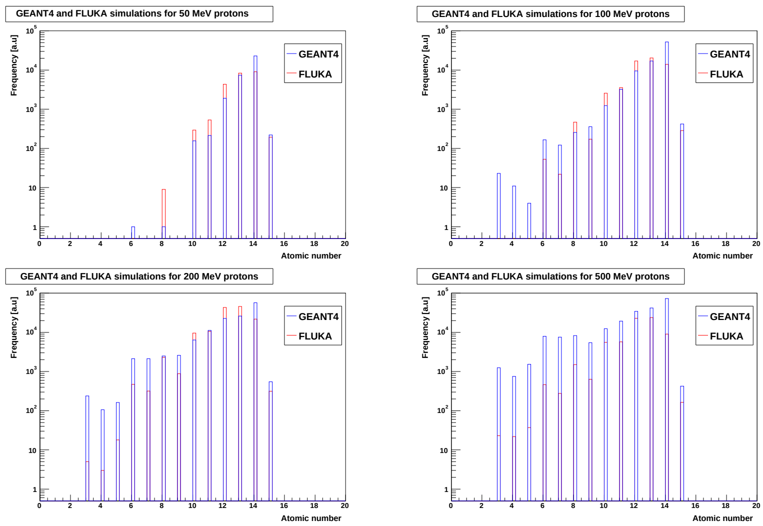

Fig. 1 – Recoil spectrums as a function of atomic number for 50, 100, 200 and 500 MeV protons on silicon by using GEANT4 and FLUKA tools.

Figure 2 shows the representative energy spectrums of carbon and magnesium recoils for protons in this energy range, respectively. It has been observed that the energy spectrums of carbon and magnesium recoils from GEANT4 simulation are mostly compatible with FLUKA simulation. Figure 2 shows the energy distributions of carbon and magnesium recoils produced by 50, 100, 200 and 500 MeV protons. It has been noticed that in FLUKA simulation, the maximum energy of magnesium recoils for 500 MeV protons is lower about 53% compared to GEANT4 simulation and literature [9]. Apart from that, the maximum energies of carbon and magnesium recoils for 50 to 500 MeV protons from GEANT4 and FLUKA simulations were found to be in good agreement with those cited in the literature [9].

2.3. LINEAR ENERGY TRANSFER (LET)

LET is defined as the energy loss per unit path length of a particle as it passes through a material. It represents energy fraction to ionization process. In other words, it is the rate at which energy is deposited by ionizing particles. LET is given in unit of the energy loss per unit path length (in MeV/cm) and it is normalized by the density of the target material (in $\mathrm{mg/cm^3}$) [4]. LET of the recoil heavy ions produced by 50 to 500 MeV protons in silicon has been simulated by using GEANT4 and SRIM tools. Figure 3 shows LET distributions as a function of energy of the recoil heavy ion. As shown in Figure 3, GEANT4 simulation are compatible with SRIM.

Figure 4 represents LET distributions for carbon, magnesium, aluminium and phosphorus recoils in silicon, which have been simulated by GEANT4 tool.

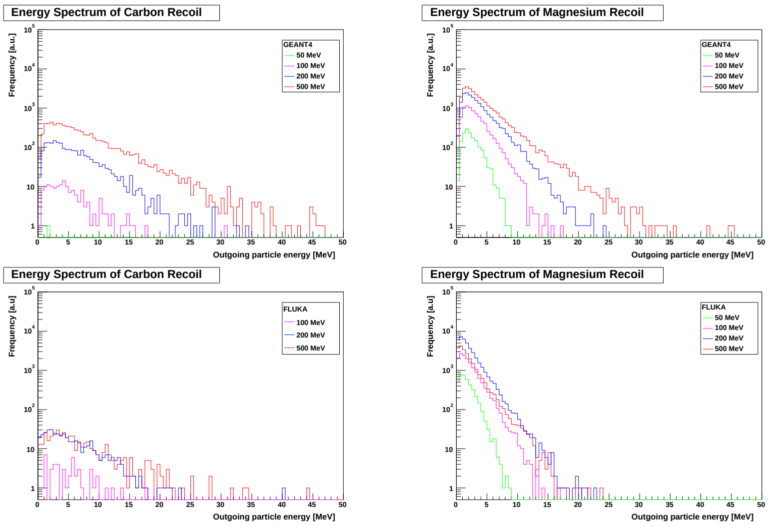

Fig. 2 – Energy spectrums of carbon and magnesium recoils for 50, 100, 200 and 500 MeV protons on silicon. GEANT4 simulation (top) and FLUKA simulation (bottom).

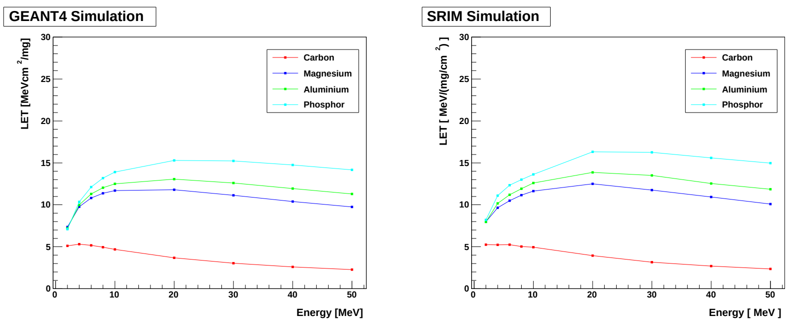

Fig. 3 – LET spectrums of some recoil heavy ions produced by 50, 100, 200 and 500 MeV protons on silicon. GEANT4 simulation (left) and SRIM simulation (right)

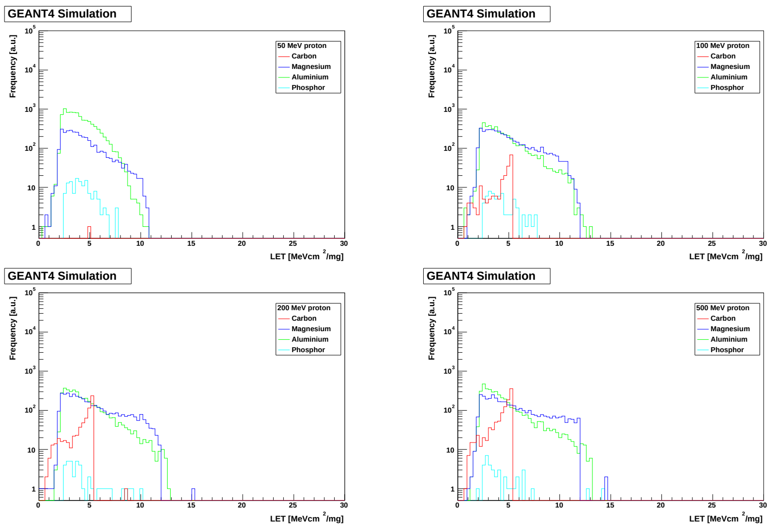

Fig. 4 – LET spectrums for carbon, magnesium, aluminium and phosphorus recoils produced by 50, 100, 200 and 500 MeV protons on silicon by using GEANT4 tool.

2.4. NON-IONIZING ENERGY LOSS (NIEL)

Another energy loss mechanism in a semiconductor can be due to NIEL, which is the analogue of LET for ionising events. NIEL represents the rate of energy loss due to atomic displacements during a particle traverses a material. NIEL shows the same function to the displacement damage energy deposition as the stopping power to the total ionizing dose (TID). NIEL is very useful for correlating effects of displacement damage caused by particles in semiconductor or optical devices [6]. NIEL is given in unit of the energy (in MeV) deposited in a material in GEANT4 simulation and it is divided by the density of the target material (in $\mathrm{mg/cm^3}$) and range (in cm) and it is converted to units of MeV $\mathrm{cm^2/mg}$.

Figure 5 shows distributions of non-ionizing energy deposited in silicon by some recoil heavy ions, which are produced by 50 to 500 MeV protons in GEANT4 simulations. It has been calculated damage energies and NIEL interaction rates for the recoils of carbon, magnesium, aluminium and phosphorus produced by 50 to 500 MeV protons from GEANT4 simulations. Table 1 represents GEANT4 simulation and literature [8] results of damage energy of the recoil heavy ions for 150 MeV protons. NIEL interaction rates of the recoil heavy ions for 150 MeV protons can be seen in Table 2.

It has been found that for carbon, magnesium, aluminium and phosphor recoils, NIEL and NIEL interaction rates obtained by GEANT4 are compatible with literature [8] as seen in Table 1 and Table 2, respectively.

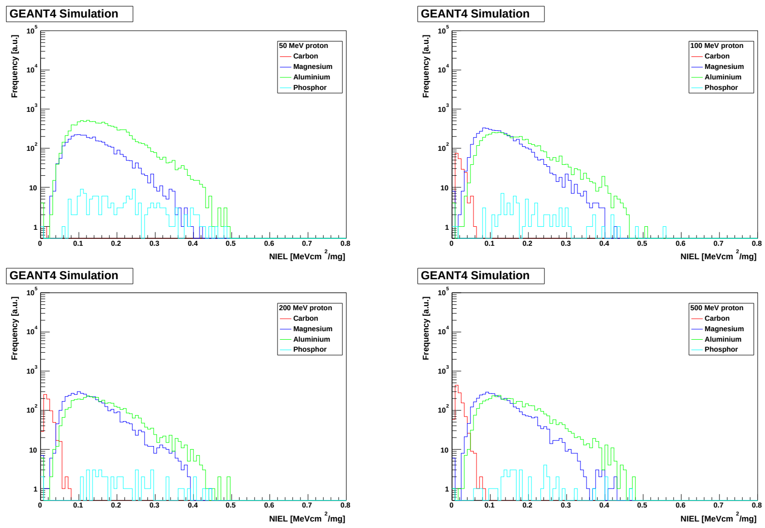

Fig. 5 – NIEL spectrums for carbon, magnesium, aluminium and phosphorus recoils produced by 50, 100, 200 and 500 MeV protons on silicon by using GEANT4 tool.

Table 1

NIEL values of carbon, magnesium, aluminium and phosphorus recoils for 150 MeV protons.

Recoil	Average NIEL [MeV] [8]	Average NIEL [MeV] (GEANT4)
Phosphorus	0.133	0.117
Aluminium	0.145	0.0818
Magnesium	0.147	0.082
Carbon	0.0182	0.0241

Table 2

Values of NIEL interaction rate of carbon, magnesium, aluminium and phosphorus recoils for 150 MeV protons.

Recoil	Interaction Rates [8]	Interaction Rates (GEANT4)
Phosphorus	0.00395	0.00420
Aluminium	0.219	0.225
Magnesium	0.258	0.246
Carbon	0.00466	0.0256

3. SUMMARY

GEANT4 and FLUKA simulations give products of the recoil heavy ions at different rates, but the recoil spectra are in acceptable accuracy. For instance, the difference in magnesium recoil rates over all proton energies are about 50% on average. However, the recoil heavy ions spectra were found to be compatible with literature [9]. The recoil energies from GEANT4 and FLUKA simulations are compatible in acceptable level. GEANT4 simulation gives useful and accurate results for the recoil heavy ions produced by 50 to 500 MeV protons on the calculation of LET and NIEL having a significant impact on the performance silicon devices.

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