The Estimation of Radiation Induced Damages on Nano-structured Nuclear Radiation Detectors

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Abstract. Silicon detectors have been widely used in high energy and nuclear physics experiments despite suffering severe radiation damage leading to degradation in the sensor performance. Such degradation include significant changes in detector efficiency, leakage current, bulk resistivity, space charge concentration, and free carrier trapping. In this work, neutron induced damages in silicon nanopillar detectors, the nanopillars dimensions being 10 nm diameter and 10 μm height was analyzed. The geometry was simulated in Geant4 and the nuclear interactions were evaluated by using ENDF/B-VII nuclear data library. Results showed that there are significant damages to the nano-pillars due to heavy charged particles and neutrons bombardment. Compared to the alpha (α) projectile, recoiled silicon produce more point defects with a higher yield. Neutrons also produce significant damage to the crystal lattice of Si nanopillars through point defects and it was also found that there is an increment in the production of ^{31}P as the diameter of the nanopillar increases which further reduces the detector performance. The study demands optimization of pillar thickness for detection efficiency and damage. Hence with the detailed understanding of radiation effects on silicon devices combined with simulation techniques produces an impact on device design that predicts the behavior of specific devices when exposed to a radiation field of interest.

INTRODUCTION

During the evolution of technology towards creation of faster and lesser power consuming devices, Silicon, being the active and basic material of radiation detectors, is the key component of integrated circuits. Among the other spectroscopic methods, detection of neutron continues to be one of the problems in the field of radiation dosimetry, as no single method provides the combination of energy response, sensitivity, orientation dependence characteristics, accuracy etc which necessitates the need of a neutron spectrometer. Current solid-state detectors for neutrons suffer from poor resolution, moderate to poor field-ability, inconvenient geometries, low absolute efficiency, lack of directional information and energy linearity with respect to the spectrum. Based on the recent developments, small sensitive volume and higher density circuits eventually increases the detection efficiency of Silicon based solid state neutron detectors. Typically highly doped PIN semiconductor, under reverse bias, is chosen for detecting neutrons, where the intrinsic layer will act as the medium for neutron detection and the P and N layers will act as contacts to the intrinsic layer for successive collection of charge pairs.

However, it has also been proven that radiation-induced defects have huge impact on the bulk properties of silicon [1, 2]. This can be scrutinized by the electrical behavior of irradiated semiconductor devices. While heavy ions, protons, neutrons, and pions cause most of the damages to Silicon, photons are considered to be less damaging .The generation and types of damage are related to the process of energy deposition. The interacting particles, especially neutrons and heavy charged particles, have higher momentum due to its larger kinetic energy compared to the bond energy of crystal which results in two major defects: point defects and linear defects, which ultimately lead to change in the detector properties. This also depends on the type and size of the substrate, alignment of the detector, dopant concentration, level of compensation, type, energy and fluence of the irradiating particles.

However, the neutrons are captured by the material and induced to the nuclear reactions, as per the cross sections. This makes some impurities in the detector medium which changes its properties further.

The silicon nano-pillars based radiation detectors have been widely accepted for detecting thermal neutrons [3] .The gaps between the pillars are filled up with materials having high neutron cross-section in order to convert the incoming neutrons into a detectable charged particles. The literature results revealed that, three dimensional Silicon nano pillar based detectors with higher aspect ratio will have high radiation detection efficiency and it is dependent upon the cross sectional area of the detector, exposing to the incoming radiations [4, 5].

The efficiency of silicon detectors for charged and neutral particle detection with their relatively small thickness of few hundred microns, the flexibility to cut silicon detectors to any size and their minimal consumption of power explains the large usage of the same as dosimeters and radiation detectors in various researches on nuclear physics. With the detailed understanding of radiation effects on silicon devices combined with simulation techniques will have an impact on device design that predicts the behavior of specific devices when exposed to a radiation field of interest.

Thus with an objective of quantifying the radiation damage on silicon pillars, a simulation study of radiation damage has been performed using benchmarked nuclear data. The following sections detail the same.

MATERIALS AND METHODS

An established nano-pillar detector geometry, having 10 nm diameter and 10 μm pillar height is evenly distributed on a 1×1 cm^2, which is grown in a (100) type n-channel silicon crystal with a purity of 99.99% has been used for the simulation. The pillars were doped with boron thus forming an intrinsic junction. This geometry was simulated in Geant4. The vacancy generations with respect to 1000 events were calculated for different alpha energies. Nuclear interactions were also accounted by using ENDF/B-VII nuclear data library [6]. The same was repeated for lithium ions, which were the residues after $^{10}B(n,\alpha)^{7}Li$ reaction.

The neutron induced damages were also depending upon the energy distribution of the neutrons. In this study, the benchmarked reactor thermal neutron spectrum has been used. ENDF/B-VII nuclear data was used for calculating the neutron induced reactions. The damage due to the elastic events has been calculated via lethargy of the neutrons which is normalized to the angular scattering cross section of the neutrons. The neutron capture events $(n,\gamma)$and the kerma produced by the neutron induced events through (n,α),(n,α) events were calculated separately. The neutron induced damages and trans-mutation of elements were accounted. Further, the effects of the presence of new elements, produced by the nuclear reactions were also analyzed. The internal modifications of neutron spectrum were accounted with total neutron interaction cross section. The study has also been repeated for different pillar thickness.

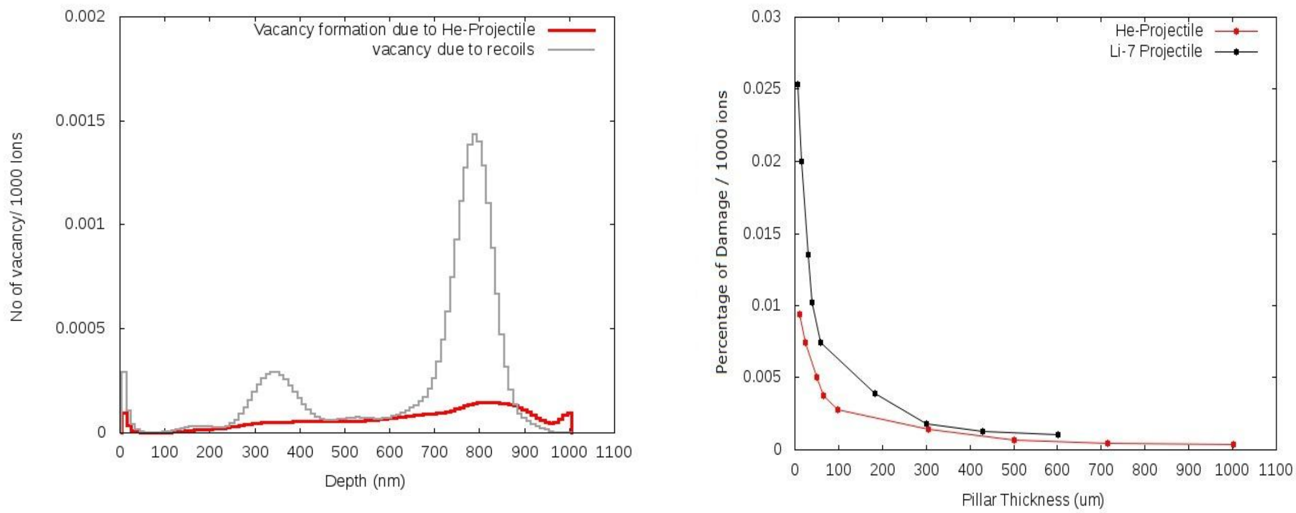
RESULTS AND DISCUSSIONS

The simulated results clearly showed significant damages to the nano-pillars due to heavy charged particles and neutrons. It has been understood that these are affecting the structural and electronic properties of the silicon nano pillars due to dislocations and changes in the doping concentration. The damages are quantified separately as charged particle and neutron induced damages, which are subsequently discussed in the following sections.

Charged Particle Induced Damages

Due to the considerable higher momentum of heavy charged particles, the silicon material was subjected to the point defect. Many of the particles along with the projectile path have been knocked out due to the higher impulse of the heavy charged particles. In addition, recoiled silicon ions, after the elastic scattering with fast projectile, also produced significant damages along the path -with a higher yield than the fast projectiles, where the recoil energy is more comparable to the bond energy.

A simulated plot of vacancies produced by alpha (α) projectile and recoiled silicon at a projectile energy of 2.7 MeV is shown in Figure. 1(a). The percentage of damage in silicon nano-pillars having varying pillar thickness for the recoiled ^{4}He and ^{7}Li projectiles are shown in fig.1 (b). This shows that higher pillar thickness can overcome radiation damages than compared to lesser thickened pillars. Thereby, it demands optimization between detection efficiency and radiation damage in the nano -structured radiation detectors.



(a) (b)

FIGURE 1: (a) Radiation damage profile due to ^{4}He projectile and Silicon Recoil. (b) Percentage of Radiation damage due to ^{4}He and ^{7}Li ions for different pillar diameters.

Neutron Induced Damages

The major percentage of neutrons produced from the thermal column of the reactor is in the thermal range, having a distribution around 0.025 eV, at the same time, having a tail to the fast neutron range. This extension produces significant damage to the crystal lattice through point defects. Because of higher elastic cross section and larger mean free path of neutrons in silicon, the damages were remarkable. Depth versus percentage of damage produced by the neutrons is shown in Figure 2(a).

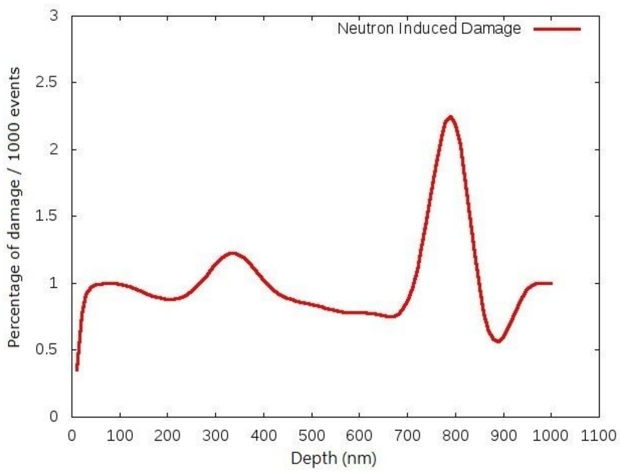
The production of 31P by the neutron capture followed by the β− decay of 30Si has also been analyzed here. This shows an increment in the production of 31P with respect to increase in the diameter, where numbers of silicon targets are getting increased. The plot between the pillar thickness and the 31P concentration, for 107 neutrons per cm2 for 1hr irradiation is shown in Figure 2(b).

The missing of the atoms from the crystal lattice produces major reductions in the force constant of the pillars. This leads to a sudden damage of the pillar, either by a projectile/recoiled atom or due to mechanical vibrations. This affects the aspect ratio and alignment of the silicon nano pillars which results in a deviation of the detector efficiency. The damage of large number of pillars cumulatively produces a change in the capacitance of the detector, which in turn leads to the change in signal behavior and voltage holding capacity of the detector. So the maximum applied voltage will be considerably reduced thereby reducing the active area of the detector.

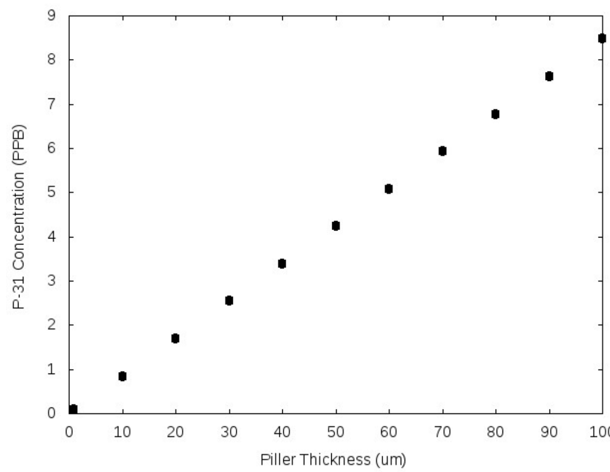
In addition, the change in the doping concentration affects the detector impedance and voltage holding capacity in reverse bias mode. This can increase the dark currents and change in band gap by the production of new degenerated energy levels. So the radiation damage shall be optimized in the construction of nano-structured nuclear radiation detectors.

CONCLUSION

The nano-structured nuclear radiation detectors are subjected to imperative radiation damages than the normal size detectors. The mechanical damage to the nano-pillars due to the projectile and recoiled ions produces a large number of vacancies in the lattice. Neutrons additionally produce capture events which leads to the production of ^{31}P, thereby changes the doping concentration. The study demands optimization between detector efficiency to the radiation damage .The net effects radically affect the mechanical and electrical characteristics of the detector. Understanding the radiation induced damages on silicon devices has an impact on their design and allows predicting the behavior of specific detector when exposed to a radiation field of interest.



(a)



(b)

FIGURE 2. (a) Neutron induced point defect profile (b) The concentration of ^{31}P with respect to pillar diameter

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