Journal of Materials Science Research; Vol. 3, No. 3; 2014
ISSN 1927-0585 E-ISSN 1927-0593
Published by Canadian Center of Science and Education

100 MeV Si^{7+} Ion Irradiation Induced Modifications in Electrical Characteristics of Si Photo Detector: An In-Situ Reliability Study

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Received: May 20, 2014 Accepted: June 13, 2014 Online Published: June 18, 2014

doi:10.5539/jmsr.v3n3p24 URL: http://dx.doi.org/10.5539/jmsr.v3n3p24

Abstract

The influence of 100 MeV Silicon (Si) ion irradiation on electrical characteristics of Si photo detectors has been analyzed using in-situ current-voltage characterization (I-V) in dark condition. The irradiation was performed over a wide range of fluences from 1×10^{11} ions/cm^2 to 1×10^{13} ions/cm^2. Key electrical parameters such as ideality factor (n), series resistance (R_s) and reverse bias leakage current (I_R) for each irradiation fluence have been extracted from the I-V characteristics. The ideality factor of the unirradiated detector is found to be 1.48 and it gradually increased up to the fluence of 5×10^{11} ions/cm^2, then it saturates around 3.4-3.5 for higher fluences. The I-V characteristics showed significant increase in forward bias and drastic increase in reverse leakage current. The value of I_R is 7.23 nA for unirradiated detector and it increases about four orders of magnitude up to 5×10^{11} ions/cm^2. Further there is no observable change in the value of I_R. However the value of R_s increases initially and slightly decrease at higher fluences. The observed results are interpreted in terms of energy loss mechanisms of swift heavy ion as it passes through the different layers of the detector. The radiation induced defects in the bulk region and activation of multiple current transport mechanisms have attributed to the observed deviations in the electrical behaviour of the device. SRIM (Stopping power and Range of Ion in Matter) and TRIM (Transport and Range of Ion in Matter) simulation results of damage induced in the device have been reported in the present study. Linear energy transfer (LET), non ionizing energy loss (NIEL) damage contributions, total ionization dose (TID) and displacement damage dose (D_d) has been correlated with the observed degradation. Quantitative estimation of radiation hardness of the Si photo detector is done by comparing with the equivalent damage created by the proton at similar penetration depth in the present device structure.

Keywords: Si photo detectors, swift heavy ion irradiation, space application, radiation hardness, current transport, NIEL, LET

1. Introduction

The Si Photo detectors are major part of several electro-optical instruments used in space and military applications. Also, these are being used extensively for energy and position measurements in particle and nuclear physics experiments (Kurokawa et al., 1995). In such experiments the detectors are exposed to typically 100 Mrad in their operational lifetime (Gill, Hall, & MacEvoy, 1997). Hence these devices need to be radiation hardened to function reliably. The effect of protons, electrons, neutrons and gamma rays on Si photo detectors of various configurations such as p-n junction/n-p junction devices and p-i-n structures are reported (Krishnan, Sanjeev, & Pattabi, 2007; Pillai et al., 2012; Moloi & McPherson, 2009). However the effect of swift heavy ion (SHI) on photo detectors, particularly high energy heavy ion has not been reported extensively. It is well documented in the literature that SHI irradiation in semiconductors can create latent tracks, induce modifications such as vacancies, di-vacancies, point defects etc (Bolse & Beate, 2002; Levalois & Marie, 1999; Kanjilal, 2001). The damage created depends largely on the type of incident particles and values of LET and NIEL. LET is the sum of electronic and nuclear energy losses and plays an important role in case of heavy ions (Leroy & Rancoita, 2009). NIEL is the rate at which energy is lost to non ionizing events. Most of the earlier work focused on NIEL induced displacement damage by lighter particles and there are limited reports on the contribution of LET and NIEL by SHI (Bourqui et al., 2008; Zelijko, Milko, Gabor, Mihlay, & Aliz, 2009; Prabhakara Rao, Praveen, Rejeena Rani, Tripathi, & Gnana Prakash, 2013). Hence the present study is of significant interest both fundamentally and technically to understand the mechanism of ion solid interaction and to improve the device fabrication technology leading to more radiation hard electronic circuitry.

The objective of this work is to study the effect of 100 MeV Si ion irradiation on the electrical characteristics of Si photo detector through in-situ I-V measurements in dark condition. The in-situ measurements are done on the same sample to avoid discrepancy in the measured parameters due to variation of initial conditions of the device. The current transport mechanism has been analyzed by extracting the key electrical parameters such as ideality factor, series resistance and revere leakage current. The interaction of ion beam with the device is analyzed by energy loss mechanisms and interpreted with the aid of SRIM code (J. Ziegler, M. Ziegler, & Biersack, 2010). The ionization and displacement damage simulation has been performed using TRIM and results are presented. The observed degradation is explained in terms of LET, NIEL, TID and D_d. Finally with the aid of SRIM, we present quantitative estimation of radiation hardness of the present device by comparing with the equivalent damage created by proton at similar penetration depth.

2. Experiment

The Silicon photo detector used in the present study having $n^+/p/p^+$ structure and the cross section of the device is as shown in Figure 1. The top n^+ layer is achieved by the implantation of phosphorous ion into mono crystalline p-Si <100> wafer of thickness 300 µm with resistivity of 10 Ω.cm. A p^+ layer of aluminum (approximately 1 µm thick) was created at the rear surface by sputtering and subsequent annealing. This will serve as both Back Surface Field (BSF) and Back Surface Reflector (BSR). On the front surface tri-layer metal coating of Ti/Pd/Ag of suitable thickness was applied for contact purpose. Similar metallic coating was done at rear surface. Silicon oxy nitride was deposited as antireflection coating on the active area of the device using ion beam sputtering process. The device is having total thickness of 305 µm approximately and area of 5 mm^2.

The Si photo detector was irradiated at room temperature with 100 MeV Si^{7+}ion from 15 UD Pelletron at Inter University Accelerator Center (IUAC), New Delhi, India. A low beam current of about 1 pnA (particle nano ampere) was maintained throughout the experiment to avoid sample heating. The vacuum of the irradiation chamber was 1×10^{-6} mbar. The irradiation was performed over wide range of ion fluences from 1×10^{10} to 1×10^{13} ions/cm^2 to study in detail the modifications induced by Si ion beam on the electrical characteristics of the detector. Schematic representation of irradiation of Si photo detector inside the vacuum chamber is depicted in Figure 2.

In-situ I-V characterization (in dark condition) was performed using Keithley 2400 source meter and LabVIEW program. The dark condition was achieved by covering all the windows of irradiation chamber and switching off the camera light inside. The I-V characteristics were recorded within 15 minutes of each irradiation fluence by stopping the ion beam momentarily using Faraday cup in the beam line. The terminals of the photo detector were floating during irradiation.

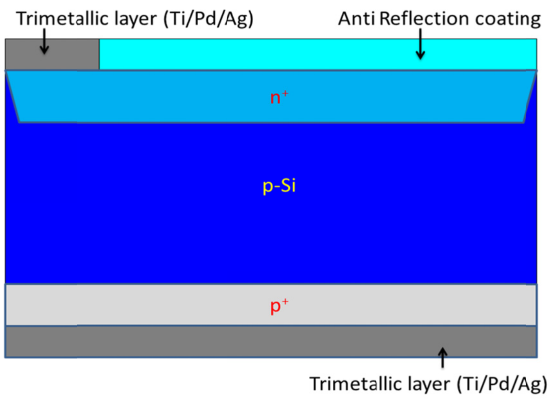


Figure 1. Structure of Si photo detector

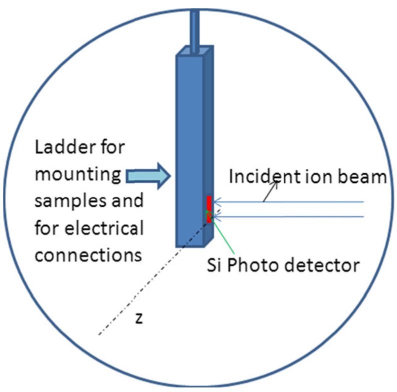


Figure 2. Schematic representation of 100 MeV Si ion irradiation on Si Photo detector inside the vacuum chamber

3. Results and Discussion

3.1 SRIM/TRIM Simulation Results

SRIM/TRIM simulation software is widely used to estimate the values of stopping power and range of ions in matter. In the present study we have used SRIM 2013 program to study the passage of 100 MeV Si ion beam through the Si photo detector. It is well known that as the swift heavy ion (SHI) traverses through the target material, the ion loses its energy via two processes:

1) Nuclear energy loss (S_n)

2) Electronic energy loss (S_e)

S_n is due to elastic scattering by target nuclei whereas S_e is due to inelastic interaction with target electrons. Also S_e is known to dominate at higher energy regime (>1 MeV/amu) compared to S_n which dominates at lower energy regime (<1 keV/amu). The observed modification in electrical properties can be understood by analyzing the possible implications of passage of ion through the device structure.

The passage of 100 MeV Si ion through different regions of the Si photo detector (only active region is considered) is analyzed through SRIM code and a plot of S_e and S_n versus depth of the material is depicted in Figure 3. It is clear from the Figure that the device suffers non uniform irradiation and the ion stops deep in the substrate away from the n^+/p junction. The value of S_e and S_n at this junction is 2.48 keV/nm and 1.96×10^{-3} keV/nm respectively. It is noteworthy that the value of S_e is almost 1000 times greater than the values of S_n. It may be recalled that nuclear energy loss is known to create defects like vacancies interstitials etc. whereas high electronic energy loss produces electron hole-pairs and trapping centers (Kanjilal, 2001; Levalois, Bogdanski, & Toulemonde, 1992; Clayes & Simoen, 2002).

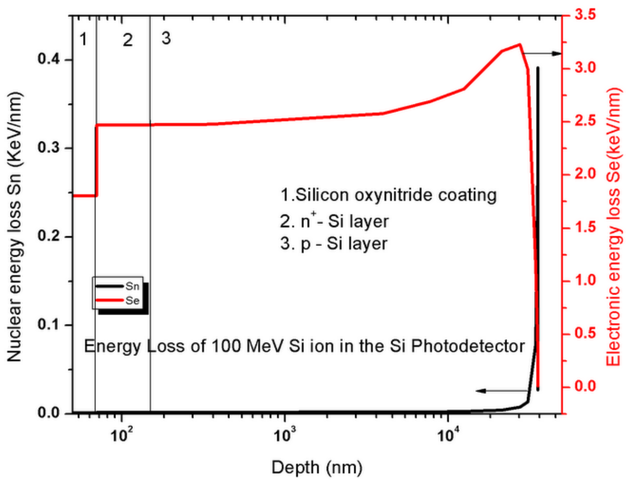
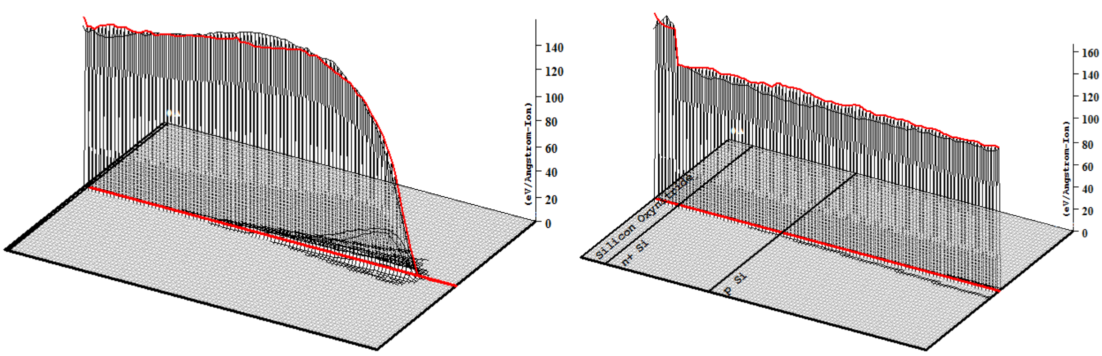


Figure 3. Passage of 100 MeV Si ion along different layers of the Si photo detector



a b

Figure 4. (a) Ionization damage (eV/Angstrom-ion) in 100 MeV Si ion irradiated Si photo detector (upto range of ion: 35.4 μm from the top surface) and (b) Ionization damage (eV/Angstrom-ion) in 100 MeV Si ion irradiated Si photo detector (upto 1 μm depth from the top surface)

The ionization and displacement damage induced by 100 MeV Si ion beam in the present device structure is shown in Figure 4a, 4b and Figure 5a, 5b respectively. It is clear from Figure 4a and 4b that the ionization damage is maximum at the beginning of the ion range and it gradually decreases along with the depth. Whereas Figure 5a and 5b shows that the displacement damage is minimum in the beginning and it is maximum at the end of the range. Therefore more number of displacements/vacancies are created due to large nuclear energy loss in the bulk Si and electron-hole pairs are created due to ionization damage mostly in AR coating region, n^+ layer and in the bulk of Si. The same has been validated by further calculations of NIEL and TID.

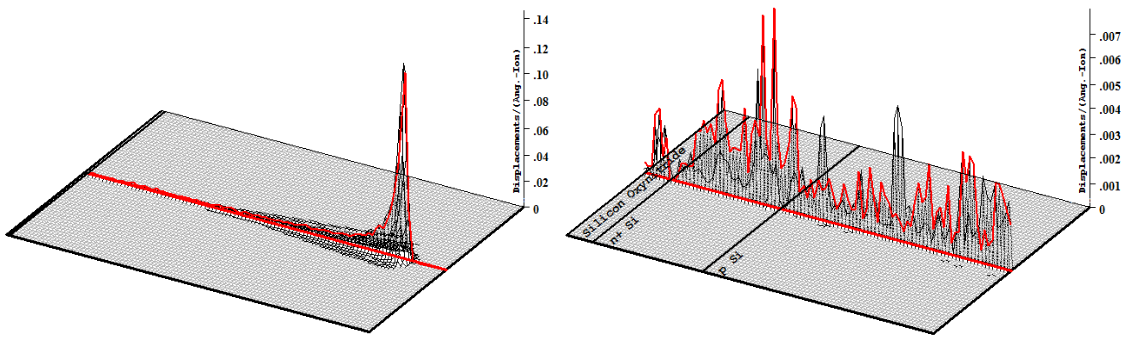


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Figure 5. (a) Displacement damage (Displacements/Angstrom-ion) in 100 MeV Si ion irradiated Si photo detector (up to range of ion: 35.4 μm from the top surface) and (b) Displacement damage (Displacements/Angstrom-ion) in 100 MeV Si ion irradiated Si photo detector (up to 1 μm depth from the top surface)

3.2 Contributions From NIEL and LET

TRIM is a comprehensive program of SRIM which provides the detailed treatment of ion damage cascades and the ion distribution within the target material. Only primary displacements due to ion cascade are considered and the quantitative estimation of the damage on the layered structure of the device is provided. The amount of charge in the ionization track per unit length is called the linear energy transfer (LET) and is measured in MeV-cm^2/g. LET is a function of particle type and incident energy (Pease, Johnston, & Azarewicz, 1988). The expression for NIEL (Messenger, Burke, Summers, & Xapsos, 1999) is given by,

$$NIEL = \frac{N}{A}\int_{\theta_{min}}^{\pi}\left[\frac{d\sigma(\theta,E)}{d\Omega}\right]T\,(\theta,E).\,L(\theta,E).\,d\Omega \tag{1}$$

Where N is the Avogadro's number, A is the atomic number and θ_{min} is the minimum scattering angle for which the recoil energy equals the threshold energy for the atomic displacements, T is the average recoil energy for the target atoms and L is the Linhard partition function which separates the energy into ionizing and non-ionizing events. NIEL is a direct analog of LET and it is usually expressed in MeV-cm^2/g. The value of NIEL is estimated from SRIM and was found to be 64.415 MeV-cm^2/g.

The TID and D_d is calculated using the relation,

$$\mathrm{TID} = 1.6\times10^{-8}\times\Phi\times\mathrm{LET} \tag{2}$$

$$\mathrm{D_d} = 1.6\times10^{-8}\times\Phi\times\mathrm{NIEL} \tag{3}$$

Where 1.6×10^{-8} is the unit conversion parameter and the unit is rad g/MeV, Φ is the ion fluence (ions/cm^2).

The damage caused due to LET and NIEL is estimated from SRIM/TRIM and tabulated in Table 1. The fluence dependent TID and D_d are tabulated in Table 2. TID is mainly dependent on the value of LET and hence in case of MeV ion, the contribution from electronic excitations is much more compared to nuclear displacements by 3 orders of magnitude.

Table 1. TRIM Calculations for 100 MeV Si in Si target

Name	Value
Range, R (μm)	35.4
Average Displacements/ion	9707
Average Vacancies/ion	8951
Average Replacements/ion	756
NIEL up to R (MeV cm^2/g)	64.415
LET ((MeV cm^2/g)	10.072 x 10^3

Table 2.Fluence dependent TID and D_d for Si target

Fluence (ions/cm^2)	1x10^{11}	5x10^{10}	1x10^{11}	5x10^{11}	1x10^{12}	5x10^{12}	1x10^{13}
TID(rad)	1.611 x10^6	8.057 x10^6	1.611 x10^7	8.057x10^7	1.611x10^8	8.057 x10^8	1.611 x10^9
D_d (rad)	1.026x10^4	5.132 x10^4	10.26 x10^4	51.32 x10^4	10.26 x10^5	51.32 x10^5	10.26 x10^6

3.3 I-V Measurements / Current Transport Mechanism

The I-V characteristics (in dark condition) of 100 MeV Si^{7+} ion irradiated Silicon photo detector in the fluence range of 1×10^{10} to 1×10^{13} ions/cm^2 is shown in comparison with pristine results in Figure 6a and 6b. The reverse I-V characteristics exhibits a drastic change compared to forward bias.

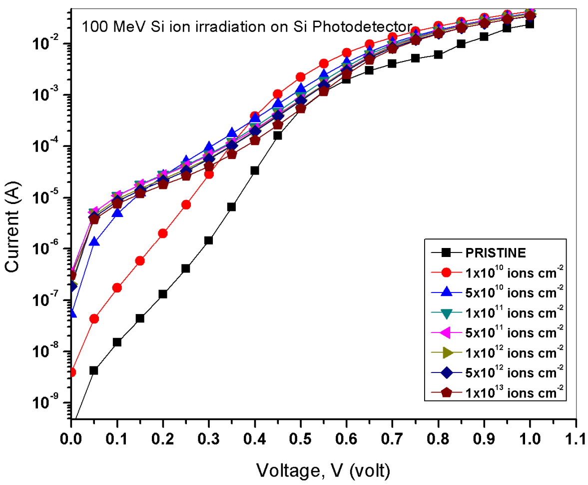

Figure 6a. Forward bias I-V characteristics of 100 MeV Si ion irradiated Si Photo detector

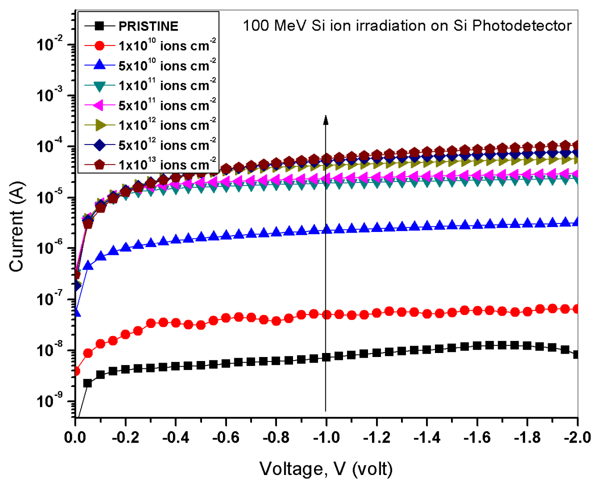

Figure 6b. Reverse bias I-V characteristics of 100 MeV Si ion irradiated Si Photo detector

To study the modification in current transport properties of the device due to Si ion irradiation, the I-V characteristics has been analyzed according to thermionic emission theory and the experimental data is fitted with thermionic emission given by (Jayavel, Udayashankar, Kumar, Asokan, & Kanjilal, 1999),

$$I = I_s\left[\exp\left(\frac{qV}{nk_BT}\right) - 1\right] \tag{4}$$

Where,

$$I_s = A^{**}T^2 \exp\left(\frac{-q\phi_B}{k_BT}\right) \tag{5}$$

Where A^{**} is the effective Richardson constant (A cm^{-2} K^{-2}); T is the absolute temperature (K), I_s is the saturation current and n is the ideality factor and other symbols have their usual significance. From the gradient of ln(I) versus V curve, the value of ideality factor is estimated using the relation,

$$n = \frac{q}{k_B T}\left[\frac{dV}{d(\ln I)}\right] \tag{6}$$

One of the important parameters of the device is series resistance and it was been calculated by using the method developed by Cheung and Cheung (Cheung & Cheung, 1986). The forward bias I-V characteristics due to thermionic emission of hetero-structures with series resistance can be expressed as Cheung functions,

$$\frac{dV}{d(\ln I)} = IR_s + n\left[\frac{kT}{q}\right] \tag{7}$$

The term IR_S is the voltage drop across the junction. The gradient of dV/d(lnI) yields the series resistance (R_S). Also reverse leakage current (I_R) at -1V has been determined from Figure 6b. All the evaluated parameters are tabulated in Table 3.

Table 3. The calculated device parameters for different ion fluences

Sl. No	Ion Fluence (ions cm^{-2})	Ideality factor (n)	Series Resistance (R_s) (ohm)	Reverse Leakage current I_R (A) (at -1 V)
1	Pristine	1.48	8.205	7.23×10^{-9}
2	1×10^{10}	1.62	8.615	4.97×10^{-8}
3	5×10^{10}	2.71	8.880	2.28×10^{-6}
4	1×10^{11}	3.40	9.022	1.19×10^{-5}
5	5×10^{11}	3.51	8.720	2.37×10^{-5}
6	1×10^{12}	3.41	8.680	4.35×10^{-5}
7	5×10^{12}	3.37	8.330	5.31×10^{-5}
8	1×10^{13}	3.34	7.960	5.38×10^{-5}

The value of ideality factor for pristine sample and at different fluences are tabulated in Table 3. The 100 MeV Si^{7+} ion irradiation increases the value of ideality factor moderately up to 3.51 for the fluence of 5×10^{11} ions/cm^2. It can be observed from the values of ideality factor that the ideality factor increases up to a fluence of 5 x 10^{11} ions/cm^2. Further the ideality factor decreases slightly with increasing ion fluence. Since the value of ideality factor lies between 1 and 2 at the initial stages the conduction mechanism is due to thermionic emission and gradually there is a contribution from generation recombination process.The generation-recombination process lead the diode to deviate from its ideal behaviour (Sharma, Shahnawaz, Kumar, Katharria, & Kanjilal, 2007). Therefore the increase in ideality factor clearly indicates that the Si ion beam induced modification in current transport mechanisms. At higher fluences magnitude of ideality factor increases by 2-3 orders and saturates around 3.4 indicating probable contribution from defect assisted tunnelling current. The activation of multiple current transport mechanisms may be attributed to the observed increase in the value of ideality factor. It is evident from the fluence dependent NIEL and TID calculations that the number of defects created by ion beam also increases along with the fluence. After the fluence of 5×10^{11} ions/cm^2 the accumulation of these defects get saturated and is reflected in the saturation value of ideality factor. The enhanced recombination probability of trap centers introduced by Si ion beam in the intrinsic region of the device may also have significant contribution for the increase in the value of ideality factor (Pillai et al., 2012).

Since the reverse leakage current of advanced silicon photo diodes used in nuclear radiation detection is very low, measurement of changes in the leakage current can be a very sensitive tool for monitoring ion irradiation (Hazdra, Haslar, & Vobecky, 1995). In the present study, the value of I_R has increased significantly. It is to be noted that pristine sample has the reverse leakage current of 7.23 nA at -1V and it has drastically increased up to 11.9 µA for the fluence of 1×10^{11} ions/cm^2, thereafter begins to saturate around 10^{-5} A. It is to be noted that I_R has increased up to four orders of magnitude when compared to pristine value. The Si ion beam induced increment in dark leakage current occurs due to the creation of trap centers which act as recombination centers in the band gap of semiconductor. These trap centers are created due to atomic displacement which leads to increase in thermal generation rate in the depletion region of the device. The increase of reverse leakage current with the fluence confirms the increase of generation-recombination (G-R) centers (Khamari et al., 2011). The value of series resistance of the device in the present investigation increases initially up to 1×10^{11} ions/cm^2 and slightly decreases at higher fluences. Series resistance is inversely proportional to the product of both mobility and carrier concentration. In general ion irradiation is known to decrease the carrier mobility and carrier concentration and thereby increase the series resistance. The 100 MeV Si beam has introduced significant number of displacements, vacancies as listed in Table 2. These defects contribute to the decrease in minority carrier lifetime and responsible for increase in the value of series resistance. As the low temperature mobility is affected by the presence of shallow levels, the mobility might not change at lower fluence, however at higher fluence the less stable shallow level may become stable and form complex defects contributing to increase in mobility (Khamari et al., 2011). At the lower fluences the series resistance increases because of the increase in number of vacancies created by the ion beam. But at higher fluences these defects get saturated and starts overlapping. The decrease in series resistance implies that the product of mobility and free career concentration has been increased. It is reported that the increase in mobility decreases the value of series resistance (Kumar, Katharria, Batra, & Kanjilal, 2007). After a certain fluence there is a dynamic equilibrium between creation and annealing of defects. The defect creation is mainly due to atomic displacements during elastic (S_n) collisions of ion with Si atoms, where as annealing of defects is due to inelastic (S_e) collisions causing excitation and ionization of atoms and their subsequent relaxation (Verma, Praveen, Kumar, & Kanjilal, 2013). The high value of electronic energy loss is known to produce partial annealing (Srour et al., 2003; Singh, Arora, & Kanjilal, 2001). At higher fluences, the device parameter starts saturating, as there will not be any effective increase in defects.

It is necessary to estimate the radiation hardness of the Si photo detector when the devices are considered for space application. Here we have followed the approach of Sciuto et al. (Sciuto, Roccaforte, & Raineri, 2008). The estimation of proton irradiation induced damage on the present device was deduced from the 100 MeV Si ion beam irradiation effects by taking into account of the nuclear stopping power (Ziegler et al., 2010; Sze, 1988). Considering the typical proton fluxes in the range of 10^2 to 10^4 ions/cm^2/s, from SRIM simulation it can be estimated that irradiation with 100 MeV Si ion beam with the fluence of 10^{11} ions/cm^2 would be equivalent to irradiation with 1.6 MeV protons for a time longer than 35 years (NASA (www.nasa.gov), Messenger & Ash, 1986). Thus in Low earth orbit, usually where the spacecrafts and satellites are operated, the detector will require very long time to achieve fluence of 10^{11} ions/cm^2 and hence it can function reliably during its operational lifetime.

4. Conclusion

Si $n^+/p/p^+$ junction photo detector has been subjected to 100 MeV Si ion irradiation at various fluences and its sensitivity for ionization and displacement damage has been systematically studied. In-situ darkI-V measurements has been performed and the present device shows increase in the value of ideality factor and reverse leakage current upto the fluence of 5×10^{11} ions/cm^2, thereafter it is almost constant indicating good radiation immunity. Si ion beam induced G-R centers in the bulk Si may be the main reason for the increase in leakage current. The higher values of ideality factor are attributed to activation of multiple transport mechanisms including multistep tunnelling. However the NIEL induced displacement damage appears to be the major effect to the observed degradation primarily in the bulk region of the device. At higher fluences these parameters improve indicating the annealing effect due to high electronic energy loss. SRIM results also validate that the displacement damage is created in the bulk Si compared to top layers of the device. The values of LET and NIEL and fluence dependent TID and D_d has been calculated and an attempt has been made to correlate with the observed degradation in electrical parameters. Radiation hardness is estimated by comparing the present study with the equivalent damage created by proton and the present device was found to function reliably for several tens of years in low earth orbit.

Acknowledgments

One of the Authors (MVK) thanks IUAC for providing financial assistance through fellowship Grant no. UFR-50310. The technical assistance provided by Pelletron group at IUAC during the beam time experiment is acknowledged. Also, the authors thank Dr. C. L. Nagendra (LEOS-ISRO, Bangalore), Dr. C. M. Dinesh (Govt. first grade college, Kolar, India) and Dr. Prabha Sana (MANIT, Bhopal) for their useful discussions.

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