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75 MeV boron ion irradiation studies on Si PIN photodiodes

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ABSTRACT

The highly sensitive silicon PIN photodiodes were fabricated to use in radiation environments. The Si PIN photodiodes are coated with 150 nm silicon dioxide (SiO_2) as anti-reflective (AR) coating. The presence of AR coating on the performance of irradiated PIN photodiodes is studied up to a total dose of 10 Mrad. The effects of 75 MeV boron (B^{5+}) ions and ^{60}Co gamma radiation on the *I–V*, *C–V* and spectral responses of PIN photodiodes were studied systematically to understand the radiation tolerance of the devices. The 75 MeV B^{5+} irradiation results are compared with ^{60}Co gamma irradiated results in the same dose range for 1 mm × 1 mm and 10 mm × 10 mm active area PIN photodiodes. The irradiation results show that the ion irradiated PIN photodiodes show more degradation when compared ^{60}Co gamma irradiated devices. The irradiation results are presented in this paper and the possible mechanism behind the degradation of photodiodes is also discussed in the paper.

1. Introduction

The development of indigenous, cost-effective, radiation hard Si detectors for radiation rich environment is very much essential in the context of international market. Among several semiconductor detectors, Si PIN photodiodes are offered at lesser price without any compromise in quality. The best qualities of Si PIN photodiodes are smaller size, fast response, better energy resolution, room temperature operation, etc. [1]. The performance levels of PIN photodiodes may be tuned by varying several parameters during fabrication processes [2,3]. The response of photodiode to particular wavelength region can be achieved but at the same time minimizing the leakage current is a challenge. The thin film dielectrics used as passivation layers should not absorb maximum energy of the incident radiation to be detected. Additionally, the PIN photodiodes have to be radiation hard to fetch reliable data even after 5–10 years of operation in radiation environment like in large hadron collider (LHC), CERN [3,4]. The silicon detectors will be used extensively in experiments at the LHC where intense proton beams will be collided with a total center-of-mass energy of 14 TeV. The silicon detectors will be employed to measure the trajectories of proton beam and in consequence, will be exposed to high levels of radiation, typically 100 Mrad over the operational lifetime [5]. The damage creation in PIN photodiodes depends on the particle type and energy of incident radiation and these factors define the non-ionizing energy loss (NIEL) of the radiation. There is a significant difference between the type of damages created by light particles (photons, and low energy electrons) and heavy particles (protons, neutrons and heavy ions). The different types of damages are created in the PIN photodiodes because of the NIEL of different incident radiation. We have shown that the irradiation time taken to reach high total doses (100 Mrad (Si)) can be drastically reduced for testing the reliability of different semiconductor devices to work in radiation environments [6–16]. In case of heavy ion irradiation it is appropriate to define linear energy transfer (LET) instead of NIEL [17]. The LET is the sum of electronic energy loss (S_e) and nuclear energy loss (S_n) of ions in the host material. The large LET of heavy ions can be utilized to study the radiation hardness of Si PIN photodiodes in short period of time. Therefore it is interesting to study the radiation tolerance of Si PIN photodiodes after heavy ion irradiation. In this context, the radiation responses of different active area Si PIN photodiodes are studied by exposing the photodiodes to 75 MeV B^{5+} ion and ^{60}Co gamma radiation. The *I–V*, *C–V* and spectral response of Si PIN photodiodes were measured before and after irradiation. The B^{5+} ion irradiation results are compared with ^{60}Co gamma irradiation results in the total dose ranging from 600 krad to 10 Mrad. The irradiation results are presented in this paper and the possible damage mechanism behind the degradation of photodiodes is also discussed in the paper.

2. Experiment

The Si PIN photodiodes of two different active area [1 mm × 1 mm and 10 mm × 10 mm] were designed using CADENCE tools.

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The photodiodes were fabricated in an IC fabrication facility having class 1000/100 environment which is present at Bharat Electronics Limited (BEL), Bangalore, India. The 4 inch (450 μm thick) N-type phosphorus doped, double side polished, <1 1 1> orientation, float zone (FZ), high purity silicon wafers (life time >1 ms) having resistivity of 5–8 KΩ-cm are used for the fabrication of silicon PIN photodiodes. On the top of photodiode, SiO_2 is used as anti-reflective (AR) coating with a thickness of 150 nm and SiO_2 is tuned to a desirable wavelength (λ = 400–1100 nm). The SiO_2 will act as the passivation layer to the chip to protect from the moisture and mechanical damages. The structure of the fabricated Si PIN photodiode is shown in Fig. 1. The Si PIN photodiodes were irradiated with 75 MeV boron [B^{5+}] ions and ^{60}Co gamma radiation for different total doses from 600 krad to 10 Mrad (Si). In case of ^{60}Co gamma radiation, the radiation total dose range in sievert is 6–100 kSv and in case of 75 MeV boron ions the radiation total dose in sievert is 120 kSv to 2 MSv [18]. The ion and gamma irradiation were done at 15 UD Pelletron accelerator and gamma chamber 1200 respectively, at Inter University Accelerator Centre (IUAC), New Delhi, India. The ion beam current during 75 MeV B^{5+} ion irradiation was about 0.5 p-nA (particle-nano ampere) and the dose rate for gamma radiation is 200 rad/s. The ion beam was scanned over the samples in an area of 10 mm × 10 mm by magnetic scanner in order to get uniform dose on the PIN photodiodes. The terminals of the PIN photodiode were floating during ion and gamma irradiation.

3. Results and discussions

The SRIM/TRIM simulation program is the most commonly used software for calculating the stopping power and range of ions in matter. The expanded form of SRIM is "Stopping and Range of Ions in Matter". The SRIM 2011 [19] simulation program is used to study the interaction of 75 MeV B^{5+} ion with Si PIN photodiode. Figs. 2 and 3 shows the displacement damage and ionization damage in 75 MeV B^{5+} ion irradiated Si PIN photodiode. From the SRIM-2011 simulation data it is revealed that each 75 MeV B^{5+} ion can create around 17 vacancies in active region of the photodiode before it stops in the intrinsic region. The ionization damage creates electron–hole pair in the photodiode. The ionization damage is dominant for B^{5+} ions till the ion range and at the end of ion range displacement damages are more dominant. Therefore more number of displacement damages were created in the intrinsic region of the PIN photodiode.

The reverse bias current of Si PIN photodiodes should be low for radiation detection. Therefore the change in the reverse bias current is studied for monitoring the operating performance of irradiated Si PIN photodiode. In an ideal PIN photodiode, the leakage current is the direct evidence of diffusion current but practically, in addition to diffusion current, photodiodes comprises of leakage currents from the impurities, contaminations, process induced defects and interface states at Si/SiO_2 interface. The maximum current generated by a pulse of radiation will produce around 1 μA of leakage current in less than pico-seconds. When the Si PIN photodiodes are working in the radiation environment, the leakage current should be minimal. However it is interesting to know if the anti reflective coating (SiO_2) of thickness 150 nm contribute to leakage current after irradiation. Therefore it is essential to measure the reverse biased leakage current of different active area Si PIN photodiodes after exposing to radiation. Figs. 4 and 5 shows the reverse *I–V* characteristics for B^{5+} ion and gamma irradiated Si PIN photodiodes respectively. In case of B^{5+} ion irradiation the reverse leakage current was found to increase by four orders of magnitude after 10 Mrad of total dose. The leakage current saturates at around 1 μA for the different active area PIN photodiodes. However, the leakage current does not saturate after gamma

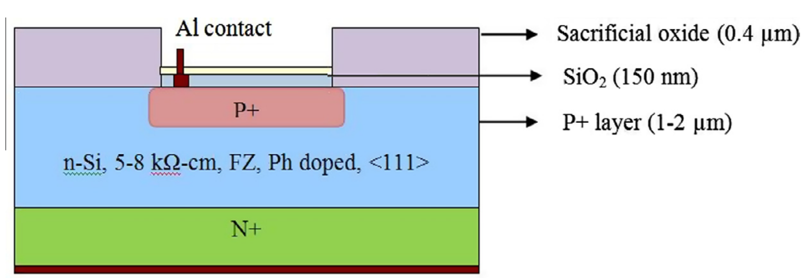

Fig. 1. Structure of Si PIN photodiode.

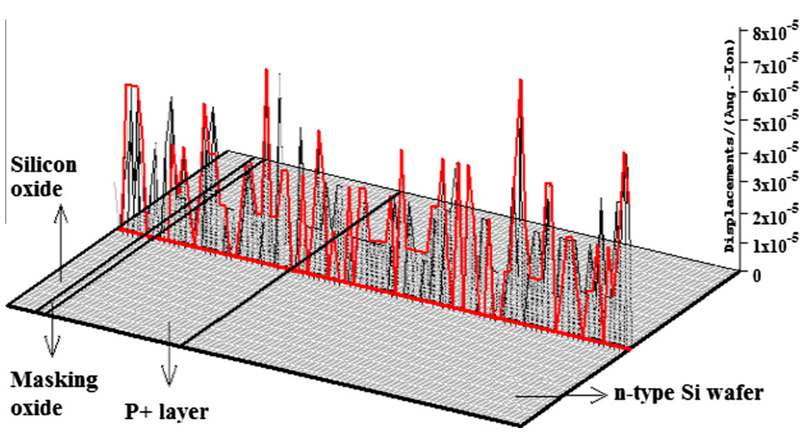

Fig. 2. Displacement damage (displacements/Å-ion) in 75 MeV B^{5+} ion irradiated Si PIN photodiode.

irradiation. The increase in leakage current is due to the generation of radiation induced trapped charges which act as generation–recombination (G/R) centres in the active region of the photodiode [20–22]. The range of 75 MeV B^{5+} ions is 166.07 μm, hence the B^{5+} ions stops in the intrinsic region of PIN photodiode. The defects are formed only in the ARC film, P^+ layer and near the P^+ layer of intrinsic region but not in the complete device structure. Therefore leakage current reaches a saturation level due to concentrated defect formation after B^{5+} ion irradiation [23]. The gamma radiation completely ionizes the photodiode and creates electron–hole pairs throughout the photodiode. In the case of gamma irradiation, ^{60}Co photons have energy 1.17 and 1.33 MeV and bulk damage occurs primarily as a result of the interactions of Compton electrons with the host atoms. The scattered electrons from ^{60}Co photons typically have energies of only a few hundred keV which is insufficient to displace more than one or two silicon atoms from their lattice positions. The introduction of divacancy states is therefore limited and most defects are of the vacancy-impurity type distributed uniformly throughout the PIN photodiode [5]. The density of defects increase with the increase in total dose, therefore the increase in leakage current can be observed after different cumulative dose for gamma irradiated PIN photodiode.

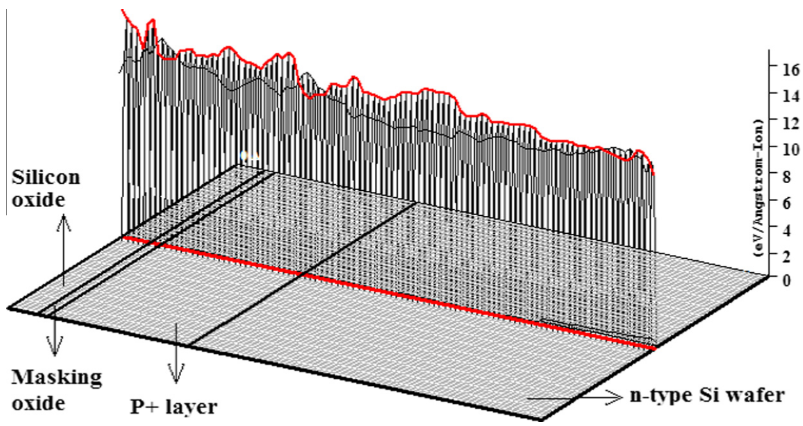

Fig. 3. Ionization damage (eV/Å-ion) in 75 MeV B^{5+} ion irradiated Si PIN photodiode.

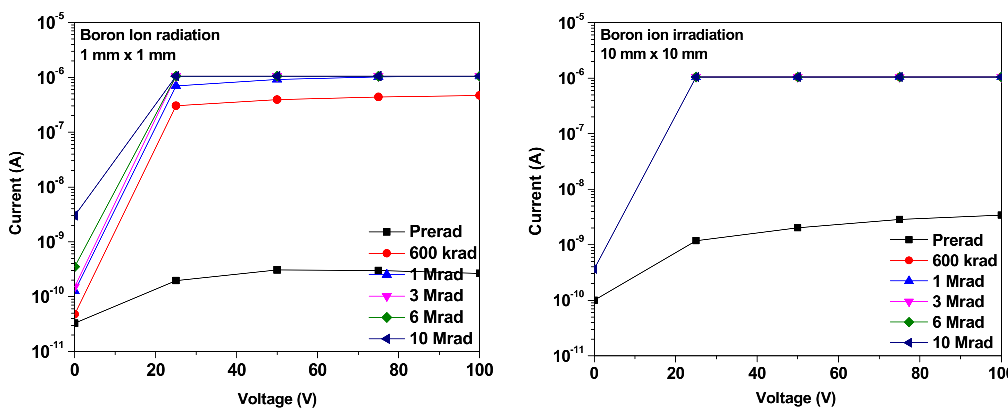

Fig. 4. Reverse biased *I*–*V* characteristics for boron irradiated PIN photodiodes.

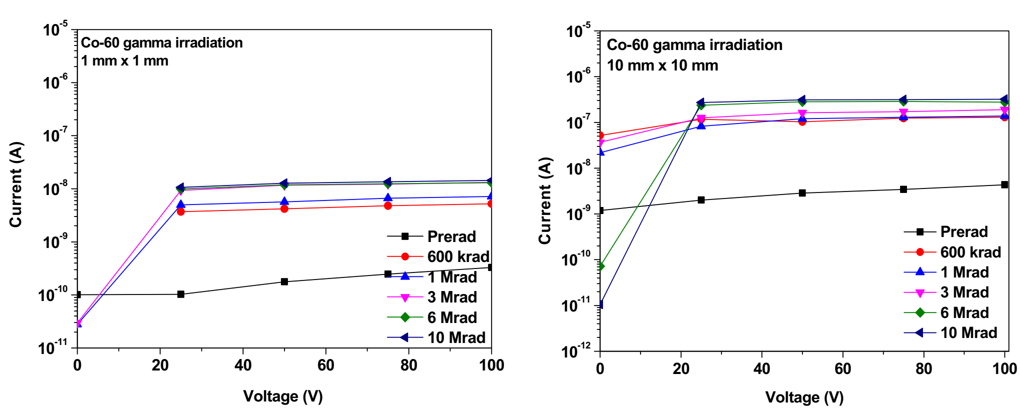

Fig. 5. Reverse biased *I*–*V* characteristics for Co-60 gamma irradiated PIN photodiodes.

The capacitance of PIN photodiode in reverse bias condition is given by the equation; $C = dQ/dV = \varepsilon A/X$ where the charge $Q = qN_{eff}AX$, here A is the diode area, N_{eff} is effective dopant concentration and X is the depletion depth. The capacitance decreases proportionally to $1/\sqrt{V}$ until the full depletion is achieved. For applied bias voltages larger than the full depletion voltage, the capacitance remains constant and a plateau region can be observed. The capacitance at full depletion voltage corresponds to the geometrical capacitance of the diode which is considered as a parallel plane plate capacitor [24]. The capacitance–voltage characteristics of B^{5+} ion and gamma irradiated Si PIN photodiodes are shown in Figs. 6 and 7, respectively. The capacitance was found to decrease with increase in total dose. As the dose increases, the capacitance decreases since the depletion depth (W) and the effective carrier concentration (N_{eff}) increases which indicates the modulation of depletion region. The large number of electron–hole (e–h) pairs

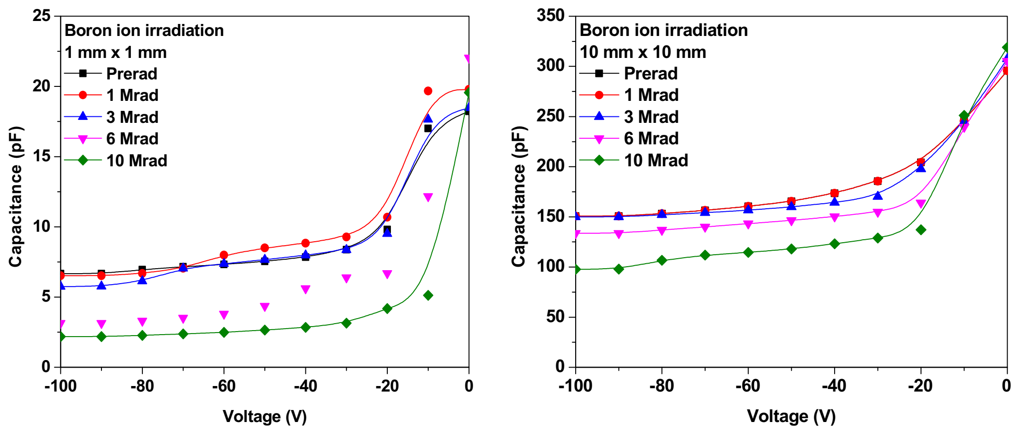

Fig. 6. *C–V* characteristics for boron irradiated PIN photodiodes.

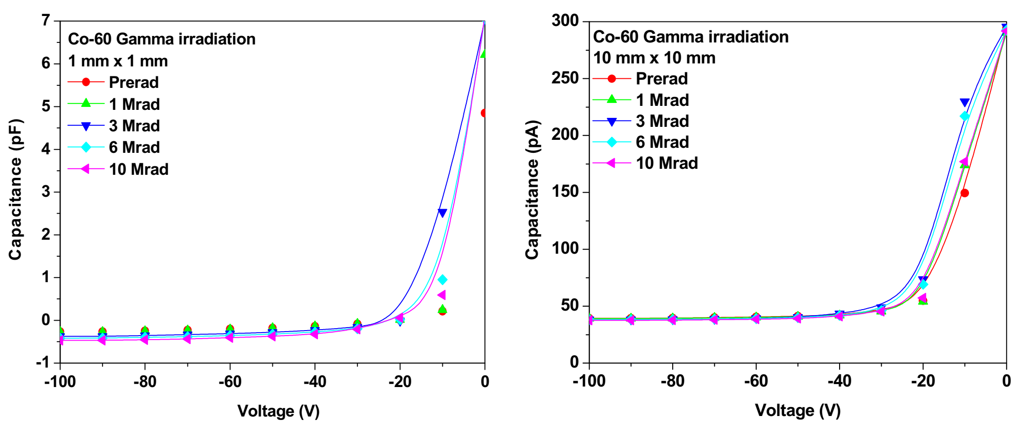

Fig. 7. *C–V* characteristics for gamma irradiated PIN photodiodes.

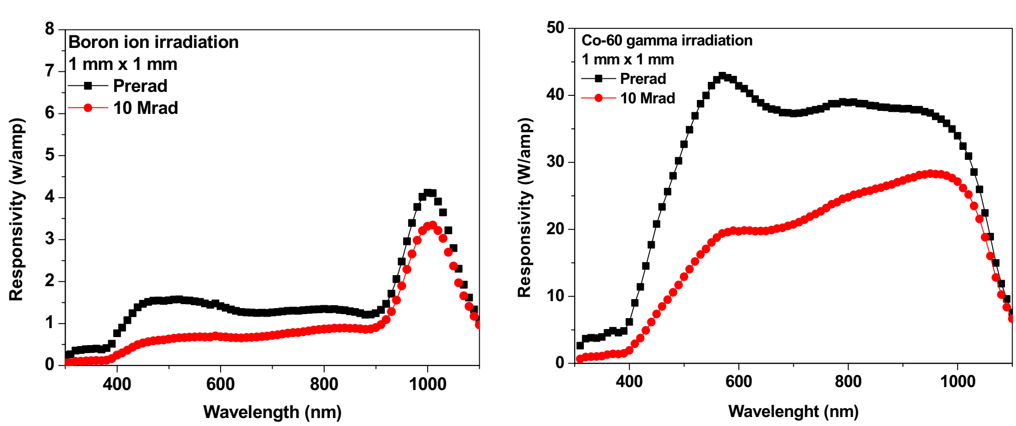

Fig. 8. Spectral response of boron and gamma irradiated PIN photodiodes.

that are ejected out of the depletion region to opposite electrodes contribute to the measured current and it increase the depleted width [25]. For gamma irradiated Si PIN photodiode, the capacitance slightly increases up to a certain voltage (−30 V) and as the reverse bias increases the capacitance almost reaches saturation. The wide plateau curve at above −30 V shows that the diode is fully depleted. Hence below −30 V the capacitance increases with increase in gamma dose. It can be also observed that, the capacitance slightly decreases in saturation region with increase in gamma dose.

The PIN photodiode with two different active areas [1 mm × 1 mm and 10 mm × 10 mm] were irradiated with different doses of 75 MeV B^{5+} ions and ^{60}Co gamma radiation. The spectral response of PIN photodiodes was studied by operating the photodiode in photoconductive mode. The photo response of PIN photodiodes is in the visible and near-infrared region. The peak spectral response of photodiodes is around 950 nm. Fig. 8 shows the spectral response of boron B^{5+} ion and gamma irradiated PIN photodiodes with an active area of 1 mm × 1 mm. The peak optical spectral response is found to decrease slightly after irradiation. The same trend was observed in the spectral response for 10 mm × 10 mm active area PIN photodiode. This degradation is attributed to radiation induced degradation of the minority carrier diffusion length in the base layer [26]. The change in the width of the spectral response curve is small and the peak position remains unaltered after gamma and ion irradiation. Therefore the PIN photodiodes detect the radiation in the same wavelength region even after irradiation but with less responsivity when compared to unirradiated devices.

4. Conclusions

The total dose effects of 75 MeV B^{5+} ions and ^{60}Co gamma radiation on electrical characteristics of Si PIN diodes were studied up to a total dose of 10 Mrad. The *I–V* characteristic of the irradiated PIN photodiodes show that the leakage current increases after irradiation. The radiation induced G/R trapped charges are responsible for the increase in leakage current. The study of *C–V* characteristics show that the capacitance decreases with increase in total dose. There is no drastic change in the spectral response after B^{5+} ion irradiation. Hence the fabricated Si PIN photodiodes with 150 nm anti reflective coating are found to be radiation hard up to a total dose of 10 Mrad.

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