The Effects of ^{60}Co Gamma Irradiation on Si PIN Photodiode Coated with Si_3N_4 as Anti-Reflective Coating

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***Abstract*—The Si PIN photodiodes are used as radiation and charged particle detectors in different ionizing radiation environments. The PIN photodiodes were fabricated on high resistivity (3-5 kΩ-cm) wafers to operate the photodiodes in high biasing voltage with low leakage current. The conventional silicon planar technology was chosen to fabricate the photodiodes with silicon nitride (Si_3N_4) as anti-reflective coating (ARC). The effects of Si_3N_4 thickness on the electrical and optical performance of photodiodes are studied. The radiation tolerance of Si_3N_4 coated photodiode was investigated with ^{60}Co gamma irradiation up to total dose of 10 Mrad (Si). The results show that the I-V and C-V characteristics were found to degrade after ^{60}Co gamma irradiation. However the spectral response was found to improve by two orders of magnitude after 10 Mrad of total dose. The I-V, C-V and spectral response results are systematically presented and discussed in this paper.**

Keywords*—Si PIN photodiode, silicon nitride, anti-reflective coating, ^{60}Co gamma irradiation.

I. INTRODUCTION

The Si PIN photodiodes are used to detect the radiation and charged particles in high dose radiation environment. The photodiodes are highly sensitive to different ionizing radiation like gamma radiation, protons, neutrons and high energy heavy ions [1]. The high energy radiation creates defects such as point defects, cluster of defects and dislocations in Si PIN photo diodes in addition to ionization of charge carriers. The defects introduce the intermediate energy levels in the bandgap of Si PIN photodiode and such levels act as generation and recombination centres. The radiation induced defects result in the increase of leakage current and degrade the electrical performance of photodiode [2]. The PIN photodiodes should be radiation hard to operate in radiation environments like LHC for a period of 5 to 7 years [3-5]. The leakage current should be in the range 1 nA/mm^2 to 10 nA/mm^2 during the operational lifetime of the photodiode. The development of radiation hard photodiodes requires excellent choice of fabrication materials, better device layout and processing methods in the fabrication process. In the previous work, the photodiodes with low leakage current were fabricated using novel fabrication techniques without the implementation of radiation-hard-by-design (RHBD) layout [6]. Further, the effects of ^{60}Co gamma irradiation effects were studied on the electrical characteristics and spectral response of Si PIN photodiode coated with silicon dioxide as anti-reflective coating (ARC). The photodiodes show degradation to ionizing radiation and leakage current increases by two orders of magnitude [7-8]. In the present investigation Si PIN photodiodes were fabricated with similar fabrication techniques but with silicon nitride (Si_3N_4) as anti-reflective coating (ARC). It is reported that Si_3N_4 is radiation tolerant material and can withstand 10's of Mrad when used as stack of SiO_2 and Si_3N_4. Therefore, the effects of ionizing radiation on the electrical and spectral performance of Si PIN photodiode coated with Si_3N_4 are investigated up to total dose of 10 Mrad. The current-voltage (I-V), capacitance-voltage (C-V) characteristics and spectral response of Si PIN photodiodes were measured before and after irradiation. The irradiation results are presented in this paper and the possible damage/recovery mechanisms are discussed.

II. EXPERIMENTAL

The Si PIN photodiodes of three different active areas [1 mm x1 mm, 2 mm x 2 mm and 10 mm x10 mm] were designed using Cadence design tools. The 4 inch (300 µm thick) n-type phosphorus doped high purity silicon wafers (life time > 1 ms) having resistivity of 3-5 kΩ-cm are used for the fabrication of silicon PIN photodiodes. The silicon wafers were double side polished, with <111> orientation and float zone (FZ) type. The Si PIN photodiodes were fabricated using the conventional silicon planar technology [9]. The detailed process steps involved in the fabrication of Si PIN photodiode with SiO_2 as ARC are presented in the previous work [6]. In the PIN structure, above the p-type layer, 50 nm SiO_2 is thermally grown to assist the deposition of silicon nitride (Si_3N_4) as anti-reflective coating (ARC). The Si_3N_4 of 50 nm and 150 nm thickness is deposited over thermally grown SiO_2 (TGO) and Si_3N_4 will act as the passivation layer to protect the chip from moisture and mechanical damages.

The schematic diagram of the Si PIN photodiode is shown in figure 1. The Si PIN photodiodes were irradiated in Gamma Chamber 1200 located at Inter University Accelerator Centre (IUAC), New Delhi, India. In order to control the dose in the active region of the device the samples were enclosed with 1.5 mm of lead and an inner layer of 0.7 mm aluminium. The photodiodes were irradiated with the dose rate of 200 rad/s (Si) up to a total ionizing dose (TID) ranging from 600 krad (Si) to 10 Mrad (Si) with all the terminals floating. The terminals floating condition was chosen to study the worst case irradiation effects in photodiodes [10-11]. The different gamma radiation doses given to PIN photodiodes were 600 krad, 1 Mrad, 3 Mrad, 6 Mrad and 10 Mrad. The I-V, C-V characteristics and spectral response were measured before and after irradiation using the computer interfaced Keithley 2612 source meter. The devices were characterized within 30 min after irradiation following MIL-STD 750 to avoid time dependent annealing, which changes the electrical effects of damage formation.

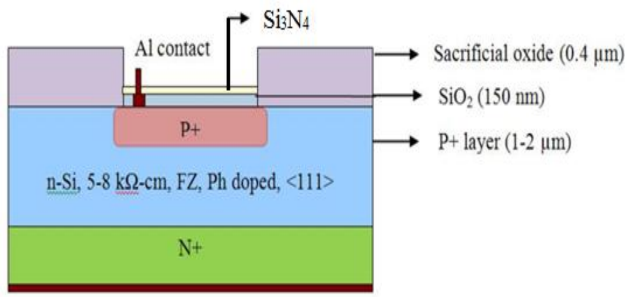

Figure 1: Schematic cross–section of Si PIN photodiode with Si_3N_4 ARC

III. RESULTS AND DISCUSSIONS

The gamma radiation is energetic electromagnetic radiation which ionizes the photodiode and creates electron-hole pairs in the bulk of the photodiode. In case of ^{60}Co gamma irradiation, photons have energy 1.17 and 1.33 MeV and bulk damage occurs primarily as a result of the interactions of secondary electrons with the silicon atoms. The secondary electrons typically have energies of 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 defects distributed uniformly throughout the PIN photodiode [12]. In addition to bulk damage the surface defects play a major role in increasing the leakage current of photodiode. The Si_3N_4/SiO_2 and SiO_2/Si interface contribute as additional leakage current to the bulk leakage current. However, the leakage current from the interface and bulk are indistinguishable.

The figures 2, 3 and 4 shows the reverse I-V characteristics of ^{60}Co gamma irradiated 1 mm^2, 4 mm^2 and 100 mm^2 PIN photodiodes respectively.

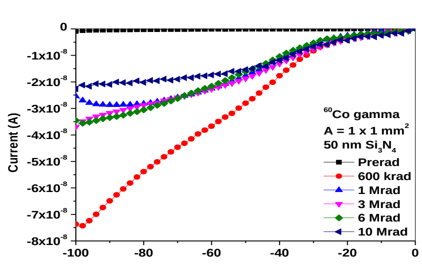

Figure 2a: I-V characteristics of ^{60}Co gamma irradiated 1x1 mm^2 PIN photodiodes with 50nm Si_3N_4

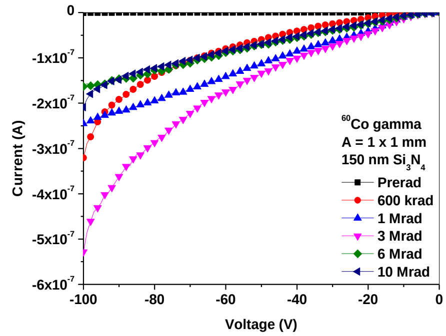

Figure 2b: I-V characteristics of ^{60}Co gamma irradiated 1x1 mm^2 PIN photodiodes with 150 nm Si_3N_4

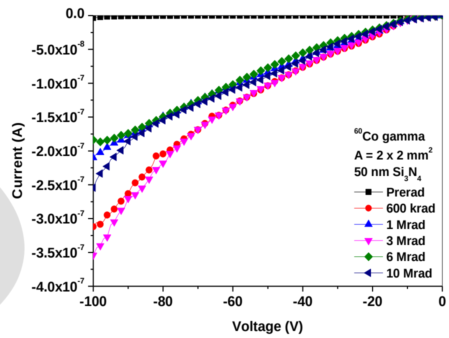

Figure 3a: I-V characteristics of ^{60}Co gamma irradiated 2x2 mm^2 PIN photodiodes with 50nm Si_3N_4

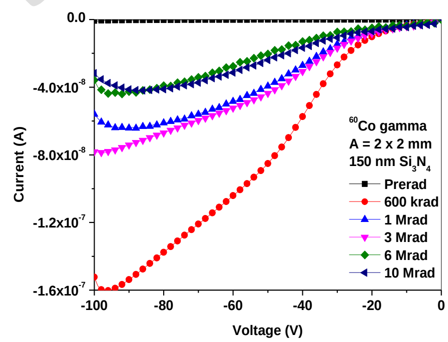

Figure 3b: I-V characteristics of ^{60}Co gamma irradiated 2x2 mm^2 PIN photodiodes with 150nm Si_3N_4

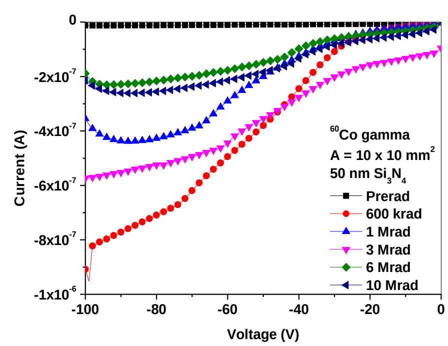

Figure 4a: I-V characteristics of ^{60}Co gamma irradiated 10x10 mm^2 PIN photodiodes with 50nm Si_3N_4

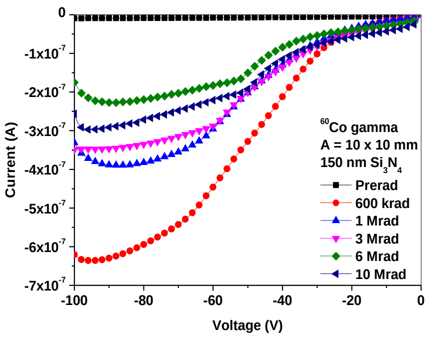

Figure 4b: I-V characteristics of ^{60}Co gamma irradiated 10x10 mm^2 PIN photodiodes with 150nm Si_3N_4

It can be seen from the figures that the leakage current increases at lower total dose range i.e., 600 krad to 3 Mrad. The increase in leakage current is due to radiation induced generation-recombination centres in the Si photodiode. After the initial increase in leakage current, recovery was observed at higher total dose range say 3 Mrad to 10 Mrad. At lower total dose the radiation induced charge build-up takes place in the oxide and nitride stack. Further as the total dose increases, the radiation induced charges recombine at the nitride and oxide interface. The high density of electronic states in Si_3N_4 are very much effective in recombining the radiation induced charges at the Si_3N_4/SiO_2 interface [13] and therefore the leakage current recovers in the total dose range between 3 Mrad to 10 Mrad. The recovery in leakage current was due to the bond re-arrangement in the Si_3N_4/SiO_2 and SiO_2/Si interface. The radiation induced interface states generation is suppressed by the nitride/oxide composite, especially the presence of nitrogen near the Si_3N_4 and SiO_2 interface.

The capacitance of PIN photodiode in reverse bias condition is given by the equation; $C = dQ/dV = \varepsilon A/X$, where the charge $Q = q\ N_{eff}\ AX$, here A is the diode area, N_{eff} is effective dopant concentration and X is the depletion depth. At bias voltages larger than the full depletion voltage, the capacitance remains constant because capacitance is inversely proportional to the square root of the applied voltage. The capacitance at full depletion voltage corresponds to the geometrical capacitance of the diode which is considered as a parallel plane plate capacitor. Any change in the capacitance is measure of effective dopant concentration or the change in depletion width of the photodiode.

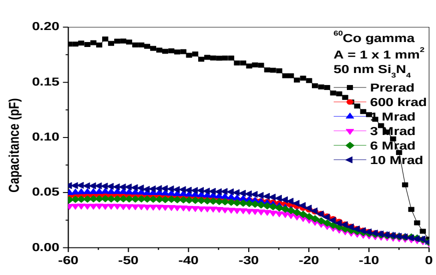

Figure 5a: C-V characteristics of ^{60}Co gamma irradiated 1x1 mm^2 PIN photodiodes with 50nm Si_3N_4

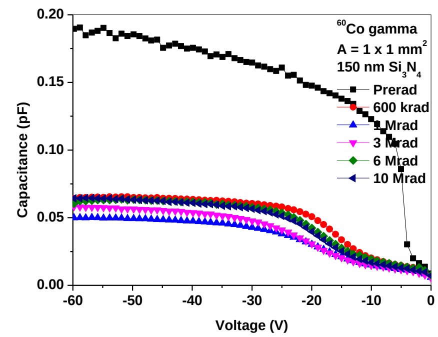

Figure 5b: C-V characteristics of ^{60}Co gamma irradiated 1x1 mm^2 PIN photodiodes with 150nm Si_3N_4

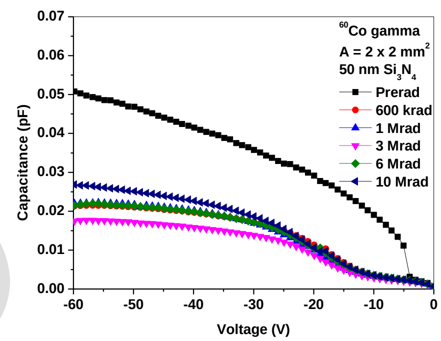

Figure 6a: C-V characteristics of ^{60}Co gamma irradiated 2x2 mm^2 PIN photodiodes with 50nm Si_3N_4

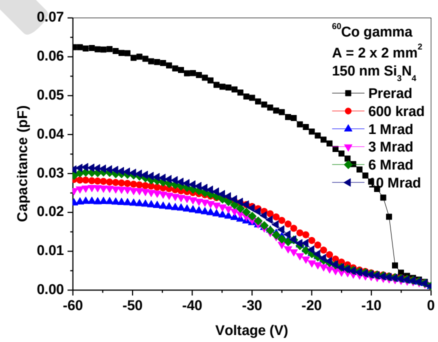

Figure 6b: C-V characteristics of ^{60}Co gamma irradiated 2x2 mm^2 PIN photodiodes with 150nm Si_3N_4

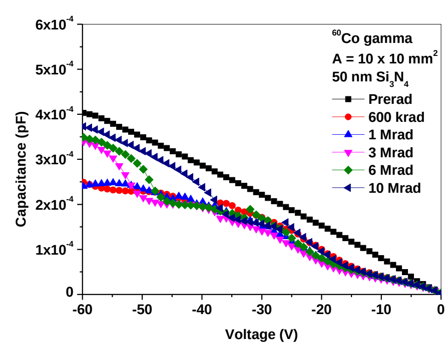

Figure 7a: C-V characteristics of ^{60}Co gamma irradiated 10x10 mm^2 PIN photodiodes with 50nm Si_3N_4

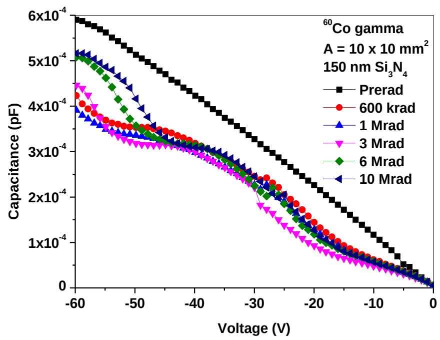

Figure 7b: C-V characteristics of ^{60}Co gamma irradiated 10x10 mm^2 PIN photodiodes with 150nm Si_3N_4

The C–V characteristics of ^{60}Co gamma irradiated Si PIN photodiodes are shown in figures 5, 6 and 7 for 1 mm^2, 4 mm^2 and 100 mm^2 devices respectively. It can be clearly seen from the figures that in case of 50 nm Si_3N_4 ARC photodiodes, the capacitance was found to decrease with increase in total dose up to 3 Mrad. But in case of 150 nm Si_3N_4 ARC photodiodes, the capacitance decreases up to 1 Mrad of total dose. Further the recovery in capacitance was observed up to total dose of 10 Mrad. The capacitance decreases because 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 that are ejected out of the depletion region to opposite electrodes contribute to the current and it increase the depleted width. As the radiation total dose increases the radiation induced trapped charges are decreasing. The radiation induced trapped charges recombine at the Si_3N_4/SiO_2 interface reducing the charge build-up at higher total doses. Therefore, the depletion region decreases at higher total dose and the capacitance results are consistent with the I–V results.

The change in depletion region and effective dopant concentration can affect the light sensitivity of PIN photodiode. The spectral responses of different active area (1 mm^2, 4 mm^2 and 100 mm^2) PIN photodiode are measured in photovoltaic mode.

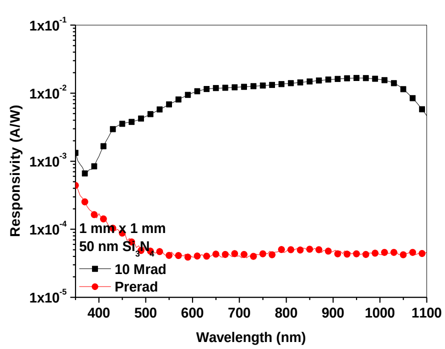

Figure 8a: Spectral response of ^{60}Co gamma irradiated 1x1 mm^2 PIN photodiodes with 50nm Si_3N_4

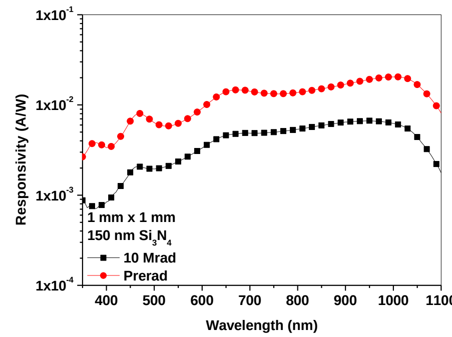

Figure 8b: Spectral response of ^{60}Co gamma irradiated 1x1 mm^2 PIN photodiodes with 150nm Si_3N_4

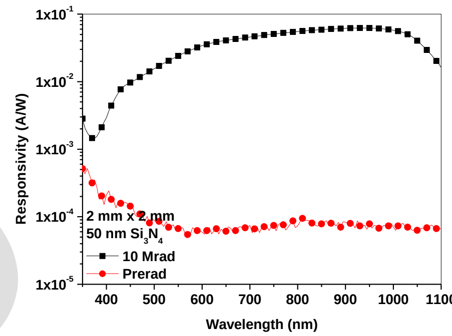

Figure 9a: Spectral response of ^{60}Co gamma irradiated 2x2 mm^2 PIN photodiodes with 50nm Si_3N_4

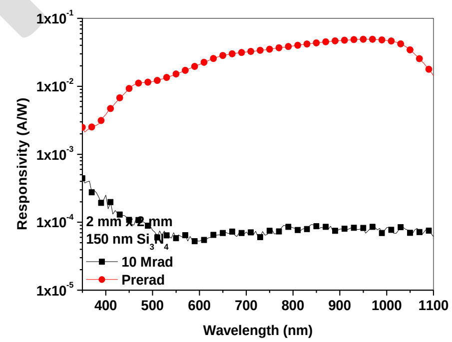

Figure 9b: Spectral response of ^{60}Co gamma irradiated 2x2 mm^2 PIN photodiodes with 50nm Si_3N_4

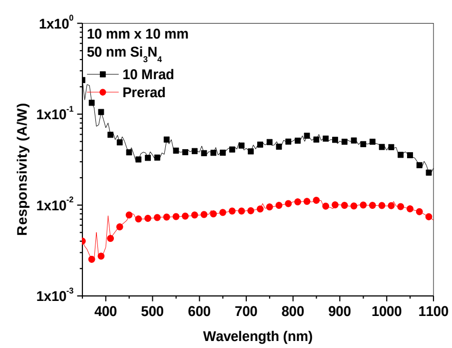

Figure 10a: Spectral response of ^{60}Co gamma irradiated 10x10 mm^2 PIN photodiodes with 50nm Si_3N_4

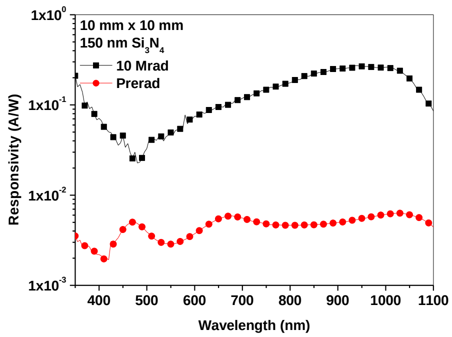

Figure 10b: Spectral response of ^{60}Co gamma irradiated 10x10 mm^2 PIN photodiodes with 150nm Si_3N_4

The spectral responses of 1 mm^2, 4 mm^2 and 100 mm^2 active area PIN photodiodes after ^{60}Co gamma irradiation are shown in figures 8, 9 and 10 respectively. It is evident from the figures that after 10 Mrad of total dose, the spectral response was found to increase for ^{60}Co gamma irradiated photodiode when compared to the un-irradiated photodiode. In case of un-irradiated photodiode, there may be more reflection of the incident spectral light from the Si_3N_4 layer. However in case of irradiated photodiode, the incident spectral light is completely absorbed by the Si_3N_4 layer due to bond re-arrangement after ^{60}Co gamma irradiation. The radiation induced interface trapped charges are at the Si/SiO_2 and Si_3N_4/SiO_2 interface and these trapped charges reduce at higher total dose. The trap centres assisted scattering of incident spectral light decreases in ^{60}Co gamma irradiated photodiode and hence the spectral response increase for higher total doses. The elipsometer measurements show that the thickness of Si_3N_4 layer was around 48.28 nm and after 10 Mrad of total dose the thickness was found to be 48.72 nm. The increase in nitride layer thickness is due to the irradiation induced relaxation of Si_3N_4 layer [14]. Therefore the reflection of incident spectral light reduces in ^{60}Co gamma irradiated photodiode due to the relaxed Si_3N_4 layer and hence the spectral response increases. However the spectral response reduces in case of smaller active area (1 mm^2 and 4 mm^2) Si PIN photodiodes coated with 150 nm Si_3N_4. In smaller active area photodiodes, relaxation of Si_3N_4 layer was not observed after ^{60}Co irradiation and therefore the radiation induced trapped centres scatter the incident spectral light and reduce the spectral response. The relaxation of Si_3N_4 is depending on Si_3N_4 thickness to photodiode area ratio. Therefore in smaller active area photodiode coated with 150 nm Si_3N_4, the spectral response of ^{60}Co gamma irradiated photodiode decreases when compared to un-irradiated photodiode.

The nitride/oxide composite is composed of nitrogen-rich region at the interface and a lower concentration of nitrogen in the bulk of the film [15-16]. In oxide/nitride composites, nitrogen plays an important role to improve the trapping properties of the near interfacial oxide in which border traps are found. The suppression of interface state generation in the nitride/oxides is related to the build–up of nitrogen near the Si_3N_4 and SiO_2 interface. The radiation induced trapped charges in nitride/oxide composite readily recombine in very short time when compared to the trapped charges generated in SiO_2. However in SiO_2, the radiation induced charges are very mobile in nature and are usually transported out of the oxide in very short interval of time (in picoseconds). The remaining holes are not very much mobile and are transported in the oxide by a complicated hopping process. The holes accumulated near the SiO_2 and Si_3N_4 interface assist the recombination of radiation induced trapped charges at the nitride/oxide interface [14]. The capture and recombination of radiation induced trapped charges will result in the relaxation of the Si_3N_4 layer. The irradiation induced relaxation nature of Si_3N_4 layer will allow more radiation to pass through the ARC and hence the spectral response improves by an order of magnitude. Therefore, the ARC with Si_3N_4 and SiO_2 composite act as excellent radiation hard material to ionizing radiation up to a total dose of 10 Mrad. However further studies are required to understand the behaviour of nitride-oxide composite at higher total doses.

CONCLUSIONS

The silicon PIN photodiodes of different active area were designed and fabricated using planar technology. The photodiodes were deposited with different thickness Si_3N_4 layer as ARC. The effects of ^{60}Co gamma radiation on nitride coated PIN photodiodes were studied up to total dose of 10 Mrad. The degradation in the I–V characteristics at 600 krad is mainly due to radiation induced generation–recombination centres in the bulk of the photodiode. The recovery in the I–V, C–V characteristics and spectral responses at higher total dose is due to recombination of charges at the nitride/oxide interface and relaxation of the nitride layer. The radiation–induced charge movement in SiO_2 and charge capturing by nitride ARC is a major advantage with oxide and nitride stacks as ARC. Therefore the oxide and nitride stack will act as excellent radiation hard ARC on Si PIN photodiodes up to 10 Mrad of total dose.

REFERENCES

[1] J. Srour, C. J. Marshall, and P. W. Marshall, "Review of displacement damage effects in silicon devices," *IEEE Transactions on Nuclear Science,* vol. 50, pp. 653-670, 2003.

[2] S. M. Sze, *Semiconductor Devices: Physics and Technology* John Wiley & Sons, 2008.

[3] F. Gianotti, M. L. Mangano, T. Virdee, S. Abdullin, G. Azuelos, A. Ball, *et al.*, "Physics potential and experimental challenges of the LHC luminosity upgrade," *The European Physical Journal C,* vol. 39, pp. 293-333, 2005.

[4] G. Lindström, M. Ahmed, S. Albergo, P. Allport, D. Anderson, L. Andricek, *et al.*, "Radiation hard silicon detectors—developments by the RD48 (ROSE) collaboration," *Nucl Instrum Meth A,* vol. 466, pp. 308-326, 2001.

[5] K. Gill, G. Hall, and B. MacEvoy, "Bulk damage effects in irradiated silicon detectors due to clustered divacancies," *Journal of Applied Physics,* vol. 82, pp. 126-136, 1997.

[6] Y. P. Prabhakara Rao, K. C. Praveen, Y. R. Rani, and A. P. Gnana Prakash, "Novel methods to reduce leakage current in Si PIN

photodiodes designed and fabricated with different dielectrics," *Indian Journal of Pure and Applied Physics,* 2014.

[7] Y. P. Prabhakara Rao, K. C. Praveen, Y. Rejeena Rani, A. Tripathi, and A. P. Gnana Prakash, "75 MeV boron ion irradiation studies on Si PIN photodiodes," *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms,* vol. 316, pp. 205-209, 2013.

[8] Y. P. Prabhakara Rao, K. C. Praveen, Y. R. Rani, and A. P. Gnana Prakash, "Reliability studies on Si PIN photodiodes under Co-60 gamma radiation," *AIP Conference Proceedings,* vol. 1512, pp. 1028-1029, 2013.

[9] J. Kemmer, "Improvement of detector fabrication by the planar process," *Nucl. Instr. and Meth. A,* vol. 226, pp. 89-93, 1984.

[10] M. Ullán, S. Díez, M. Lozano, G. Pellegrini, D. Knoll, and B. Heinemann, "Radiation damage of SiGe HBT Technologies at different bias configurations," presented at the Topical Workshop on Electronics for Particle Physics, Naxos, Greece, 2008.

[11] M. Ullán, S. Díez, M. Lozano, G. Pellegrini, D. Knoll, and B. Heinemann, "Combined effect of bias and annealing in gamma and neutron radiation assurance tests of SiGe bipolar transistors for HEP applications," *Solid-State Electronics,* vol. 56, pp. 179-184, 2011.

[12] S. K. Khamari, V. K. Dixit, T. Ganguli, S. Porwal, S. D. Singh, S. Kher, *et al.*, "Effect of ^{60}Co γ-ray irradiation on electrical properties of GaAs epilayer and GaAs p–i–n diode," *Nucl Instrum Meth B,* vol. 269, pp. 272-276, 2011.

[13] N. S. Saks, M. Simons, D. M. Fleetwood, J. T. Yount, P. M. Lenahan, and R. B. Klein, "Radiation effects in oxynitrides grown in N_2O," *IEEE Transactions on Nuclear Science,* vol. 41, pp. 1854-1863, 1994.

[14] S. T. Chang, N. Johnson, and S. Lyon, "Capture and tunnel emission of electrons by deep levels in ultrathin nitrided oxides on silicon," *Applied Physics Letters,* vol. 44, pp. 316-318, 1984.

[15] D. Fleetwood and N. Saks, "Oxide, interface, and border traps in thermal, N_2O, and N_2O nitrided oxides," *Journal of Applied Physics,* vol. 79, pp. 1583-1594, 1996.

[16] F. Terry Jr, R. Aucoin, M. Naiman, and S. Senturia, "Radiation effects in nitrided oxides," *IEEE Transaction on Electron Device Letters,* vol. 4, pp. 191-193, 1983.