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Radiation Effects in Ultraviolet Sensitive Pd/4H-SiC Schottky Detectors

Sirisha J*, Bhavana D, Shobha V, Sumesh M A, Vijesh T V & S P Karanth

Laboratory for Electro-Optics Systems, Indian Space Research Organization, Bengaluru 560 058, India

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4H-SiC, by virtue of its intrinsic properties, is a very promising semiconductor material for fabricating rad-hard UV detectors suitable for harsh radiation environments. This paper aims to investigate the radiation tolerance of indigenously developed Pd/4H-SiC Schottky detectors, in order to determine their feasibility for space applications. 4H-SiC detectors of active area 1 × 1 mm^2 were irradiated with electrons of energy 10 MeV at fluence of 2×10^{13} e^-/cm^2 and gamma rays from a Co-60 source with a total dose of 1 Mrad. The impact of these irradiations on electro-optical characteristics of the devices was studied by analyzing the changes in electrical parameters like reverse saturation current (I_s), ideality factor (n), barrier height (ϕ_B), effective doping concentration (N_{eff}) derived from I-V and C-V characteristics as well as in the UV spectral responsivity (*i.e.,* from 248 to 365 nm) of the irradiated detectors. The electron irradiated device showed negligible change in I-V and C-V characteristics whereas its UV spectral responsivity at the peak wavelength of 290 nm reduced by 48.7 %. Gamma irradiated device displayed a noticeable variation in its electrical characteristics and 15.8 % reduction in the spectral responsivity (optical characteristics) at the peak wavelength. The results show that the radiation hardness of 4H-SiC detectors is better than that of conventional semiconductor ones, making it a more appealing choice as radiation detectors in space systems.

Keywords: 4H-SiC UV detectors; Electron irradiation; Gamma irradiation; I-V characteristics; C-V characteristics; UV spectral responsivity

1 Introduction

The employment of semiconductor radiation detectors for space applications is often hindered by the harsh radiation environment which can result in performance degradation and even total failure of the device. The major radiation damage mechanisms are lattice displacement and ionization. Lattice displacement leads to formation of defects in the semiconductor crystal due to impinging of energetic particles like electrons, protons and α-particles on its surface. Ionization is induced in the dielectric layers of the device by exposure to ionizing electromagnetic radiation like gamma-rays[1,2]. The extent of degradation depends on the type of impinging particles, its energy, dose, exposure time, etc. The annual radiation dosage encountered by an object in the Low-Earth Orbit (LEO) is around 0.3 krad and it can go as high as 100 krad in the Geosynchronous-Earth Orbit (GEO)[3,4]. Hence, space-borne sensors need to be rad-hard so as to sustain doses of the order of hundreds of krads for several years without performance degradation.

4H-SiC is an outstanding semiconductor material, with a wide bandgap (3.2 eV), excellent thermal conductivity (4.9 W/cm.K) and high displacement threshold energy (22-35 eV), all of which result in superior radiation hardness, resistance to variability in operating temperature and low dark currents along with high sensitivity[5,6]. This gives it a significant advantage over conventional narrow band-gap semiconductors such as silicon, in harsh radiation conditions. Even a wide band-gap semiconductor like GaN, which has a similar radiation hardness to 4H-SiC, pales in comparison to the latter in terms of the highest operating temperature (SiC: 973 K, GaN: 600 K), detectivity (SiC: 10^{16} $cmHz^{-1/2}W^{1}$, GaN:10^{13} $cmHz^{-1/2}W^{-1}$), and low dark current densities (SiC: 10^{-16} A/cm^2, GaN: 10^{-13} A/cm^2). Applications of 4H-SiC detectors include, but are not limited to, UV photometers in interplanetary missions to Mars and Venus, active radiation dosage trackers for manned space missions and UV instruments for monitoring trace gases in the Earth's atmosphere[7-9]. For these on-board applications, studies on the degradation of UV responsivity of the 4H-SiC detector due to harsh space radiation environment are crucial. Effects of high energy ionizing radiation on the UV spectral responsivity of 4H-SiC have not been reported.

This study focuses on the effects of gamma irradiation of dose 1 Mrad (Si) and electron irradiation with energy 10 MeV and fluence of 2×10^{13} e^-/cm^2 on

*Corresponding author:
(E-mail: sirisha_j@leos.gov.in)

indigenously developed Pd/4H-SiC Schottky UV detectors. These levels are chosen to simulate the outer space radiation environment and their effects on the electro-optical characteristics, with an onus on UV spectral responsivily.

2 Experimental Details

2.1 Device structure and fabrication

The Schottky UV photo detectors were fabricated on an n^--4H-SiC epitaxial layer of 5 µm thickness with nitrogen as dopant. Ion beam sputtering was used to deposit the Si_3N_4 film on n^--4H-SiC epi layer to provide envelope for the active area 1 × 1 mm^2. A Pd film of thickness 25Å which acts as Schotty contact, was deposited using ion beam sputtering system, which acts as the Schottky contact. Ohmic contact was formed by sputter deposition of titanium (750 Å) and silver (2000 Å) to form a 500 µm wide contact pad along one side of the active area, followed by rear side metallization. After fabrication, the detector chips were packaged in TO-5 Kovar packages in compliance with the HMC packing procedures and fit with UV transparent fused silica windows (Corning HPFS 7980) as shown in Fig. 1. The details of the fabrication as well as the electro-optical performance of the detectors can be found elsewhere[10].

2.2 Irradiation details

Four detector devices were subjected to electron irradiation and five detector devices for gamma irradiation. All these nine devices were randomly chosen from the same fabrication batch. Devices without top lid as shown in Fig. 1(a) were irradiated with electrons of energy 10 MeV using the electron linear accelerator (LINAC) located in Bhabha Atomic Research Center (BARC), Mumbai at a fluence of 2×10^{13} e^-/cm^2 to accumulate a total dosage of 4.7 Mrad. All the four devices that underwent electron irradiation were found to exhibit similar behavior post-irradiation. Hence, results of one such detector (identified as D1) from the tested lot is presented.

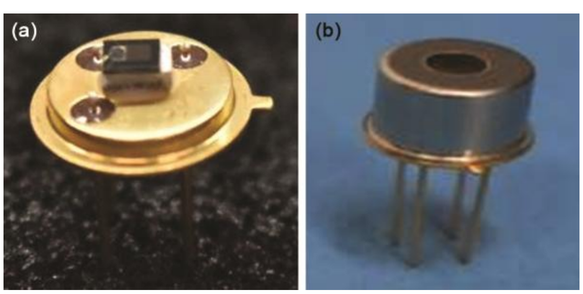

Fig. 1 — 1 mm × 1 mm Pd/4H-SiC detector chip packaged in TO-5 package (a) without top lid (b) with top lid.

Gamma irradiation was done using Co-60 source in gamma chamber GC–1200 located at ISRO Satellite Integration and Test Establishment, Bengaluru. The radiation dose rate of the Co-60 gamma source during irradiation was 135 rad/sec. Detector (D2) with top lid was exposed for a period of two hours to accumulate radiation dose of 1 Mrad to meet space qualification requirements. One more detector (D5) with top lid was subjected to different doses of 100 krad, 1 Mrad, 2 Mrad, 4 Mrad and 6 Mrad to study the effect of gamma irradiation on UV spectral responsivity of 4H-SiC devices at various dosages.

During both gamma and electron irradiation no bias was applied and detector terminals were left floating.

2.3 Electro optical characterization

2.3.1 Electrical characterization

Electrical characterization of the devices was carried out *ex situ*, immediately after exposure. I-V characteristics of the Pd/4H-SiC Schottky photo detectors in both forward bias and reverse bias are measured at room temperature 298K under dark conditions, using a Keithley 6517A electrometer/ high-resistance meter. For the C-V characteristics, capacitance measurements are performed using a multi frequency LCR meter HP4263A at room temperature, by imposing a sinusoidal carrier frequency 100 kHz with amplitude 500 mV on DC voltage varying from 0 V to 30 V under reverse bias.

2.3.2 Spectral characterization

Spectral responsivity of the detectors in UV region is measured using a xenon arc lamp as a source and a set of narrow-band UV filters (with FWHM of 10 nm) covering the wavelength region from 248 nm to 365 nm. A standard detector of active area 1.8 mm^2 (SgLux, Germany) with known spectral responsivity is used as reference detector for calibrating the test setup. The photo-current corresponding to each spectral band is measured using a Keithley 2000 Digital Multimeter. From the known UV irradiance on the detector pixel and its photo-current, spectral responsivity of the Pd/4H-SiC Schottky detector is determined.

3 Results and Discussion

3.1 Effects of electron irradiation

3.1.1 On fused silica window

To study the effect of electron irradiation on 1 mm thick fused silica window that is used as a top lid, transmission spectra are taken in the wavelength range from 250 to 400 nm, before and after irradiation using Cary 7000-Universal measurement spectrophotometer. It is observed from the Fig. 2 that transmission has reduced by 1.5% in the UV wavelength range down to 290 nm, which can be attributed to the development of color center absorption bands[11]. At shorter wavelengths, the degradation is steeper. To study the effect of electron irradiation on detector alone, devices without top lid are subjected to electron irradiation.

3.1.2 I-V characteristics

The electrical performance of diodes was evaluated by recording the current/voltage (I/V) characteristics at room temperature with the applied voltage range from 0 to 2.1 V and reverse bias of 0 to -20 V. Fig. 3 shows the forward and reverse I-V characteristics of a device before and electron irradiation. It is observed from Fig. 3(a) that electron irradiation does not significantly affect the forward I-V characteristics. The forward current at 2.1 V bias reduced from 10.9 mA to 10.1 mA after electron irradiation. The reverse current is almost constant over the range of voltage (0 to -20 V) before irradiation, with the value less than 4 pA as seen in Fig. 3(b). After irradiation, the reverse current increases with bias voltage and reaches 10 pA at -20 V. This increase in reverse current can be attributed to electron induced interface defects in 4H-SiC.

For metal/semiconductor Schottky diodes, according to the thermionic emission theory[12], the diode current is expressed by

$$\frac{q\phi_B}{\quad} \qquad \frac{\quad}{\quad} \qquad \dots (1)$$

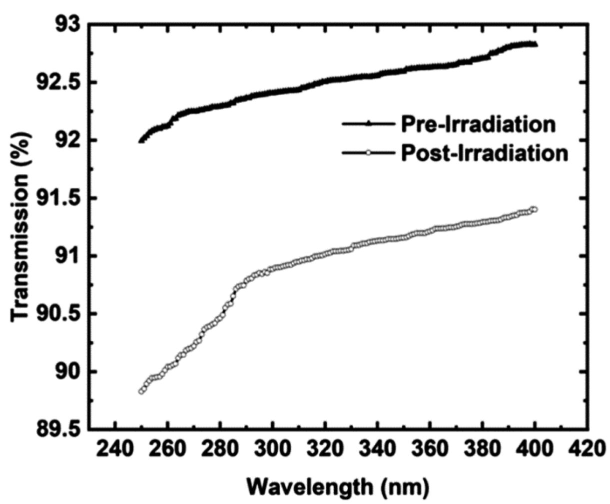

Fig. 2 — Transmission spectra of pre and post electron irradiated fused silica window.

where, n = (ideality factor), k_B = (Boltzmann's constant) = 1.38×10^{-23} J/K, ϕ_B = (barrier height), T = (Temperature) = 298 K, q = (Charge of electron) = 1.6×10^{-19} C, S = Area of Photodiode = 0.01 cm^2, (Richardson constant) = 146 $AK^{-2}cm^{-2}$

Further, the saturation current, I_s of the Schottky diode is expressed as:

$$\frac{q\phi_B}{\quad} \qquad \dots (2)$$

The values of ideality factor and barrier height for pre- and post-irradiated devices were calculated using (3) and (4) by determining the slope of linear region of forward I-V characteristics.

$$\frac{\quad}{\quad}\frac{\quad}{\quad} \qquad \dots (3)$$

$$\phi_B \quad \frac{\quad}{\quad} \quad \frac{\quad}{\quad} \qquad \dots (4)$$

A linear fit of the forward I-V characteristics was carried out using the ORIGIN Pro software and the saturation current, I_s was found from the extrapolating the linear region of the forward I-V curves at zero voltage. The values are given in Table 1.

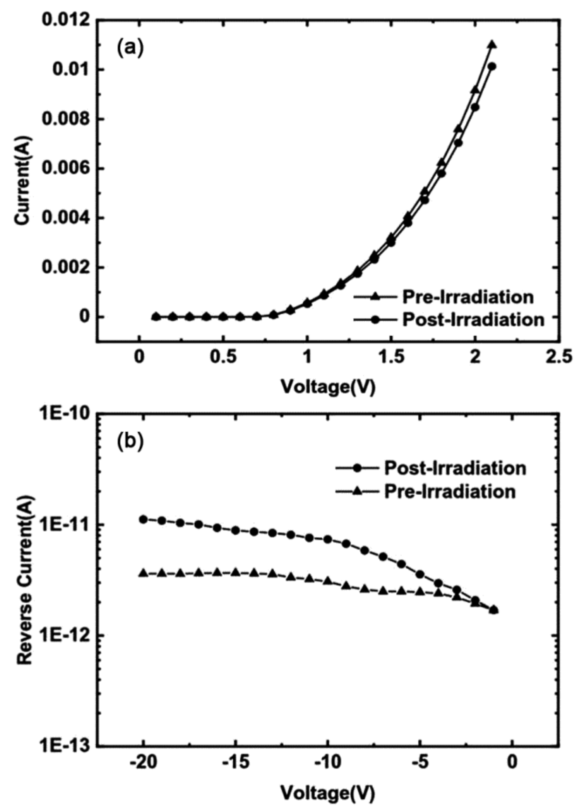

Fig. 3 — The (a) forward and (b) reverse I-V characteristics of the 4H-SiC Schottky detector before and after electron irradiation of energy 10 MeV.

Table 1 — Pre and post electron irradiation values of I_s, ϕ_b, n derived from I-V characteristics

Sl. No	Parameter	Pre-Irradiation	Post-Irradiation
1	Saturation Current, I_S (A)	1.58×10^{-16}	1.68×10^{-16}
2	Barrier Height, ϕ_B (eV)	1.24	1.24
3	Ideality Factor, n	1.11	1.12

A minor increase is observed in the reverse saturation current and ideality factor post irradiation while the barrier height remains unchanged. This observation is in accordance with the earlier reports[12, 13].

3.1.3 C-V characteristics

The variation in capacitance with voltage under reverse bias for the 4H-SiC detector before and after electron irradiation is shown in Fig. 4(a). The junction capacitance of the diode decreases with bias voltage up to -15 V, after which it saturates at 41 pF and remains unchanged up to a bias voltage of -30 V. From 0 V to -15 V, the junction capacitance of the irradiated device is lower than that of the un-irradiated device. The effective doping density N_{eff} is calculated by plotting the reciprocal of the squared capacitance as a function of the bias voltage as expressed in (3).

… (5)

where; q is the charge of electron, : 9.66 × 8.854 × 10^{-12} F/m, S: 1 mm × 1 mm.

The value of N_{eff} is obtained as 3.65×10^{15} /cm^3 for the preirradiated device and it reduces to 2.92×10^{15}/ cm^3 post irradiation. This lowering of N_{eff} indicates the formation of acceptor-like levels due to electron irradiation. This observation is supported by results reported in previous studies[12,14], where the effective doping density of 4H-SiC is unaffected by an electron fluence of 1×10^{14} e$^-$/cm^2. A similar behavior is exhibited by its counterparts like GaN which also shows a slight degradation in the carrier concentration[15] at these electron fluencies. This indicates that effect of electron irradiation is similar is both 4H-SiC and GaN.

The capacitance values are also used to calculate the width of the depletion region and the variation in depletion width with reverse bias voltage is plotted in Fig 4(b). After irradiation, the depletion width increases from 0.88 µm to 1.19 µm at zero bias condition. As the bias voltage increases, the difference between the pre and post irradiated depletion width decreases and they both settle at a value of 2.04 µm after -15 V.

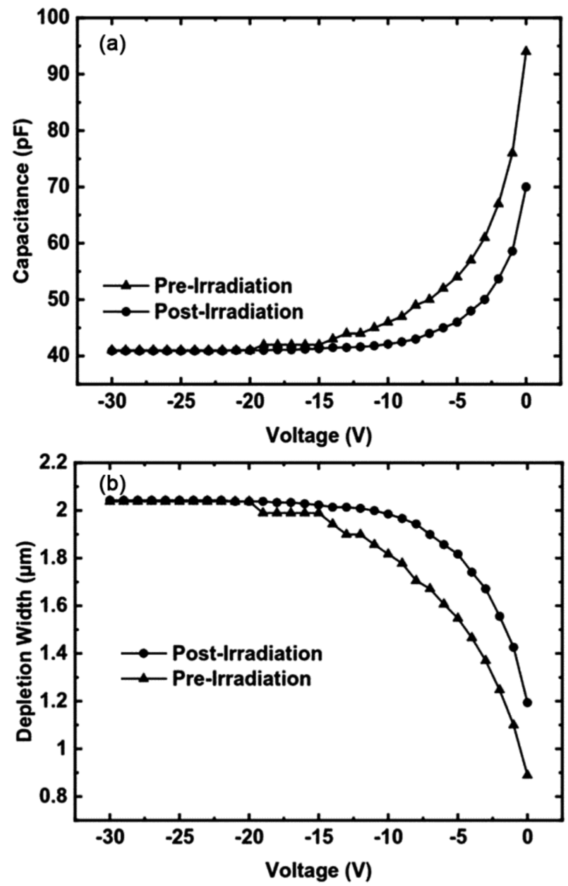

Fig. 4 — The (a) reverse C-V characteristics and (b) variation in depletion width with reverse bias voltage before and after electron irradiation of energy 10 MeV.

3.1.4 UV spectral responsivity

Figure 5 shows the change in the spectral responsivity of a device due to electron irradiation in the wavelength range of 248-365 nm. The highest responsivity value (122.8 mA/W) corresponds to a wavelength of 290 nm and it decreases to 63.6 mA/W after irradiation. It is seen from the results that with the same incident optical power, responsivity has significantly reduced by 48 % after irradiation at the peak wavelength of 290 nm.

The degradation in responsivity due to electron irradiation is observed to be lower at shorter wavelengths and higher in the longer wavelength region. The responsivity depreciates by only 11.4 % at a shorter wavelength of 248 nm, whereas at 365 nm, responsivity value is reduced from 1 mA/W to 0.3 mA/W, which corresponds to a reduction of 71 % in responsivity after 4.7 Mrad of irradiation. This implies the formation of electron irradiation induced defects deeper in the bulk of 4H-SiC epitaxial layer.

Due to these defects, it is likely that the charge collection efficiency reduces[16], which leads to the recombination current dominating over the diffusion current resulting in shorter life time of the carriers which reduces the photo generated current and thus the responsivity.

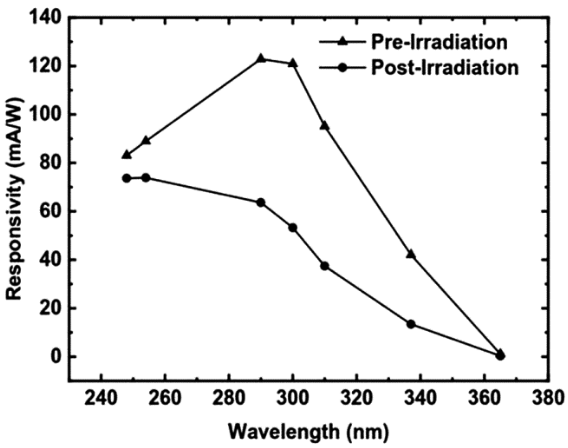

Fig. 5 — Spectral responsivity characteristics of the 4H-SiC Schottky detector before and after electron irradiation of energy 10 MeV.

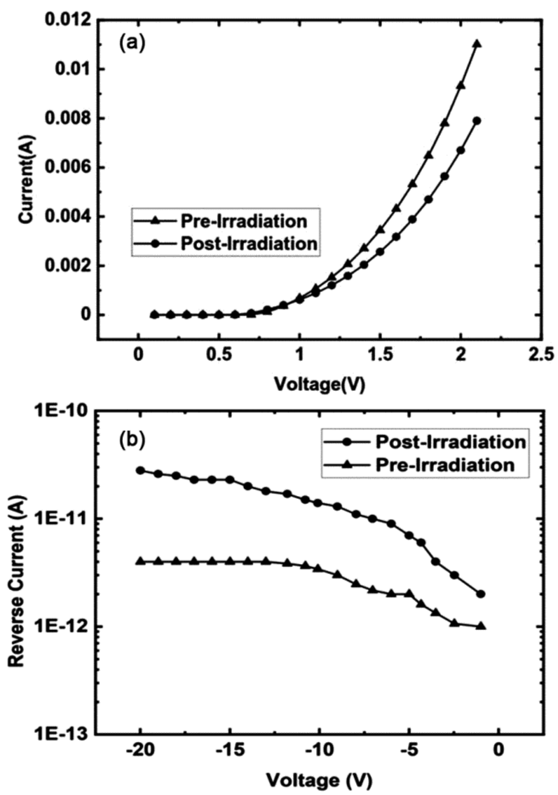

Fig. 6 — The (a) forward and (b) reverse I-V characteristics of the 4H-SiC Schottky detector before and after gamma-ray irradiation of total dose 1 Mrad.

3.2 Effects of gamma irradiation

3.2.1Effect on fused silica window

After the exposure of gamma irradiation of dose 1Mrad on fused silica window, no change was observed in the transmission characteristics of fused silica. Hence, effect of gamma irradiation of 1Mrad on detectors can be even known by exposing the sealed devices as there is no effect on the top lid.

3.3.2 I-V characteristics

Figure 6 shows the I-V characteristics for 4H-SiC Schottky diodes before and after gamma irradiation. After gamma irradiation, the forward current at 2.1 V decreases by 28 %. The reverse dark current is found to increase after irradiation, reaching 12 pA at a bias voltage of -20 V.

To investigate further, saturation current, barrier height and ideality factor are calculated from the linear region of Fig. 6(a) and listed in Table 2.

From the calculated values, it is seen that, post-irradiation, the reverse saturation current increases by two orders and ideality factor increases from 1.06 to 1.28 whereas the barrier height decreases from 1.23 to 1.08 eV. According to thermionic emission theory[17], as per the diode current equation for semiconductor Schottky diodes, the decrease in forward current may be due to increase in resistance in the bulk of the crystal, while decrease in barrier height is responsible for increase in reverse current. In comparison, GaN devices, as reported in literature[18], have two orders of magnitude higher leakage currents (10^{-10}A) than that of 4H-SiC devices, but the post irradiation effects on the characteristics of GaN is similar to that of 4H-SiC. This shows that 4H-SiC is as rugged as GaN, and better than the latter in terms of UV detectivity and leakage current densities compared to GaN under harsh radiation environments.

3.3.3.C-V characteristics

C-V characteristics before and after irradiation of Schottky detector are shown in Fig. 7.

The post irradiated device C-V characteristics follow the same trend as the pre-irradiated ones, *i.e.*, in both the cases the junction capacitance saturates at

Table 2 — Pre and post gamma irradiation values of I_s, ϕ_b, n derived from I-V characteristics

Sl No	Parameter	Pre-Irradiation	Post-Irradiation
1	Saturation Current, I_S (A)	2.09×10^{-16}	6.02×10^{-14}
2	Barrier Height, ϕ_B (eV)	1.23	1.08
3	Ideality Factor, n	1.06	1.28

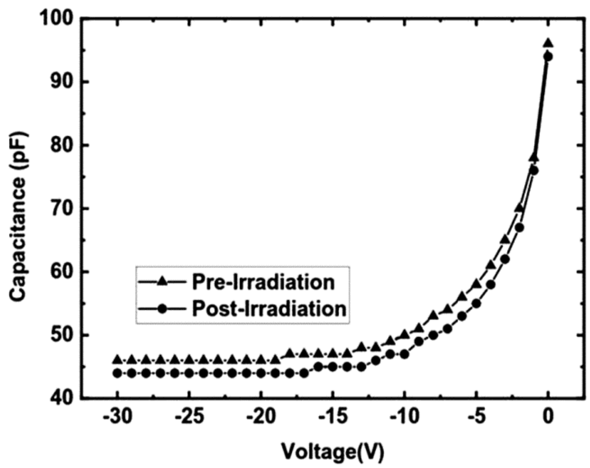

Fig. 7 — The reverse bias C-V characteristics of the 4H-SiC Schottky detector before and after gamma-ray irradiation of total dose 1 Mrad.

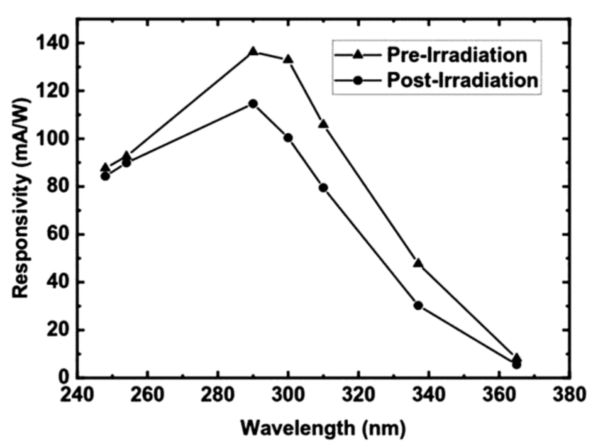

Fig. 8 — The variation in spectral responsivity of the 4H-SiC Schottky detector before and after gamma-ray irradiation of total dose 1Mrad.

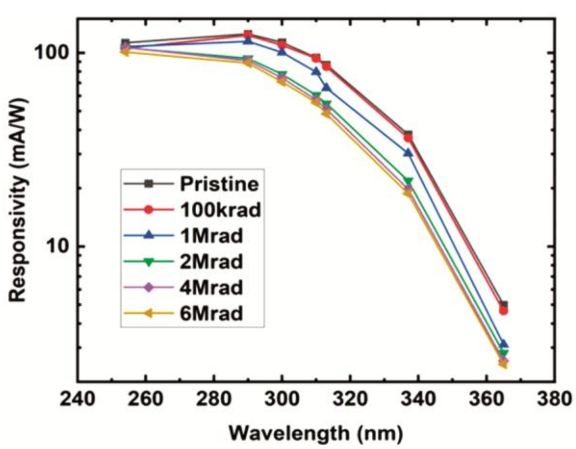

Fig. 9 — Spectral responsivity characteristics of the 4H-SiC Schottky detector after exposure to various doses of gamma radiation.

a bias of -13 V. The effective doping density N_{eff}, derived from $1/C^2$ *Vs*. V curve, is found to remain the same at $3.65 \times 10^{15}/cm^3$ even after gamma irradiation.

3.3.4 UV spectral responsivity

Figure 8 shows the effect of gamma irradiation on the spectral responsivity of the 4H-SiC detector (D2) for space applications. A degradation of 15.8% (from 136.26 mA/W to 114.6 mA/W) in the spectral responsivity is observed at the peak wavelength of 290 nm. As earlier study[19] reports a higher degradation in responsivity (about 45 %) at the peak wavelength of 275 nm for the same total dose. At shorter wavelengths, no significant degradation is observed, *i.e*., at 248 nm, there is only a 3.8 % reduction in responsivity. Fig. 9 represents the variation of UV spectral responsivity of detector D5 at different gamma dosages. We observe that the degradation in responsivity at peak wavelength (at 290 nm) increases with increase in dosage. The degradation of UV spectral responsivity at peak wavelength is 1.53 %, 25.13 %, 27.17 % and 29.23 % for 100 krad, 2 Mrad, 4 Mrad and 6 Mrad respectively. Ionizing effects created by gamma radiation leads to accumulation of radiation induced defects in the bulk of 4H-SiC detector, which seem to affect the responsivities of longer wavelengths more than the shorter wavelengths. These point defects act as recombination points leading to reduction of diffusion length and carrier life-time that results in a significant deterioration in responsivity[20].

4 Conclusion

The radiation tolerance of Pd/4H-SiC Schottky detectors developed for space applications is investigated by exposing them to high levels of electron and gamma radiation and studying variations in electro-optical and UV spectral responsivity characteristics. After electron irradiation of energy 10 MeV with a fluence of 2×10^{13} e^-/cm^2, negligible changes are observed in the electrical parameters, and the spectral responsivity at peak wavelength of 290 nm drops from 122.8 mA/W to 63.6 mA/W. The gamma irradiated device shows a discernible deterioration in the parameters derived from its electrical characteristics, but its spectral responsivity is not greatly affected *i.e*., only 15.8 % degradation at 1 Mrad and 29.63 % degradation at 6 Mrad is observed at peak wavelength of 290 nm. Furthermore, degradation in responsivity is lower at shorter wavelengths after both electron and gamma irradiations. The radiation induced defects in the bulk region and activation of recombination mechanism could have contributed to the observed deviations in the electro optical characteristics of 4H-SiC detectors. Nevertheless, the results of both gamma and electron irradiation are very promising for the use of these devices in satellite systems as they have been exposed to ionizing radiation at doses much higher than that expected even for the most severe space conditions where the sensor is deployed with no shielding. This demonstrates their suitability over other wide band gap semiconductors (GaN) as rad-hard detectors for space missions.

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