# Effect of $^{60}$Co $\gamma$-irradiation on the nature of electronic transport in heavily doped n-type GaN based Schottky photodetectors

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GaN Schottky photodetectors are fabricated on heavily doped n-type GaN epitaxial layers grown by the hydride vapour phase epitaxy technique. The effect of $^{60}$Co $\gamma$-radiation on the electronic transport in GaN epilayers and Schottky detectors is studied. In contrast to earlier observations, a steady rise in the carrier concentration with increasing irradiation dose is clearly seen. By considering a two layer model, the contribution of interfacial dislocations in carrier transport is isolated from that of the bulk layer for both the pristine and irradiated samples. The bulk carrier concentration is fitted by using the charge balance equation which indicates that no new electrically active defects are generated by $\gamma$-radiation even at 500 kGy dose. The irradiation induced rise in the bulk carrier concentration is attributed to the activation of native Si impurities that are already present in an electrically inert form in the pristine sample. Further, the rise in interfacial contribution in the carrier concentration is governed by the enhanced rate of formation of nitrogen vacancies by irradiation, which leads to a larger diffusion of oxygen impurities. A large value of the characteristic tunnelling energy for both the pristine and irradiated Au/Ni/GaN Schottky devices confirms that the dislocation-assisted tunnelling dominates the low temperature current transport even after irradiation. The advantage of higher displacement energy and larger bandgap of GaN as compared to GaAs is evident from the change in leakage current after irradiation. Further, a fast recovery of the photoresponse of GaN photodetectors after irradiation signifies their compatibility to operate in high radiation zones. The results presented here are found to be crucial in understanding the interaction of $^{60}$Co $\gamma$-irradiation with $n^+$-GaN epilayers. *Published by AIP Publishing.* https://doi.org/10.1063/1.5013102

## I. INTRODUCTION

Gallium nitride and its related ternary alloys involving Al and In have gained substantial attention of the semiconductor community due to their numerous applications in ultraviolet (UV) and visible light emitters and detectors. The imperceptible rate of intrinsic carrier generation and high breakdown voltage facilitate nitride semiconductor based micro-electronic devices to operate at high power, high temperature, and under high radiation.[1–4] Compared to Si and GaAs-based devices, nitride devices are more radiation tolerant because of high displacement energy, which is inversely proportional to the lattice constant.[5] This makes GaN a suitable candidate for applications in high radiation environments like nuclear reactors, particle accelerators, and spacecraft. The study of high-energy irradiation induced defects on the operational characteristics is an essential objective for estimating the long-term reliability of GaN based optoelectronic devices in a harsh radiation environment.

Exposure of GaN semiconducting layers to high energy radiation/particles leads to the creation of vacancy and interstitial point-defects through the displacement of Ga and N atoms from their respective lattice sites. It introduces new energy levels in the forbidden gap which act as scattering centres and can be donor, acceptor, or recombination centres. Hence, the introduction of radiation induced defect levels significantly influences the electrical transport and optical properties of the material and subsequently the performance of semiconductor devices.[5–7] However, isolated defects may endure thermally activated defect migration and formation of defect clusters through the interaction among themselves and also with the native defects even at room temperature. Such an observation was made by Chow *et al.*, where interstitial Ga defects generated by 2.5 MeV electrons were found to be stable at low temperature which became mobile at room temperature.[8] Since the probability of cluster formation is enhanced by the presence of native defects in the material, the effect of irradiation induced defects on the electrical transport properties critically depends on the background carrier concentration.[9] Although a large amount of literature is available on the effect of irradiation on moderately doped GaN, a systematic study on the electronic transport in heavily doped n-type GaN is missing. Only one group has reported that the effect of Gamma ($\gamma$) radiation induced defects in GaN varies as a function of carrier concentration. However, no efforts were made by them to understand the origin of defects.[9] In a previous article, we have shown that the carrier transport in $n^+$-GaN epilayers can be significantly influenced by the presence of charge dislocations that are generally present at the GaN/Sapphire interface.[10] Therefore, the

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impact of irradiation induced defects on electrical transport is not a trivial matter since interfacial transport of carriers might dominate over the thermally activated bulk transport in specific cases. This aspect is not yet highlighted while studying the effect of irradiation on heavily doped n-type GaN samples.

In this article, the effect of $\gamma$-radiation on the electrical transport in heavily doped n-type GaN is meticulously studied by considering the effect of interfacial dislocations. Experiments are conducted by irradiating the GaN samples with varying $\gamma$ ray dose. Contribution of interfacial dislocations in carrier transport is isolated from that of the bulk layer in both pristine and irradiated GaN samples using a two-layer model. Activation energy of defect levels is estimated by using the charge balance equation. It allows us to comment about the microscopic origin of radiation induced defects in a comprehensive manner. Further, the effect of radiation induced defects on the performance of GaN based Schottky devices is analysed and demonstrated to be less significant as compared to GaAs based Schottky devices. The importance of greater radiation tolerance of GaN based optoelectronic devices is also manifested through self-recovery within a day after irradiation even with a sizable dose of $^{60}$Co $\gamma$ rays.

## II. EXPERIMENTAL DETAILS

GaN epilayers are procured from a commercial vendor and possess a room temperature carrier concentration of $1 \times 10^{18}\,cm^{-3}$. The epitaxial layers are of 5 $\mu$m thickness and are grown on the c-plane Sapphire substrates by the hydride vapour phase epitaxy (HVPE) technique. In our work, suitable organic cleaning is carried out before contact fabrication, by boiling the samples in trichloroethylene, acetone, methanol and finally rinsing with de-ionized water. Samples are then dipped into HCl: $H_2O$ (1:1) solution for 15 s. In order to make low resistance Ohmic contacts, Indium (In) dots are placed on the samples which are subsequently annealed at 375 °C for 30 s in nitrogen ambient. Hall measurements on each sample are performed using van der Pauw geometry at 1 mA current and under 0.4 Tesla magnetic field.[10,11] For studying the effect of irradiation induced damage on Schottky diode properties, Ni (100 nm)/Au (250 nm) Schottky contact pads are deposited on GaN using the thermal evaporation technique under a base pressure of $4 \times 10^{-6}$ mbar through a metal mask of circular dots of 0.8 mm diameter. The photo-response of the device is measured in ring contact geometry where Ti (20 nm)/Al (60 nm)/Ni (20 nm)/Au (150 nm) multi-layer Ohmic contacts are fabricated using metal mask (ring type) and are subsequently annealed at 850 °C for 45 s under nitrogen ambient. Afterwards, Ni (100 nm)/Au (250 nm) Schottky contacts are deposited in the centre of the ring as shown in Fig. 1. Since the Sapphire substrate is insulating, both Ohmic and Schottky contacts are fabricated on the top of the GaN epilayer as shown in Fig. 1.

Room temperature $\gamma$-irradiation is carried out in a 2490 Curie $^{60}$Co $\gamma$-chamber, and electronic transport experiments are carried out immediately after the exposure. In order to evaluate the impact of self-recovery, transport measurements were performed at room temperature within

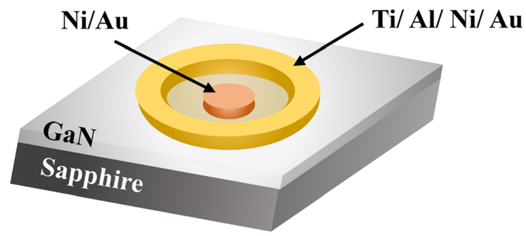


FIG. 1. Schematic diagram of the GaN UV photodetector.

15 min of irradiation. After this, the sample was cooled down to 50 K and temperature dependent data were collected within ~4 h. In the end, measurements were again repeated at room temperature. No appreciable difference was observed between the two room temperature measurements. Note that the sample was kept at low temperature during most of the measurement period. Hence, chances of self-recovery are rather low during the period of measurements. The typical dose rate of the irradiation system is 1 kGy/hr. More details about the $\gamma$-radiation chamber are reported elsewhere.[12] In this article, wherever dose is mentioned, it is the total dose emitted by the $^{60}$Co source to which our samples are exposed. Since the attenuation length of $^{60}$Co $\gamma$ in GaN is large (~1 cm) in comparison to the thickness of the GaN sample (5 $\mu$m), it can be safely assumed that the entire device is uniformly irradiated. Temperature dependent current-voltage (I-V-T) and Hall measurements are performed over a wide temperature range using two Keithley 236 source/measure units and one 2361 trigger controller unit interfaced with computer. Further, the room temperature photo-response of the device is measured using a 100 W Xenon lamp (excitation source), a 320 mm focal length monochromator, and a lock-in amplifier.

## III. RESULTS AND DISCUSSION

### A. Irradiation effect on the GaN epitaxial layer

In order to understand the effect of $^{60}$Co $\gamma$-radiation on the carrier concentration and mobility of GaN epitaxial layers, temperature dependent Hall measurements are performed over a wide temperature range varying from 60 to 300 K and the results are shown in Fig. 2. It is observed that the carrier concentration increases while mobility decreases with the rise in radiation dose.

An important observation of the present study is the unusual behaviour of the carrier concentration and mobility at temperature below 80 K. In the low temperature range, the carrier concentration slightly increases and then remains almost independent of temperature. Further, the rise in the carrier concentration is more prominent in the case of irradiated samples. Such an observation confirms the presence of a degenerate, n-type shallow donor level with a high density of dislocations at the GaN/sapphire interface.[10,13] Clustering of impurities at these dislocation sites forms an impurity band at the interface. In the case of GaN, a localized impurity band is formed by oxygen impurities which occupy nitrogen sites.[14] Look *et al.* reported a considerable increase in the oxygen concentration close to the GaN/sapphire interface by performing SIMS measurements.[15] Recently, we also reported the presence of such a degenerate layer in commercially available

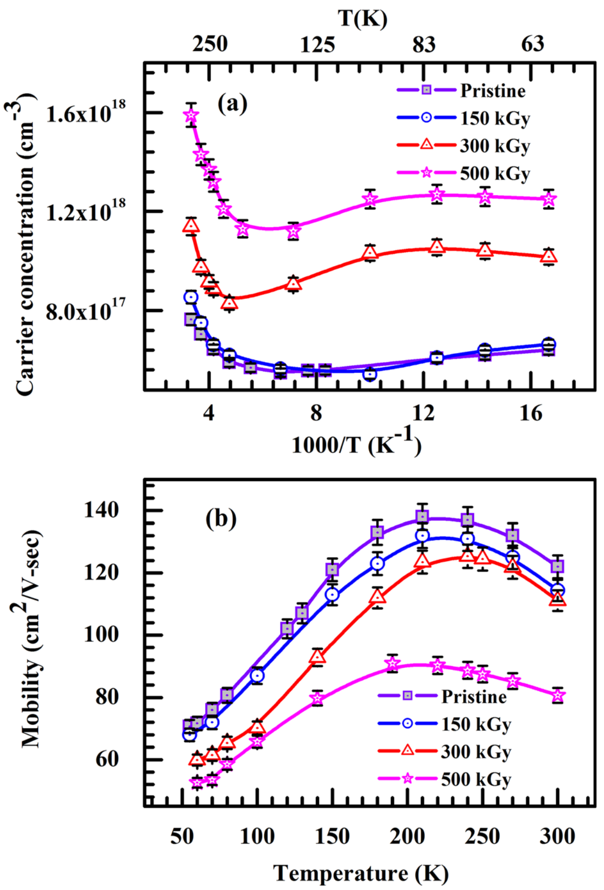


FIG. 2. Temperature dependence of (a) carrier concentration and (b) mobility for the pristine and $^{60}$Co $\gamma$-irradiated samples. The data points are shown with 3% error bar that includes both the statistical and instrumental errors.

HVPE grown GaN templates and also discussed its adverse effect on the performance of optoelectronic devices grown on such templates.[16] Particularly, at low temperature, when electrons are frozen on their parent donors, electrical conduction is dominated by carriers activated from the temperature-independent interfacial donor level. To understand this phenomenon in more detail, we adopt a model proposed by Look and Molnar[17] which separates the contribution of temperature dependent and independent parts of carrier concentration from the measured values of the carrier concentration in Hall data.[10] Assuming the temperature independent carrier concentration and mobility to be the contribution arising from the degenerate donor level at the interface, the contribution of the non-degenerate donor energy level in the measured carrier concentration is extracted and is plotted in Fig. 3. As can be seen from this figure, a pronounced increase in the thermally activated carrier concentration is observed after irradiation.

An important observation can be made from Fig. 3, where carrier density is found to increase monotonically with irradiation at a given temperature. It is a unique observation since most of the researchers report a clear fall of carrier density subsequent to irradiation. It includes studies based on $\gamma$ and electron irradiation, since the nature of irradiation induced defects is quite similar in both the cases.[6] For example, in electron irradiated samples with moderate doping ($\sim 10^{16}$–$10^{17}\,\mathrm{cm}^{-3}$), both the carrier concentration and mobility decrease with irradiation.[3,18,19] On irradiation with

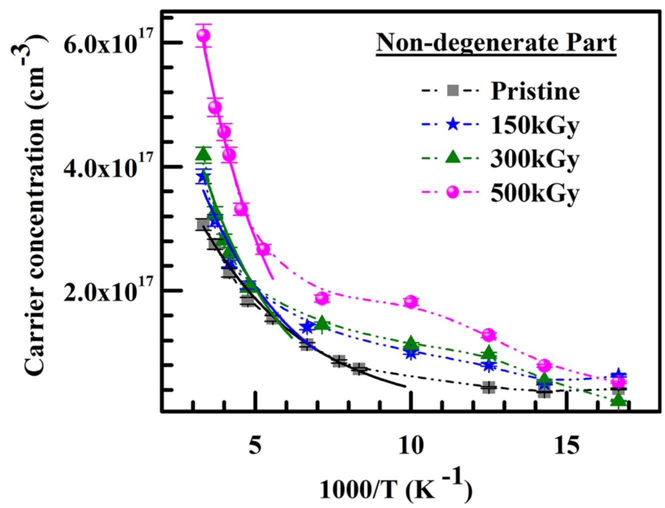


FIG. 3. Temperature dependent carrier concentration before and after $^{60}$Co $\gamma$-irradiation extracted from the uncorrected Hall data in Fig. 2 using Look's model[17] where solid lines represent numerical fit to the experimental data over a selective temperature range using Eq. (1). The data points are shown with 3% error bar that includes both the statistical and instrumental errors.

a high energy electron ($\sim$0.7–1 MeV), Look *et al.* showed that the room temperature carrier concentration was reduced from $8.4\times10^{16}\,\mathrm{cm}^{-3}$ to $6.9\times10^{16}\,\mathrm{cm}^{-3}$ via the creation of N Frenkel pairs involving $V_N$ shallow donors and $N_I$ deep acceptors where the radiation induced donor level lies at around 60 meV below the conduction band edge.[6] It is only in the articles from Ioffe Institute, Russia,[9,20,21] where a rise in the carrier concentration with $\gamma$-irradiation is reported for heavily doped GaN samples. It is also reported by them that the electron concentration decreases after $\gamma$-irradiation for slightly doped epilayers, while it increases for heavily doped GaN epilayers.[9] However, no reason for the same is given by the respective authors. Nevertheless, it gives enough indications that the nature of the temperature dependent carrier concentration profile of $\gamma$-irradiated GaN samples is somehow associated with the donor concentration of the GaN sample. A quantitative analysis is therefore necessary to understand such a complex observation. Since both the degenerate and non-degenerate parts of the carrier concentration increase after $\gamma$-irradiation, we have separately investigated the origin of donor levels giving rise to present observations. To estimate the activation energy and dopant concentration of thermally activated donors in pristine and irradiated samples, we fit the non-degenerate part of the carrier concentration shown in Fig. 3, by the charge balance equation[6,19]

$$n + N_A = \frac{N_D}{1 + n/\phi}, \tag{1}$$

where $\phi = (1/2)N_C^{/}T^{3/2}\exp(-E_D/kT)$. Here, $N_C^{/}$ is the effective density of states at 1 K ($N_C^{/} = 4.98\times10^{14}\,\mathrm{cm}^{-3}$ for $m^* = 0.22\ m_0$).[6,19] $N_D$ and $E_D$ are the donor concentration and donor energy level, and $N_A$ is the acceptor concentration. A single donor fit of the carrier concentration profile of the pristine sample is also shown in Fig. 3. This gives $N_{D1} = (6\pm0.2)\times10^{17}\,\mathrm{cm}^{-3}$, $E_{D1} = 32\pm1\,\mathrm{meV}$, and $N_A = (1\pm0.5)\times10^{16}\,\mathrm{cm}^{-3}$. While fitting the irradiation induced carrier concentration data, we surprisingly found that no new donor levels are needed to be considered. Rather, all the data can be fitted by considering the activation of the single donor level located at about 32 meV. Note that the value of $N_D$ increases by several folds in the case of the 500 kGy irradiated sample when compared with the pristine sample, as shown in Table I. It should be noted here that the values of measured parameters are free from the influence of the interfacial layer and are solely governed by the donors present in the bulk GaN layer. It is known that Si impurities act like shallow donors in GaN where an activation energy of $30.18 \pm 0.1$ meV is reported in the case of HVPE grown GaN samples by Moore *et al.*[22] Hence, the defect levels identified in the pristine sample in our case correspond to Si impurities. It is also known that $^{60}$Co $\gamma$-radiation gives rise to the appearance of point defects like vacancies and self-interstitials.

For example, Umana-Membreno *et al.*[23] reported generation of $\gamma$ irradiation induced three shallow donor levels located at about 88, 104, and 144 meV which they attributed to nitrogen–vacancy related defects. On the other hand, Look *et al.* reported the generation of ($V_N$ –$N_I$) Frenkel pairs with $V_N$ as shallow donors and $N_I$ as deep acceptors while irradiating moderately doped GaN samples with 1 MeV electrons. Look *et al.*[6,19] reported that the defect donor lies 60–80 meV below the conduction band. However, in our case, the activation energy of the donor level remains constant at 32 meV, even after irradiation with 500 kGy radiation dose. Note that the donor level of the same activation energy also exists even in the pristine sample which is associated with silicon impurities. This indicates that either no new electrically active defects are generated or their activation energy is close to that of the silicon donors. The rise in the donor concentration in irradiated samples can be understood in terms of the activation of radiation induced electrically inactive complexes via their interaction with native defects. Activation of Si donors, which are present in the pristine sample in the electrically inactive form, by $\gamma$-irradiation is the main mechanism behind this observation. Such a hypothesis is already proposed in GaN[9] and GaAs[24] materials.

Next, it is worth discussing the effect of $^{60}$Co $\gamma$-irradiation on the temperature independent degenerate carrier concentration where the measured value increases from $6 \times 10^{17}$ to $1.2 \times 10^{18}$ cm$^{-3}$ after exposure to 500 kGy dose as shown in Fig. 2(a). Note that in the low temperature region (<150 K), a degenerate interfacial layer lying at the GaN/Sapphire interface dominates the conduction process. One finds in Fig. 2(a) that the carrier concentration first increases and then becomes almost constant in the low temperature range. This is a clear indication of the presence of a degenerate layer in our sample. Such an observation is already made by several other researchers.[6,10,13,17,19] Under such conditions, the low temperature Hall data shown in Fig. 2(a) shall be corrected for a low value of degenerate layer thickness which is reported to be of the order of 0.3 $\mu$m.[6,13] One gets a typical value of the low temperature carrier concentration of the order of $1 \times 10^{19}$ cm$^{-3}$ (pristine) by using 0.3 $\mu$m as the layer thickness. This clearly supports the presence of a degenerate layer in our sample. However, such a correction is not essential since (1) it will create confusion because the sheet density obtained from Hall measurements needs to be divided by the two different thicknesses in the two temperature ranges and (2) one needs to consider different thicknesses of the two layers for estimating the value of the carrier concentration using the parallel conduction method given in Ref. 17. Further, the exact values of the interfacial layer thickness and temperature where transition from degenerate to non-degenerate occurs are not known. Moreover, it does not pose a serious limitation for understanding the response of GaN layers to radiation exposure where the overall trends will remain rather unaltered irrespective of the condition whether the particular correction is incorporated or not. Since the carrier concentration increases with radiation exposure as shown in Fig. 2(a), the Fermi level moves further up in the conduction band at low temperature. Considering the movement of the Fermi level with radiation exposure, it can be concluded that the radiation induced degenerate donors in our sample are rather shallow. Further, the origin of such a temperature independent donor behaviour is related to the diffusion of oxygen impurities occupying nitrogen site. High energy $\gamma$ irradiation enhances the probability of formation of nitrogen vacancies increasing the rate of oxygen impurity diffusion at the interface.[15] It leads to a substantial increase in density of interfacial donors and hence carrier transport through the GaN/sapphire interface.

TABLE I. Electrical transport parameters before and after $^{60}$Co $\gamma$-irradiation obtained by fitting the experimental data shown in Fig. 3 with Eq. (1).

| Dose (kGy) | $N_{D1}$ (cm$^{-3}$) | $E_{D1}$ (meV) | $N_A$ (cm$^{-3}$) |
|---|---|---|---|
| Pristine | $6 \pm 0.2 \times 10^{17}$ | $32 \pm 1$ | $1 \pm 0.5 \times 10^{16}$ |
| 150 | $9 \pm 0.5 \times 10^{17}$ | $32 \pm 1$ | $7 \pm 1 \times 10^{16}$ |
| 300 | $1.3 \pm 0.5 \times 10^{18}$ | $32 \pm 1$ | $2 \pm 0.5 \times 10^{17}$ |
| 500 | $2.6 \pm 0.2 \times 10^{18}$ | $32 \pm 1$ | $3 \pm 1 \times 10^{17}$ |

### B. Effect of gamma irradiation on GaN Schottky diodes

The defect complexes produced by $\gamma$ irradiation in GaN are expected to affect the performance of Schottky diodes. In order to get a quantitative estimate of damage, current-voltage (I-V) characteristics of pristine and irradiated Au/Ni/GaN Schottky diodes are compared at room temperature as shown in Fig. 4.

The reverse I–V characteristics shown in Fig. 4 manifest a gradual degradation of Schottky contact with increasing radiation dose. At a reverse bias of 2 V, the leakage current increases from a pre-irradiation level of $6.5 \times 10^{-7}$ A to $7.7 \times 10^{-5}$ A after exposure to 450 kGy of $^{60}$Co $\gamma$-radiation. Such a large increase in leakage current is a direct consequence of radiation induced activation of defects. In addition to this, the radiation induced degradation of Schottky junction parameters like ideality factor and barrier height is also studied from the forward I–V characteristics. In the forward bias region, each plot consists of a linear region with varying slopes over an intermediate-bias range. The measured I-V characteristics can be analysed by using the conventional

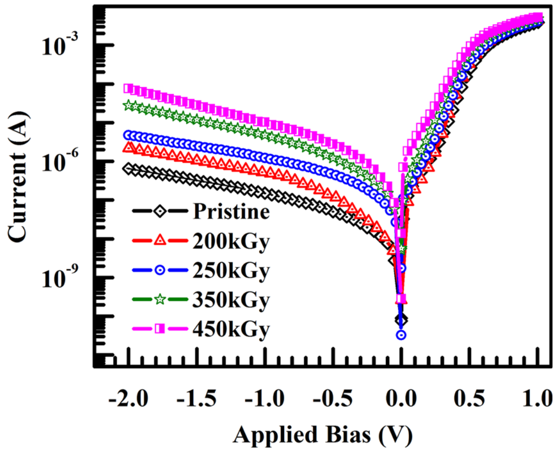


FIG. 4. I–V characteristics of Au/Ni/GaN Schottky diodes before and after exposure to $^{60}$Co $\gamma$ rays.

thermionic emission model which is described by the following equation:[10,25,26]

$$I_F = I_{SF}\left[\exp\left(\frac{qV}{\eta_F kT}\right)\right], \tag{2}$$

where $I_F$, V, and $\eta_F$ are the diode current, applied voltage, and ideality factor under forward bias, $q$ is the electronic charge, and $I_{SF}$ is the forward bias saturation current given by[10,25,26]

$$I_{SF} = AA^*T^2\exp\left(-\frac{\phi_B}{kT}\right), \tag{3}$$

where the barrier height of the Au/Ni/GaN Schottky junction is represented by $\phi_B$, A is the area of the Schottky diode, and $A^*$ is the effective Richardson constant. In the present study, the theoretical value of Richardson's constant for GaN is taken as $A^* = 26.9$ A cm$^{-2}$K$^{-2}$.[27] From Eq. (2), the ideality factor can be expressed as[25,26]

$$\eta_F = \frac{q}{kT}\left(\frac{dV}{d\ln I_F}\right). \tag{4}$$

The variation of the ideality factor and barrier height as a function of $^{60}$Co $\gamma$-radiation dose obtained from forward bias I-V characteristics using Eq. (4) is plotted in Fig. 5.

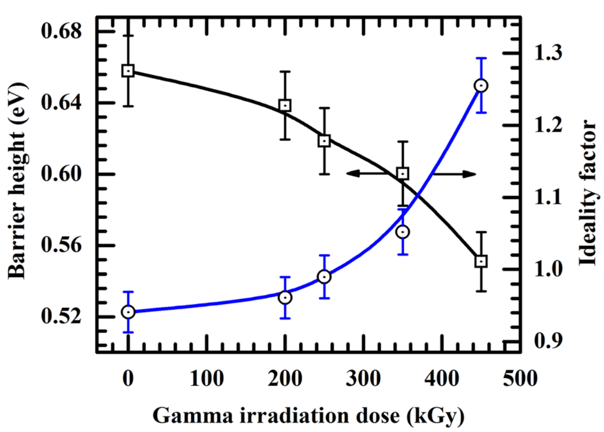


FIG. 5. Room temperature Schottky barrier height and ideality factor as a function of $\gamma$ irradiation dose determined from the forward current-voltage characteristics. The data points are shown with 3% error bar that includes both the statistical and instrumental errors.

As can be seen, the barrier height value of the pristine GaN sample is much lower than the theoretical Schottky-Mott barrier height of 1.04 eV for Ni/GaN contact.[28] A similar deviation of the estimated values of Schottky junction parameters from theoretically predicted values is already reported by other researchers.[29,30] Surface states, interfacial defects, material non-uniformity, dislocation-related current paths, etc., are proposed to be linked with this kind of non-ideal behaviour of Schottky junction parameters.[16,29,31] In addition, a non-ideal behaviour modifies the ideality factor significantly. Irradiation induced defect complexes enhance the current flow through the non-ideal paths, which further decrease the barrier height and enhance the ideality factor. This is clearly observed in Fig. 5 where the barrier height decreases from 0.66 ($\pm$0.02) eV to 0.56 ($\pm$0.016) eV while the ideality factor increases from 0.94 ($\pm$0.03) to 1.26 ($\pm$0.04).

The radiation induced modification of the current transport mechanism is expected to be more prominent at low temperature where thermally activated carriers freeze on their parent dopant atoms and carrier transport is mainly governed by carrier tunnelling. To investigate this point further, temperature dependent I-V characteristics for pristine and 300 kGy irradiated samples are performed. The estimated values

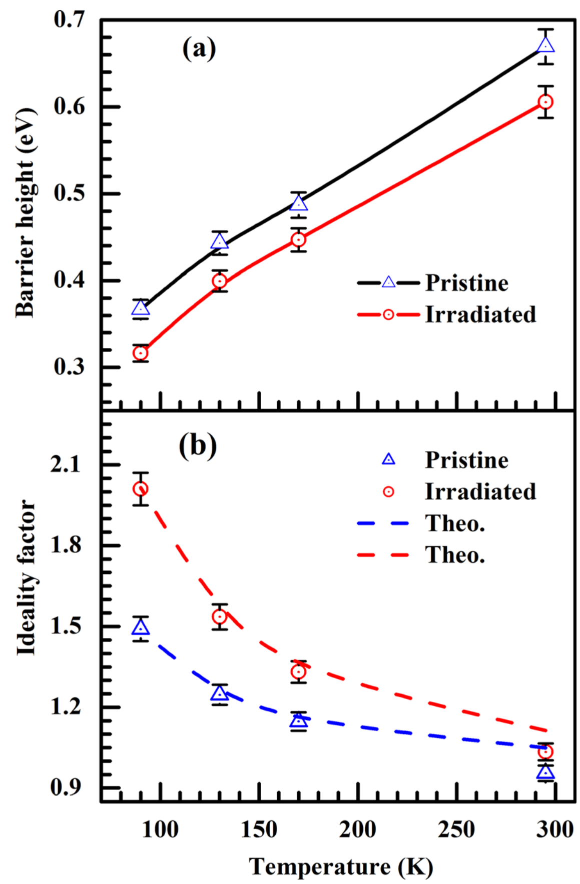


FIG. 6. (a) Variation of the barrier height with temperature for pristine and $\gamma$ irradiated samples obtained from the temperature dependent I-V characteristics of Au/Ni/GaN Schottky diodes. (b) Ideality factor plotted as a function of temperature for pristine and 300 kGy irradiated samples. The red and blue dotted lines show the numerically calculated curves using the two values of characteristic tunnelling energy ($E_{00}$). The experimental data points are shown with 3% error bars that include both the statistical and instrumental errors.

of the barrier height and ideality factors are shown in Figs. 6(a) and 6(b), respectively.

As obvious from Fig. 6(a), the barrier height decreases on lowering the temperature for both pristine and irradiated samples. Reduction in the barrier height endorses the fact that the tunnelling contribution to current transport increases at low temperature which is also discussed in our earlier article.[16] However, the effect of irradiation is more evident in the temperature dependence of the ideality factor.[32] For both irradiated and pristine samples, the ideality factor increases monotonously on lowering the temperature as shown in Fig. 6(b). However, the two curves are well separated at low temperature and their separation decreases with the rise in temperature. The carrier transport mechanism responsible for this kind of behaviour of ideality factor can be quantitatively explained by evaluating the values of characteristic tunnelling energy ($E_{00}$). A comparison of $E_{00}$ with thermal energy $k$T, where $k$ is the Boltzmann constant, shows that the thermionic emission dictates the carrier transport for $kT > E_{00}$, whereas thermionic-field emission dominates when $k$T $\sim E_{00}$. In the extreme case of $kT < E_{00}$, the field emission process governs the carrier transport across metal-semiconductor Schottky diodes.[26] The dependence of the ideality factor on $E_{00}$ can be expressed as[16,33]

$$\eta_F = \frac{E_{oo}}{kT}\coth\left(\frac{E_{oo}}{kT}\right). \tag{5}$$

One can easily estimate the value of $E_{00}$ by fitting the temperature dependent ideality factor data with Eq. (5) as shown by the dotted line in Fig. 6(b). It is observed that two different values of $E_{00}$ have to be considered to reproduce the temperature dependence of the ideality factor for pristine and irradiated samples. For the pristine sample, $E_{00}$ is estimated to be $9 \pm 0.5$ meV, which increases to $14 \pm 0.5$ meV after irradiation. Since a large value of $E_{00}$ (in comparison to $k$T) indicates suppression of the thermionic emission mechanism, the rise in the value of $E_{00}$ subsequent to irradiation shows that the dislocation assisted tunnelling of carriers across the Schottky junction is enhanced after irradiation.

In order to gain an insight into the current transport mechanisms, we correlate the dopant concentration of GaN epilayers obtained from the two values of $E_{00}$ with a value obtained from Hall measurements using the following equation:[16,26,33]

$$E_{00} = E_{00}(N_D) = \frac{\hbar q}{2}\sqrt{\frac{N_D}{m^* \varepsilon_s \varepsilon_0}}, \tag{6}$$

where $\hbar$ is the Planck constant, $N_D$ is the dopant density, m* is the effective mass, $\varepsilon_s$ is the dielectric constant of GaN, and $\varepsilon_0$ is the permittivity of vacuum. The $N_D$ values obtained from Eq. (6) for the two values of $E_{00}$ are $5 \pm 0.5 \times 10^{17}\,\text{cm}^{-3}$ and $1.14 \pm 0.08 \times 10^{18}\,\text{cm}^{-3}$ for pristine and 300 kGy irradiated samples. Interestingly, these values of $N_D$ are in good agreement with the donor concentration obtained from the flat region of low temperature Hall data shown in Fig. 2(a). It certifies that the dislocation assisted carrier transport, which dominates the low temperature Hall experiments, also governs the carrier transport across Schottky junction in both pristine and 300 kGy $\gamma$ irradiated samples.

After studying the effect of $\gamma$ irradiation on carrier transport in bulk and Au/Ni/GaN Schottky junctions, it is of prime importance to compare the radiation induced degradation of GaN with that of the well-established GaAs Schottky junctions. It is already known that the displacement energy of Ga and N in GaN is 20.5 and 10.8 eV, respectively, which is larger than the corresponding values for GaAs.[6,34] Hence, it is expected that the radiation induced damage in GaN based devices will be less when compared with GaAs devices. To illustrate this point further, we compare the change in leakage current after $^{60}$Co $\gamma$ irradiation in GaN and GaAs based Schottky diodes. The room temperature carrier concentration of GaN and GaAs is chosen to be of the same order ($\sim 10^{18}\,\text{cm}^{-3}$).

The leakage current in pristine and 200 kGy irradiated GaN and GaAs detectors of identical geometry is plotted in Fig. 7. As can be seen from Fig. 7, there is a two order increase in leakage current after irradiation in GaAs, whereas only a nominal rise in leakage current is observed in the case of GaN. A similar observation has been made by Fauzi *et al.* under neutron irradiation.[35] In contrast to the forward bias I-V, the reverse bias leakage current is primarily governed by generation-recombination (g-r) centres within the depletion width. The current due to g-r centres depends on two major parameters, namely, the number density of g-r centres and the bandgap of the material.[36] Because of high displacement

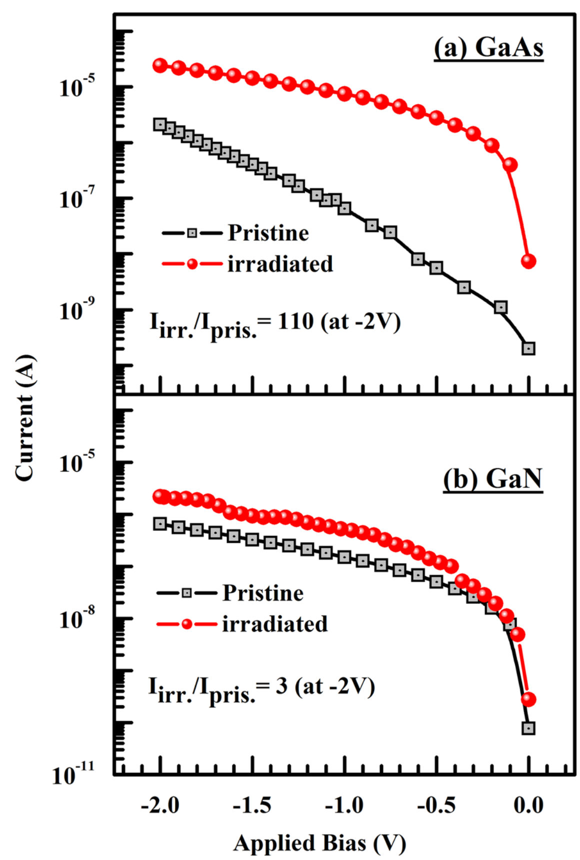


FIG. 7. Reverse bias current-voltage characteristics of (a) GaAs and (b) GaN Schottky diodes. $I_{pris.}$ and $I_{irr.}$ stand for the reverse current for pristine and 200 kGy irradiated samples at a reverse bias of −2 V.

energy, the number density of g-r centres after irradiation will be less in GaN. The large bandgap of GaN further restricts the increase in g-r current, leading to only a nominal increase in leakage current in comparison to GaAs.

### C. Irradiation effect on the Au/Ni/GaN Schottky photodetector

Next, it is worth investigating the impact of $\gamma$ irradiation on the charge collection efficiency of GaN based Schottky photodiodes. Here, exposure to $\gamma$-radiation primarily affects the charge collection efficiency by reducing the lifetime of the photo-generated carrier.[37] In order to explore this point further, I-V characteristics of Au/Ni/GaN Schottky diodes exposed to $^{60}$Co $\gamma$-radiation are recorded and are found to recover within a day as shown in Fig. 8(a). Further, the spectral response of pristine and 200 kGy irradiated GaN Schottky photodiodes is compared in the range of 300–400 nm as shown in Fig. 8(b). The two curves are normalized to the peak response of the pristine photodetector in order to make a direct comparison. It is observed that the peak spectral response decreases by 60% after irradiation, which can be attributed to the reduction of charge collection efficiency. Note that the excitonic feature which is clearly observed in the pristine sample at 360 nm also disappears after irradiation. This is attributed to the irradiation induced decrease in exciton lifetime because of the presence of non-radiative centres. A similar observation in GaAs has been made by Parenteau *et al.*[38] Interestingly, the photoresponse partially recovers after 16 h of irradiation which is found to recover completely within a day. Such a recovery of the spectral response is attributed to the room temperature annealing of irradiation induced defects states. However, the rate of recovery observed in this work is rather surprising since the recovery time of several weeks at room temperature is usually reported in the literature.[39] Self-annealing of irradiation induced defects at room temperature is reported over a month period in the case of the InGaAs/GaAs quantum well by Dhaka *et al.*[40] Similarly, a self-recovery of neutron irradiated AlGaN/GaN high electron mobility transistor (HEMT) devices is reported by Kim *et al.*[41] where the electrical response of the device completely recovered within 3 weeks of irradiation. The only difference is that our devices recover within a day which might be governed by the extent of damage caused by a different type of irradiation in our experiments.

## IV. CONCLUSION

GaN Schottky photodetectors are fabricated on n$^+$-GaN epitaxial layers grown by HVPE, and the effect of irradiation on the electronic transport in the epitaxial layer and Schottky detectors is studied by varying $^{60}$Co $\gamma$ irradiation dose. In contrast to the usual trends seen in moderately doped GaN, a steady rise in the carrier concentration is observed with irradiation dose. Using a two layer model, the contribution of the bulk layer in the measured carrier concentration is extracted and is fitted by considering the charge balance equation. It is observed that no new electrically active defect levels are generated after irradiation since the activation energy of the donor level remains constant at 32 meV even after irradiation with 500 kGy dose. However, even the bulk carrier concentration increases after irradiation. It implies about the radiation induced enhancement in activation of native Si impurities which are already present in the electrically inert form in the pristine sample. It is a unique observation especially for n$^+$-GaN samples. It is also seen that the irradiation induced nitrogen vacancies stimulate the diffusion of oxygen impurities, leading to the observed increase in the interfacial carrier concentration after irradiation. It is correlated with the characteristic energy values obtained from the temperature dependent ideality factor variation of pristine and 300 kGy irradiated Au/Ni/GaN Schottky devices, which confirms that the dislocation-assisted tunnelling dominates the low temperature current transport even after irradiation. Further, the leakage current of the GaN photodetector is compared with that of GaAs which clearly demonstrates a high radiation tolerance of GaN. The recovery of the photoresponse of the GaN photodetector is also studied after 200 kGy $^{60}$Co $\gamma$-irradiation which showed an outright recovery of the spectrum at room temperature within a day. The present work considerably helps in understanding the effect of $^{60}$Co $\gamma$-irradiation on the electronic transport in

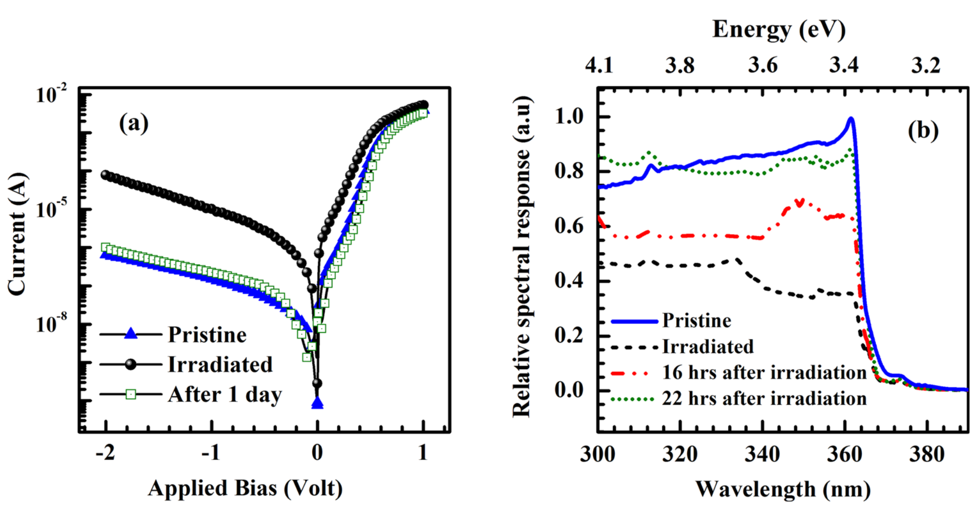


FIG. 8. Recovery of (a) I-V characteristics of the Au/Ni/GaN Schottky diode and (b) photoresponse of the GaN Schottky photodetector after irradiation with the $^{60}$Co $\gamma$ source.

$n^+$-GaN epilayers which are an integral part of nitride devices. The understanding developed here might be very useful in studying the behaviour of nitride based optoelectronic devices in a radiation harsh environment.

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