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Leyla Barghamadi

Iran University of Science and Technology

Shahab Norouzian Alam (✉ norouzian@iust.ac.ir)

Iran University of Science and Technology

Bijan Ghafari

Iran University of Science and Technology

Seyed Hassan Sedighy

Iran University of Science and Technology

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The effect of low dose γ -irradiation on the optoelectric properties of n-GaN based MSM structure

Leyla Barghamadi¹, Shahab Norouzian Alam^{*1}, Bijan Ghafari¹, Seyed Hassan Sedighy²

1-Photonics Group, Physics Department, Iran University of Science and Technology, Tehran, Iran

2- School of Advanced Technologies, Iran University of Science and Technology, Tehran, Iran

Abstract

The room temperature effect of a low dose rate (10^{-4} rad (Si)/s) ^{60}Co γ -irradiation on the structural properties and dark current of the GaN-based metal-semiconductor-metal (MSM) structure has been studied. In contrast to previous studies, a non-monotonous dependence of the dark current with the γ -irradiation dose is observed. The intensity and linewidth of the photoluminescence (PL) peaks correlate with the changes in electrical characteristics and eventually degrade after prolonged exposure to the γ -radiation. The abnormal behavior of the MSM structure and particularly its I-V and PL characteristics are explained by considering the carrier transfer mechanism in the localized states. These phenomena are associated with the decrease of shallow donors' density in localized states and the activation of the non-radiative centers as radiation dose increases. These experimental results and the mechanism presented are essential for understanding the interaction of the γ -irradiation with *n*-GaN and for estimation of reliability of GaN-based (opto)electronics in harsh conditions of γ -radiation (space applications, liquidation of consequences of technogenic catastrophes, etc.).

Keywords: GaN, MSM structure, photoluminescence, γ -irradiation, localized states

Introduction

Gallium nitride (GaN) and its related alloys such as $\text{Al}_x\text{Ga}_{1-x}\text{N}$ and $\text{In}_x\text{Ga}_{1-x}\text{N}$ are widely used in the ultraviolet (UV) and visible spectrum regions, especially as the active region of photodetectors (PD)¹. III-nitride-based PDs are particularly commonly used in harsh environments such as space applications^{2,3}. Meanwhile, the wide bandgap (3.4 eV²), high breakdown voltage⁴, thermal and chemical stability, and irradiation resistance introduce GaN as a suitable candidate to use in harsh and irradiated environments.^{5,6}

Exposure of the GaN layers with electromagnetic irradiation and/or high-energy particles has been shown to lead to the vacancy generation and defects in the crystal structure such as Ga and/or N atoms displacements from their respective lattice sites⁷. This phenomenon generates new energy levels in the bandgap, which act as scattering centers such as donor, acceptor, or recombination centers^{1,8}. Therefore, it is crucial to study the irradiation effects on semiconductor devices to understand the behavior of optoelectric devices in irradiation environments and fulfill the materials and design requirements consequently. There are significant differences between low and high dose rate irradiation effects on the semiconductor devices because the dose rate required to achieve maximum damage is different for various devices⁹⁻¹¹. Although some devices are not sensitive to dose-rate below 1 rad (Si)/s, some other ones are significantly affected by dose rate even at 10^{-3} rad (Si)/s¹². It has been shown that the more extensive damages occurred in semiconductors under low dose-rate conditions than that for the higher dose^{9,10}. The low dose-rate effects up to 10^{-3} rad (Si)/s were reported for linear bipolar transistors in Ref.¹² and it was shown that the effect of the lower dose-rate is larger than that for the higher ones.

This paper discusses low dose-rate test results for basic *n*-GaN-based metal-semiconductor-metal (MSM) structure, presenting data at dose rates as low as 10^{-4} rad(Si)/s. To analyze the optoelectronic behavior of the device under radiation, current-voltage (I-V), X-ray diffraction (XRD), scanning electron microscopy (SEM) and photoluminescence (PL) spectroscopy were implemented. To the best of our knowledge, it is the first study of the effect of the low dose rate γ -irradiation on the GaN-based MSM structure and it is believed to be helpful with complying with the MSM structure device requirements in terms of materials and design.

Experiment Details

The gallium nitride epilayer with the thickness of $1.5 \mu\text{m}$ was grown on a standard *c*-plane sapphire substrate using a metal-organic vapor phase epitaxy (MOVPE) technique. The GaN epitaxial layer was doped with Si up to a concentration of 10^{17}cm^{-3} . More details about the growth condition can be found elsewhere¹³. To establish electrical connections, a silver paste was used as a Schottky contact in MSM structure, as depicted in Figure 1. For convenience, the characteristics of the MSM structure are summarized in Table 1.

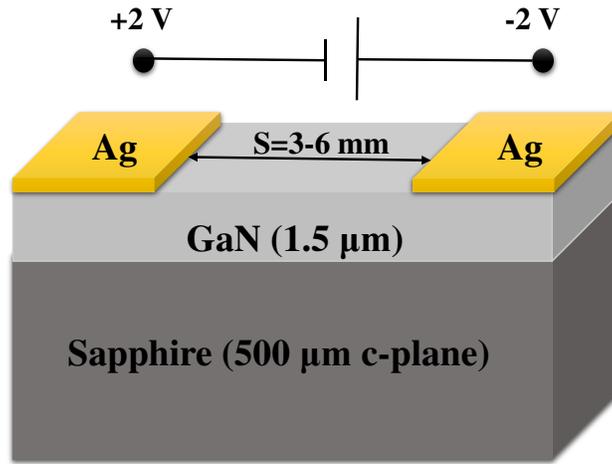


Fig. 1. Schematic diagram of the GaN-based UV MSM structure

Table 1- Summarized experimental parameters

Structure	MSM, n-GaN
Substrate	<i>c</i> -plane Al_2O_3
Active layer	$1.5 \mu\text{m}$ GaN
Dopant	10^{17}cm^{-3} Si
Active width (S)	3-6 mm
Contacts	Ag
γ -irradiation dose rate	$10^{-4} \text{rad}(\text{Si})/\text{s}$

The effects of ^{60}Co γ -irradiation on the dark current of the MSM structure at room temperature were studied. The ^{60}Co source with $2\mu\text{Ci}$ activity used in this work and the design of the experiment are shown in Figure 2. Since the γ - ^{60}Co attenuation length in GaN is 1cm^{-1} , which is much larger than the thickness of the GaN epilayer ($1.5\mu\text{m}$), it is considered that the sample is irradiated uniformly in the proposed test setup. The gamma source was located exactly in front of the detector surface to prevent gamma energy loss due to the absorption by air molecules. The current-

voltage (I-V) characteristics were measured at room temperature with a -2 V to +2 V range using the Palmsens EmStat2 system.

The total radiation dose by the ^{60}Co source on a MSM structure was calculated using the following equation below:

$$rad(si) = exposure\ time \times rad(si) / s \quad (1)$$

Two similar MSM structures were considered in the test procedure: MSM structure-I and MSM structure-II. The MSM structure-I is irradiated for 2 hours (equivalent to 0.72 rad (Si)) and then followed by three steps each lasting for 30 minutes (equivalent to 0.18 rad (Si) at each step). The electrical measurements were promptly performed after each step. At the end of the last step, the sample was annealed for 24 hours at room temperature, and the electrical current was measured again. To study the dependence of the irradiation time on the I-V characteristics, the MSM structure-II was irradiated in four steps (30 minutes irradiation time at each step) and then irradiated additionally for 2 hours in a row. The I-V characteristics were measured upon each step. Table 2 shows the experiment process and parameters.

Table 2. Irradiation experiment details

MSM structures	Active area width	First dose	Second dose	Total dose
structure-I	6 mm	2 hours (0.72 rad (Si))	0.9 rad(Si) (30 minutes)	1.26 rad(Si)
structure-II	3.5 mm	30 minutes (0.18 rad(Si))	0.36 rad(Si) (30 minutes)	1.44 rad(Si)

To evaluate the γ irradiation-induced changes on the crystalline structure of the active layer, the X-ray diffraction (XRD) patterns of the thin films were recorded before and after the γ -irradiation. For XRD analysis, a high-resolution X-ray diffraction spectroscopy (XRD Model: PANalytical X'pert PRO) with Cu-K α radiation of 1.54 \AA wavelength was applied. The XRD data consisted of 2θ - ω symmetric (002) scan and the corresponding rocking curves (ω -scans) providing information on any changes in the corresponding interplanar spacings (effectively, lattice parameters) and dislocation densities, respectively. To examine the surface morphology, a Vega2 Tescan scanning electron microscope (SEM) was used. Photoluminescence spectroscopy (PL) analysis was carried out using PerkinElmerLS55 (equipped with Xe lamp) at an excitation wavelength of 250 nm, to analyze the optical behavior of the pristine and γ -irradiated samples. During the measurements, the samples were held in dark conditions to minimize the disturbance from the environment.

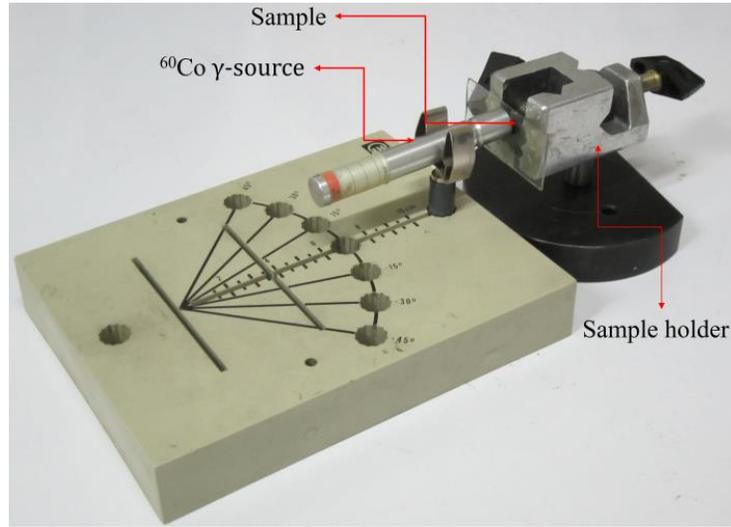


Fig. 2. ^{60}Co γ -irradiation source used for test setup

Results and Discussions

I. Radiation effect on n -GaN epilayer structure

High-resolution X-ray diffraction spectroscopy consisted of 2θ - ω symmetric (002) scan were performed, and dislocation density was calculated as shown in Table 3. in Fig. 3 and therefore the calculated dislocation density is slightly higher for the irradiated sample, which indicates the dislocation density development after the γ -irradiation¹⁴. Similar results were obtained for the skew-symmetric reflectance.

Assuming a random distribution of dislocations when a Gaussian-like shape of the diffraction profile is observed, the dislocation density ρ can be determined using the equation (2)^{15,16}:

$$\rho = \frac{\beta^2}{9b^2} \quad (2)$$

Where b is Burger's vector and integral breadth, β , is related to the FWHM peak width, H , by

$$\beta = 0.5H \left(\frac{\pi}{\ln 2} \right)^{\frac{1}{2}} \quad (3)$$

The structural parameters calculated from the XRD data for GaN epilayer are listed in Table 3 for the conditions before and after γ -irradiation.

Table 3. The XRD result for PD-II

Sample	(hkl)	FWHM (°)	Dislocation density $\times 10^9$ (cm ⁻¹)
Pristine	(002)	0.067	2.10
1.44 rad(Si)	(002)	0.072	2.43

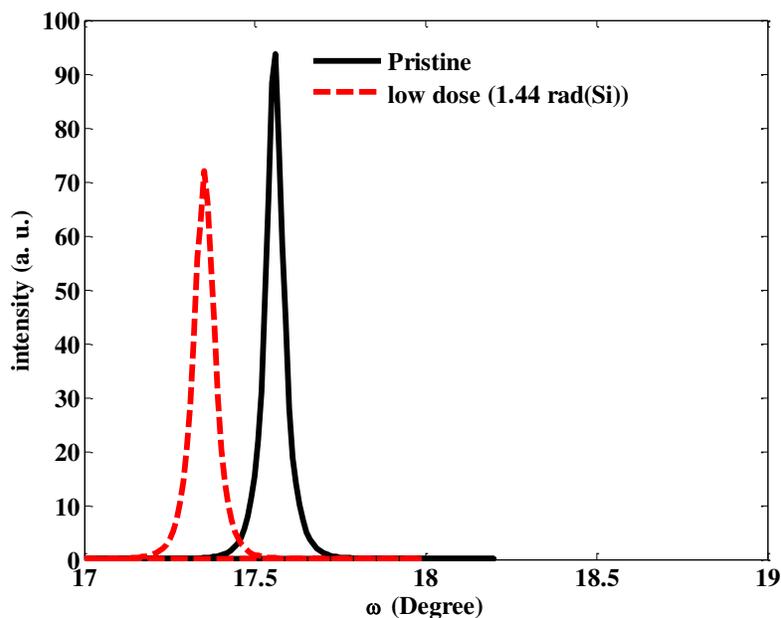


Fig. 3. Comparison of XRD pattern of MSM structure-II in pristine and after γ -irradiation at 1.44 rad (Si) on a (002)-plane

To understand the γ -irradiation effects on the surface morphology of MSM structure-II, the scanning electron microscope (SEM) images were recorded. Figure 4 depicts the MSM structure SEM images before and after irradiations. There was no significant deformation at a low dose, which was expected based on previous observations¹⁷.

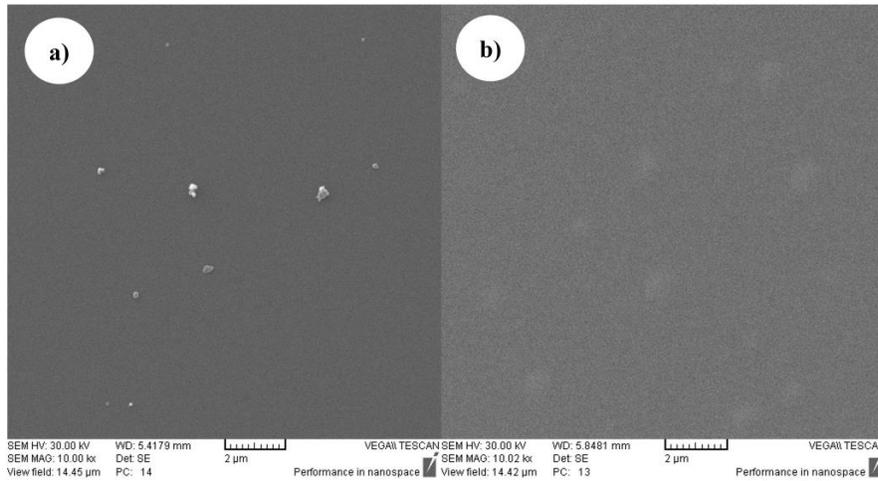


Fig. 4. The typical SEM micrographs GaN thin film of thickness 1.5 μ m, exposed to the γ -radiation dose of (a) 0 rad (Si), (b) 1.44 rad (Si)

II. Radiation effect on I-V characteristic of n-GaN MSM structure

Dark current as noise is one of the key parameters in explaining the quality of a device. Actually, the decrease or increase of dark current indicates the improvement or destruction of an electronic component. As mentioned, we measured the dark current. Because the structure of the MSM detector was almost symmetrical, the electric current in the positive and negative bias became almost symmetrical. The pristine MSM structures I and II had dark current amount 19.78 μ A and 0.61 μ A in +2 volt, respectively. To better see the rate of change of dark current in terms of voltage, we plotted the logarithmic form of the current.

To evaluate the effects of γ -irradiation on the electronic characterization of pristine and irradiated Ag/n-GaN MSM structure, I-V characteristics of samples are compared, as shown in the following figures (Fig. 5 – Fig. 7). In Figure 5, the MSM structure-I was exposed for 2 hours (equivalent to 0.72 rad (Si)) in the first step, followed by three exposure steps as described earlier. The dark current increased to 61.65 μ A in +2 volt in first step. An initial current enhancement at the first step followed by a gradual decrease upon gamma dose increasing in the next shorter steps, as shown in the inset picture for 1.4 V. This observation is not similar to the earlier observations for the higher doses^{1,18–21}. Thereafter, the sample left for 24 hours and then repeated the I-V test. As depicted in Figure 6, although there is an indication of current reduction, it did not go back to the values observed for the pristine sample. Therefore, one can conclude that the accumulated dose effect on the sample remained, and therefore no full curing occurred after 24 hours of room temperature annealing.

Sample MSM structure-II, was initially irradiated for 30 minutes (for comparison with the sample MSM structure-I, which was initially irradiated for 2 hours), then similar to the sample MSM structure-I, followed by another three 30 min irradiation steps. The dark current increased to 1.28 μA in +2 volt in first step. Similar to MSM structure-I, current enhancement was observed, followed by the gradual decrease in the next steps, as shown in Fig. 7(a). Ultimately, sample MSM structure-II was irradiated for 2 hours and observed the current elevation, approximately 200 times, as a consequence, as illustrated in Figure 7(b). The dark current increased to 120.88 μA in +2 volt in this step.

These observations proving that the electrical behavior of semiconductor structures is dependent on the gamma irradiation dose/duration, even at very low doses, but these dependencies need to be understood in detail.

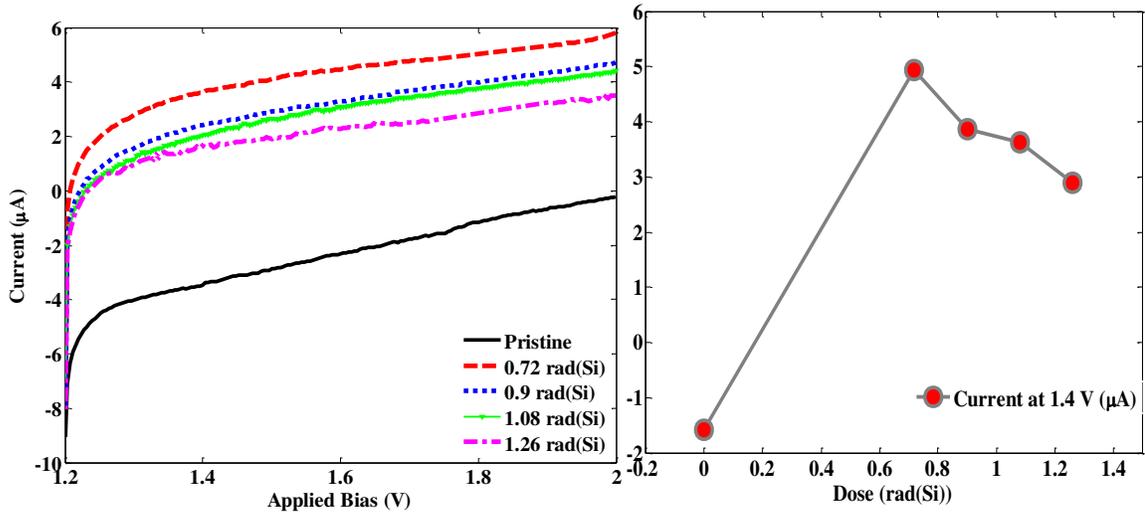


Fig. 5. I-V characteristics of GaN MSM structure-I before and after exposure to ^{60}Co γ rays in 2 hours and then followed by three 30 minutes steps

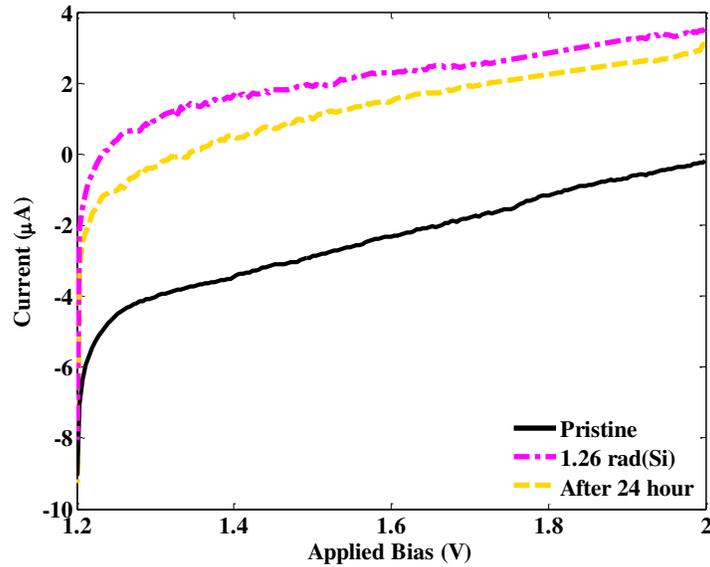


Fig. 6. Approximate recovery of I-V characteristics of GaN MSM structure-I after irradiation with the ^{60}Co source with a total dose of 1.26 rad (Si).

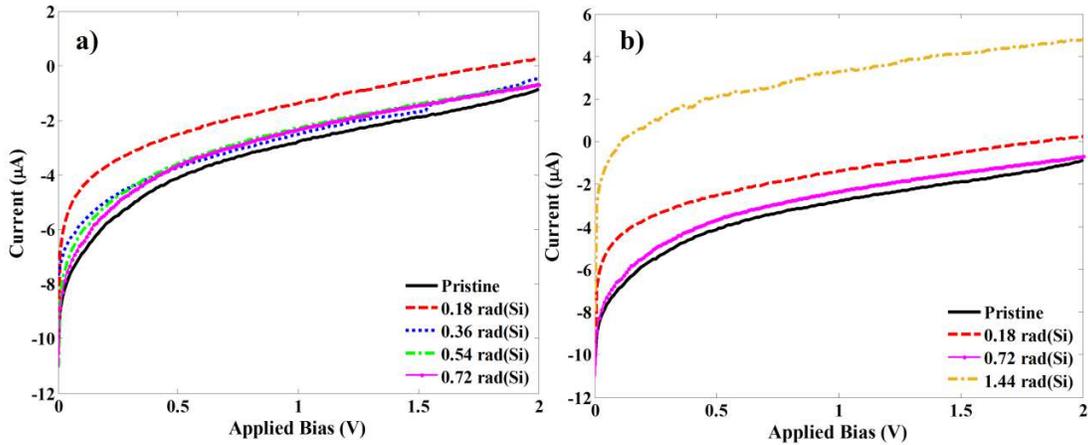


Fig. 7. Comparison of I-V characteristics of GaN MSM structure-II after exposure to ^{60}Co γ rays in a) four-step for 30 minutes and b) Comparison between two steps, one after the first step for 30 minutes and another after 2 hours continuous exposure

To explain the abnormal behavior of these MSM structures, the carrier transfer mechanism in the localized states can be suggested. The theory of carrier localization is generally used to justify the high efficiency of III-N light-emitting diodes (LEDs) and some other related, despite the high density of defects^{22–25}. This behavior of carriers in localized states has also been recognized in organic materials with a large number of defects²⁶. The localized states are minimum energy levels

induced by potential fluctuations due to cluster and/or interstitial atoms in III-V semiconductors and depends on the dopant type, dopant density, semiconductor thickness, material composition, and processing conditions of crystal growth²². In the III-V LEDs, carriers are generated by excitation power and stay at the minimum energy levels of localized states (within quantum wells), prevented from being trapped by the defects. This means that the emission efficiency is less affected by a large number of defects^{14,27,28}. In Figure 8, the schematic diagram indicating the possible mechanism of the carriers transfer in the localized states is shown. The localized states can be observed by spectroscopy techniques such as cathodoluminescence (CL), photoluminescence (PL) spectroscopy, and low energy electron-excited nano luminescence (LEEN) by varying temperature or excitation power density^{29,30}.

Here, the carrier transfer mechanism in the localized states is suggested to explain the transfer mechanism of carriers by γ -irradiation in n-GaN MSM structure.

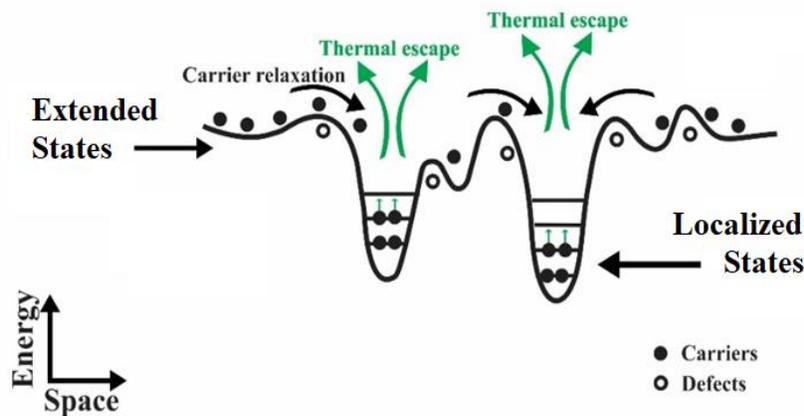


Fig. 8. Schematic illustration of the mechanism of carrier transport inside the Localized States

By exposure, the detector's to the gamma radiation, high energy γ -photons produced carriers which we call its γ -photocarriers. γ -photocarriers density in the GaN epilayer can be varied, which can affect the electrical current when a driving voltage is applied, as depicted in Figures 5 and 7. Initial exposure causing the γ -photocarriers in the extended states to achieve energy to overcome the barriers and relax into the localized states, which will continue until saturation of the localized states³¹⁻³³. Therefore a smaller fraction of carriers would be involved in the voltage induced current, resulting in the decreasing of the current measured by I-V, as depicted in Figure 5 and 7(a). When the MSM structure continuously irradiated for 2 hours, a higher gamma dose would be causing the generation of more γ -photocarriers. In continuous irradiation, the rate of the carriers' generation is higher

in comparison with the rate of carriers' recombination, localization, and/or carriers trapped in defects. These delocalized carriers would involve in the current observed in I-V characteristics. As a result, the measured current shows a significant increase, as shown in Figure 7(b) (and (5)).

The PL spectroscopy analysis was performed to study the optoelectronic performance of the samples before and after 1.44 rad(Si) irradiation in more details. For comparison, all peaks were fitted using the Gaussian model in MATLAB software (R2014a, V8.3), as depicted in Table 4. Figure 9 depicts the PL spectra before and after 1.44 rad (Si) irradiation. These graphs contain a near band-edge emission (NBE) - (peak1), violet emission peak centered at 3.149 eV - (peak2) - and a yellow luminescence (YL). The peak2 can be associated with the excitons bound to defects, *c*-axis screw dislocations Ga and N vacancies, deep level impurities, and amorphous phases^{34,35}.

To have more insight into the effect of γ -irradiation on PL, the integrated intensities and linewidths of the PL emissions were compared before and after irradiation. For comparison, all peaks were fitted using the Gaussian model in MATLAB software (R2014a, V8.3), as depicted in Table 4. Figure 9 depicts the PL spectra before and after 1.44 rad (Si) irradiation. These graphs contain a near band-edge emission (NBE) - (peak1), violet emission peak centred at 3.149 eV - (peak2) - and a yellow luminescence (YL). The probability of non-radiative recombination is higher for delocalized carriers, which causes the PL intensity quenching, consequently.

The reduction of linewidth and integrated intensity of the peak2 after the irradiation can be again explained by the carriers' delocalization and the decrease of shallow donors' density. Thus the rate of non-radiative recombination in shallow states increases in comparison with radiative recombination through the localized states. Another possible interpretation is the activation of non-radiative centers close to the shallow states after radiation^{14,36}. In summary, after irradiation, carriers can be trapped by defects, recombine non-radiatively, therefore reducing the carrier distribution in extended states and hence, narrowing the PL linewidth. Additionally, the role of regular thermalization of carriers at room temperature can be ignored because the depth of the localized states is large enough³⁷. Moreover, the depth has not changed after irradiation. The depth is equal to 187 ± 5 meV and calculated from the formula below:

Depth of the localized states from PL emissions=

$$\text{Emission Energy peak2} - \text{Emission Energy peak1}$$

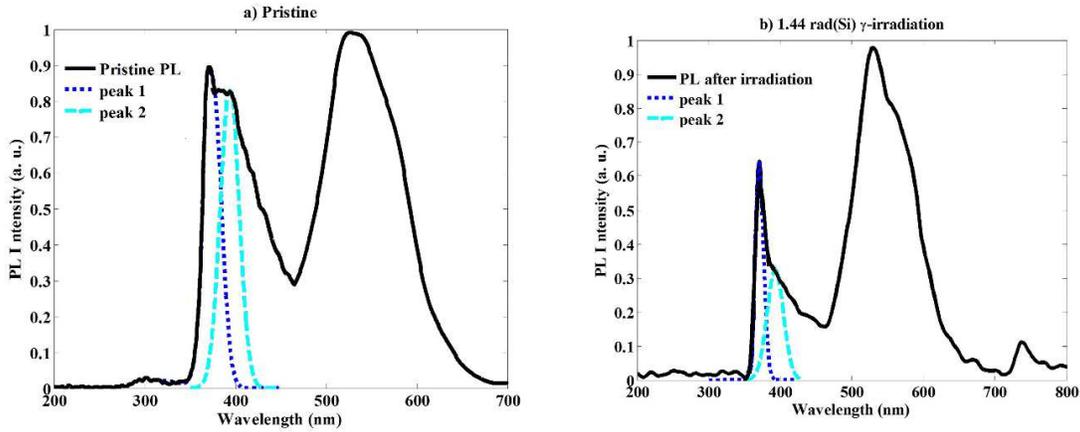


Fig. 9. PL measurements of MSM structure-II, a) before and b) after 1.44 rad(Si) γ -irradiation.

Table 4. PL measurements

Parameter	PL PP1 (nm)	Emission Energy (eV)	FWHM1 (nm)	PL PP2 (nm)	Emission Energy (eV)	FWHM2 (nm)
Pristine	371.3	3.339	66.9	393.8	3.148	24.6
1.44 rad(Si)	371.1	3.341	19.3	393.1	3.154	27.2

Conclusion

In summary, the effect of room temperature ^{60}Co γ -irradiation at a very low dose rate (0.0001 rad(Si)/s) on the behavior and I-V characteristic of MSM structure based on the n-GaN epitaxial layer has been investigated. In contrast to earlier observations, by increasing the gamma dose, an initial increase of the dark current followed by its gradual decrease has been observed. This abnormal behavior is explained here by considering the carrier transfer mechanism in localized states. To prove the correctness of this model, XRD, SEM and, PL analyses were performed. These analyses confirmed that behavior.

We found that in low doses, the radiation has not requisite intensity to destroy the structure of the semiconductor. However, the high energy of radiation is remarkably effective on the carriers to transfer in the semiconductor. The radiation causes a change in the conductivity of the semiconductor and its effect on electric current. Therefore, even in low doses, the response of semiconductors to radiation is significant. This research helps in understanding the effect of ^{60}Co γ -irradiation at a very low dose on the electronic transference in n-GaN epilayers, which are used in numerous radiation environment applications nowadays.

This work is an initial study to investigate the effect of radiation on the carrier transfer mechanism in localized states. More research can help us to understand the behavior of semiconductors, especially III-Nitride, and could lead to more applied results in the future.

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