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Investigation of Proton Radiation Effect on Indium Gallium Nitride Light Emitting Diodes

Tamana Baba[1], Yasir Javed[2], Zafar Iqbal Khan[2], Turab Ali[3], Nurul Fadzlin Hasbullah[1*]

[1] Department of Electrical and Computer Engineering, Kulliyyah of Engineering, International Islamic University Malaysia, P.O.B. 10, 50728, Selangor, Malaysia
[2] College of Computer Science and Information Sciences, Prince Sultan University, P.O.B. 66833, Riyadh 11586, Saudi Arabia
[3] National Centre for Physics, P.O.B. 2141, Shahdra valley road, Islamabad, Pakistan
[*] Corresponding author, e-mail: nfadzlinh@iium.edu.my

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Abstract

This paper investigates the effects of proton radiation on the electrical and optical properties of InGaN light-emitting diodes (LEDs). InGaN LEDs are known for their high brightness and efficiency, making them useful in various applications. However, they are vulnerable to radiation damage, which can degrade their performance over time. In this study, InGaN LEDs were exposed to proton radiation with the fluences of 1×10^{13} cm^{-2}, 3×10^{13} cm^{-2} and 3×10^{14} cm^{-2} and their electrical and optical properties were measured before and after irradiation. Results show that proton radiation causes asignificant increase in the reverse leakage current. The light intensity also increases due to radiation. These changes are attributed to radiation-induced defects created in the LED material. The findings of this study provide important insights into the reliability and durability of InGaN LEDs in space and other radiation environments.

Keywords

Light Emitting Diodes (LEDs), Indium Gallium Nitride (InGaN), proton radiation, degradation

1 Introduction

Wide bandgap semiconductors, such as SiC and GaN, have attracted much interest recently [1, 2]. In addition to this, alloys of Indium with other materials like Aluminum have also been receiving much attention [3]. The wide band gap in these materials indicates the presence of strong covalent bonds [4]. InGaN LEDs (Indium Gallium Nitride Light Emitting Diodes) have revolutionized the lighting industry with their high efficiency, long lifetime, and low power consumption [5]. The development of InGaN LEDs has been a breakthrough in the lighting industry, providing significant benefits in cost-effectiveness, and environmental sustainability [6]. However, their use in space and other radiation-prone environments is limited due to their susceptibility to radiation-induced degradation, which can significantly affect their electrical and optical properties [7]. The Earth has radiation belts caused by its magnetic field. The inner radiation belt, or Van Allen Belt, consists of ionizing radiation in the form of very energetic protons by products of collisions between GCR and atoms of Earth's atmosphere. The outer radiation belts contain protons and electrons [8]. Sources of radiation in space include trapped particles, Cosmic rays, solar energetic particles. Protons, electrons, alpha particles are a few types of trapped particles present in space [9]. Galactic cosmic rays contain both charged and uncharged particles like electrons or neutrons respectively [10]. In addition to this, the sun also produces high energy particles during solar flares and coronal mass ejections [11]. Various sources of radiation in space are summarized in Fig. 1 below.

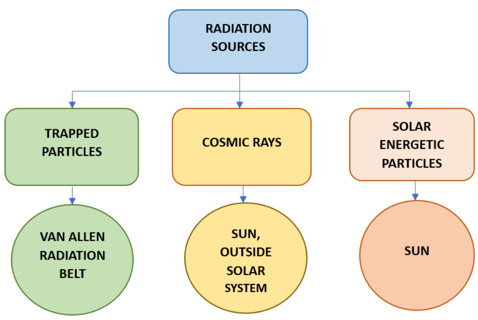

Fig. 1 Radiation sources in space

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The degradation of InGaN LEDs under proton radiation is a complex phenomenon that involves various physical and chemical mechanisms, including displacement damage, defect formation, carrier trapping, and recombination [12–14]. Therefore, understanding the degradation behavior of InGaN LEDs under proton radiation is essential to design and developing radiation-hardened LED devices for space and other high-radiation environments [15]. Several studies have investigated the effect of proton radiation on the performance of InGaN LEDs [16–18]. For instance, the study in [19] reported that proton irradiation caused a significant increase in the forward voltage of InGaN LEDs due to the generation of defects in the p-n junction. The same study also observed a reduction in the reverse leakage current of the LEDs, which was attributed to the radiation-induced passivation of deep-level defects. Similarly, the authors saw an increase in the series resistance and the ideality factor in [20]. These findings imply that the development of non-radiative recombination centers close to the active zone was caused by irradiation. In addition to the electrical properties, the optical properties of InGaN LEDs are also affected by proton radiation [16, 21].

Apart from this, a study in [22] reported that proton irradiation caused a significant decrease in the external quantum efficiency of InGaN LEDs due to the radiation-induced reduction in the carrier density and the consequent decline in the recombination rate. The same study also observed a reduction in the lifetime of the LEDs, which was attributed to the radiation-induced degradation of the material quality. The authors observed a reduction in light output power and the external quantum efficiency of InGaN/GaN Blue LEDwith fluence after 80 MeV irradiation in [23]. Research also shows that quantum well structures are generally better as far as recombination degradation is concerned [24]. Overall, these studies indicate that proton radiation can significantly alter the electrical and optical properties of InGaN LEDs. While mostly the characteristics are degraded, an improvement in the properties can also be seen in some cases, which is attributed to the passivation of the defects due to radiation [7, 25]. The degradation is mainly attributed to the generation of defects, and radiation-induced damage to the active layer [26].

In this article, we aim to analyze the radiation degradation of InGaN LEDs under the influence of proton radiation. The remainder of the paper is arranged as follows: In Section 2, the methodology used is explained, and followed by Section 3, where the results obtained are presented. In Section 4, a discussion of the results obtained is presented. Finally, section 5 concludes the paper.

2 Experimental

2.1 Device under test

InGaN LEDs manufactured by "Visual Communication Company" are used in this paper. Three devices from a single model are used. These high-intensity LEDs are based on InGaN/Sapphire material technology. These devices are equipped with a water-transparent lens. Using water-transparent lenses in LEDs can improve their durability and longevity in harsh environments and enhance their performance and efficiency. The specifications of the samples used are given in Table 1.

2.2 Electrical and optical characterization

The electrical and optical characterization of the blue Light InGaN LEDs was per-formed before radiation. The electrical characterization is done at the microelectronics laboratory, IIUM, Malaysia, using the measurement equipment Keithley 4200 Semi-conductor Characterization System. The Keithley 4200 Semiconductor Characterization System can measure various electrical parameters, including voltage, current, capacitance, resistance, and other device parameters. To perform electrical characterization using the Keithley 4200, the LED is connected to the measurement modules. The measurement parameters are then configured using the system's software interface, which allows users to specify the measurement type, voltage range, current range, and other relevant parameters. The considered LED was placed in the device holder slot as shown in Fig. 2. The considered source-meter enables output voltages not exceeding 200 V and output currents attains up to 1 A [27]. These characteristics were measured by the pulse method at room temperature. Electrical characterization involves the measurement of forward current, reverse current and capacitance corresponding to voltage.

The optical measurements were conducted with HORIBA i320 electroluminescence setup. The HORIBA i320 electroluminescence utilizes electroluminescence, a phenomenon where a material emits light when an electric current is passed through it, to measure the optical properties of the device. To perform electroluminescence measurement

Table 1 Sample specifications

Model	VAOL-5LWY4
Manufacturer	Visual Communication Company
Material	InGaN
Reverse Voltage	5V
Reverse Current	50 μA
Forward Voltage	4V
Forward Current	30 mA

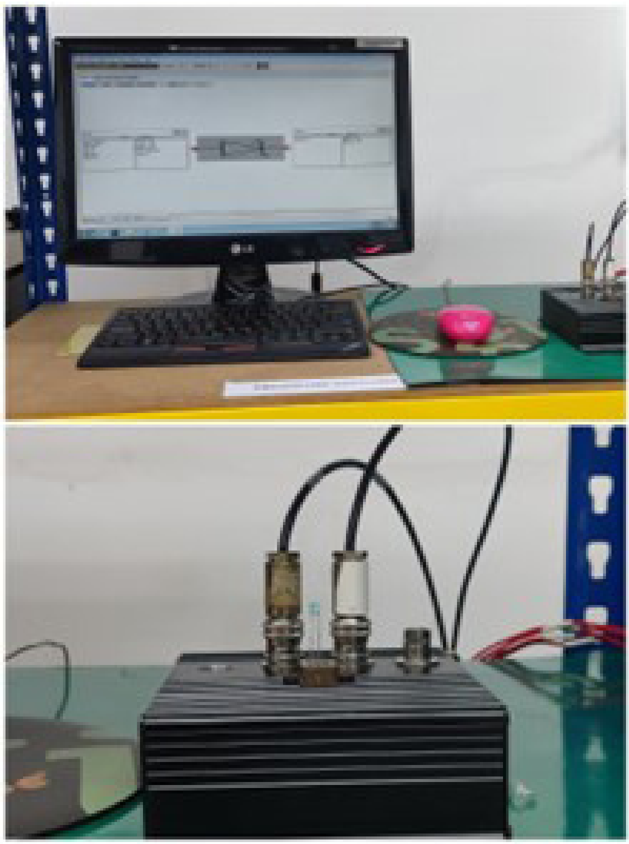

Fig. 2 Keithley 4200 SCS electrical characterization set-up

using the HORIBA i320 setup, the LED is first placed in a dark environment to ensure no interference from external light sources. An electrical current is then passed through the device using a specialized current source, and the camera captures the resulting electroluminescence signal. The light intensity with respect to wavelength was measured for different injection currents. Fig. 3 shows the setup for performing the optical characterization of the LEDs.

2.3 Proton irradiation

Proton radiation in space can have energies ranging from a few kilo-electron volts (keV) to hundreds of giga-electron volts (GeV) or even higher. However, Proton radiation with energies ranging from a few MeV to several GeV is exciting to space scientists and engineers, as it can pose a significant radiation hazard to spacecraft and astronauts. The irradiation to the surface of the samples was performed at the National Centre of Physics, Islamabad, Pakistan. The Proton radiation facility has a 3 MeV proton beam accelerator, which can deliver proton beams with energy ranging from a few keV to 3 MeV. The facility has a range of beam currents, from a few nano amperes to several microamperes, and a spot size of 1 mm in diameter. The specifications of the accelerator are shown in Table 2.

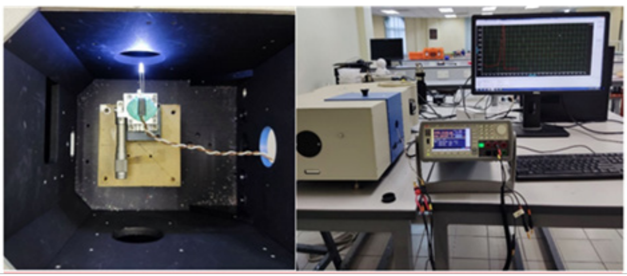

Fig. 3 Horiba i320 optical characterization set-up

The irradiation was done at room temperature with proton fluences of 1×10^{13} cm^{-2}, 3×10^{13} cm^{-2} and 3×10^{14} cm^{-2} and an energy of 2 MeV. The incident current for an energy of 2 MeV is taken as 2 nano amperes. Charge collection for 1×10^{13} cm^{-2} is 0.8 micro coulomb, for 3×10^{13} cm^{-2} is 2.4 micro coulomb and for 3×10^{14} cm^{-2} is x micro coulomb. The time taken to radiate the devices with fluences of 1×10^{13} cm^{-2}, 3×10^{13} cm^{-2} and 3×10^{14} cm^{-2} can be calculated by dividing the respective charge collection by incident current as shown in Table 3. The proton beam is delivered in a vacuum environment, which reduces the effect of air scattering and allows for more precise measurements. Post irradiation, the samples were kept at room temperature for almost a month, and then the electrical and optical measurements were repeated to estimate the radiation-induced degradation.

Table 2 Proton beam accelerator specifications

Model	5UDH-2
Manufacturer	NEC, USA
Technical Voltage	5 MV (Maximum)
Charging	Pelletron charging system
Ion Sources	Two (SNICS and RF)
Ion Beams	H, He, B, C, Si, P, Fe, Ni, Cu & Au
Beam Lines	Two (15° and 30°)
Beam energy	400 keV to 40 MeV
Beam current	0.5 nA – 300 nA
Beam Size	0.5 mm – 10 mm (Diameter)
Sample Type & Size	Solid ≥ 4mm / 4 mm
Model	5UDH-2
Manufacturer	NEC, USA

Table 3 Radiation time calculation

Incident current	Fluence	Charge collection	Time
2 na	1×10^{13} cm^{-2}	0.8 μC	400 sec
2 na	3×10^{13} cm^{-2}	2.4 μC	1200 sec
2 na	3×10^{14} cm^{-2}	24 μC	12000 sec

Fig. 4 shows the schematic diagram of the accelerator. S1 is the source named SNICS (Source of Negative Ions by Cesium Sputtering). Hydrogen cathode is used for negative hydrogen ion/proton beam. Thes ions are moved towards a big tank by switching magnet shown with black color in the Fig. 4. Inside the tank, high positive potential is generated by the pelletron method. Before this high positive potential, there is an environment of stripper gas (nitrogen in our case) where the electrons of those negative ions are stripped of/removed. This converts negative ion to positive ion, and the same potential, which was attracting earlier, now would repel the ions. Hence the energy of ions would be E = (q0 + q1) V, where q0 represents attraction and q1 repulsion. In this way with hydrogen ion or proton beam a potential of 8Mev is achieved with 4MV. When the ion beam leaves the tank, there is quadrupole which is used to converge the beam which otherwise would diverge due to same positive charges. Then there are 15- and 30-degree beamlines and chambers at the end where samples are placed. To avoid any other charge state or impurities, the experiments cannot be done in a straight line. Whichever charge state of any ion is required is switched towards 15-degree beam line (red color magnet). There are beam profile monitors on both low energy side (labelled 01) and high energy side (02) for optimizing profile of beam. The set up also has faraday cups for measuring currents. Vacuum pumps are placed at each stage and at the end chamber. Rotary, turbo, and ion pumps all are used to get high vacuum ranging from 10^{-6} to 10^{-10}. S2 source is only for helium beam which is not relevant to this experiment. Fig. 5 shows the overall methodology of this research.

3 Results and discussion

3.1 Current voltage characteristics

Fig. 6 (a), (b) and (c) show the forward IV characteristics of the device. The results show no major changes in the forward current of the LEDs after radiation. The behavior of an InGaN LED is usually affected by radiation due to the ionization of atoms within the material, which can introduce

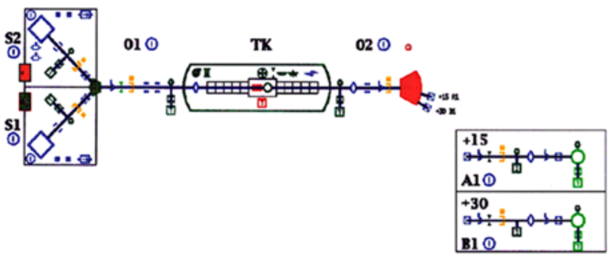

Fig. 4 Schematic Diagram of the accelerator

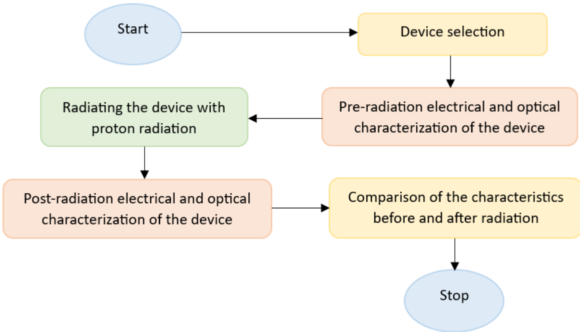

Fig. 5 Overall methodology of the research

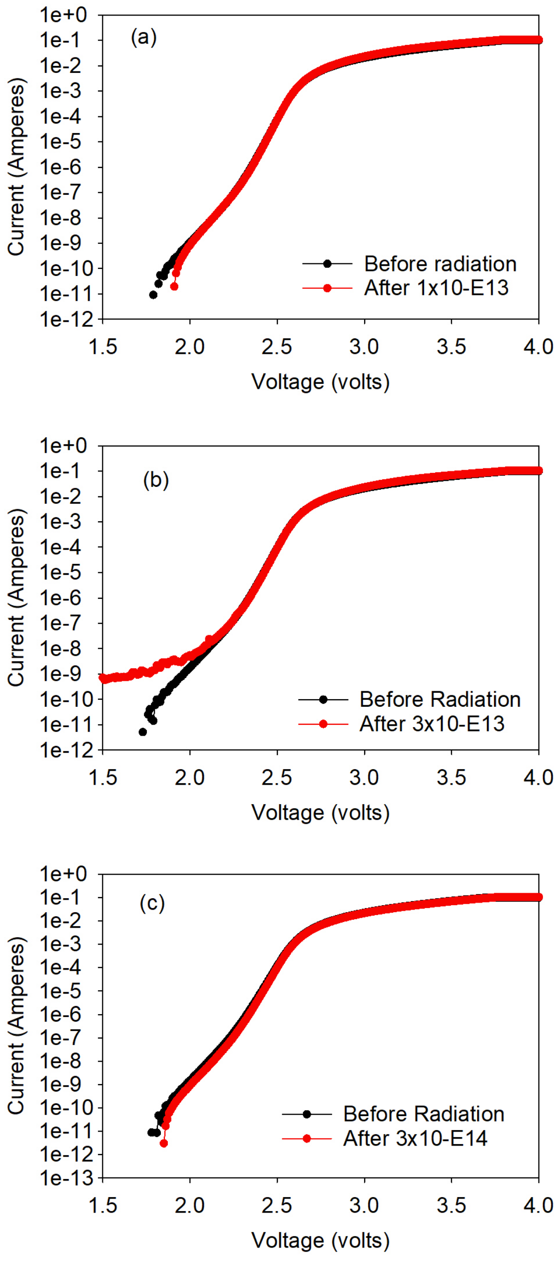

Fig. 6 Forward IV characteristics of devices exposed to (a) 1×10^{13} cm^{-2}, (b) 3×10^{13} cm^{-2} and (c) 3×10^{14} cm^{-2}

defects or alter the electronic properties of the material. However, in some cases, the forward current of an InGaN LED may not show much change even after exposure to radiation. This can happen for a variety of reasons. One possibility is that the radiation energy is not sufficient to cause a significant change in the forward current of the LED. In other words, the radiation dose is too low to affect the electronic properties of the InGaN material [28]. If this radiation were to cause defects or damage to the LED's p-n junction (the region where the p-type and n-type semiconductor materials meet), it could increase the reverse current, which may be measurable. However, if the damage is not severe enough to affect the forward-biased operation of the LED, the forward current may remain essentially unchanged. It can be seen in Fig. 6(a) that after the first dose there is not much change in the current. This is because the dose is not high enough to alter the forward current of an LED. However, in Fig. 6(b), an increase in the forward current can be seen after the second dose. At moderate doses of proton radiation, the radiation induced defects lead to a rise in the current. As the dose increases, the defects create deep energy levels that trap carriers and reduce the recombination efficiency of the LED, leading to a decrease in the current as shown in Fig. 6(c). This pattern can also be seen in [29].

Fig. 7 (a), (b) and (c) show the reverse IV characteristics of the device. It is found that the reverse current mainly increases after radiation. This behavior can be attributed to several factors, including defect creation and annealing processes. Following irradiation, traps develop in the bandgap and cause recombination and generation, increasing reverse leakage current. Similar trends of increase in reverse current can be seen in [30, 31].

This increase in reverse current can have several implications for the operation of InGaN LEDs. For example, it can lead to increased power consumption, decreased efficiency and reduced lifetime due to degradation effects [32]. It is, therefore, important to carefully evaluate the performance of InGaN LEDs after radiation exposure and to take appropriate measures to mitigate any adverse effects.

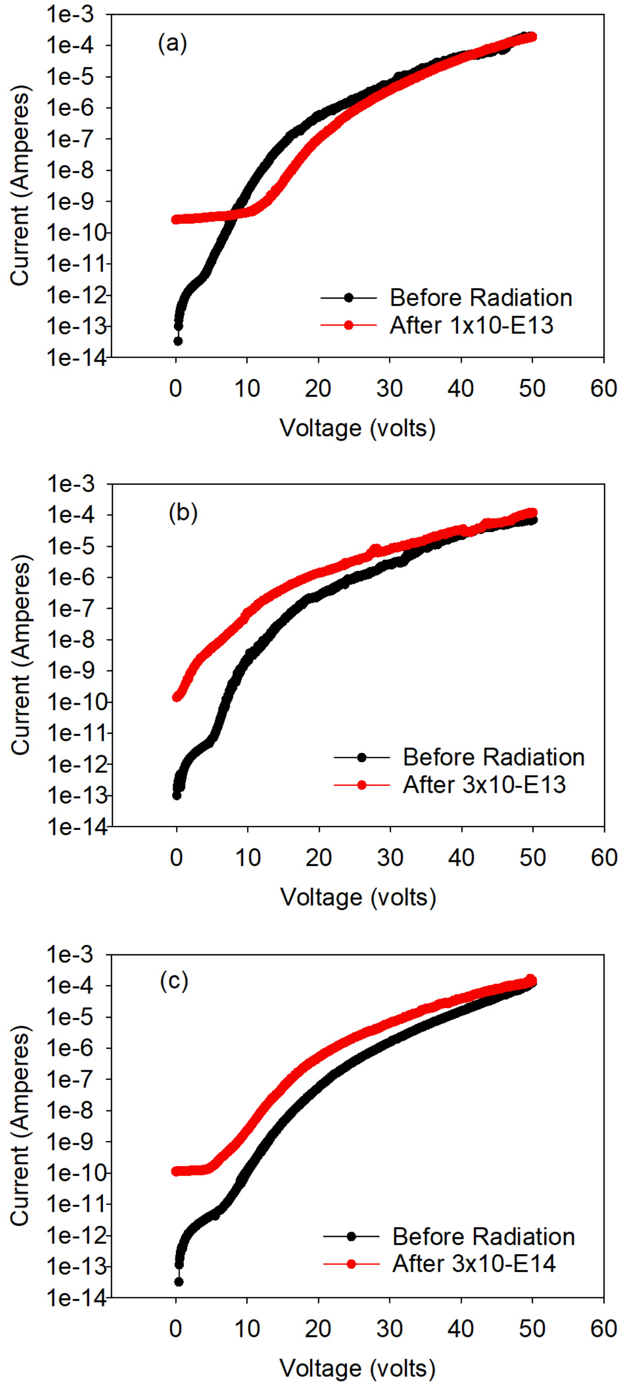

Fig. 7 Reverse IV characteristics of devices exposed to (a) 1×10^{13} cm^{-2}, (b) 3×10^{13} cm^{-2} and (c) 3×10^{14} cm^{-2}

3.2 Capacitance voltage characteristics

Fig. 8 (a), (b) and (c) show the CV characteristics of the device. When electronic devices are exposed to ionizing radiation, such as high-energy protons, the radiation can cause damage to the materials in the device and alter its electrical properties. However, in the case of InGaN LEDs, it has been found that the capacitance remains mostly un-changed after proton radiation, as shown in Fig. 8. If the radiation dose is low enough or the energy of the protons insufficient to cause significant damage to the LED materials, the capacitance is not affected, as shown in Fig. 8(a) [33]. After the second dose, the displacement of atom within the LED material is relatively low, so the number of defects created is also low. As a result, the capacitance of the LED decreases, but only by a small amount. However, as the dose of proton radiation increases, the displacement of atoms within the LED

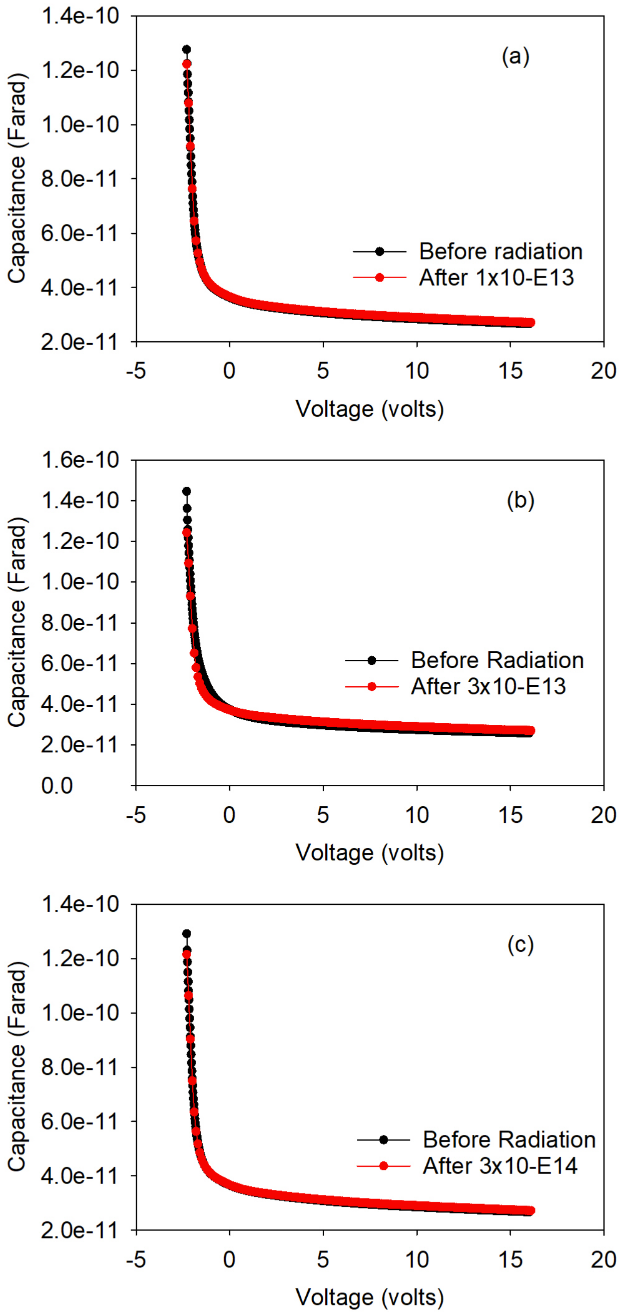

Fig. 8 CV characteristics of devices exposed to (a) 1×10^{13} cm^{-2}, (b) 3×10^{13} cm^{-2} and (c) 3×10^{14} cm^{-2}

material also increases, resulting in more defects. At some point, however, the number of defects reaches a saturation point, beyond which further exposure to proton radiation does not significantly increase the number of defects. At this point, the capacitance of the LED no longer decreases with increasing dose because the number of defects has reached a maximum level, as seen in Fig. 8(c). The electrical characterization results indicate that the LEDs' forward current and capacitance did not change significantly after radiation [34]. However, the reverse current increased.

3.3 Optical characteristics

The light intensity corresponding to wavelengths for different injection currents pre and post all three radiation doses is shown in Fig. 9 (a), (b) and (c). The bold line in each color represents the light intensity of unexposed device for a particular current, whereas the dotted line represents current for exposed device. It is observed that InGaN LEDs show an increase in light intensity after

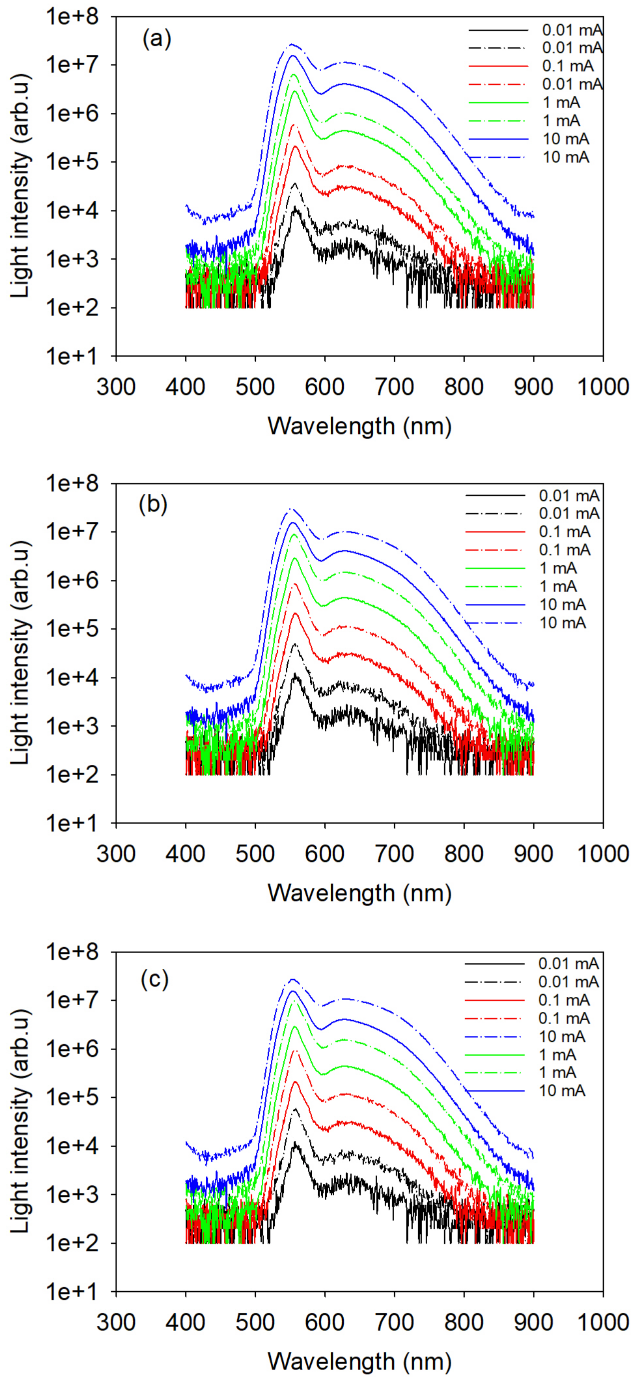

Fig. 9 Light intensity for different injection currents of devices exposed to (a) 1×10^{13} cm^{-2}, (b) 3×10^{13} cm^{-2} and (c) 3×10^{14} cm^{-2}

proton radiation. The introduction of radiative centers by oxygen following radiation exposure is one potential reason for the rise in optical intensity. While AlGaN is being annealed, oxygen molecules are either adsorbed onto its surface or can be found in the complex as a dopant. The rise in optical intensity is attributed to free-electron recombination from the exceedingly degenerate components coupled to this oxygen. These defects are electrically inactive and only contribute optically, as explained in [35].

Another observation that can be made is that the optical intensity increases with the injection current. This is due to higher radiative recombination at higher injection currents [36]. Fig. 10 shows the light intensity of the device at different radiation doses for a constant injection current of 1 mA.

An increase in the reverse current of an LED is usually accompanied by a decrease in the optical output. However, in the case of defects that are only electrically active and optically inactive or vice versa, we can notice unusual trends in the properties of the LEDs [37]. Additionally, proton radiation is more likely to decrease the light intensity of LEDs rather than increase it. An investigation in [16] revealed that proton irradiation caused a significant decrease in the light output power of InGaN LEDs due to radiation-induced

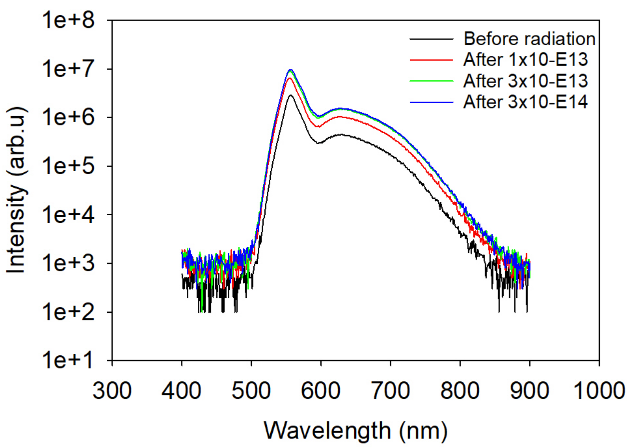

Fig. 10 Light intensity at 1 mA for different radiation doses

damage to the active layer. However, there are studies that reported an increase in the light output of LEDs after proton irradiation, particularly at low doses of radiation. For example, a study in [21] reported an increase in the light output of InGaN/GaN blue LEDs after proton irradiation at low fluences. The researchers at-tributed the increase to the removal of defects that were present in the as-grown material. The increase in optical intensity after radiation is an exciting result, as it suggests that radiation may benefit the performance of InGaN LEDs in specific scenarios. In this study, this increase in optical intensity is attributed to oxygen related defects that are optically active.

4 Conclusions

In conclusion, the effect of proton radiation on InGaN LEDs has been investigated in this paper. The results show that the forward current and capacitance remain mostly unaffected after radiation. However, the reverse current and light intensity increase, indicating a deviation in the device performance. While InGaN LEDs are known to be relatively radiation-resistant compared to other semiconductor materials, this study highlights the importance of considering radiation effects when designing and operating devices in harsh environments such as space or high-energy particle accelerator facilities. Further research is needed to understand better the underlying mechanisms of radiation-induced degradation in InGaN LEDs and to develop mitigation strategies to improve their radiation tolerance.

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