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Effect of proton radiation on gallium nitride light emitting diodes

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ABSTRACT

The compound semiconductor gallium nitride offers enormous potential for facilitating economic expansion in the silicon-based semiconductor industry, which is currently seeing decreasing performance returns compared to investment costs. Its high electron mobility and electric field strength at the material level have already demonstrated enormous potential for photonics and high-frequency communications applications. However, its application in devices used in the radiation-prone environment is hindered by degradation and failure caused by the radiation. In this paper, the effect of proton radiation on the electrical properties of InGaN light emitting diodes (LEDs) for the fluence range of 1×10^{14} cm^{-2} to 3×10^{14} cm^{-2} is performed. On comparing the results before and after radiation, it is found that radiation mainly affected the reverse IV characteristics of the device with little or no effect on forward IV or CV characteristics. Apart from the electric properties, the optical properties of the LEDs show improvement after radiation as the light intensity increases post-irradiation.

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1. INTRODUCTION

Vast number of light emitting diodes (LEDs) are available today, each with unique light-emitting area structures, technical specifications, and performance characteristics [1]. Gas-discharge emitters or lightbulbs are successfully replaced by semiconductor light emitters, especially LEDs [2]. LEDs stand out among other sources due to their high efficiency, low inertia, and limited luminescence spectrum, in addition to their inexpensive cost, excellent mechanical strength, and lengthy service life [3]. One of the most significant sources of light in the visible spectrum that has been used in solid-state lighting applications is the InGaN based LED [4]. SiC and GaN, two wide bandgap semiconductors, are already marketted as power devices for the automotive, wireless, and industrial markets [5]. However, their use in space and avionic applications is constrained by their vulnerability to catastrophic failure and long-term degradation due to radiation exposure [6]. Although these device's efficiency is extremely high, improvements are still required before they can be widely used in optoelectronic systems [7]. A deeper understanding of the device's performance under challenging operating conditions is necessary to broaden applications into new fields [8]. For instance it is crucial to understand the radiation tolerance of electronics and the elements that affect this tolerance in space applications [9]. The impact of radiation on LED devices has generally been the subject of extensive investigation in recent years [10]. However, InGaN LEDs are yet to receive the special attention they deserve. Although some research have shown that radiation can significantly degrade these devices' functionality, other studies have shown that these devices are generally radiation hard [11]. Radiation effects on InGaN LED devices appear to depend on a variety of parameters, including the radiation's type and intensity, the duration of exposure, the devices' design and manufacture, and others [12].

GaN LEDs subjected to 2-MeV electrons and 70-MeV protons in [13] observe device characteristics degradation and restoration. The capacitance decreases after irradiation whereas the reverse current rises. LEDs were irradiated with electrons at 1000 and 1500 kGy [14]. Samples were evaluated for the capacitance and voltage characteristics both before and after irradiation. Reverse leakage current showed an increase after irradiation, but forward current and capacitance show drop. Wang *et al.* [15] investigated the deterioration of InGaN/GaN multiple quantum wells (MQWs) LEDs while being revealed to silicon ions. Radiation-induced bandgap flaws and the carrier removal effect have increased the threshold voltage and leakage current of LEDs. The effect of proton radiation on LEDs with wavelengths of 1050 nm and 1550 nm is examined by the authors in [8]. The results are contrasted with an AlGaAs double heterojunction LED. After radiation exposure, the long wavelength LED's light output damage differed from that of the AlGaAs LED; greater damage was observed at lower forward currents.

Lee *et al.* [16] investigate the effects of radiation on the material, GaN/InGaN was exposed 6 MeV electron irradiation. The drop in electroluminescence in LEDs under fluences exceeding 5×1015 cm^{-2} was directly related to the increased concentration of electron traps in the active multi-quantum-well area. Similar trends were observed in [17]. Boutillier *et al.* [18], it has been assessed how well LEDs resist displacement damage. Almost all the tested samples' output power was sustained up to 2.5×1015 cm^{-2} (50 MeV). This hardening might be connected to the material selected for the active layer. Irom *et al.* [19] shows that the phototransistor and LED of the Micropac 66296 optocoupler have proton damage. The results demonstrate that the optocoupler current transfer ratio (CTR) data is affected by the phototransistor gain. Analysing the test results reveals interesting data, such as how photocurrent and irradiation impact phototransistor gain.

The effect of the optocoupler's LED production process on reaction time was investigated by [20]. Amphoteric doped LEDs show shorter response times than heterostructure LEDs because the minority carriers have longer lifetimes. Simulation and modelling techniques can also be used to evaluate the dependability of these devices [21]–[23]. Irom *et al.* [24] shows proton damage to the phototransistor and LED of the Micropac 66179 optocoupler. The findings show that the gain explicitly depends on the irradiation amount in a significant way. Gamma deterioration was investigated in AlGaInP LEDs with wavelengths in the 590 nm region [25]. When exposed to rapid neutrons, protons, electrons, and gamma rays, all LEDs suffer from the same stages of degradation, according to a comparison of research results employing different semiconductor architectures.

InGaN LEDs can emit over a wide range and are find applications in different spheres of life. The research that has been going on is often limited in scope and sometimes contradictory. All this makes the reliability testing of InGaN LEDs even more critical. Therefore, the main objective of this work is to demonstrate the effects of increasing doses of proton radiation on the electrical and optical properties of InGaN LEDs. This research will not only focus on the effects of radiation but also the origin of defect creation due to radiation. This work can help to better understand the mechanisms by which proton radiation degrades InGaN LEDs. Overall, the ramifications of this research on the effect of proton radiations on InGaN LEDs could be significant, both for the development of new applications for these LEDs and for the improvement of their radiation hardness.

2. METHOD

This research employs the methodology tried, tested, and verified by researchers in past. Pre and post irradiation characterization of semiconductor devices to analyze radiation degradation has been going on for the past few years [26], [27]. However, there is still a lot that is unknown about the effects of proton radiation on InGaN LEDs. This research will only focus on two samples of white InGaN LEDs. The samples that will be used are OVLAW4CB7 (OPTEK Technology) [28] and VLHW4100 (Visual Communication Company) [29]. Two devices from each model are chosen. Each model has its own specifications. Table 1 provides further information on each model.

The electrical characterization of the devices was done pre and post irradiation at the Microelectronics Laboratory, IIUM, Gombak, Malaysia. Electrical characterization was done using the Keithley 4200 semiconductor characterization system (SCS) measurement equipment. It is a versatile and high-precision tool used to test and analyze semiconductor devices. Keithley 4200 SCS allows to perform various electrical measurements on devices such as transistors, diodes, and integrated circuits. The system consists of a mainframe unit and various plug-in modules, each providing a specific measurement capability. These modules can be combined to create customized measurement set-ups for specific applications. The electrical characteristics of the LEDs were obtained using this set-up. All the measurements were done in an atmospheric environment at a constant room temperature.

Table 1. The LED specifications

Model	OVLAW4CB7	VLHW4100
Manufacturer	TT Electronics	Vishay
Material	InGaN	InGaN
Reverse voltage	5 V	5 V
Reverse current	10 μA	50 μA
Forward voltage	4 V	4 V
Forward current	20	15.3

The optical measurements were performed with a HORIBA i320 electroluminescence set-up. The HORIBA i320 electroluminescence set-up is a high-performance tool characterizing photovoltaic devices as shown in Figure 1. In this research, the optical characterization of the LEDs was done by Electroluminescence. This technique involves applying a voltage to a device and measuring the resulting light emission. This provides valuable information about the performance and quality of the device.

The samples were irradiated at the National Center of Physics, Islamabad. Two samples from each model were used. The irradiation was done in a vacuum atmosphere at room temperature with proton fluences of 1×10^{14} cm^{-2}, 3×10^{14} cm^{-2} and an energy of 2 MeV. The proton beam is delivered in a vacuum environment, which reduces the effect of air scattering and allows for more precise measurements. The schematic diagram of the proton beam accelerator can be seen in Figure 2. S1 is the source named source of negative ions by cesium sputtering (SNICS). Hydrogen cathode is used for negative hydrogen ion/proton beam. There are beam profile monitors on both low energy side (labelled 01) and high energy side (02) for optimizing profile of beam. S2 source is only for helium beam which is not relevant to this experiment. Post irradiation, the samples were kept at room temperature for almost a week, and then the electrical and optical measurements were repeated to estimate the radiation-induced degradation. Table 2 shows the samples and the respective fluences.

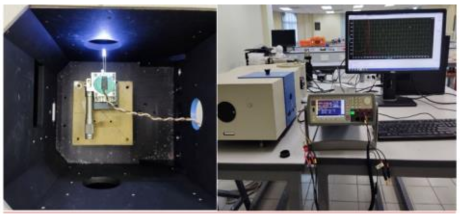


Figure 1. Horiba i320 optical characterization set up

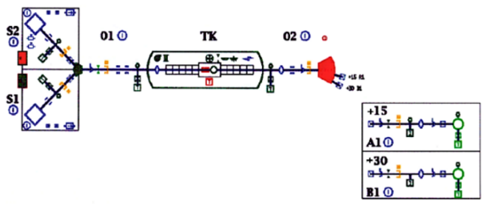


Figure 2. Schematic diagram of the proton beam accelerator

Table 2. The LED specifications

Model	Device	Dose (cm^{-2})
OVLAW4CB7	Device 1	1×10^{14}
	Device 2	3×10^{13}
VLHW4100	Device 1	1×10^{14}
	Device 2	3×10^{13}

3. RESULTS AND DISCUSSION

The outcomes of irradiating the samples are shown in this section. For every device in both versions, the forward and reverse IV characteristics as well as the CV characteristics have been provided. Plots of the IV and CV characteristics are semi-logarithmic. This section also includes a presentation of the optical characteristics.

3.1. Forward IV characteristics

Figure 3 shows the IV characteristics of OVLAW4CB7 after irradiating it with the first dose of 1×10^{14} cm^{-2}. As seen in the figure, the recombination current, also known as the forward leakage current, shows no notablechange after irradiation. This figure is representative as the recombination shows no change even after radiating the device with a higher dose of 3×10^{14}cm^{-2}. In addition, the other model's forward IV characteristics (VAOL-5LWY4) also show no changes after irradiation with both doses. This is because forward biasing of the device involves injecting majority carriers into the material, which are not significantly affected by proton radiation. Therefore, the forward IV characteristics are relatively unaffected. Diffusion is the main factor controlling current for GaAs-based LEDs operating in a high injection domain. However, a separate mechanism known as "trap-assisted tunnelling" typically limits current transport in GaN-based LEDs. The lifespan-damaged relationship would then be irrelevant. The resilience of those LEDs to displacement consequences in the forward bias may also be explained by this theory [11].

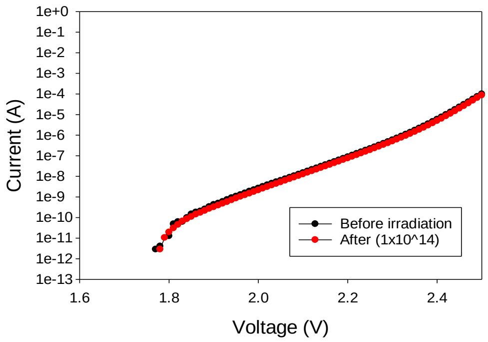


Figure 3. Forward IV characteristics of OVLAW4CB7 before and after the irradiation with dose $1{\times}10^{14}$ cm^{-2}

3.2. Reverse IV characteristics

Figures 4 and 5 show the reverse IV characteristics of both models. Figures 4(a) and (b) show the reverse current after dose $1{\times}10^{14}$ cm^{-2} for OVLAW4CB7 and VAOL-5LWY4, respectively. Similarly, Figures 5(a) and (b) shows the reverse current after $3{\times}10^{14}$ cm^{-2} for both models. In every instance, the reverse leakage current is rising. The radiation-induced flaws that cause gadget degradation are to blame for this. After irradiation, traps may appear in the bandgap and cause recombination and generation, increasing reverse leakage current [30]. Reverse biasing of the device involves the flow of minority carriers across the junction, and proton radiation can introduce defects and traps in the material that can capture and release these minority carriers. As a result, the reverse current in the device can increase after proton radiation, leading to changes in the reverse IV characteristics. The rise in the bulk density of traps is what is responsible for this increase in current. The radiation exposure and the LED sample had an impact on the degree of degradation. When the devices are irradiated with a higher fluence, the reverse leakage current becomes low compared to the reverse leakage current at a lower dose. This phenomenon is believed to rise due to the substantial compensation of the n-GaN cap layer [31]. Similar trends were seen in [32]. The Figures 4 and 5 clearly depict an increase in reverse current post irradiation. This increase is typically predominant at lower voltages. The increase in the reverse leakage current after irradiation at some specific voltages has been calculated for both models in numerical form and can be seen in Table 3.

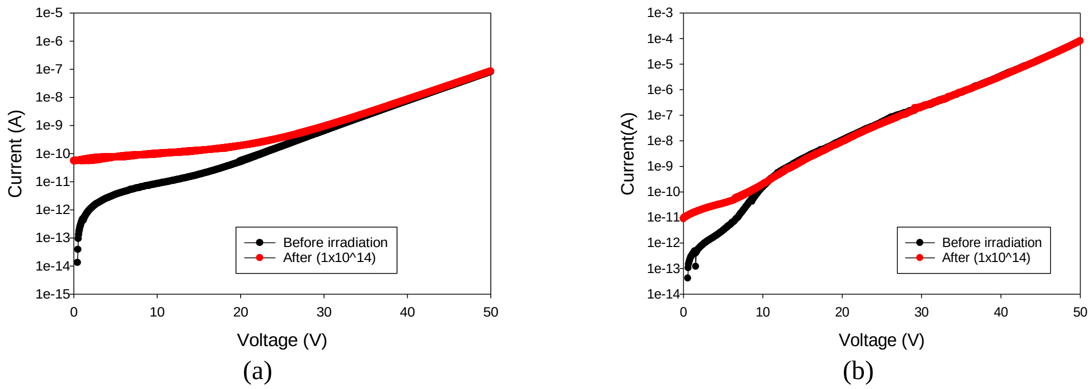
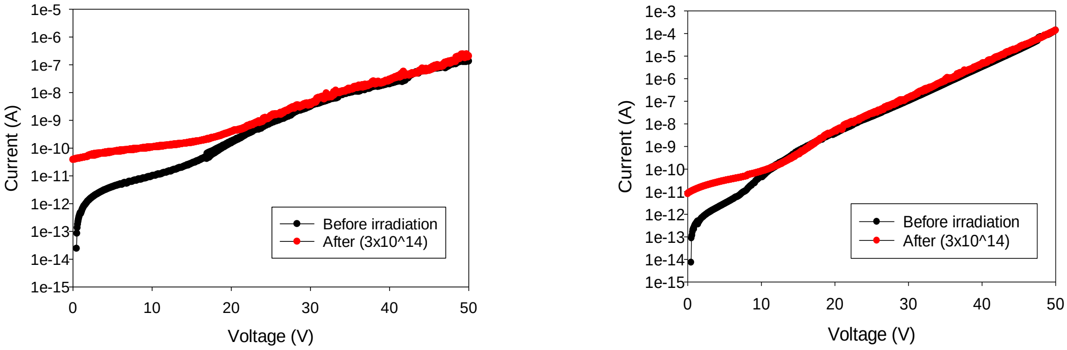


Figure 4. Reverse IV characteristics after dose 1x10^{14} cm^{-2}; (a) OVLAW4CB7 and (b) VLHW4100

As seen in the Table 3, the degradation is quite predominant for both models; however, the degradation in OVLAW4CB7 is more severe than in VAOL-5LWY4. Another interesting fact that can be deduced from the results is that with the increase in dosage, the variation (increase) of the reverse current decreases. When the devices are irradiated with a higher fluence, the reverse leakage current becomes low compared to the reverse leakage current at a lower dose. Polyakov *et al.* [30] have seen an alike trend for the case of high doses. This situation is said to rise due to the substantial compensation of the n-GaN cap layer.



(a) (b)

Figure 5. Reverse IV characteristics after dose 3×10^{14} cm^{-2}; (a) OVLAW4CB7 and (b) VLHW4100

Table 3. The LED specifications

Model	Dose (cm^{-2})	Increase in current at 5 V	Increase in current at 10 V
OVLAW4CB7	Device 1	12×	12×
	Device 2	18×	11×
VLHW4100	Device 1	11×	1.3×
	Device 2	10×	1.7×

3.3. CV characteristics

Figure 6 shows the CV characteristics of OVLAW4CB7 after the irradiation with 1×10^{14} cm^{-2}. As shown in Figure 6, the CV characteristics are unaffected for the device after irradiation. Even after irradiation with a higher fluence, the device's CV characteristics remain unchanged. Similarly, the CV characteristics of VAOL-5LWY4 are also unchanged after irradiation.

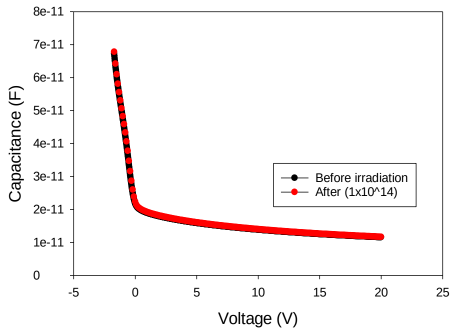
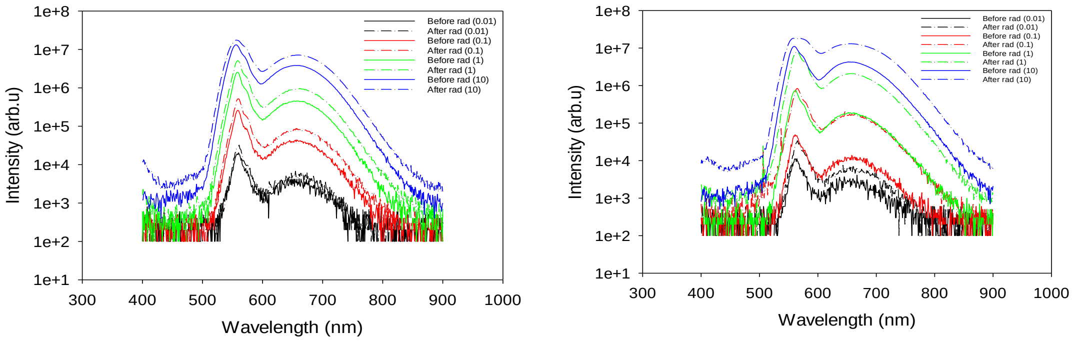


Figure 6. CV characteristics of OVLAW4CB7 before and after the irradiation with dose 1×10^{14} cm^{-2}

3.4. Electroluminescence characteristics

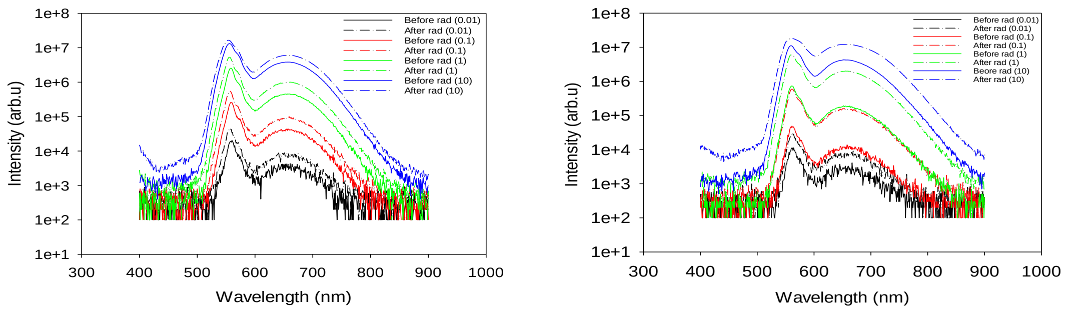
Figures 7(a) and (b) show the optical intensity of OVLAW4CB7 and VLHW4100 after irradiation with dose 1×10^{14} cm^{-2} for different injection currents. Figures 8(a) and (b) show the devices' optical intensity after dose 3×10^{14} cm^{-2}. The figures reveal that the optical intensity increases after radiation for both devices. A possible mechanism for the increase in optical intensity is the introduction of radiative centres by oxygen after irradiation. Oxygen molecules are adsorbed onto the surface of AlGaN while annealing or can also be present as a dopant in the compound. The free-electron recombination from the extremely degenerate portions connected to this oxygen is said to be the cause of the increase in optical intensity [33]. Similar trends were found in [34] and the authors attributed it to a decrease in non-radiative recombination rates.

Another interesting result that can be noted is the increase in optical intensity with the increase in injection current. The intensity of the emitted light is directly proportional to the number of electron-hole pairs that recombine per unit of time, which is, in turn, proportional to the injection current. Thus, an increase in injection current causes a higher rate of electron-hole recombination and, therefore an increase in the optical intensity of the LED [35]. Despite the radiation-induced degradation seen in the INGaN LEDs, this behaviour might be helpful in some circumstances. For instance, the increased reverse current or optical intensity may be used in radiation detection or dosimetry systems to indicate the presence or level of radiation exposure.



(a) (b)

Figure 7. Electroluminescence intensity before and after dose 1×10^{14} cm^{-2}; for (a) OVLAW4CB7 and (b) VLHW4100



(a) (b)

Figure 8. Electroluminescence intensity before and after dose 3×10^{14} cm^{-2}; for (a) OVLAW4CB7 and (b) VLHW4100

4. CONCLUSION

This research studied the effect of proton radiation on Indium Gallium Nitride LEDs. The electrical and optical characteristics of the LEDs were compared before and after radiation. The results show that the reverse leakage current increases after radiation. This increase is ascribed to the traps and defects created due to radiation. In addition to the leakage current, the optical intensity also increases. The increase in optical intensity is caused by the oxygen related defects that are only optically active. However, the forward current and capacitance of the devices show no major changes. This is because the majority carriers are not significantly affected by the radiation. The degrading characteristics presented in the current study might help engineers make well-informed choices while using electrical devices based on GaN in hostile environments or open areas. However, the impact of radiation on InGaN LED devices appears to be complicated and influenced by several variables. More research is required in future to comprehend the detailed mechanisms underlying this effect and create tactics for enhancing these devices' radiation tolerance.

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REFERENCES

[1] S. Nakamura, "Nobel Lecture: Background story of the invention of efficient blue InGaN light emitting diodes," *Reviews of Modern Physics*, vol. 87, no. 4, 2015, doi: 10.1103/RevModPhys.87.1139.

[2] S. Nakamura and M. R. Krames, "History of Gallium–Nitride-Based Light-Emitting Diodes for Illumination," *Proceedings of the IEEE*, vol. 101, no. 10, pp. 2211–2220, Oct. 2013, doi: 10.1109/JPROC.2013.2274929.

[3] S. J. Pearton, F. Ren, E. Patrick, M. E. Law, and A. Y. Polyakov, "Review—Ionizing Radiation Damage Effects on GaN Devices," *ECS Journal of Solid State Science and Technology*, vol. 5, no. 2, pp. Q35–Q60, 2016, doi: 10.1149/2.0251602jss.

[4] Z. W. Zheng *et al.*, "Modulation Characteristics of GaN-Based Light-Emitting-Diodes for Visible Light Communication," *ECS Journal of Solid State Science and Technology*, vol. 6, no. 9, pp. R135–R138, Sep. 2017, doi: 10.1149/2.0301709jss.

[5] T. Baba, N. F. Hasbullah, and N. B. Saidin, "Degradation of InGaN LEDs by Proton Radiation," in *2023 8th International Conference on Business and Industrial Research (ICBIR)*, May 2023, pp. 932–936, doi: 10.1109/ICBIR57571.2023.10147696.

[6] S. J. Pearton *et al.*, "Review—Radiation Damage in Wide and Ultra-Wide Bandgap Semiconductors," *ECS Journal of Solid State Science and Technology*, vol. 10, no. 5, May 2021, doi: 10.1149/2162-8777/abfc23.

[7] R. K. Mozhaev, A. A. Pechenkin, D. S. Ukolov, A. V. Ulanova, and A. Y. Nikiforov, "Evaluation of Organic Light-Emitting Diodes Total Ionizing Dose Sensitivity in Temperature Range," in *2021 IEEE 32nd International Conference on Microelectronics (MIEL)*, Sep. 2021, pp. 357–360, doi: 10.1109/MIEL52794.2021.9569164.

[8] H. N. Becker and A. H. Johnston, "Proton damage in LEDs with wavelengths above the silicon wavelength cutoff," *IEEE Transactions on Nuclear Science*, vol. 51, no. 6, pp. 3558–3563, Dec. 2004, doi: 10.1109/TNS.2004.839168.

[9] D. S. Ukolov, N. A. Chirkov, R. K. Mozhaev, and A. A. Pechenkin, "Radiation Hardness Evaluation of LEDs Based on InGaN, GaN and AlInGaP Heterostructures," in *2019 IEEE 31st International Conference on Microelectronics (MIEL)*, Sep. 2019, pp. 197–200, doi: 10.1109/MIEL.2019.8889651.

[10] C. Shen *et al.*, "Semipolar InGaN-based superluminescent diodes for solid-state lighting and visible light communications," Feb. 2017, pp. 1–10, doi: 10.1117/12.2251144.

[11] A. H. Johnston, "Radiation Effects in Optoelectronic Devices," *IEEE Transactions on Nuclear Science*, vol. 60, no. 3, pp. 2054–2073, Jun. 2013, doi: 10.1109/TNS.2013.2259504.

[12] W. Chen *et al.*, "High-performance, single-pyramid micro light-emitting diode with leakage current confinement layer," *Applied Physics Express*, vol. 8, no. 3, pp. 1–4, Mar. 2015, doi: 10.7567/APEX.8.032102.

[13] H. Ohyama *et al.*, "Degradation of GaN LEDs by electron irradiation," *Materials Science and Engineering: B*, vol. 173, no. 1–3, pp. 57–60, Oct. 2010, doi: 10.1016/j.mseb.2010.03.018.

[14] Y. Abdullah, A. S. Hedzir, N. F. Hasbullah, N. Muridan, C. R. Che Hak, and S. Mahat, "Radiation Damage Study of Electrical Properties in GaN LEDs Diode after Electron Irradiation," *Materials Science Forum*, vol. 888, pp. 348–352, Mar. 2017, doi: 10.4028/www.scientific.net/MSF.888.348.

[15] L. Wang *et al.*, "Multiple Angle Analysis of 30-MeV Silicon Ion Beam Radiation Effects on InGaN/GaN Multiple Quantum Wells Blue Light-Emitting Diodes," *IEEE Transactions on Nuclear Science*, vol. 65, no. 11, pp. 2784–2792, Nov. 2018, doi: 10.1109/TNS.2018.2872582.

[16] I.-H. Lee *et al.*, "Point defects controlling non-radiative recombination in GaN blue light emitting diodes: Insights from radiation damage experiments," *Journal of Applied Physics*, vol. 122, no. 11, pp. 1–6, Sep. 2017, doi: 10.1063/1.5000956.

[17] I.-H. Lee *et al.*, "Deep Electron and Hole Traps in Electron-Irradiated Green GaN/InGaN Light Emitting Diodes," *ECS Journal of Solid State Science and Technology*, vol. 6, no. 10, pp. Q127–Q131, Oct. 2017, doi: 10.1149/2.0131710jss.

[18] M. Boutillier, O. Gilard, G. Quadri, S. Lhuillier, L. S. How, and S. Hernandez, "Commercial Light Emitting Diodes Sensitivity to Protons Radiations: IEEE Radiation Effects Data Workshop Record," in *2014 IEEE Radiation Effects Data Workshop (REDW)*, Jul. 2014, pp. 1–6, doi: 10.1109/REDW.2014.7004557.

[19] F. Irom, L. D. Edmonds, G. R. Allen, and B. G. Rax, "A Method to Separate Proton Damage in LED and Phototransistor of Optocouplers," *IEEE Transactions on Nuclear Science*, vol. 65, no. 8, pp. 1553–1560, Aug. 2018, doi: 10.1109/TNS.2018.2819960.

[20] R. K. Mozhaev, M. E. Cherniak, A. V. Ulanova, and A. Y. Nikiforov, "Estimation technique for LED sensitivity to structural damage based on minority carriers lifetime measurements," in *2017 IEEE 30th International Conference on Microelectronics (MIEL)*, Oct. 2017, pp. 161–164, doi: 10.1109/MIEL.2017.8190092.

[21] R. Touileb and A. Abbou, "Simulation and optimization of hydrogen consumption in a fuel cell/battery hybrid vehicle," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 14, no. 2, pp. 662–672, Jun. 2023, doi: 10.11591/ijpeds.v14.i2.pp662-672.

[22] M. Haidoury and M. Rachidi, "Dynamic fuel cell model improvement based on macroscopic energy representation," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 13, no. 3, pp. 1430–1439, Sep. 2022, doi: 10.11591/ijpeds.v13.i3.pp1430-1439.

[23] I. Alhamrouni, M. Salem, A. Jusoh, and T. Sutikno, "A proton-exchange membrane fuel cell and ultra-capacitor system model for stand-alone residential applications," *TELKOMNIKA (Telecommunication Computing Electronics and Control)*, vol. 20, no. 5, pp. 1172–1180, Oct. 2022, doi: 10.12928/telkomnika.v20i5.24292.

[24] F. Irom, G. R. Allen, L. D. Edmonds, and B. G. Rax, "Proton damage in LED and phototransistor of micropac 66179 optocoupler," in *2016 16th European Conference on Radiation and Its Effects on Components and Systems (RADECS)*, Sep. 2016, pp. 1–7, doi: 10.1109/RADECS.2016.8093208.

[25] K. N. Orlova, A. V. Gradoboev, and I. A. Asanov, "Gamma degradation of light-emitting diodes based on heterostructures AlGaInP," in *2012 7th International Forum on Strategic Technology (IFOST)*, Sep. 2012, pp. 1–4, doi: 10.1109/IFOST.2012.6357528.

[26] S. M. Khanna, D. Estan, A. Houdayer, H. C. Liu, and R. Dudek, "Proton radiation damage at low temperature in GaAs and GaN light-emitting diodes," *IEEE Transactions on Nuclear Science*, vol. 51, no. 6, pp. 3585–3594, Dec. 2004, doi: 10.1109/TNS.2004.839105.

[27] X. Fu *et al.*, "Fast neutron irradiation effects on AlGaN deep ultraviolet light emitting diodes," *Results in Physics*, vol. 27, Aug. 2021, doi: 10.1016/j.rinp.2021.104532.

[28] "White High-Intensity LED Lamp (3 mm, 40° Viewing Angle) OVLAW4CB7 Description," *TT Electronics*. OPTEK Technology, pp. 1–5, 2018. [Online]. Available: www.ttelectronics.com. Accessed date: Jan. 10, 2023.

[29] "LED Through Hole 5mm (T-1 3/4) White 5000 mcd 3.5V - VCC," *VCC*. 2022. [Online]. Available: https://vcclite.com/product/vaol-5lwy4/. Accessed date: Jan. 10, 2023.

[30] A. Y. Polyakov *et al.*, "Electron Irradiation Effects in GaN/InGaN Multiple Quantum Well Structures," *Journal of The*

Electrochemical Society, vol. 155, no. 1, pp. H31–H35, 2008, doi: 10.1149/1.2803517.
[31] A. Hedzir, N. Muridan, Y. Abdullah, and F. Hasbullah, "Effect of electron irradiation on the electrical and optical characteristics of gallium-nitride light emitting diodes," *Ukrainian Journal of Physical Optics*, vol. 20, no. 3, pp. 124–131, 2019, doi: 10.3116/16091833/20/3/124/2019.
[32] A. Floriduz and J. D. Devine, "Modelling of proton irradiated GaN-based high-power white light-emitting diodes," *Japanese Journal of Applied Physics*, vol. 57, no. 8, pp. 1–5, Aug. 2018, doi: 10.7567/JJAP.57.080304.
[33] R. Y. Korotkov, F. Niu, J. M. Gregie, and B. W. Wessels, "Investigation of the defect structure of GaN heavily doped with oxygen," *Physica B: Condensed Matter*, vol. 308–310, pp. 26–29, Dec. 2001, doi: 10.1016/S0921-4526(01)00658-5.
[34] J. J. Jimenez *et al.*, "Proton radiation effects in high power LEDs and IREDs for Optical Wireless Links for intra-Satellite communications (OWLS)," in *2006 IEEE Radiation Effects Data Workshop*, Jul. 2006, pp. 77–84, doi: 10.1109/REDW.2006.295472.
[35] M. E. Raypah, M. Devarajan, and F. Sulaiman, "Influence of injection current and ambient temperature on intensity and wavelength of low-power SMD LED," in *2016 IEEE 37th International Electronics Manufacturing Technology (IEMT) & 18th Electronics Materials and Packaging (EMAP) Conference*, Sep. 2016, pp. 1–6, doi: 10.1109/IEMT.2016.7761989.

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