Wavelength Optimization for AlGaN Radiation Hard Fusion Diagnostics Platforms

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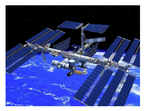
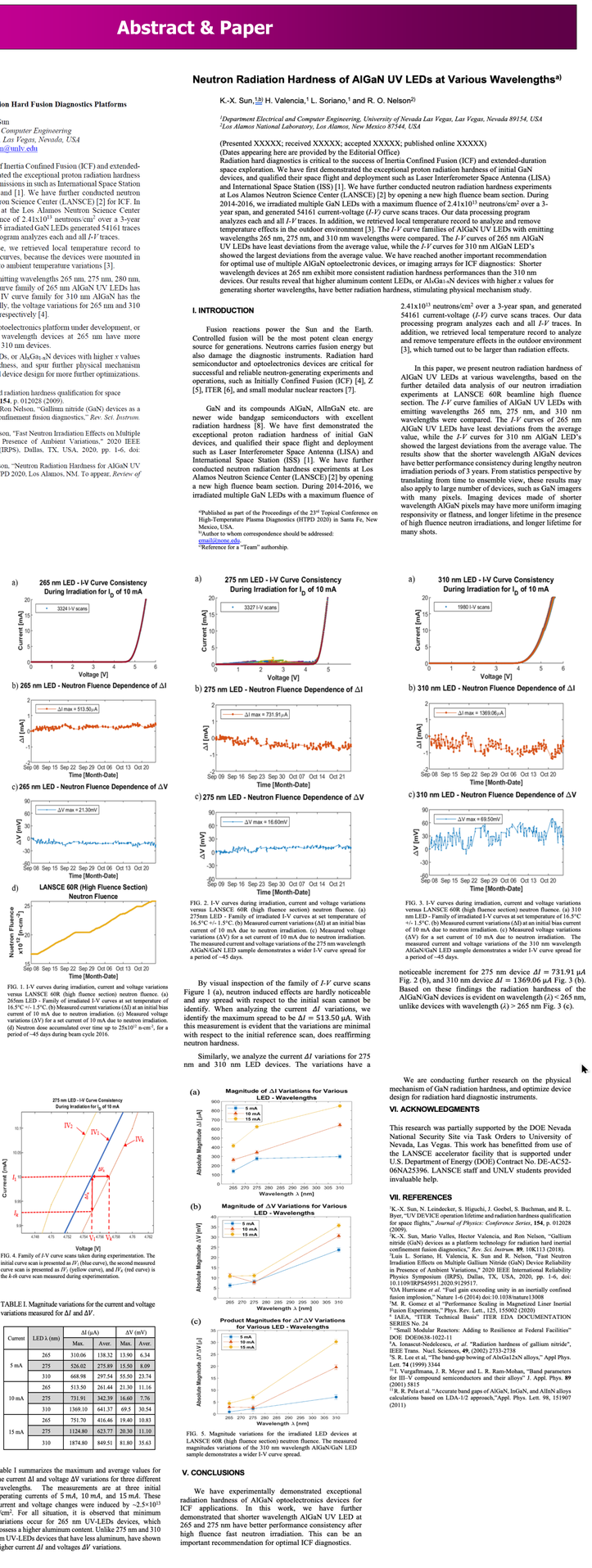


Abstract & Paper



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Radiation hard diagnostics is critical to the success of Inertia Confined Fusion (ICF) and extended-duration space exploration. We have first demonstrated the exceptional proton radiation hardness of initial GaN devices, and qualified them for space missions in such as International Space Station (ISS) Laser Interferometer Space Antenna (LISA) and [1]. We have further conducted neutron radiation hardness experiments at Los Alamos Neutron Science Center (LANSCE) [2] for ICF. In 2014, we opened new high fluence beam section at the Los Alamos Neutron Science Center (LANSCE) from 2014-2016 with a maximum fluence of $2.41x10^{13}$ neutrons/cm^2 over a 3-year span. The current-voltage (I-V) curve scans for the 25 irradiated GaN LEDs generated 54161 traces in total, and 4.4 GB of data. Our data processing program analyzes each and all *I-V* traces.

In addition to monitoring neutron fluence increase, we retrieved local temperature record to analyze and remove temperature effects on the *I-V* curves, because the devices were mounted in an open-bottom weather cover, and were subjected to ambient temperature variations [3].

The *I-V* curve families of AlGaN UV LEDs with emitting wavelengths 265 nm, 275 nm, 280 nm, and 310 nm wavelengths were compared. The IV curve family of 265 nm AlGaN UV LEDs has least deviations from the average value, while the IV curve family for 310 nm AlGaN has the largest deviations from the average value. Specifically, the voltage variations for 265 nm and 310 nm devices at 15 mA current are 0.08V and 0.28V, respectively [4].

We have reached another optimization for AlGaN optoelectronics platform under development, or imaging arrays for nuclear diagnostics: Shorter wavelength devices at 265 nm have more consistent radiation hardness performances than the 310 nm devices.

Our results reveal that higher aluminum content LEDs, or $Al_xGa_{1-x}N$ devices with higher *x* values for shorter wavelengths, have better radiation hardness, and spur further physical mechanism study. We are modeling AlGaN material physics and device design for more further optimizations.

1. K.-X. Sun *et al.* "UV LED operation lifetime and radiation hardness qualification for space flights," *Journal of Physics: Conference Series*, **154**, p. 012028 (2009).
2. K.-X. Sun, Mario Valles, Hector Valencia, and Ron Nelson, "Gallium nitride (GaN) devices as a platform technology for radiation hard inertial confinement fusion diagnostics," *Rev. Sci. Instrum.* **89**, 10K113 (2018).
3. Luis L. Soriano, H. Valencia, K. Sun and R. Nelson, "Fast Neutron Irradiation Effects on Multiple Gallium Nitride (GaN) Device Reliability in Presence of Ambient Variations," 2020 IEEE International Reliability Physics Symposium (IRPS), Dallas, TX, USA, 2020, pp. 1-6, doi: 10.1109/IRPS45951.2020.9129517.
4. K.-X. Sun, L. Soriano, H. Valencia, and R. Nelson, "Neutron Radiation Hardness for AlGaN UV LEDs at Various Wavelengths," Presented at HTPD 2020, Los Alamos, NM. To appear, *Review of Scientific Instruments*

We have reached another important recommendation for optimal use of multiple AlGaN optoelectronics devices, or imaging arrays for ICF diagnostics: Shorter wavelength devices at 265 nm have more consistent radiation hardness performances than the 310 nm devices.

II. AlGaN BANDGAPS AND ALUNMINUM CONTENTS

AlGaN has strong ionic-covalent bond strength and wide bandgap. Aluminum content *x* in $Al_xGa_{1-x}N$ compound impacts the bandgap size of AlGaN material, the emitting and absorption wavelengths [9-11]. Specifically, the bandgap can be approximated as [9]:

$$E_g(x) = f(x) - bx(1-x) \quad (1)$$

where b is the bowing parameter, and $f(x) = (1-x)E_g(0) + xE_g(1)$ is the linear compositional dependence of the bandgap in the absence of bowing. $E_g(0) = 3.413\ eV$ for GaN and $E_g(1) = 6.413\ eV$ for AlN at temperature 295K. While the bowing parameter b is determined device structure and growth process, these equations indicate that higher Al contents yield larger bandgaps, thus shorter wavelengths. Larger bandgap size is typically indicative of higher bond strength, and better radiation hardness. More detailed theoretical and computational study will be needed to further clarify these understandings.

III. EXPERIMENT

The experiment was conducted at the Los Alamos Neutron Science Center (LANSCE). The facility produces neutrons with a broad distribution of energies through a spallation process. In order to expose our AlGaN/GaN devices to high neutron energy ranges of 0.1 to 800 MeV, a new outdoor irradiation section ~10 meters away from the neutron source at the 4FP60R had to be created. The experiment expanded over the neutron beam cycles 2014-2016 [2]. AlGaN/GaN devices with different wavelength ranges from 265 nm up to 310 nm were selected. A partial weather cover protected devices from rain and snow, exposing the devices to local temperature variations over 3 years, and adding the rigor of environmental testing. To monitor and record data continuously, a reliable automated measurement was implemented. The computer interface was operated by our LabVIEW program. In a record three-year continuous beam cycle, we collected 54161 curve scans [2]. More details are referred to references [1, 2].

To determine the neutron effects induced on the AlGaN/GaN devices, we first remove the temperature effects from the collected data. To remove the effects, we bring all the measured *I-V* curve scans to a common temperature within variation of $+/-1.5°C$. [3].

Experimental observations in the last year (2016) of the neutron irradiation are shown in Fig. 1-3. Firstly, as shown by *I-V* scan curves overlay in subfigures (a), devices of all wavelengths maintained operations. However, the *I-V* curve overlays Fig.1(a), Fig. 2(a), and Fig. 3(a) for AlGaN LEDs of wavelengths 265, 275, and 310 nm shows incrementally wider spread.

IV. DATA ANALYSIS

A. Neutron Induced ΔI and ΔV Variations

To determine the neutron induced damages on the AlGaN/GaN devices, we analyze the *I-V* curve scans with respect to an initial reference measurement see Fig. 4. Let I_1 be the diode current I_D for the first measured *I-V* scan curve during the experiment and recorded at 10 mA. Similarly let V_1 be diode voltage V_D that corresponds to current $I_1 = 10\ mA$ for the first measured *I-V* scan curve.

It should be noted that V_1 will be different for each diode and initial setup parameters. The noted 'first *I-V* curve' belongs to a family of *I-V* curve scans at a constant temperature. Based on the graph shown on Fig. 4, we define ΔI_k as

$$\Delta I_k = I_k - I_1 \quad (2)$$

where I_k is the diode current I_D for a bias voltage $V_B = V_1$ for each scan curve measured for the family of *I-V* curve scans. In the same manner ΔV_k is define as

$$\Delta V_k = V_k - V_1 \quad (3)$$

where V_k is the diode voltage V_D of every measured *I-V* curve scan for a given family of *I-V* curves at a bias current $I_1 = 10mA$.

The magnitude variations measured from the *I-V* scan curves are shown on figure 2 as ΔV *vs wavelength* (λ). The measured magnitudes for ΔV (mV) vs wavelength (λ), ΔI (μA) vs wavelength (λ) and $\Delta I\Delta V$ vs wavelength (λ) were obtained from the measurements variation on table I.

$$\Delta I_{max} = Maximum\ value\ of\ the\ set\ of\ values\ \Delta I_k \quad (4)$$

$$\Delta V_{max} = Maximum\ value\ of\ the\ set\ of\ values\ \Delta V_k \quad (5)$$

$$\Delta V_{aver} = \frac{1}{n}\sum_{k=1}^{n} \Delta V_k \quad (6)$$

$$\Delta I_{aver} = \frac{1}{n}\sum_{k=1}^{n} \Delta I_k \quad (7)$$

where n is the number of *I-V* curve scans measured at a constant temperature for the selected LED.

Neutron Radiation Hardness of AlGaN UV LEDs at Various Wavelengths[a)]

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(Presented XXXXX; received XXXXX; accepted XXXXX; published online XXXXX)
(Dates appearing here are provided by the Editorial Office)
Radiation hard diagnostics is critical to the success of Inertia Confined Fusion (ICF) and extended-duration space exploration. We have first demonstrated the exceptional proton radiation hardness of initial GaN devices, and qualified their space flight and deployment such as Laser Interferometer Space Antenna (LISA) and International Space Station (ISS) [1]. We have further conducted neutron radiation hardness experiments at Los Alamos Neutron Science Center (LANSCE) [2] by opening a new high fluence beam section. During 2014-2016, we irradiated multiple GaN LEDs with a maximum fluence of $2.41x10^{13}$ neutrons/cm^2 over a 3-year span, and generated 54161 current-voltage (*I-V*) curve scans traces. Our data processing program analyzes each and all *I-V* traces. In addition, we retrieved local temperature record to analyze and remove temperature effects in the outdoor environment [3]. The *I-V* curve families of AlGaN UV LEDs with emitting wavelengths 265 nm, 275 nm, and 310 nm wavelengths were compared. The *I-V* curves of 265 nm AlGaN UV LEDs have least deviations from the average value, while the *I-V* curves for 310 nm AlGaN LED's showed the largest deviations from the average value. We have reached another important recommendation for optimal use of multiple AlGaN optoelectronic devices, or imaging arrays for ICF diagnostics: Shorter wavelength devices at 265 nm exhibit more consistent radiation hardness performances than the 310 nm devices. Our results reveal that higher aluminum content LEDs, or $Al_xGa_{1-x}N$ devices with higher *x* values for generating shorter wavelengths, have better radiation hardness, stimulating physical mechanism study.

I. INTRODUCTION

Fusion reactions power the Sun and the Earth. Controlled fusion will be the most potent clean energy source for generations. Neutrons carries fusion energy but also damage the diagnostic instruments. Radiation hard semiconductor and optoelectronics devices are critical for successful and reliable neutron-generating experiments and operations, such as Initially Confined Fusion (ICF) [4], Z [5], ITER [6], and small modular nuclear reactors [7].

GaN and its compounds AlGaN, AlInGaN etc. are newer wide bandgap semiconductors with excellent radiation hardness [8]. We have first demonstrated the exceptional proton radiation hardness of initial GaN devices, and qualified their space flight and deployment such as Laser Interferometer Space Antenna (LISA) and International Space Station (ISS) [1]. We have further conducted neutron radiation hardness experiments at Los Alamos Neutron Science Center (LANSCE) [2] by opening a new high fluence beam section. During 2014-2016, we irradiated multiple GaN LEDs with a maximum fluence of $2.41x10^{13}$ neutrons/cm^2 over a 3-year span, and generated 54161 current-voltage (*I-V*) curve scans traces. Our data processing program analyzes each and all *I-V* traces. In addition, we retrieved local temperature record to analyze and remove temperature effects in the outdoor environment [3], which turned out to be larger than radiation effects.

In this paper, we present neutron radiation hardness of AlGaN UV LEDs at various wavelengths, based on the further detailed data analysis of our neutron irradiation experiments at LANSCE 60R beamline high fluence section. The *I-V* curve families of AlGaN UV LEDs with emitting wavelengths 265 nm, 275 nm, and 310 nm wavelengths were compared. The *I-V* curves of 265 nm AlGaN UV LEDs have least deviations from the average value, while the *I-V* curves for 310 nm AlGaN LED's showed the largest deviations from the average value. The results show that the shorter wavelength AlGaN devices have better performance consistency during lengthy neutron irradiation periods of 3 years. From statistics perspective by translating from time to ensemble view, these results may also apply to large number of devices, such as GaN imagers with many pixels. Imaging devices made of shorter wavelength AlGaN pixels may have more uniform imaging responsivity or flatness, and longer lifetime in the presence of high fluence neutron irradiations, and longer lifetime for many shots.

[a)]Published as part of the Proceedings of the 23rd Topical Conference on High-Temperature Plasma Diagnostics (HTPD 2020) in Santa Fe, New Mexico, USA.
[b)]Author to whom correspondence should be addressed: email@nsnc.edu.
[2)]Reference for a "Team" authorship.

FIG. 1. I-V curves during irradiation, current and voltage variations versus LANSCE 60R (high fluence section) neutron fluence. (a) 265nm LED - Family of irradiated I-V curves at set temperature of 16.5°C +/- 1.5°C. (b) Measured current variations (ΔI) at an initial bias current of 10 mA due to neutron irradiation. (c) Measured voltage variations (ΔV) for a set current of 10 mA due to neutron irradiation. (d) Neutron dose accumulated over time up to $25x10^{12}$ n-cm^{-2}, for a period of ~45 days during beam cycle 2016.

FIG. 2. I-V curves during irradiation, current and voltage variations versus LANSCE 60R (high fluence section) neutron fluence. (a) 275nm LED - Family of irradiated I-V curves at set temperature of 16.5°C +/- 1.5°C. (b) Measured current variations (ΔI) at an initial bias current of 10 mA due to neutron irradiation. (c) Measured voltage variations (ΔV) for a set current of 10 mA due to neutron irradiation. The measured current and voltage variations of the 275 nm wavelength AlGaN/GaN LED sample demonstrates a wider I-V curve spread for a period of ~45 days.

FIG. 3. I-V curves during irradiation, current and voltage variations versus LANSCE 60R (high fluence section) neutron fluence. (a) 310 nm LED - Family of irradiated I-V curves at set temperature of 16.5°C +/- 1.5°C. (b) Measured current variations (ΔI) at an initial bias current of 10 mA due to neutron irradiation. (c) Measured voltage variations (ΔV) for a set current of 10 mA due to neutron irradiation. The measured current and voltage variations of the 310 nm wavelength AlGaN/GaN LED sample demonstrates a wider I-V curve spread for a period of ~45 days.

FIG. 4. Family of *I-V* curve scans taken during experimentation. The initial curve scan is presented as *IV*$_1$ (blue curve), the second measured curve scan is presented as *IV*$_2$ (yellow curve), and *IV*$_k$ (red curve) is the *k*-th curve scan measured during experimentation.

TABLE I. Magnitude variations for the current and voltage variations measured for ΔI and ΔV.

Current	LED λ (nm)	ΔI (μA) Max.	ΔI (μA) Aver.	ΔV (mV) Max.	ΔV (mV) Aver.
5 mA	265	310.06	138.32	13.90	6.34
	275	526.02	275.89	15.50	8.09
	310	668.98	297.54	55.50	23.74
10 mA	265	513.50	261.44	21.30	11.16
	275	731.91	342.39	16.60	7.76
	310	1369.10	641.37	69.5	30.54
15 mA	265	751.70	416.46	19.40	10.83
	275	1124.80	623.77	20.30	11.10
	310	1874.80	849.51	81.80	35.63

Table I summarizes the maximum and average values for the current ΔI and voltage ΔV variations for three different wavelengths. The measurements are at three initial operating currents of 5 mA, 10 mA, and 15 mA. These current and voltage changes were induced by ~2.5×10^{13} n/cm^2. For all situation, it is observed that minimum variations occur for 265 nm UV-LEDs devices, which possess a higher aluminum content. Unlike 275 nm and 310 nm UV-LEDs devices that have less aluminum, have shown higher current ΔI and voltages ΔV variations.

By visual inspection of the family of *I-V* curve scans Figure 1 (a), neutron induced effects are hardly noticeable and any spread with respect to the initial scan cannot be identify. When analyzing the current ΔI variations, we identify the maximum spread to be $\Delta I = 513.50\ \mu A$. With this measurement is evident that the variations are minimal with respect to the initial reference scan, does reaffirming neutron hardness.

Similarly, we analyze the current ΔI variations for 275 nm and 310 nm LED devices. The variations have a noticeable increment for 275 nm device $\Delta I = 731.91\ \mu A$ Fig. 2 (b), and 310 nm device $\Delta I = 1369.06\ \mu A$ Fig. 3 (b). Based on these findings the radiation hardness of the AlGaN/GaN devices is evident on wavelength (λ) < 265 nm, unlike devices with wavelength (λ) > 265 nm Fig. 3 (c).

FIG. 5. Magnitude variations for the irradiated LED devices at LANSCE 60R (high fluence section) neutron fluence. The measured magnitudes variations of the 310 nm wavelength AlGaN/GaN LED sample demonstrates a wider I-V curve spread.

V. CONCLUSIONS

We have experimentally demonstrated exceptional radiation hardness of AlGaN optoelectronics devices for ICF applications. In this work, we have further demonstrated that shorter wavelength AlGaN UV LED at 265 and 275 nm have better performance consistency after high fluence fast neutron irradiation. This can be an important recommendation for optimal ICF diagnostics.

We are conducting further research on the physical mechanism of GaN radiation hardness, and optimize device design for radiation hard diagnostic instruments.

VI. ACKNOWLEDGMENTS

This research was partially supported by the DOE Nevada National Security Site via Task Orders to University of Nevada, Las Vegas. This work has benefitted from use of the LANSCE accelerator facility that is supported under U.S. Department of Energy (DOE) Contract No. DE-AC52-06NA25396. LANSCE staff and UNLV students provided invaluable help.

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Current/Voltage Induced Variations due to Neutron Fluence

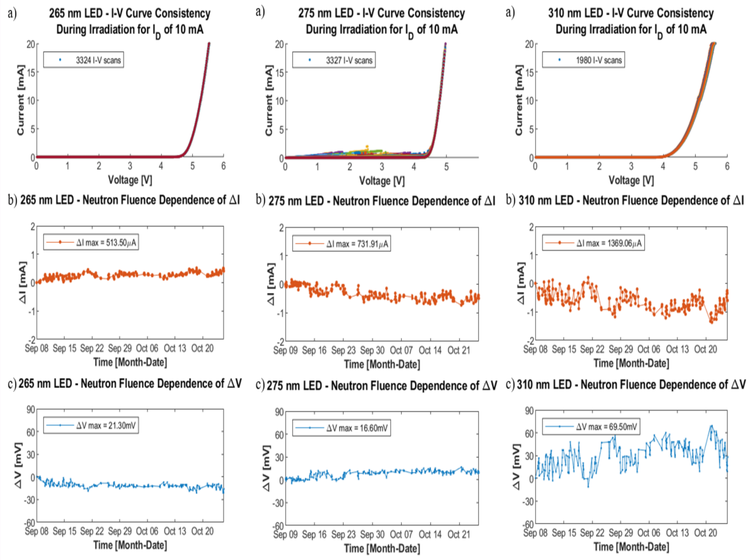

FIG. 1. Real time neutron irradiation measurements. (a) 265 nm LED family of *I-V* curves taken during neutron irradiation. (b) Current variations due to neutrons. (c) Voltage variations during neutron irradiation .

FIG. 2. (a) 275 nm LED family of *I-V* curves taken during neutron irradiation. (b) Current variations due to neutrons. (c) Voltage variations due to neutrons. Neutron effects are identifiable for the 275 nm wavelength device.

FIG. 3. (a) 310 nm LED family of *I-V* curves taken during neutron irradiation. (b) Current variations due to neutrons. (c) Voltage variations due to neutrons. The 310 nm wavelength device display an abrupt voltage – current swing induced by neutrons.

265nm & 275nm LED I-V Curve Spread

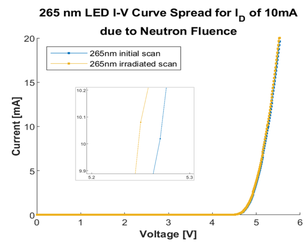

FIG. 4. 265 nm LED device curve spread plot of I-V traces. Blow-up image displays initial (non-irradiated) and the irradiated I-V curve scan.

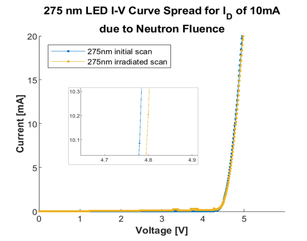

FIG. 5. 275 nm LED device curve spread plot of I-V traces. Blow-up image displays initial (non-irradiated) and the irradiated I-V curve scan.

310nm LED I-V Curve Spread

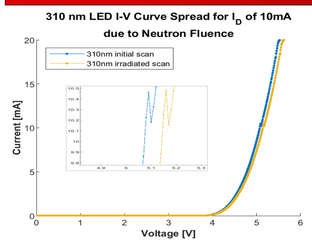

FIG. 6. 310 nm LED device curve spread plot of I-V traces. Blow-up image displays initial (non-irradiated) and the irradiated I-V curve scan, spread noticeable.

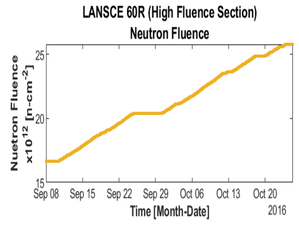

FIG. 7. Neutron fluence recorded over a 45 days period, total measured fluence: $25.1x10^{12}$ n/cm^2

Neutron Fluence Induced Variations on AlGaN Various Wavelengths

TABLE I. Magnitude variations for the current ΔI and voltage ΔV.

Current	LED λ (nm)	ΔI (μA) Max.	ΔI (μA) Aver.	ΔV (mV) Max.	ΔV (mV) Aver.
5 mA	265	310.06	138.32	13.90	6.34
	275	526.02	275.89	15.50	8.09
	310	668.98	297.54	55.50	23.74
10 mA	265	513.50	261.44	21.30	11.16
	275	731.91	342.39	16.60	7.76
	310	1369.10	641.37	69.5	30.54
15 mA	265	751.70	416.46	19.40	10.83
	275	1124.80	623.77	20.30	11.10
	310	1874.80	849.51	81.80	35.63

TABLE I – The maximum and average values for the current ΔI and voltage ΔV variations for three different wavelengths. The measurements are at three initial operating currents of 5 mA, 10 mA, and 15 mA.

Data Analysis Algorithm for Calculations of Voltage & Current Variations

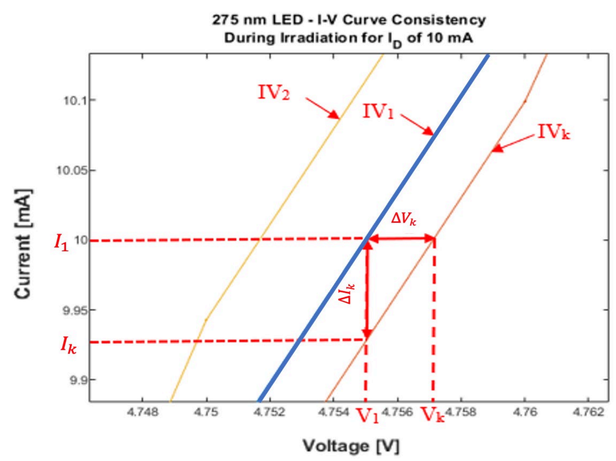

FIG. 8. Family of I-V curve scans taken during experimentation. The initial curve scan is presented as IV_1 (blue curve), the second measured curve scan is presented as IV_2 (yellow curve), and IV_K (red curve) is the k-th curve scan measured during experimentation.

Voltage and Current Variations vs. Wavelengths

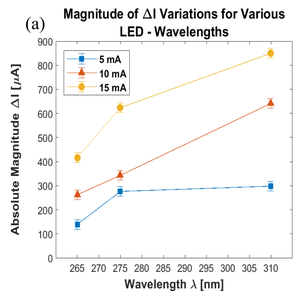

FIG. 9. Average absolute variations of ΔI for various wavelengths at three operating currents. At higher wavelengths, the neutron induced variations are evident.

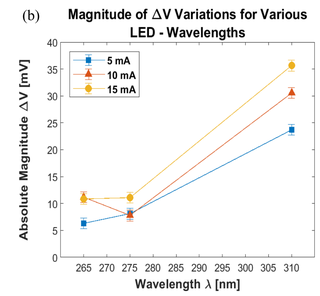

FIG. 10. Average absolute variations of ΔV for various wavelengths at three operating currents. At higher wavelengths, the neutron induced variations are evident.

Voltage and Current Product Variations vs. Wavelengths

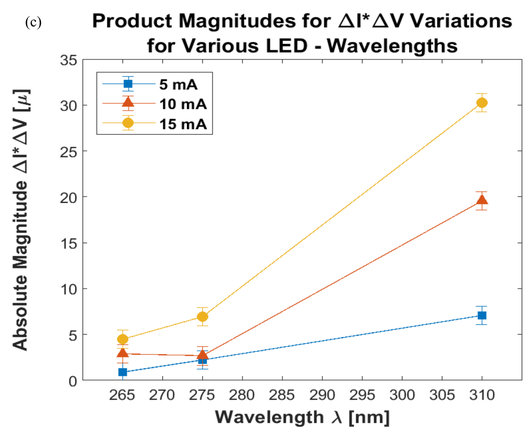

FIG. 11. Average absolute product variations of ΔI* ΔV for various wavelengths at three operating currents. At higher wavelengths, the neutron induced variations are evident.

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Conclusions

- **After three run cycles of fast neutron irradiation with fluences up to 2.41×10^{13} n/cm^2 at LANSCE, the 265nm, 275nm, and 310 AlGaN/GaN UV LED devices maintained their electrical performances.**
- **Ambient temperature effects are analyzed and shown greater impact to *I-V* curves than neutron irradiation over short term**
- **Shorter wavelength AlGaN UV LEDs at 265 and 275 nm exhibit smaller current & voltage than 310 nm devices.**
- **Suggest using shorter wavelength AlGaN detectors and imagers for ICF applications**

This work has benefitted from use of the LANSCE accelerator facility that is supported under U.S. DOE Contract No. DE-AC52-06NA25396. LANSCE staff and UNLV students provided invaluable help.