Electrical performances of commercial GaN and GaAs based optoelectronics under neutron irradiation

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Abstract. This paper aims to demonstrate the effects of displacement damage caused by high energetic neutron particle towards the electrical performances of gallium arsenide (GaAs) and gallium nitride (GaN) p-n based diodes. The investigations are carried out through current-voltage (I-V) and capacitance-voltage (C-V) measurements using Keithley 4200 SCS. Two different commercial optoelectronics diodes; GaN on SiC light emitting diode (LED) and GaAs infrared emitting diode (IRED) were radiated with neutron using pneumatic transfer system (PTS) in the PUSPATI TRIGA Mark II research reactor under total neutron flux of $1 \times 10^{12}$ neutron/cm$^2$.s. Following the neutron exposure for 1, 3 and 5 minutes, the I-V forward bias and reverse bias leakage current increase for GaAs IREDs, but minimal changes were observed in the GaN LEDs. The C-V measurements revealed that the capacitance and carrier concentration of GaAs IREDs decrease with increasing radiation flux.

1. Introduction
Optoelectronics diodes are extensively used in many electronics devices for various applications including devices that require robust performance in radiation environment. Due to economics and time constraints, commercial diodes are often chosen for the ground and space operations. Devices used in the radiation harsh environments where commercial diodes are applicable includes; radiation detectors and optical link readouts used in CERN and ATLAS tracking systems, sensors and detectors mounted on search and rescue robots used in nuclear facilities, optocouplers and solar cells in satellites and space station on-board circuitries[1, 2]. These off-the-shelf devices need to be tested to comply with specific requirements of radiation tolerance since the use of these devices in radiation harsh environment will cause degradation in the performance which leads to permanent failure. Two significant effects of radiation on semiconductor devices known so far are the displacement damage(DD); damage that is caused by high energy particles and the ionisation damage (ID); damage that is caused by energetic charged particles. In semiconductor material physics, DD is associated with the creation of vacancy-interstitial pair caused by the displacement of atom from its lattice site when collided with heavy particles (i.e:neutron particles). ID is the damage instigated from the accumulation of charges discharge into a device by charged particles (i.e:x-ray,gamma ray). Other possible damages caused by ID are single event upset (SEU) and single latch-up upset (SLEU) which are able to alter the state of a device through the flow of free charges in the material [3].
In this paper, we report studies on the application of diode-based devices in a nuclear environment, where high neutron flux is continuously generated in the nuclear reactor. The DD effect is highly significant in the nuclear reaction compared to the secondary effect, ID induced by the gamma ray product. However, one must not overlook at the effect that can be caused by ID as the gamma-ray product is considerably generated through the decay of radioactive fission products and radiative capture process which, if accumulated, can cause crucial damage [4].

Reports from past years have proven that gallium-nitride (GaN)-based devices are highly radiation tolerant compared to gallium arsenide (GaAs)-based devices to some magnitude. This paper is presented to investigate the changes in electrical performances of both diodes subjected to thermal neutron radiation with the analysis of both displacement damage as well as ionisation damage taken into consideration. A critical way to observe the impact of neutron radiation besides output power and peak wavelength measurements is through current-voltage (I-V) and capacitance-voltage (C-V) characterisation [5]. These methods are proven to provide subtle information on the contact resistance as well as changes in electrical performances occur in the junction.

2. Experimental Details
Two commercial optoelectronics diodes; GaAs grown by liquid phase epitaxy (LPE) IREDs (CQY37N) and GaN on SiC technology grown by metal-organic chemical vapor deposition (MOCVD) LEDs (TLHB5800) from Vishay were used in this investigation. The GaAs IRED, have a current rating of 100 mA while the GaN LED have a less maximum rating of 20 mA. Mostly, the devices can only be allowed to perform under its maximum rating to prevent from device-wearout. The schematic cross section diagrams of the devices are provided in Figure 1 (a) and (b) respectively.

![Figure 1. Schematic Cross Section Diagram of (a) GaAs IRED and (b) GaN LED [6, 7]](image)

The diodes were exposed to thermal neutrons (E<0.5 eV) by means of pneumatic transfer system (PTS) operated at a power rating of 750kW in the PUSPATI TRIGA Mark II research reactor, Malaysian Nuclear Agency (ANM). The PTS in PUSPATI TRIGA Mark II is designed to transport the samples to ring G20 of the reactor core which has a standard neutron flux of $1 \times 10^{12}$ neutron/cm$^2$.s. Three samples for each model with technically the same pre-irradiation I-V and C-V characteristics were used to achieve reproducibility and consistency in readings. All samples were encapsulated in polyethylene (PE) vials and radiated in the PTS for 1 minute, 3 minutes and 5 minutes of maximum corresponding neutron fluence; $6 \times 10^{13}$, $1.8 \times 10^{14}$ and $3 \times 10^{14}$ neutron/cm$^2$. The pre and post-irradiation I-V and C-V measurements were performed in a room temperature using Keithley 4200 semiconductor characterization system (SCS) via Keithley’s Interactive Testing Environment (KITE) software. To ensure no deviation in the photocurrent results, samples were placed in Keithley 8101-4TRX during measurement. The wearout factor; that is the defects caused in normal operation [8] is neglected as the study is primarily concerning on the changes in the electrical performance due to the alteration of atomic structure. Furthermore, the limited space of the PTS’s transportation pipeline disallowed such experimentation to be conducted.
3. Results and Discussion

3.1 The Current-voltage (I-V) Characteristics

The room-temperature forward and reverse biased I-V characteristics for both GaAs and GaN based diodes were plotted in a semi-log I versus V with current compliance set to a constant value of 0.01 A (to prevent the diode from self-heating). The forward-bias I-V results of pre and post neutron irradiation for GaAs and GaN diodes are presented in Figure 2(a) and (b) respectively. The forward leakage current of GaAs IREDs increased substantially after being irradiated with $6 \times 10^{13}$, $1.8 \times 10^{14}$ and $3 \times 10^{14}$ neutron/cm$^2$ of neutron fluence. In general, the maximum corresponding current increment observed is in 3 orders of magnitude. The relative percentage leakage current increments for each irradiation time at specified voltages are tabulated in Table 1. The difference in the relative percentage leakage current increments between $1.8 \times 10^{14}$ to $3 \times 10^{14}$ n/cm$^2$ of neutron fluence was determined to be marginal. In Figure 2(b), the forward leakage current of the GaN LEDs exhibited no change under the same irradiation conditions. After additional 1 and 5 minutes, similar trends were also observed. Small reductions in the leakage current for both devices were noted over higher reverse-bias voltage which is attributed by the ohmic effect [9].

![Figure 2](image_url)

**Figure 2.** Forward Bias Dark I-V Characteristics of (a) GaAs IRED and (b) GaN LED

| Applied Voltage | 1 min % | 3 min % | 5 min % |
|-----------------|---------|---------|---------|
| 0.4             | 117.9%  | 417.5%  | 572.4%  |
| 0.8             | 58.6%   | 213.6%  | 276.2%  |
| 1.2             | 71.2%   | 162.2%  | 184.4%  |

The difference in radiation hardness between both devices can be perceived in Figure 3(a) and 3(b); an extrapolation of reverse bias I-V characteristics of the GaAs and GaN based diodes. In reverse-bias, the leakage current of GaAs IREDs, were observed to increase with increasing radiation fluence. After a maximum neutron exposure $3 \times 10^{14}$ n/cm$^2$, the reverse breakdown voltage is found to increase from 34V to 43.6V. The reverse-bias characteristics of GaN LEDs indicated no sign of degradation even though the samples were exposed to another additional neutron fluence of $6 \times 10^{13}$ and $3 \times 10^{14}$ n/cm$^2$. 
Figure 3. Reverse Bias Dark I-V Characteristics of (a) GaAs IRED and (b) GaN LED

The ideality factor, series resistance as well as saturation current of the diodes were modelled by the ideal Shockley equation given as follows [10, 11];

\[ I = I_s \left[ \exp \left( \frac{qV}{n k T} \right) - 1 \right] \]

(1)

With the existence of series resistance, \( R_s \) the real diode model can be further expressed as [12];

\[ V = \left( \frac{n k T}{q} \right) \ln \left( \frac{I}{I_s} \right) + I R_s \]

(2)

where \( n \) is the ideality factor, \( k \) is the Boltzmann constant, \( T \) is the measured diode temperature, \( q \) is the electron charge and \( I_s \) is the saturation current. The ideality factor is included to account for the imperfection of the junction in a commercial diode. Essentially, it is used as an indicator to determine the dominant current mechanism contributing to the generated current inside the diode. The diffusion is said to be the dominant mechanism if \( n = 1 \) (ideal) and generation-recombination (GR) is the dominant mechanism if \( n = 2 \). It may occur that both mechanisms operates at the same time if \( n \) is in the range of 1 to 2 [13].

The increment in the leakage current of GaAs diode is known to be predominantly caused by the formation of non-radiative generation-recombination (GR) centers or traps in the forbidden band gap [14, 15]. Due to displacement defects, these induced acceptor-like traps lead to the increment rate of GR of holes and electrons, hence, increment of both radiative and non-radiative recombination current [16, 17]. The minority carrier lifetime however, decreases to increasing number of traps which can be quantify as;

\[ \tau_0^{-1} = \tau_R^{-1} + \tau_{NR}^{-1} \]

(3)

where \( \tau_0 \) is the initial total lifetime, \( \tau_R \) and \( \tau_{NR} \) is the associated radiative and non-radiative lifetime respectively [18]. The traps density was observed to vary proportionally with irradiation time. Due to that, a reduction in the total carrier lifetime is expected relative to the exposure time.

On top of that, the increase in the rate of GR process might be contributed by the transition of additional vacancy-interstitial pairs; caused by preceding high energy interstitial atom or primary knock-on atoms (PKAs) [3]. In elastic collision between high energetic neutrons with the material’s atomic structure, further vacancy-interstitial pair can be created by the preceding interstitial atom. This atom can cause damage similar to DD if high kinetic energy is being transferred by the neutron.
particles. Considering the secondary effects of ionizing damage, the changes in the dark current of a diode may also be resulted from gamma induced electron-hole pair [17]. Based on the minor differences in the relative percentage current increment between 3 and 5 minutes, we can deduced that the induced vacancies led to a self-annealing process which cures the defects to minimal as reported by [19, 20].

The ideality factor, the saturation current and the series resistance were obtained by fitting the derived equation (2) onto the linear region of the experimental $I-V$ data. The ideality factor of GaAs IRED increases from 1.76 to 1.9 with respective to irradiation fluence of $6 \times 10^{13}$ to $3 \times 10^{14}$ n/cm$^2$. This suggests that trap-assisted GR mechanism is responsible for the carrier transport in the depletion region as described above. The trap formed at the mid band is assumed to be shallow; otherwise deep trap would lead to reduction in magnitude of the leakage current. The ohmic effect mentioned in the previous discussion can be explained by the increment in the series resistances of the GaAs diode. The results were recorded to have increased from 0.5Ω to 3Ω after a maximum exposure fluence of $3 \times 10^{14}$ n/cm$^2$.

Since there are fairly no changes in GaN diode’s leakage current, neither the ideality factor nor the series resistance were observed to have changed. This is due to the GaN’s wide bandgap energy, higher thermal stability and small thermal neutron capture cross section of nitride; 1.91 compared to arsenic; 4.3[21]. The ideality factor and series resistance however were measured to have high values of 5.3 and 50Ω respectively. High value of $n$ and $R_s$ indicates that high formation of defect density in the device layer is formed, which may be contributed by the excessive metal- p-type contact resistance of GaN [22, 23]. Due to high ideality factor, the recombination process in GaN LED could not be simply modelled by SRH recombination statistics.

One of the valid reasons in the increment of the resistance in both devices is due to the effects of neutron transmutation doping (NTD). NTD occur when neutron particles undergo inelastic interaction with the material, and consequently change the type of the material from n-type to p-type and vice versa [3].

3.1 The Capacitance-voltage (C-V) Characteristics

The room temperature C-V analysis of the samples was realized to obtain the approximation values of the doping profile and width of the depletion region. Results were obtained at a frequency of 500 kHz and supply voltage $V_{rms}$ of 100mV. Assuming the diodes are abrupt junction, the C-V characterisation is carried out using the expression below [11];

$$C = \frac{A}{2} \sqrt{\frac{2q\varepsilon_0\varepsilon_s N_B}{(V_o - V_a)}}$$

(4)

where $C$ is the capacitance, $A$ is the active area, $q$ is the charge, $\varepsilon_0$ and $\varepsilon_s$ are the vacuum and material’s relative permittivity respectively, $N_B$ is the doping concentration and $V_a$ is the applied voltage.

The width of the depletion region is defined as;

$$W = \frac{\varepsilon_0\varepsilon_s A}{C}$$

(5)
and the carrier concentration at specified width is given by:

\[
N_d(W) = \frac{2}{q\varepsilon_0\varepsilon_r A^2} \left| \frac{d}{dV_a} \left( \frac{1}{C^2} \right) \right| \tag{6}
\]

Since the active area for both GaAs and GaN devices are undisclosed by the manufacturers, we assumed it to be equivalent to 0.09 mm\(^2\) (minimum active area for such commercial devices). The relative doping concentration versus width of the depletion region is represented as in Figure 4. After a maximum exposure to neutron fluence of \(3 \times 10^{14}\) n/cm\(^2\), the capacitance of GaAs diode was observed to decrease. As illustrated in Figure 4(a), the decrement in capacitance signifies that the doping concentration has also decreased. The decrement is interpreted as the effects of carrier removal. The formation of deep traps in the near mid-band causes low-energy carriers to be trapped, which reduces the concentration of the free carriers. Reduction in the carrier concentration causes the series resistance of the diode and the width of the depletion region to increase [3, 24]. Hence, this explains the fact that the GR process of the carriers can only be achieved through trap-assisted emission as band-to-band emission is barely impossible to occur at wider bandgap. As for GaN LEDs, the capacitance as a function of voltage is constant after similar maximum neutron fluence of \(3 \times 10^{14}\) n/cm\(^2\). Hence, there is relatively no significant change observed in the doping profile of the diode depicted in Figure 4(b).

![Figure 4. The Doping Profile of (a) GaAs IRED (inset is the C-V Characteristics) and (b) GaN LED.](image)

4. Conclusion

The effects of thermal neutron towards the electrical characteristics of commercial GaAs and GaN optoelectronic diodes have been studied in this paper. The results demonstrated that GaAs IREDs suffered degradation resulted from neutron’s displacement damage and gamma’s ionisation damage. The defects are indicated by the increment in the values of FB and RB leakage currents, ideality factor, series resistance as well as the saturation current. Further investigation reveals that the DD induced defects caused the value of the carrier concentrations to decrease whilst the depletion region increase with respective irradiation time. However, the GaN based LEDs showed no signs of degradation towards the thermal neutron under the same experimental conditions. Hence, this would approved that GaN based devices are more radiation tolerant than its competitors.
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