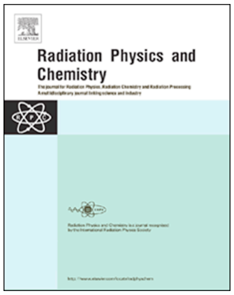

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Neutron Radiation Hardness Testing of 650V / 7.5 A GaN power HEMT

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Abstract: We have performed neutron radiation hardness testing for commercially available 650V/7.5A GaN power HEMT. The devices were tested at Los Alamos Neutron Science Center (LANSCE) inside Irradiation of Chips Electronics, ICE house-1 at a flux density of 10^6 n/cm^2-s and energy level above 1 MeV, which is approximately 10^6 times higher than neutron radiation at airliner flight height (30,000ft). During the experiments, the devices were stressed electrically, thermally and irradiated with neutron radiation. We have observed degradation of AlGaN layer due to accelerated neutron radiation (1.54×10^{10} n/cm^2 above 1.5 MeV neutron energy) under electrical stress condition. We have performed parametric defect analysis through step-by-step application of neutron irradiation, thermal stress and electrical bias, and observed highest degradation of threshold voltage (0.14V) for combined electrical stress and neutron irradiation.

Introduction: There is an increasing demand for high-frequency, high-power wide bandgap (WBG) power electronics in Military applications, satellite communications, radar operation, aerospace, electric vehicles, and all-electric warships [1]. Due to their lower power loss, higher-temperature operation, higher operating frequency compared to Si-based device, WBG power devices are excellent candidates for AC-DC converters and inverters [2]. In between two major WBG power devices, GaN demonstrated less static power consumption, less switching loss [3] and higher electron mobility compared to SiC, which makes it an outstanding candidate for satellite, space and outer space applications. However, there is not sufficient experimental data available for GaN power devices reliability for those harsh environment, especially for HEMT.

In this work, we have characterized degradation of GaN power HEMT's static characteristics in a neutron radiation environment. The devices were tested at Los Alamos Neutron Science Center (LANSCE) inside Irradiation of Chips Electronics, ICE house-1 at a flux of 10^6 n/cm^2-s above 1 MeV energy which is around 10^6 times higher than neutron radiation at airliner flight height [4]. Exposure of a device for 1 hr at LANCSE neutron source provides neutron radiation reliability for more than 100 yrs of flight time at the height of 30,000 feet. Devices were stressed with/without, single/combined electrical and thermal stress while irradiating devices at neutron radiation environment. The effect of those stressors on device behavior were measured through static change in electrical properties.

Experimental Details: The performance of a commercially available 650 V/ 7.5 A GaN Power HEMT were tested under neutron irradiation.

The power devices were irradiated with constant neutron fluence. The beam diameter of the neutron ejection nozzle was varied between 1 inch and 3 inch based on the experimental set-up. A shutter was used to control neutron irradiation time. Total neutron count is approximately proportional to duration of irradiation. The neutron energy spectra and corresponding neutron flux of a particular experiment was *in-situ* monitored. The neutron energy spectra are divided into two energy spectra: neutron with integrated energy above 1.5 MeV and neutron with integrated energy above 10 MeV as illustrated in Table 1.

Table 1: Neutron Fluence Per Count

Energy spectrum	**1 inch beam**	**3 inch beam**
> 1.5 MeV	347399 n/cm^2 * count (minimum)	47105.5 n/cm^2 * count (minimum)
> 10 MeV	168232 n/cm^2 * count (minimum)	23866.5 n/cm^2 * count (minimum)

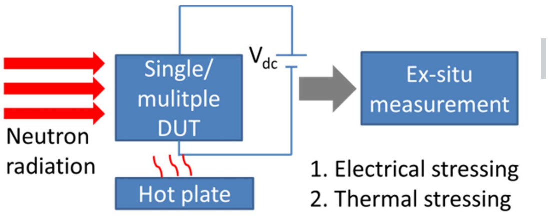

Figure 1: Experimental set-up for irradiating device in neutron radiation environment at LANSCE

During the experiment, single/multiple devices under test (DUTs) were exposed to neutron radiation and stressed in three different methods:
1a Stressed by neutron radiation
1b Stressed by heat and irradiated with neutron radiation
1c Stressed by bias voltage, heat and irradiated with neutron radiation

Each power devices were characterized using an Agilent 1505A power semiconductor parameter analyzer before and after irradiation. Three different types of static electrical characterizations were performed:
2a Drain-source voltage was fixed at 0.1 V, and gate-source voltage was varied from 0 to 5 V and corresponding drain-source current was measured. Linear approximation method was used to calculate threshold voltage from the measured data.
2b Gate-source voltage (V_{gs}) was fixed constant at 0; the drain-source voltage (V_{ds}) was varied from -10 V to 15 V and corresponding drain-source current (I_{ds}) was measured.
2c Drain-source voltage (V_{ds}) was fixed constant at 0 V; the gate-source voltage (V_{gs}) was varied from -10 V to 10 V and corresponding gate-source current (I_{gs}) was measured.

Results and Discussion: The variation of threshold voltage for the GaN HEMT for 3 selected devices before and after irradiation are summarized in Table 2. The *in-situ* stress conditions were varied from one device to another in order to distinguish their effects.

Table 2: Variation of threshold voltage at different stress conditions

Device no	Neutron Irradiation* (n/cm^2)	Electrical stress, V_{gs}	Thermal stress	V_{th} before stress	V_{th} after stress
1	1.54×10^{10}	0	No	1.13 V	1.11 V
2	1.57×10^{10}	5 V	No	1.23 V	1.37 V
3	1.61×10^{10}	5 V	150 °C	1.19 V	1.20 V

*above 1.5 MeV neutron energy

From Table 2, it could be observed that for the device stressed electrically during neutron irradiation showed a significant change in threshold voltage from 1.23 V to 1.37 V (device #2). For device 1 & 3 there was not any significant change in threshold voltage. Silvera *et al.* [4] observed a large variation of threshold voltage for GaN power MOSFETs due to neutron irradiation which was caused by the degradation of gate dielectric material. McClory has observed similar effect in GaN HFET [5] when HFET was *in-situ* biased electrically during neutron irradiation. The author explained that charged atoms produces secondary ionization during neutron irradiation which are displaced by the energetic neutrons. This creates electron hole pairs that are moved through the gate by the Coulombic force presented by the electric field. This field is the result of the Schottky junction, the spontaneous piezoelectric force at the interface, and the applied bias. The author observed a shift in threshold voltage in C-V measurement after irradiation which was caused by the accumulation of charge in AlGaN layer [5].

The positive shift in the threshold voltage for GaN could be explained by Fig. 2 with the help of McClory's discussions. The electron hole pairs generated by the secondary ionization during neutron irradiation, drift toward opposite direction, accelerated by the electric field. As hole has lower mobility than electron, once irradiation and electrical bias has been removed, few positive charges trap inside the

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AlGaN layer. The trapped positive charges eventually give rise to the positive shift of the threshold voltage.

Another set of experiments were run with a GaN power HEMT (device # 4) biased at drain-source, V_{ds} instead of biasing gate-source and irradiated with neutron irradiation of 2.83×10^{10} n/cm^2. The threshold voltage before (V_{th} = 1.24 V) and after (V_{th}= 1.20 V) irradiation didn't show any significant difference. This dictates that there was not any/ much charge accumulation happened in AlGaN layer which can contribute for a large shift of threshold voltage. Drain-source current usually follows lower resistive path through 2DEG channel (inside the GaN layer) in a GaN HEMT and the bias voltage (V_{ds}) didn't contribute for any charge accumulation/ trapping in the gate dielectric layer. This also demonstrates the gate driving voltage cause ultimate damage of the gate dielectric layer in between drain-source and gate-source voltage.

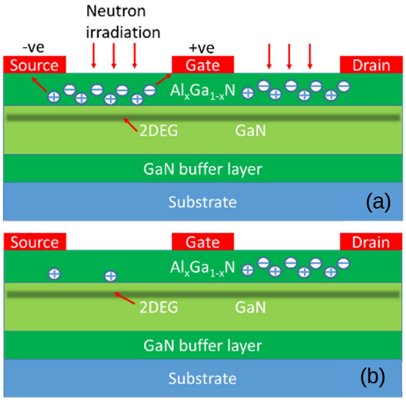

Fig. 2: (a) Device during *in-situ* electrical bias during neutron irradiation, (b) after stressing and irradiation (simplified device layer stack has been demonstrated for explanation purpose only, and not scaled accurately)

Fig. 3 shows gate-source leakage current for those three device as measured by the technique, *2c*. The leakage current, I_{gs} changes abruptly for device 2, while device 1 & 3 didn't show any significant variation in leakage current after irradiation. McClory explained that the elastic collisions from electrons and neutrons with the atoms in the AlGaN layer can form point defects that act as traps through which gate electrons can tunnel. The band structure of the heterostructure makes this tunneling possible [5].

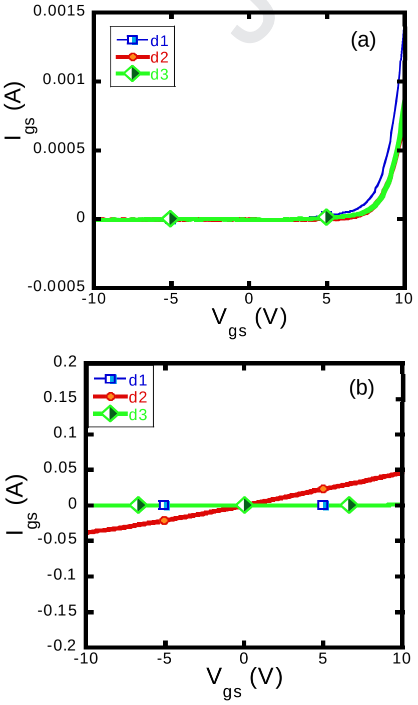

Figure 3: Variation of gates-source leakage current before (a) and after (b) neutron irradiation for device # 1, # 2 and #3.

Fig. 4 shows drain-source leakage current as measured by the technique *2b*. There is no observable difference in V_{ds}-I_{ds} after irradiation. The drain-source current, I_{ds} which propagates through two-dimensional electron gas (2DEG) of the GaN layer in a GaN HEMT, doesn't show any variation in I_{ds} after neutron irradiation. It also explains that any degradation happened in the AlGaN layer which strengthen our earlier explanation and conforms with McClory's explanation [5]. In device 2, an annealing at 500 ^{o}C for 1 hr was done. But there was no significant difference between pre- and post-annealing static characteristics (e.g. V_{th}, V_{gs}-I_{gs} curve) observed. This signifies the neutron ionizing damage was total ionizing displacement (TID) damage and the activation energy for the recovery of the device could not be measured.

For the device thermally stressed (device# 3) during neutron radiation showed a very small change in threshold voltage, which reflects the recovery of device from defects by thermal stressing. High temperature operation can help GaN power HEMT to self-recover in a neutron radiation environment. Moreover, thermal annealing can help to recover devices from the trap centers inside gate dielectric or near gate-dielectric/semiconductor interface caused by the radiation generated charge carriers, which was also mention at ref [6]. Each set of testing have been performed for two sets of devices, similar results have been obtained. The GaN power HEMT devices have been tested for a minimum of 500 yrs in an accelerated neutron radiation environment at 30,000 feet height.

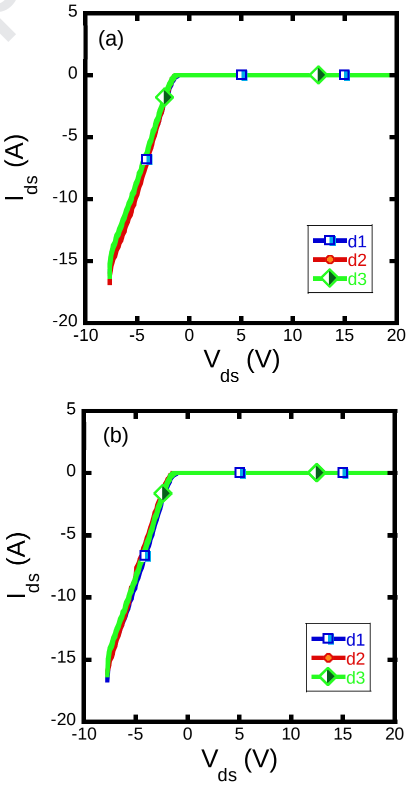

Figure 4: Variation of drain-source current before (a) and after (b) neutron irradiation for device # 1, # 2 and #3.

Conclusion: In this study, 650 V/ 7.5 A GaN power HEMT devices have been tested using accelerated neutron radiation. The devices showed degradation of gate dielectric material due to *in-situ* gate source bias voltage during neutron irradiation. Experiments revealed that the high temperature operation at 150 ^{o}C self-anneals GaN HEMT at a harsh radiation environment. Self-annealing helps to avoid defect formation introduced by ionizing radiation.

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1. 650 V/ 7.5 A GaN Power HEMT tested in neutron radiation environment
2. In-situ thermal and electrical bias was applied during irradiation
3. Static characterization were performed before and after irradiation
4. Devices showed variation in threshold voltage