Journal of Physics: Conference Series

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To cite this article: A.C.V. Bôas *et al* 2022 *J. Phys.: Conf. Ser.* **2340** 012045

COTS Tolerant to Total Ionizing Dose (TID): AlGaN/GaN-based transistor 10 KeV X-ray Analysis

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Abstract. Gallium nitride commercial transistors (GaN FET) are great candidates as power devices tolerant to the effects of Total ionizing dose (TID). Therefore, we have evaluated its robustness by analysing parameters in its characteristic parameters. Devices were exposed to a 10 keV X-ray source accumulating a total of 350 krad(Si). However, results indicate that the tested components are more tolerant to the effects of TID when in on-state mode rather than the off-mode, that is, when the device is working, which is good news for COTS applications in environments subject to the effects of ionizing radiation.

1. Introduction

More recently, many applications are taking advantage of III-V heterostructures-based transistors [1,2,3,4], such as radar arrays, nuclear physics tools, medic tools or satellites [4]. Therefore, AlGaN/GaN Field Effect devices should be thoroughly analyzed regarding their robustness to the effects of ionizing radiation, as they promise to be tolerant due to their high mobility characteristics observed in the two-dimensional electron gas (2DEG) [1,2].

One of the biggest challenges is in the fabrication process of the heterostructure created at the interface with GaN, where the thin layer of AlGaN is normally used in the barrier between the gate and the electron conduction channel. AlGaN and GaN have different lattice constants, therefore different lattice parameters, causing a forced fit at the interface between the two materials, creating stresses in the crystal lattice [5]. The higher the aluminum concentration in the AlGaN barrier, the greater the mismatch between the lattice constants greater the voltage in the crystal lattice [5, 6]. This mismatch created by the heterostructure can cause reproducibility problems between samples. For those reasons, it is essential to characterize the behaviour of the Gallium Nitride based devices exposed to the effects of ionizing radiation [4].

2. Experimental Methodology

A tolerance systematic study on the GS61008T [7], GaN-on-silicon transistor were performed, with respect to total ionizing dose accumulated in the device during irradiation by 10-keV X-ray source. The samples were exposed to radiation at *Laboratório dos Efeitos da Radiação Ionizante* (LERI) at the FEI University Center using a Shimadzu XRD-6100 diffractometer. All Electrical characterization was conducted with a National Instruments PXI test platform managed by a LabView application [8, 9].

2.1. Experimental Details

The devices under test (DUT) were characterized before, during and after being exposed to X-ray beam, in a room with temperature of 21ºC. The I-V characteristic curves were acquired, determining the main electrical parameters which dictates the functionality of the device. Parameters, such as Threshold voltage (V_{TH}), Maximum transconductance (gm_{max}), subthreshold slope (S) and cut off currents (I_{off}) were used as the methodology analysis. V_{TH} was acquired through the peak of the 2nd derivative of the I_D-V_G curve, gm_{max} through the peak of the 1st derivative of the curve, S and I_{off} through the analysis of the monolog curves [6].

Additionally, for better understanding of the 2DEG behaviour to TID, different devices were kept in off (non-polarized) or in on (polarized) mode, [8, 9]. In off mode, all device terminals were kept grounded, while in on mode, the gate terminal was polarized with V_{GS} = 3.0 V while the source and drain terminals were grounded.

2.2. Pre-irradiation Characterization

The pre-irradiation (pre-rad) electrical characterization counted with four device samples from the same batch, being two prepared to be irradiated in the off-mode and other two in the on-mode. Measurement details can be found in reference [8, 9].

Important to say that gm_{max} has a smaller variation between the samples when V_D = 10 mV, therefore this was the voltage chosen to acquire the I_D-V_G curves during and after irradiation [8, 9].

3. Irradiation Methodology

The DUT were perpendicular to the 10 keV X-ray beam, to establish field radiation area homogeneity. The dose rate calibration was performed by taking measurements of the exposure using an ionization chamber. The dose rate in silicon was estimated using silicon and air mass attenuation coefficients [8, 9]. The calibrated dose rate for the experiment was of about (114 ±15) krad(Si)/h.

Irradiation consisted in two steps, so that we could observe the effects of thermal annealing at two different cumulative doses. In the first step, the transistor was exposed for an hour at the experimental dose rate, accumulating in total 114 krad(Si); following this step, there was an intermediate step during which the DUT stayed for seven days at room temperature (R.T.A), with the intent of charge stabilization. In the second step, the devices were exposed for two more hours at the same dose rate, reaching a total ionizing dose (TID) of about 350 krad(Si) in the two steps summed.

4. Results and discussions

The functional behaviour of the devices was expected to change when exposed to 10 KeV X-ray. For purposes of characteristic parameters comparison, the devices were characterized before exposure to the effects of ionizing radiation, the pre-rad reference values are V_{TH} = (1.98 ± 0.02) V, S = (120 ± 25) mV /decade, whereas the maximum transconductance gm_{max} = (638 ± 62) mS at V_G = 1.72 V.

Figures 1 and 2 depicts on- and off-mode I_D-V_G characteristic curves, (a) during the first step of irradiation, and (b) during the second step. It might be noticed that the characteristic curve for 114 krad(Si) in Figures 1a/2a was obtained right after the first step, while the 114 krad(Si) curve in Figure 1b/2b was traced immediately before the second step of irradiation, that is, after the transistor 7-days Room temperature annealing (R.T.A.). Radiation exposure caused a negative shift during irradiation. After R.T.A. it returned very close to the reference value.

During the 2nd irradiation step, another negative shift was observed (more noticeable at table 1). It is worth noticing that, in both irradiation steps, the negative shift appears to saturate after some kilorads are added to the initial state of each step. The maximum negative shift recorded during the irradiation steps was $\Delta V_{on}{}^{VTH}{}_{max}$= -310 mV for the on mode and $\Delta V_{off}{}^{VTH}{}_{max}$= -460 mV for the off mode.

A left, wirch means a negative, shift on the threshold voltage was observed during the exposure, it can be credited to the charging of the donor states at the AlGaN surface by electrons created during irradiation at the AlGaN layer, which enhances the 2DEG sheet density, reducing V_{TH}.

After the 1st and 2nd step of irradiation, the V_{TH} shift shows no significant difference. This may be indicative of a saturation of the electric charge traps in the device, limiting the TID effect.

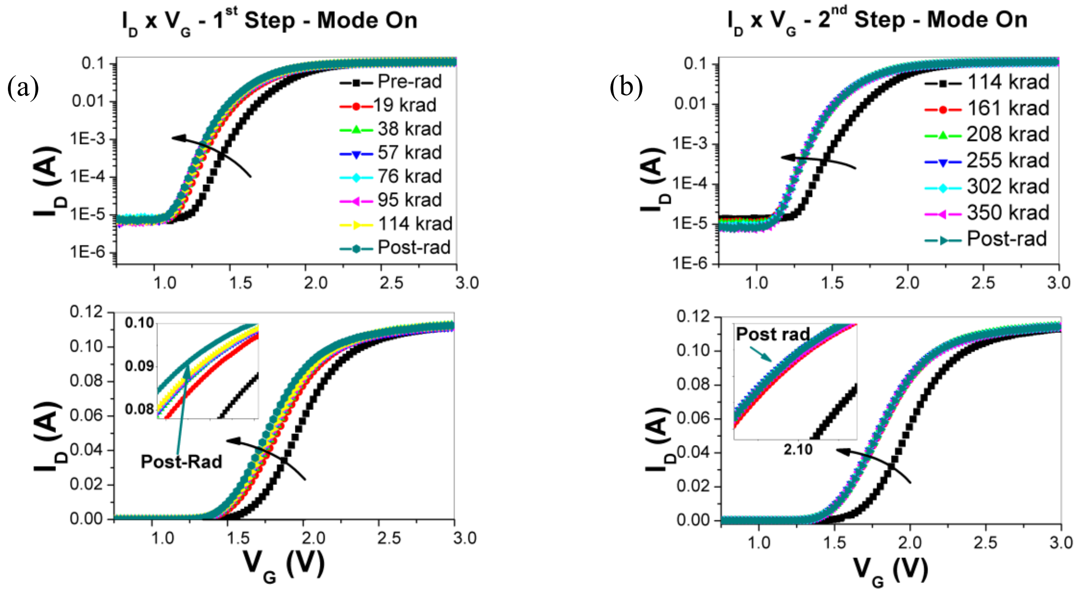

Fig. 1: I_D-V_G curves (on-mode). (a) First step (from zero to 114 krad/Si accumulated) and (b) second step (from 114 krad to 350 krad/Si accumulated). The graphs are presented in linear and logarithmic scales for better and different visualization.

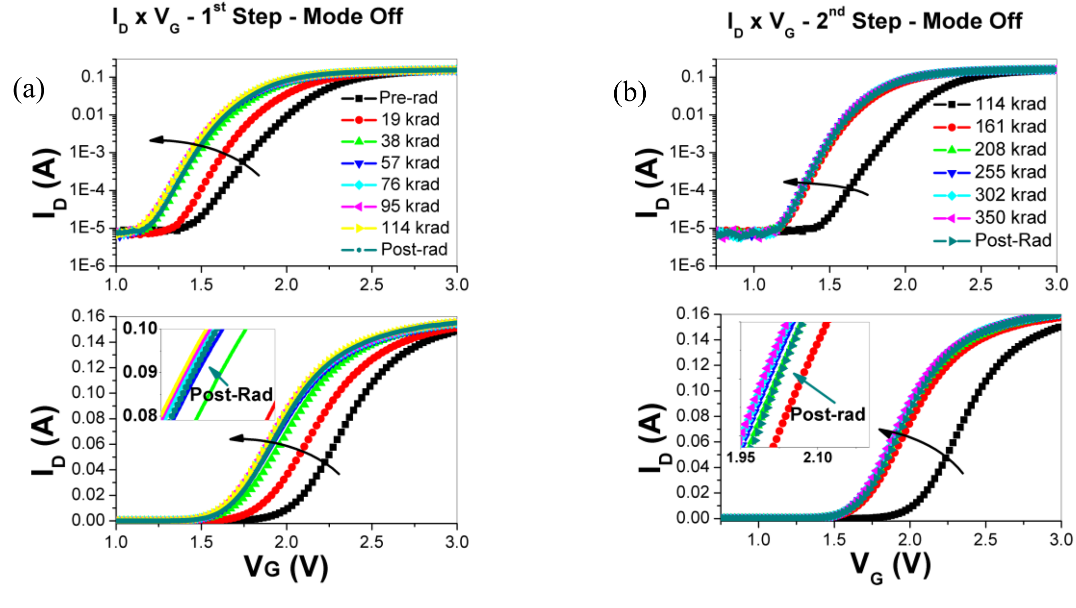

Fig. 2: I_D-V_G curves (off-mode). (a) First step (from zero to 114 krad/Si accumulated) and (b) second step (from 114 krad to 350 krad/ Si accumulated). The graphs are presented in linear and logarithmic scales for better and different visualization.

The threshold voltage (V_{TH}) of the devices after R.T.A. returned to their pre-irradiation values. After the entire two-step irradiation process, current I_{off} increased slightly in the on-mode, signalling a possible increased power consumption. More information in Reference [8, 9].

As presented in table 1 the greatest shift in V_{TH} occurs at the beginning of the irradiation process, that is, the effects of TID saturate rapidly. This is an indicates few defect states for trapping positive charges. Post annealing (350 krad accumulated), the device shows almost total recovery of V_{TH}, that can be result of trapped holes releasing in the AlGaN layer, and/or their neutralization by electrons. In the cases of not total recovery, it demonstrates that the system stabilize with some charges were retained in the material traps, not having energy enough to escape.

Table 1: V_{TH} with respect to the reference value before and after each irradiation step, in both modes.

Total Dose (krad)	**ΔV_{th} Mode-On (V)**	**ΔV_{th} Mode-Off (V)**	**$\lvert\Delta V_{th}(On–Off)\rvert$ (V)**
Pre-rad	0.00	0.00	0.00
19	-0.20	-0.20	0.00
38	-0.25	-0.35	0.10
57	-0.27	-0.41	0.14
76	-0.27	-0.42	0.15
95	-0.30	-0.43	0.13
114	-0.31	-0.46	0.15
Post R.T.A.	0.00	0.00	0.00
160	-0.26	-0.37	0.11
209	-0.27	-0.42	0.15
256	-0.27	-0.43	0.16
304	-0.27	-0.44	0.17
350	-0.28	-0.45	0.17
Post R.T.A.	-0.05	-0.10	0.05

*** R.T.A.: Room-Temperature Annealing**

Figures 3 and 4 shows the shift of the maximum transconductance (gm_{max}) as a function of the dose accumulated for both modes. The shifts in the maximum transconductances were more pronounced when the transistor was irradiated in on-mode. On the other hand, after the two-step's irradiation process, the transistor irradiated in on-mode was presented the end positive shift of the maximum transconductance, while the transistor irradiated in off-mode still presented a final negative Δgm_{max}. The referent value used in the graph was g_{max}^{ref} = (638 ± 62) mS.

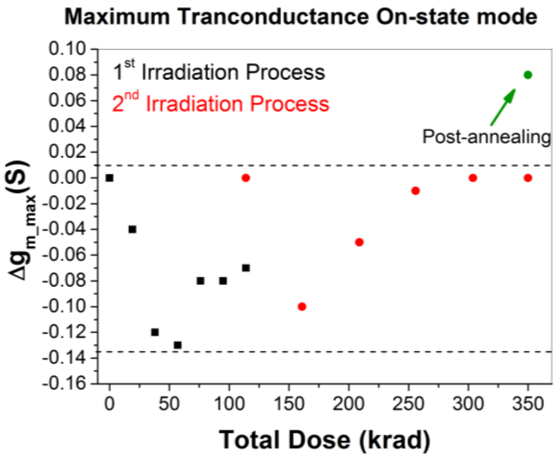

Fig. 3: Shift of gm_{max} on-state mode.

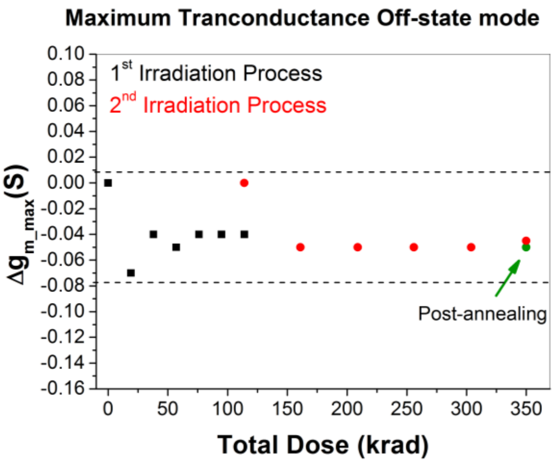

Fig. 4: Shift of the gm_{max} off-state mode.

The gm_{max} results suggests that X-ray generates impurities ionized in the bandgap of the Gallium Nitride layer, then, increasing electron scattering at these impurities degrades mobility of the 2DEG affecting negatively the transconductance.

Figure 5 shows the on- and off-modes, for the subthreshold slope (S) values (variation of S referring to the pre-rad value) acquired graphically. The vertical dashed lines indicate the end of the first and the second irradiation steps, while the horizontal dashed line represents the "zero" pre-rad reference value.

The rectangles called by the acronym R.T.A., demonstrate the 7-days room temperature annealing. The referent value used in the graph was S_{ref} = (120±25) mV/decade.

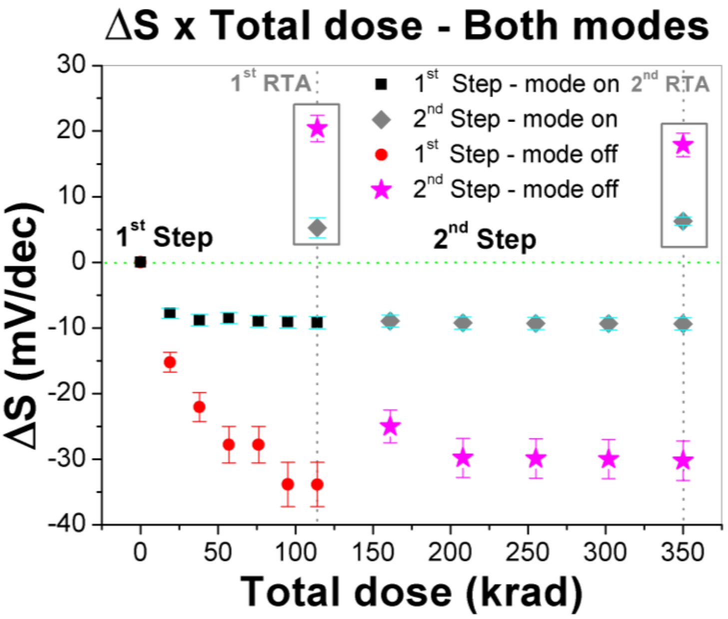

Fig. 5: ΔS for both steps in both modes

During the process of irradiation, both modes (on- and off- modes) depicted a decrease in the slope (S), which means an increase in the transistor switching "speed" of the device. Important to notice, the off-mode, again, more abrupt compared to the on-mode. The greatest variation also occurred at the beginning of the process and was equal to $\Delta S = -(35 \pm 3)$ mV/decade. Meanwhile, DUT, also, showed an increase in the slope after R.T.A., stabilizing at positive values equal to $\Delta S_{finalON} = (7 \pm 1)$ mV/decade and $\Delta S_{finalOff} = (18 \pm 2)$ mV/decade. As a result of the increase in S, after R.T.A. the device should also increase its characteristic rise and fall times, more in off-mode than in on-mode [6].

The two primary ways in which the effects of ionizing radiation affect the functionality of the AlGaN/GaN-2DEG-based transistor are by changing the electronic density and/or modifying electronic mobility. That is because carrier concentration in a 2DEG is changed by charge trapping, causing changes in the electric field in the interface. So, if we consider that the accumulated positive charges of the AlGaN layer will increase the electric field at the interface, we will have a higher electronic density. In the other hand, if negative charge entrapment occurs at the interface, the electric field and resulting carrier density will decrease. Additionally, if the positive and negative charges are trapped in the GaN layer, the effects on device operation will be exactly opposite, changing the V_{TH} [4, 10, 11]. Therefore, as shown in the results, the robust behavior of these heterostructure field effect transistors (HFETs) both facing TID and temperature effects are mainly due to being a wide bandgap (WBG) device that drives carriers via 2DEG [10, 11].

The better performance behavior of these devices operating in the on-mode is because in off-state the electric field changes only vertically due to the voltage applied to the gate during characterization. Thus, this vertical field governs the 2DEG carrier, concentration, and mobility. In on-mode, the device is initially polarized, influenced by vertical and horizontal electric field components. In this case, the electric field between source and drain must be considered, minimizing the effects of radiation on the dynamics of trapped charges [4, 10, 11].

5. Conclusions

The GaN-HEMT COTS, GS61008T, was characterized in both modes of irradiation, depicting excellent recovery in most functionality after a 350 krad/Si accumulated. Evidencing, however, that the technology is less affected by TID when the device is being irradiated in the on-mode, that is, when it is polarized, in other words, when it is working.

The abrupter variations in V_{TH} and gm_{max} were obtained in off- and on-mode, respectively, and were both during the process of irradiation, being ΔV_{THmax} = -0.46 V and Δgm_{max} = -130 mS. Furthermore, the best recovery of d functionality after R.T.A. occurred in on-mode stabilizing at ΔV_{TH}^{RTA} = -0.05 V and Δgm_{max}^{RTA} = -45 mS.

In addition, in the S the lowest value also occurred at the beginning of irradiation, ΔS = -35 mV/déc. In the other hand, in both steps and modes show an increase in S after R.T.A. with, $\Delta S_{finalON}$ = (7±1) mV/déc, $\Delta S_{finalOff}$ = (18±2) mV/ dec.

The results confirm that, although devices based on this new GaN technology present parameter degradations during irradiation, they are quite robust to TID effects and the data obtained can be valuable for circuit designers of devices that require to operate in hazard environments, as they present a very fast and practically total recovery of the main parameters that interfere with their operation, especially when they are in the on-mode.

Acknowledgment

The authors acknowledge financial support from the funding agencies: FAPESP, Brazil 2017/18181-2; FAPESP, SPRACE Proc. 2018/25225-9; FINEP, Brazil Proc. 01.12.0224.00; INCT-FNA, Brazil Proc. 464898/2014-5; CNPq, Brazil Proc. 304437/2017- 4 and 306353/2018-0; IEAv; CITAR project.

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