Evidence of Dynamic-R_{on} degradation on low-dose ^{60}Co gamma radiation AlGaN/GaN HEMTs

P. J. Martínez, E. Maset, D. Gilabert, E. Sanchis-Kilders, J. Bta. Ejea

University of Valencia, Department of Electronic Engineering, 46100 Burjassot, Spain

Enrique.maset@uv.es

Abstract. Wide band gap semiconductors are expected to be the future technology for power semiconductors that can enable the reduction of power consumption in many applications. But, in order to use these materials, it is necessary to study their reliability. Regarding its possible use in radioactive environments, it is essential to know the response of HEMT structures based on GaN under radiation. This paper is focused on the study of the effects of gamma radiation on dynamic performance of commercial GaN HEMTs. A test campaign was performed to detect variations on dynamic on-resistance induced by irradiation, due to the relevance of dynamic resistance behavior in power switching converters. This study demonstrates an increase of the dynamic resistance in MISHEMTs structures when they are under gamma radiation together with a voltage stress in the drain region. This increase takes place especially after a hard-switching transition due to the hot-electron effect that takes place during the switching events and can not only lead to an increase of the power losses, but also a reduction in the life time of the device due to the permanent degradation that could be induced by the hot-electron effect.

1. Introduction

It is expected that about 60% of the world wide used energy in 2040 will be provided by electric power. Efficient processing of electrical energy through means of electronic switching devices that enable high frequency and high efficiency power electronics converters is mandatory for seeking a more rational use of the electric energy [1].

Due to the advances in the growth and fabrication process in GaN, high electron mobility transistors (HEMTs) have been developed. The high sheet charge density of the two-dimensional electron gas (2DEG) enables the design of transistors with a lower on-resistance, which translates into the reduction of conduction losses. The capability of GaN to work at higher temperatures allows reaching higher levels of power without causing a thermal failure. Finally, the high breakdown field (3.3 MV/cm) also allows fabricating devices with high breakdown voltage.

All the theoretical benefits of GaN power devices due to their distinctive material properties (high breakdown voltages, low on-state resistances and fast switching properties, all together) can only be of great advantage if reliability and robustness can be validated. These properties are the consequence of extremely high field and current densities that are possible per unit device volume or area, but at the same time, these high electric fields are concentrated at a very small region around the gate, which represents one of the main problems in GaN reliability. Most of the GaN related degradation mechanisms are triggered by high electric fields [2, 3].

In power application it is very important, in terms of efficiency, to reduce the conduction losses for which we need to have a transistor with a very low on-resistance and to reduce the switching losses, which is achieved with a low $R_{ON}{\cdot}Q_G$ product (product of on-resistance and gate charge). Theoretically, GaN power semiconductors can achieve these properties, however, the extended defects resulting from the heteroepitaxial growth can have a negative effect on the dynamic performance of GaN HEMTs due to the enhancement of the trapping process [4]. One critical dynamic issue of GaN power HEMTs is the so-called "current collapse" that appears in switching power applications. It is caused by electron trapping and de-trapping and appears as a transient and recoverable reduction in drain current after the application of high voltage in off-state. When the device is pulsed from the high-bias off-state into the on-state condition, an increase of the dynamic on-resistance (R_{ON_DYN}) compared to the equilibrium condition appears [5,6,7]. Such effect is related to charge trapping upsetting the dynamic performance. Maintaining a low R_{ON_DYN} during high voltage switching is essential for power switching applications. Electrons trapped in donor-like defect states near the two-dimensional electron gas (2DEG) deplete the 2DEG, causing a reduction in the device conductivity (increasing R_{ON_DYN}) until the trapped charges are able to recombine.

In space and nuclear applications, the extreme environment due to the radiation is one of the main reasons of reduced reliability. If GaN HEMTs have to be used in space or nuclear facilities, they will suffer fluxes of high-energy protons and electrons in low earth orbit as well as neutrons or gamma rays in nuclear applications. Therefore, the effect of high-energy particle irradiation should be considered when HEMTs devices are proposed to work in these extreme environments. Total ionizing dose (TID) radiation effect in AlGaN/GaN HEMTs has been studied in the past, but focusing in theoretical studies, simulations and in the effect on experimentally measured static electrical characteristics. The objective in this paper is to know if the gamma-ray irradiation could affect the switching and conduction losses due to changes in the dynamic resistance R_{ON_DYN} of these devices. In terms of reliability and in terms of DC-DC converter designers' point of view, the transient behaviour of R_{ON_DYN} during the device turn-on can reduce the future applicability of GaN HEMTs as power switch in space or nuclear applications.

2. Experimental details

For the test campaign we have selected commercially available AlGaN/GaN on Si substrate normally-off HEMTs, rated at 600 V. We have chosen two different structures: a 600 V p-doped GaN gate (p-GaN) HEMT encapsulated in a TO-220 package (manufactured by Panasonic Corporation) and a 650 V GaN Metal-Insulator-Semiconductor HEMT (MISHEMT) encapsulated with an embedded die packaging (manufactured by GaN Systems Inc.). Table 1 summarizes the key parameters of the investigated devices.

Table 1 Parameters of the investigated GaN HEMTs.

	Symbol	GaN MIS-HEMT GS66508P	p-GaN HEMT PGA26C09DV
Drain-to-source breakdown voltage	BV_{DSS}	650 V	600 V
Continuous drain current (Tc=25ºC)	I_D	30 A	15 A
Internal Gate resistance (1MHz)	$R_{G\text{-}int}$	1.1 Ω	4.4 Ω
Drain-to-source ON resistance (Tj=25 ºC)	$R_{DS(ON)}$	50 mΩ (a)	71 mΩ (b)
Input Capacitance (1MHz, 400V)	C_{ISS}	168 pF	259 pF
Total Gate Charge	Q_G	5.8 nC	11 nC

(a) Measured at 9A, (b) Measured at 8A

In order to know the gamma irradiation effect, a test campaign has taken place in the CNA-RADLAB facilities at the National Center of Accelerators, in Seville (Spain) using a ^{60}Co gamma source. Twelve commercial GaN HEMT of each type have been selected and 3 steps of irradiation have been done. In table 2, the irradiation parameters for each step are shown. Under radiation, the devices were in an off-state condition, both with or without voltage stress at the drain. Eight devices of each type were exposed to a drain voltage of 400 V, and the other four devices were connected with all their terminals shorted to ground. When applying 400 V to the drain during the irradiation experiments, a resistor of 10 kΩ was placed between the voltage supply and the drain terminal, to limit the current in case of catastrophic failure.

Table 2 TID Radiation parameters

Step	**Average Dose Rate [rad(Si)/h]**	**Irradiation time (h)**	**Accumulated Dose [krad(Si)]**
1	215.6	258.7	55.8
2	212.6	686.2	201.7
3	211.7	454.4	297.9

In addition, two more devices of each type were used as reference devices during the test campaign experiment. They were exposed to a drain voltage of 400 V, but without applying gamma radiation. The purpose of these reference devices under test (DUT) is to discard possible changes that could be only due to the high voltage stress applied but not to the radiation. All these samples have been grouped into three different batches. Table 3 shows the test bias conditions for these three batches.

Table 3. Bias conditions of irradiation samples.

	V_{GS} (V)	**V_{DS} (V)**	**Radiated**	**Nº of samples of each type**
Batch 1	0	400	Yes	8
Batch 2	0	0	Yes	4
Batch 3	0	400	No	2

In order to see the effects that radiation/voltage stress has on these GaN HEMTs devices, some electrical characterizations measurements have been done before, during and after irradiation: transconductance (I_D-V_{GS}), drain leakage characteristic (I_{DSS}-V_{DS}), parasitic capacitances (C_{ISS}, C_{OSS} and C_{RSS}) and output characteristic (I_D-V_{DS}) using the B1505A Keysight power analyzer/curve tracer.

Additionally, due to the importance of maintaining a low R_{ON_DYN} during high voltage switching, this parameter has been measured to see if gamma irradiation together with the voltage stress could generate any variation over traps in the device. For this measurement, a faster circuit compared to the B1505A set-up has been built, because it is necessary to measure the R_{ON_DYN} as soon as possible after the turn-on of the device. This circuit is shown in figure 1.

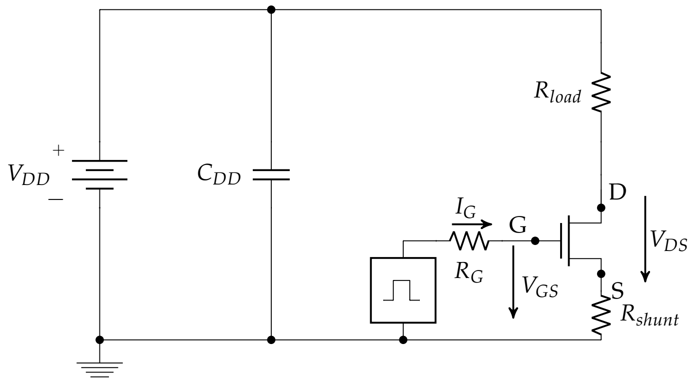

Figure 1. Circuit diagram used to measure dynamic resistance, R_{ON_DYN}

This dynamic-ON-resistance test consists on a simple hard switching test with resistive load. For the tests, a drain voltage of V_{DD} = 400 V with a load resistor of R_{load} = 220 Ω, has been used, in order to have a drain current near to 2 A through the DUT. The current level was selected high enough to have the necessary voltage drop on the device to make a good measurement but not too high to not induce a measurable self-heating of the device (that could lead to a change of the electron mobility in the 2DEG channel). To control the on-time of the DUT, a generic MOSFET gate driver (IXDN609SI) was used. In practice, a series resistor with the gate of the HEMT of R_G = 10 Ω has been used to slow down the turn-on slope and therefore avoiding undesired oscillations. When the gate pulse turns off the DUT, a high voltage (close to the supply voltage, V_{DD}) is applied to the drain, starting the stress time. During the on time of the DUT, we register the voltage drop at the channel of the HEMT and the current through it, measured with a commercial shunt resistor (SDN 414-10) of R_{shunt} = 100 mΩ. In order to determine the on-resistance, a division of voltage by current has been done using a mathematical channel of a high bandwidth digital scope (Teledyne HDO 6104).

A good precision on the on-resistance measurement is needed, but it is a difficult task because it is not easy to measure the drain-source voltage drop at the DUT. The problem is the large dynamic range of the input signal. If we select a small voltage range per division, the oscilloscope input amplifier is overloaded and an accurate determination of the on-state voltage is not achievable with standard measurement equipment. In order to avoid that problem, a voltage clamp circuit together with the passive voltage probe has been used. In our case, the voltage clamp used was the commercial clp1500V15A1 of Springburo GmbH. We have selected the low range (2 V) in the voltage clipper in order to have a faster response, which is in our case is as fast as 75 ns taking into account the passive voltage probe and the voltage clipper. Precise frequency response compensation has been done in the passive voltage probe to compensate the whole chain of clipper and voltage probe. The sequence of the pulses for the dynamic resistance test, used to obtain the R_{ON_DYN} after each radiation step is shown in figure 2, showing the key waveforms of the drain and gate voltage and drain current.

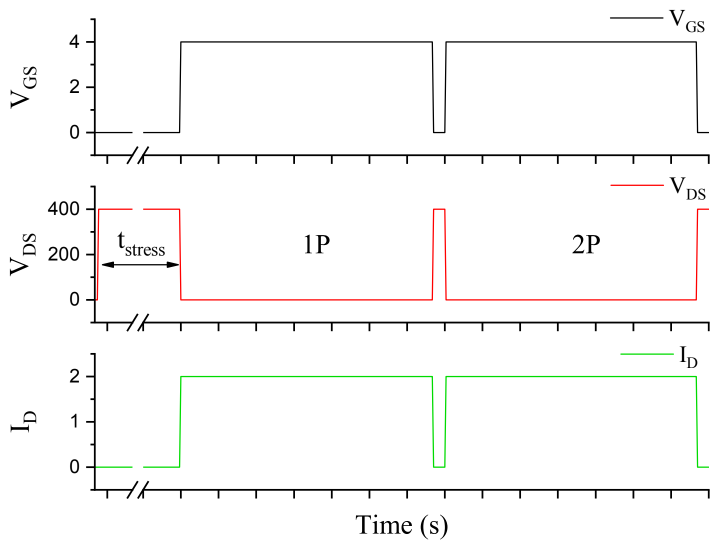

Figure 2 Time diagram of the key waveforms in the dynamic resistance test

3. Experimental Results

After the radiation test campaign, all the static electrical characteristics measured (I_D-V_{GS}, I_{Doff}-V_{DS}, C_{ISS}, C_{OSS}, C_{RSS} and I_D-V_{DS}) did not present any variation respect to the pre-radiation measurements. This invariance against gamma radiation is due to the low total dose applied 0.3 Mrad(Si), which agrees with the results reported in other studies. In [8], AlGaN/AlN/GaN HEMTs were tested and only suffered changes after 10 Mrad(Si) with a degradation pattern that depend on the bias conditions, being invariable with radiations doses of 5 Mrad(Si). Also, in [9] the AlGaN/GAN HEMTS devices suffered slight variations with much greater radiation doses, specifically, the variation was of –0,1 V of threshold voltage with a radiation applied of 600 Mrad. Different authors suggest that irradiation results in simultaneous generation of mutually compensating defects. The comparison of different studies is not possible since detailed device structure is not available. However a common trend of a negative threshold voltage shift is observed with high radiation doses. In [10] the authors have proven a non-monotonic nature of the effects of gamma irradiation, denoting discrepancies between several studies that could be due to a structure sensitive response of the defects generated during the irradiation. Additionally, [11] establishes that a single worst-case bias condition, for the electrical characteristic degradation, cannot be defined for all varieties of AlGaN/GaN HEMTs.

Regarding dynamic characteristics, the first thing to do was to study if the HEMTs are current-collapse free or not before radiation. In this way, we can evaluate whether the radiation affects the existing charges or not. To evaluate the current-collapse effect, we use the circuit shown in figure 1, applying a multiple pulses sequence. The gate pulse pattern consists on 500 ms OFF state and 6 μs ON state as shown in figure 3. The measurement of resistance will be done 5 μs after the ON pulse has started, applying enough repetitive pulses until the R_{ON_DYN} stabilizes. The test was repeated for different drain to source voltage stress (from 400 V to 600 V) and the results are shown in figure 4.

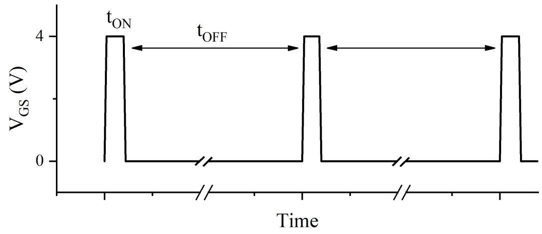

Figure 3. Time diagram of gate voltage waveforms applied to the DUT during current-collapse free evaluation measurement

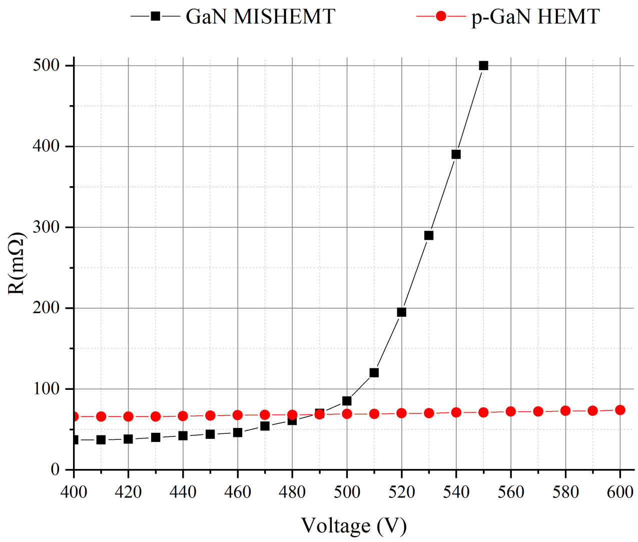

Figure 4. Measurement of dynamic ON resistance varying OFF-state voltage. 500 ms OFF time with 6 µs ON time and measuring R_{ON_DYN} 5µs after the ON state has started. Vg=4 V and R_{load}=220 Ω for both devices.

From these results it is possible to draw two conclusions. The first is the nonexistence of trapped charges in the p-GaN HEMT, due to the use of an additional drain-side p-GaN that compensates the hole emission in the epilayer at the OFF state [12] and therefore current-collapse does not appear up to its rated voltage of 600 V. The second is that GaN MISHEMT is no current collapse free and shows a trapping behaviour, which could be explained as a virtual gate effect [13]. The voltage stress starts a process of electrons trapping on the surface in donor like state, creating an excess of negative charges on the AlGaN surface (surface state charges) and/or in the AlGaN barrier layer allowing the formation of the virtual gate. Therefore, as far as this effect is gate voltage dependent it is important to choose a correct gate voltage in order to see any change produced after radiation. As shown in figure 4, the dynamic resistance of GaN MISHEMT for a gate voltage of 4 V shows an increase of R_{ON_DYN} that starts at a drain-source voltage of 420 V. Taking into account this result, the gate voltage chosen is 4 V for a drain to source voltage of 400 V. Thus, keeping the parameters constant, it will be possible to detect any variation of R_{ON_DYN} after a radiation step.

Now, returning to the main issue, the behavior of R_{ON_DYN} versus the gamma irradiation, and needing to make a good evaluation of the dynamic resistance, a specific test sequence has been defined as shown in figure 5. Considering that the trapping of charges within defects in the material is responsible of the conductivity reduction until the trapped charges are able to recombine. This trapping process takes place during both, during the OFF state and in the switching events.

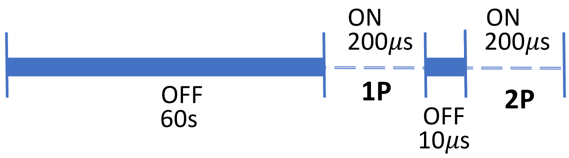

Figure 5 Pulse sequence for dynamic resistance tests.

The first 60 s, during which the HEMT is OFF and stressed with drain-source voltage, is used to evaluate the trapping of electrons induced in OFF-state stress. Therefore, after this stress time we turn-on the device with the first pulse (1P) to measure R_{ON_DYN}. Then, a second pulse (2P) is applied after another OFF state of 10 μs where the HEMT is again under voltage stress, to evaluate possible trapping mechanisms at switching events due to the high-power transitions, where hot electrons are generated in the channel and can hop into a trapped state located near the channel. These two-possible trapping mechanisms were demonstrated by other authors [14-15]. Our main objective is to know if the gamma irradiation can modify the trapping charges mechanisms and therefore affect to the dynamic ON-resistance.

A.- Devices stressed (V_{DS} = 400 V) and under gamma irradiation

Fig. 6 shows the variation produced in the dynamic resistance for p-GaN HEMT and GaN MISHEMT when gamma radiation is applied while stressing the devices with 400 V drain-source voltage and keeping gate-to-source short-circuited and at a voltage of 0 V.

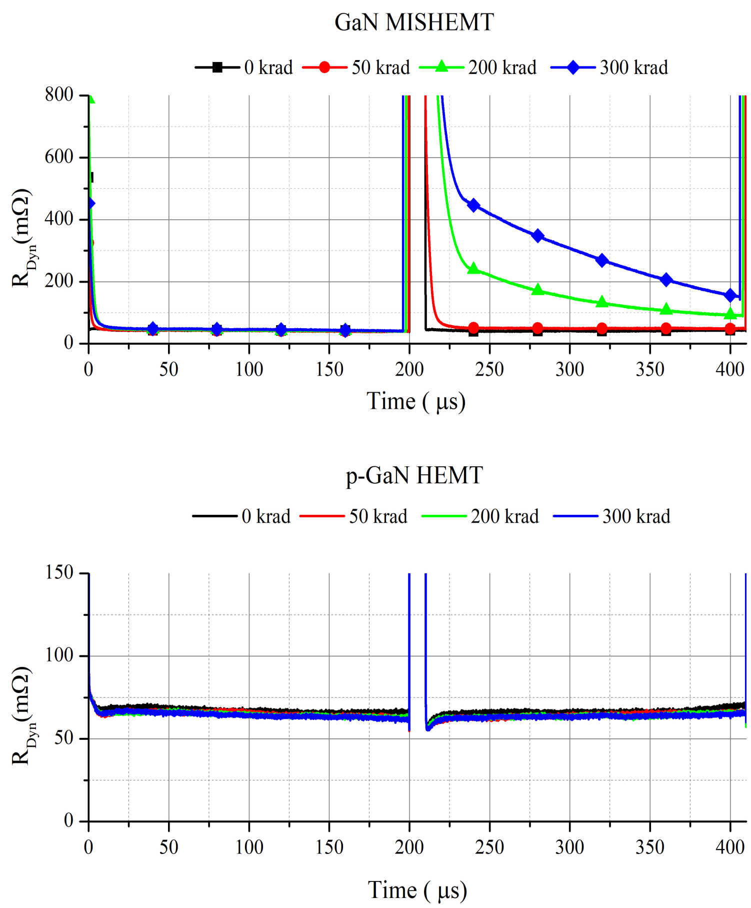

Figure 6 Dynamic resistance for p-GaN and GaN MISHEMT with 400V applied during radiation.

As seen in figure 6, there is no variation on the dynamic resistance of the p-GaN HEMT device, while the GaN MISHEMT suffers a high variation of the dynamic resistance, mainly during the second pulse. This is not a minor change since the devices with the higher rate (300krad(Si)) show an increase of R_{ON_DYN} of 1130% measured 25 μs after the second ON pulse has started (compared to the value measured at same time at 0 krad(Si)). This increase drops to 436% if we measure the R_{ON_DYN} 175 μs after the second ON pulse has started.

B.- Devices not stressed (V_{DS}= 0 V) and under gamma irradiation

In the case of the devices exposed to radiation with their terminals shorted (non-voltage stress), the variation was ~~a little~~ different. For the case of the GaN MISHEMT, the variation is shown in figure 7, and it can be seen that the variation occurred on the second pulse is much lower than in the case of devices with 400 V applied during the radiation. In fact, the increase of R_{ON_DYN} in the case of TID of 300 Krad(Si), measured 25 μs after the second pulse is about 141 %, this increase stays almost constant during the pulse, and being almost the same (R_{ON_DYN} increase of 134 %) measured 175 μs after second pulse. For the case of p-GaN HEMT no variation has been measured, as seen in figure 7.

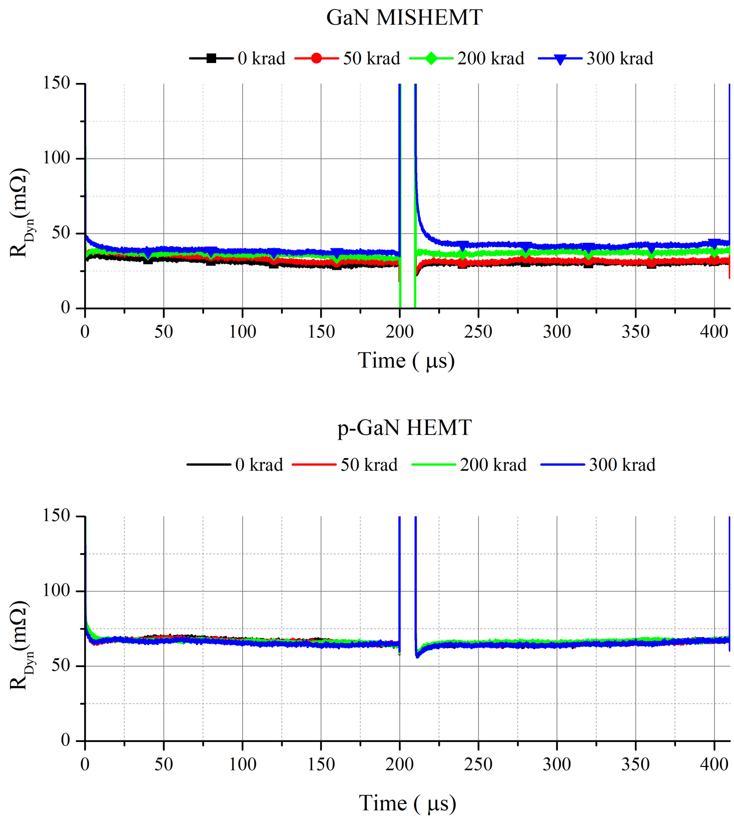

Figure 7 Dynamic resistance for p-GaN and GaN MISHEMT with terminals shorted during radiation.

C.- Devices stressed (V_{DS}= 400 V) without gamma irradiation

Finally, it is necessary to show the behaviour of the devices that were sustaining a voltage stress of 400 V without gamma irradiation, in order to discard that this voltage could induce the changes occurred in the dynamic resistance instead of the radiation. These results are shown in figure 8, where no variation appears on the R_{ON_DYN} for both types of HEMTs, which means that the variation seen in the others devices, is due to the radiation and not the 400 V drain-source voltage stress.

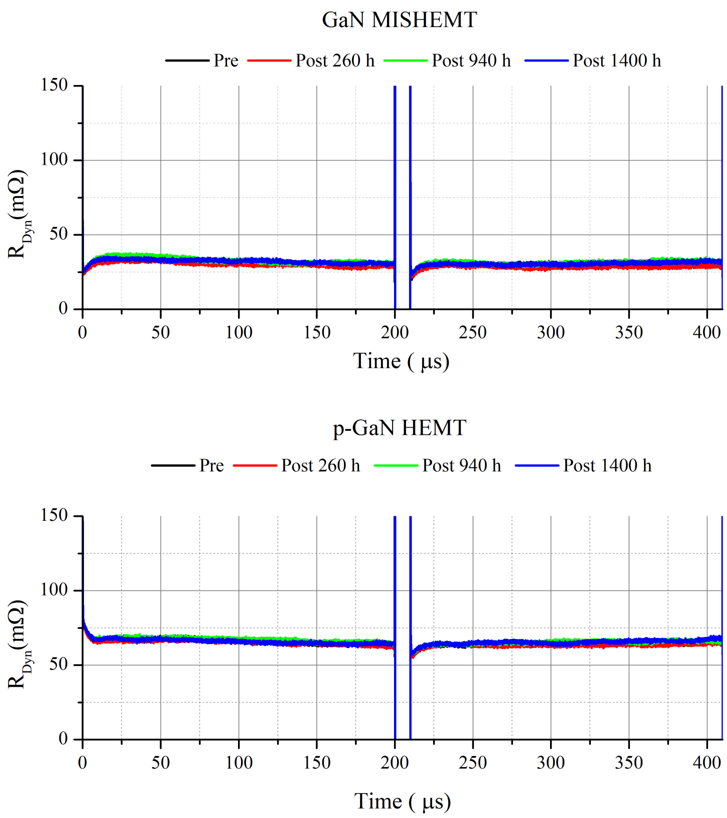

Figure 8 Dynamic resistance for p-GaN and GaN MISHEMT without applied radiation

D.- Response to annealing of the irradiated devices.

As the variation of R_{ON_DYN} discovered in GaN MISHEMT was under radiation and with a drain-source voltage (being the irradiation process responsible for this variation), it is possible that these devices can recover total or partially their original state with the use of temperature in an annealing process. To evaluate if there is a recovery in the post-radiation device performance, one measurement has been done 48 hours later followed by an annealing process at 100 ºC during 168 hours. The parameters of the annealing process are shown in table 4. Figure 9 shows the effect of the annealing process on the GaN MISHEMT devices. The devices recover partially their characteristics, reducing the dynamic resistance from 1130 % increase down to 253 % (a 77.6% of reduction), measuring the R_{ON_DYN} 25 µs after the start of the second pulse and from 436 % to 172 % (a 60.5% of reduction) measuring R_{ON_DYN} 175 µs after the start of the second pulse.

Table 4. Annealing conditions

Test	Duration	Temperature	Bias condition
Room Temperature Annealing	48h	25ºC	Unbiased
Accelerated Ageing under bias	168h	100ºC	Same as in radiation process

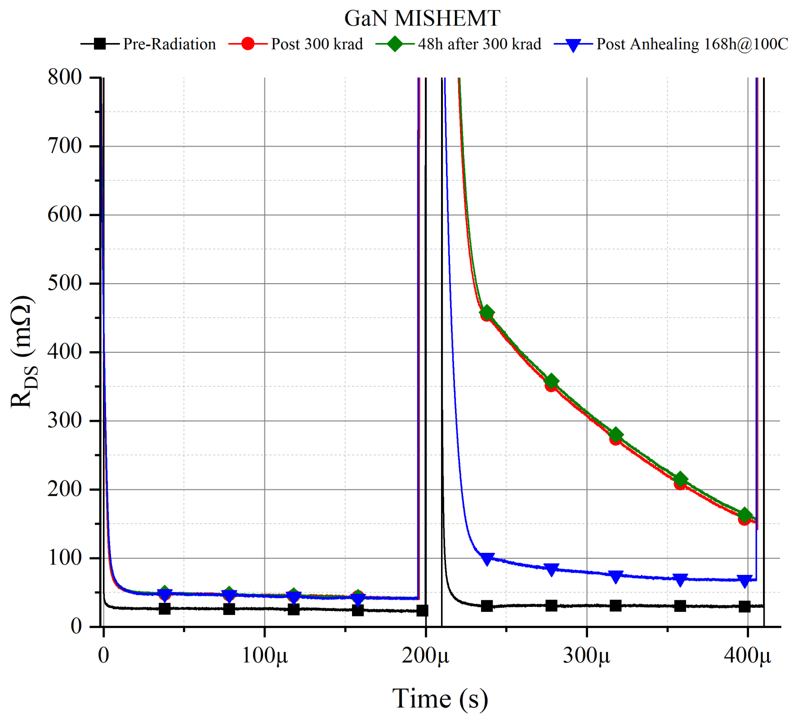

Figure 9 Dynamic resistance for GaN MISHEMT with post-annealing measurements.

4. Discussion

Regardless of the invariance of the measured static electrical characteristics under low-dose radiation in GaN HEMTs, some changes of the dynamic resistance, R_{ON_DYN}, have been reported. An increase of dynamic resistance has been measured in irradiated GaN MISHEMTs when they were exposed to simultaneous high-field stress in the drain region. Both, radiation-induced hole trapping and field-stress-induced electron trapping were responsible for the change in R_{ON_DYN}. Additionally, the use of a Metal–insulator–semiconductor (MIS) structure, which has the advantage of a lower gate leakage, could introduce extra problems when irradiated, such as an enhanced charge trapping effect due to the gate dielectric properties.

The increase in R_{ON_DYN} is shown when the GaN transistor switches from ON to OFF, where it crosses a semi-ON condition (in which voltage and current co-exist simultaneously), inducing hot-electrons trapping effects [16]. The hot-electrons from the source are accelerated by the high electric field and are trapped in the gate-drain access region depleting the 2DEG transistor channel. This trapping/degradation effect causes a reduction in the device conductivity, increasing the ON-resistance until the trapped charges are able to escape.

Therefore, when the irradiated and stressed (applying drain-source voltage) GaN HEMTs are hard switched, if the energy of the hot-electrons generated during the turn-off and turn-on transitions is enough, then the hot-electrons can hop into a trapped state located near the channel and then deplete the 2DEG which the consequent increase of the ON-resistance. Figure 6 shows the variation of the ON-resistance during the first and the second pulse. The effect is an increase of its value as the hot-electrons are generated. Figure 10 shows the effect of two different drain stress voltages in the dynamic ON-resistance. As can be seen, with 40V there is not enough energy transferred to the hot-electrons to hop into the trapped states generated basically by gamma irradiation. These asseverations are based on studies that demonstrate the trapping of charges during hard switching in turn-on and turn-off process [17,18].

We suggest, as [18], that hot carrier injection during switching events leads to a reduction of the channel charge carriers which results in current collapse and increase of R_{DS-ON}. X. Sun et al. [19] reported that when devices are exposed to simultaneous irradiation and high-field stress (e.g., a high or forward), both, radiation induced hole trapping and field-stress-induced electron trapping can be observed, and either can dominate depending on the irradiation and stress conditions. To determine the place of traps inside the device, and if hole trapping or electron trapping occurs, electroluminescence measurements would be needed. Strain relaxation could be the mechanism of generation of this new traps since strain relaxation could improve the device by native defect structural reordering but also can result in the generation of additional traps [20].

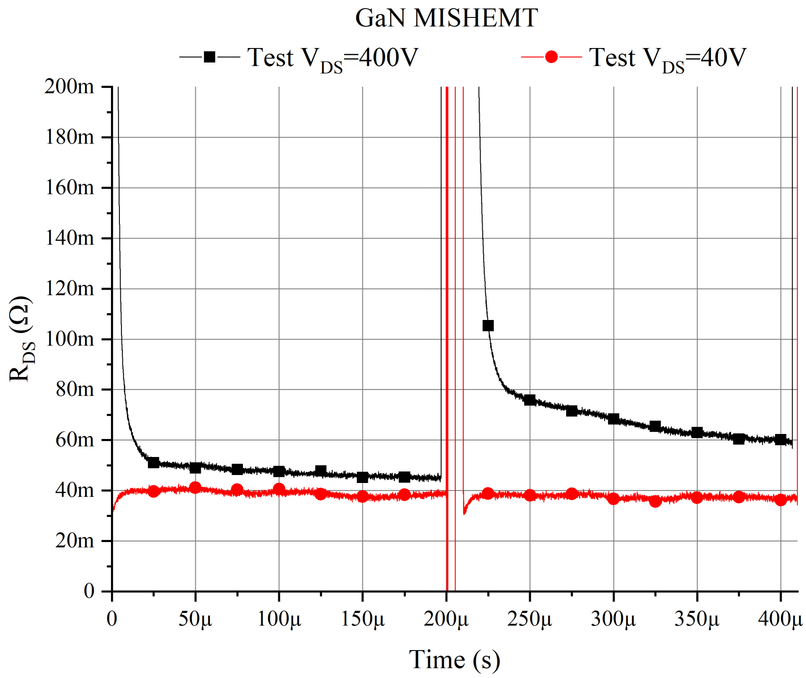

Figure 10 Dynamic Resistance for GaN MISHEMT with post-annealing varying drain stress voltage, 40V (red) and 400V (black).

Different to GaN MISHEMT, the p-GaN HEMT device did not suffer any variation on the dynamic resistance. In the p-GaN HEMT, holes are injected from the p-GaN region at the OFF state by applying high drain voltage, which effectively releases the trapped electrons during the switching process.

5. Conclusion

It was demonstrated that in GaN MISHEMT devices, the low-dose gamma irradiation causes an increase of the traps defects. In addition, this increase is higher when, under irradiation, the device sustains a high drain-source voltage stress. This could be due to the impact of the radiation over the charged traps in the device. This increase in the trapping/degradation effects causes an increase of the dynamic ON-resistance when the GaN MISHEMT has to work in hard-switching mode. The high electric field accelerate the electrons and the hot-electrons generated hop into the trapped state close to the transistor channel increasing the dynamic ON-resistance.

When the total dose applied to the devices was low, there were no changes on the static characteristics of the devices, as expected. On the other hand, p-GaN HEMT did not show any variation of its characteristics (static and dynamic resistance) because the p-GaN region injects holes contributing to compensate the hot-electrons. It can be concluded that this p-GaN HEMT structure is more robust under this type of low-dose gamma radiation.

Therefore, it is important, in applications exposed to radiation, to choose a GaN HEMT which internal structure aids to minimize the effect of current collapse [12]. Otherwise, the irradiation to which the device is exposed, will cause a large increase in the trapped charges, that can lead not only to an increase of the losses (due to the increase of the dynamic resistance), but also, a reduction in the life time of the device due to the permanent degradation that could be induced by the hot-electron effect.

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