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Moustafa Zerarka, Patrick Austin, Alain Bensoussan, Frédéric Morancho, André Durier. TCAD Simulation of the Single Event Effects in Normally-off GaN Transistors after Heavy Ion Radiation. IEEE Transactions on Nuclear Science, 2017, 64 (8), pp.2242-2249. 10.1109/TNS.2017.2710629 . hal-01556257

HAL Id: hal-01556257

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Submitted on 4 Jul 2017

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TCAD Simulation of the Single Event Effects in Normally-off GaN Transistors after Heavy Ion Radiation

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Abstract— Electrical behavior of COTS normally-off GaN power transistors under heavy ion radiation is presented based on TCAD numerical simulation for the first time in order to better understand the mechanism of Single Event Effects (SEE) in these devices. Firstly, the worst case has been defined from the Single Event Transient mechanism. Then, the decrease in the electric field observed after radiation and the traps effect have been addressed. Finally, possible mechanisms of SEE in these devices under heavy ion are proposed.

Keywords— power transistor; GaN; EPC; SEE; sensitive volume ; radiation; heavy ion; TCAD; simulation

I. INTRODUCTION

The use of Gallium Nitride (GaN) power transistor switches is very promising because this material is a more efficient semiconductor than Silicon (Si) or Silicon Carbide (SiC) in terms of "ON-resistance / breakdown voltage" trade-off, which is the most important figure of merit for a power switch. Indeed, the main benefits of this material are a good functionality at high frequency applications due to its high electron mobility with high power, due to the high critical electric field. The normally-off GaN power transistor could be specifically an attractive candidate for space and aeronautic power applications.

The use of these devices in such environment cannot be ensured without careful consideration of the effects of radiation. Natural Radiation Environment (NRE) is composed of particles of various nature and energy such as heavy ions which can cause the destruction of these devices. Single Event Effects (SEE) is one of the most menacing mechanism which could cause normally-off GaN power devices to fail in space systems. Few studies have been carried out to understand SEE in normally-off GaN power transistors.

The objective of this paper is to investigate, by 2D TCAD simulation, the mechanism of failure induced by heavy ion irradiation on commercial normally-off GaN power transistors (from EPC, Efficient Power Conversion) in order to better understand the electrical behavior after radiation, define the sensitive volume and suggest an explanation of the mechanism of Single Event Effects (SEE) for these devices.

II. STATE OF THE ART

Heavy ions inducing destructive failures have been extensively studied in RF normally-on HEMT. Most previous work has been focused on the effects of protons, neutrons and electrons. The failure generated by the protons in the AlGaIn/GaN HEMT was first examined by Cai. *et al.* [1] showing the decrease in the DC current and in the transconductance for different proton fluences. Similar studies on irradiation of protons at different energies [2] [3] show that the GaN devices are extremely hardened to radiation and that the energy of the proton has a significant effect on the amount of defects created in the 2DEG of the HEMT because of differences in the loss of non-ionizing energy [4] [5]. Several works also explain the shift of electrical characteristics before and after radiation [6] [7] [8].

Furthermore, in RF normally-on HEMTs, S. Onada *et al.* find that the largest enhanced charge occurs when ions strike

the gate electrode [9]. Other studies of normally-on RF HEMTs suggested that the largest enhanced charge occurs when ions strike between the gate and the drain [10] [11].

In the literature, few studies address phenomena generated by heavy ions in the COTS power GaN transistor. Bazoli *et al.* [12] show that COTS GaN transistors (RT240PD, 70V) are not sensitive to Single Event Burnout (SEB) under neutron and heavy ion irradiations test; however, a phenomenon similar to Single Event Gate Rupture (SEGR) was observed in these devices although no oxide is under the gate. They supposed that the defects created in AlGaIn layers by incident particles could be the origin of the gate insulation. They confirm that GaN transistors are less sensitive to Single Event Burnout than MOSFETs. Recently, different generations of this GaN technology (EPC) have been tested under heavy ion irradiation. L. Scheick assumes that the critical region seems to be near the edge of the gate on the drain side [13]. The lot-to-lot variance that has been taken into account appears to be a very significant parameter [13]. Other results consider that these devices are not as robust as expected and show that normally-off power GaN HEMTs are affected by a significant charge amplification mechanism [14] [15]. These latter consider that the mechanism of enhancement charge collection is associated with bipolar and back-channel effects.

Regarding simulation results, they are extremely rare in the literature due to the prematurity of this technology that remains uncontrolled even by manufacturers (epitaxy limited, defects, dislocations ...). Predictive approach of mobility and traps effect has been proposed by Erin *et al.* to explain the degradation of performance characteristics in RF AlGaIn/GaN HEMTs, they propose that a virtual gate effect is the cause of the increase in critical voltage and increased reliability [16]. To our knowledge, any studies address simulation of SEE generated by heavy ions in the COTS normally-off power GaN transistor and experimental results could not give a clear explanation of these failure mechanisms. Therefore, predictive modeling of these devices is strongly necessary: this is the aim of the presented work.

III. TEST VEHICLES

A reverse engineering was carried out on samples GaN EPC2019ENG 200V in order to define the technological parameters of these devices. Fig. 1 gives a cross-section view of the EPC2019 GaN HEMT that will be simulated. The structure consists of a substrate (silicon), a nucleation region comprising different AlGaIn layers with aluminum rates gradually decreasing, an unintentional doped (UID) GaN buffer layer, an AlGaIn barrier layer, a p-doped GaN layer [17] and a SiN passivation layer.

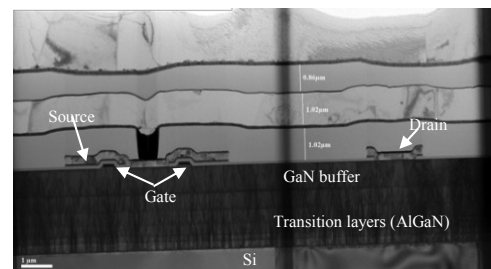


Fig. 1. Cross-section view of the active region of the GaN EPC 2019 transistor

Despite a detailed constructional analysis, some parameters always remain unknown such as intentional and unintentional doping materials and level of doping concentrations, carrier mobility, concentration and energy of traps. However, it is necessary to first validate the physical and geometrical parameters obtained thanks to the technology analysis of EPC2019 transistor and calibrate by simulation those lacking, based on the experimental electrical characteristics of the device. Simulations were carried out with SENTAURUS TCAD simulator [18]. The transport model used in simulation is The Drift-diffusion (DD) model, the current density under this model is described by the relation:

$$J_n = -qn\mu_n \nabla \Phi_n, J_p = qp\mu_p \nabla \Phi_p$$

where n and p are electrons and holes concentrations respectively, μ_n and μ_p are the electrons and holes mobility respectively, Φ_n and Φ_p are the respective quasi Fermi levels. GaN models are perfectly detailed in the work of Jon C. Freeman [19] and TCAD tools [18]. The key parameters of our calibration are the doping and traps concentrations. The most important concentrations are: an unintentional doping density of acceptor type of $1 \times 10^{16} \text{ cm}^{-3}$ in the GaN layer, an unintentional doping density of donor type of $1 \times 10^{16} \text{ cm}^{-3}$ in the AlGaIn layer, an acceptor trap density of $5.10^{17} \text{ cm}^{-3}$ with energy level of 0.45 eV from the conduction band. As shown in Fig. 2, the $I_D(V_{GS})$ transfer characteristics of the simulated structure match the ones experimentally measured [20].

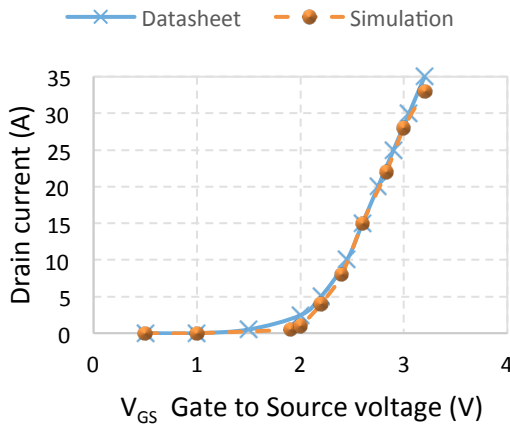


Fig. 2. Experimental (datasheet) and simulated $I_D(V_{GS})$ transfer characteristic of the 200 V EPC2019 GaN HEMT.

Concerning the off-state, manufacturers of GaN components do not provide accurate characteristics. Dislocations in the crystal lattice from the manufacture create randomly leakage currents for each device. Two components of the same type can exhibit significant differences in terms of breakdown voltage. EPC2019 devices have been tested to determine the actual values of their breakdown voltage: we found that the same component may exhibit different values (between 200 V and 420 V) when test was repeated under the

same conditions. This can be explained by the heating effect which changes the traps energy after each test, increasing the trap assisted gate tunneling mechanism. In simulation [21], the value of the breakdown voltage was adjusted to 450 V by fitting some key parameters as the traps in the GaN buffer layer and their energy level.

IV. CONDITIONS OF SIMULATIONS WITH HEAVY ION

After calibrating the simulator, we simulated the structure with different conditions detailed in Fig. 3. The aim is to investigate how the commercial power normally-off GaN switch behaves for different conditions of heavy ion irradiation (position of tracks, range and source-drain bias) while trying to find the most critical conditions for SEE and to locate the sensitive volume showing highest change in residual electric field or trap density after irradiation simulation. These conditions have been also presented in our previous works in order to determine the sensitive volume in Si power devices (VDMOS, IGBT ...) [22] [23].

In a first step, we studied the case of ions vertically generated in the volume of the cell of EPC2019, with track lengths of 2 μm generated at different x positions (see Fig. 3 solid arrow). The objective is to locate the sensitive volume.

In a second step, we simulated the impact of ions penetrating from the front side with different track lengths. The case of ions penetrating from the backside was also studied (see Fig. 3 dashed arrow). For these steps, all simulations were performed in the off-state, at the same source-drain bias corresponding to 90% of the breakdown voltage V_{br} .

We also simulated these structures with different source-drain biases (40 V, 200 V, 300 V and 400 V) in the off-state while keeping the same conditions defined in the previous step.

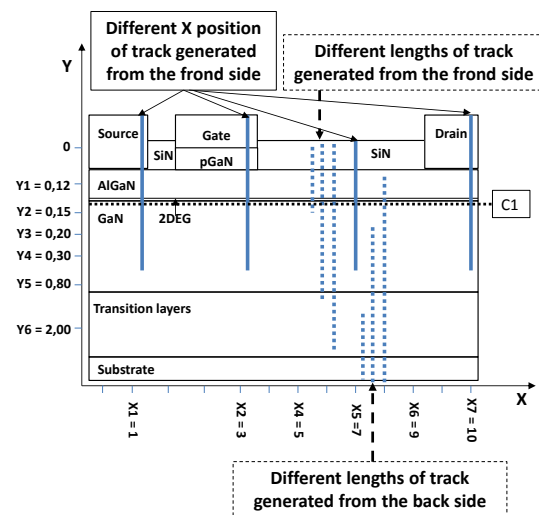


Fig. 3. Schematic conditions of simulation of heavy ion tracks impacting on normal incidence on the device from front and back side.

- Dans la fig. 3
- 1) "Different X positions" à la place de "Different X position"
 - 2) Remplacer les virgules par des points

The ionizing impact is simulated by a function allowing the generation of electron-hole pairs in a specific area of the structure. The generation rate of the created charges is described by spatial and temporal Gaussian functions [18]. The track radius is set to $0.05 \mu\text{m}$, the initial time of the charge generation is 3.10^{-13} s and the temporal Gaussian function width is 2.10^{-12} s. Detailed work on the modeling of the ion track charge and energy distribution can be found in the works of H. Dussault *et al.* in [24] [25].

V. SIMULATION RESULTS AND DISCUSSION

A. Single Event Transient mechanism

Results in Fig. 4 and 5 show the evolution of the drain current as a function of time after heavy ion impact for different LETs from the front side. Whatever the conditions (LET and bias), all failures are transient and the triggering current cannot be sustained. This transient current represents the charge enhancement. Generally, in HEMTs heterostructures, the charge enhancement mechanism is associated to two mechanisms: the bipolar and the back-channel effects. When heavy ion crosses the active area of the device, electron-hole pairs are generated, creating ionized plasma. Electrons flow toward the drain contact with high mobility, leading to an excess of holes in the GaN buffer layer, thus electrons are injected to compensate from the source, leading to the switch of the parasitic bipolar transistor [9] [26] [27]. The second charge enhancement mechanism is due to the positive charge accumulation under the gate that helps to reduce the potential barrier between the source and the channel allowing the injection of electrons from the source to the drain via the channel [9] [26] [27]. In Fig. 4, the transient drain current reaches a saturation value for LET of $1 \text{ pC}/\mu\text{m}$. These LET correspond to the maximum of charge which can be generated in the GaN buffer region at 200 V. From this amount of charge, the amplitude of transient drain current does not increase anymore, whatever the LET value is set. This phenomenon value depends especially on the bias voltage but not on the ion energy or range. Fig. 5 confirms that the amplitude values of the drain current can be multiplied by a factor 6 when increasing the drain-source bias voltage for the same charge deposited by the heavy ion [28].

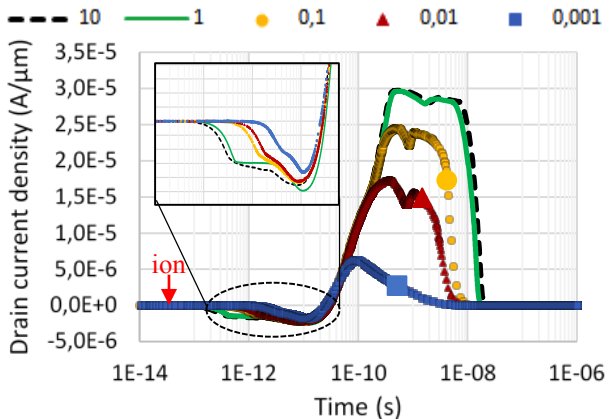


Fig. 4. Evolution of the drain current as a function of time after heavy ion impact for different LET ($\text{pC}/\mu\text{m}$) from the front side ($x = 5 \mu\text{m}$) at $V_{\text{DS}} = 200$ V in the off-state [28]

Dans la fig. 4 : remplacer les virgules par des points

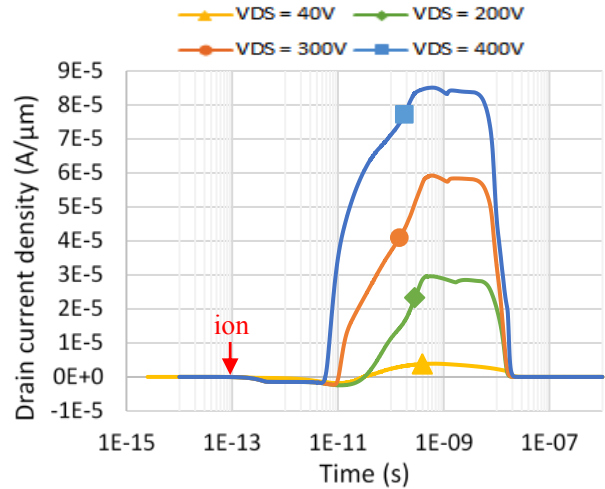


Fig. 5. Evolution of the drain current as a function of time after heavy ion impact between gate and drain electrode ($x = 5 \mu\text{m}$) for different source drain biases from the front side with $2 \mu\text{m}$ of track length and LET of $1\text{pC}/\mu\text{m}$ [28]

Dans la fig. 5 : “V_{DS}” à la place de “VDS”

Fig. 6 explains the mechanism of the transient current after the heavy ion strike. It shows that only the self-polarization of the gate by the hole current coming from ionized plasma leads to turn-on the device. The majority of the electron current coming from the source passes through the channel, reducing the electron current flowing through the GaN buffer or the whole structure to compensate for the accumulated holes, which minimizes the parasitic bipolar effect. The saturation value depends especially on the bias and not on the energy or range of the ion. Fig. 5 confirms that the amplitude values can be multiplied by increasing the drain-source bias voltage for the same charge deposited by the heavy ion. Since the ionization coefficients and detrapping are exponentially related to the electric field via the Poisson's equations, the rise of the polarization increases the detrapping and the generation of electron-hole pairs, increasing the hole current in the gate, leads to more charge enhancement [28]. This is similar to the direct characteristic $I_{\text{D}}(V_{\text{DS}})$: the saturation drain current increases with the increase in gate bias (V_{GS}).

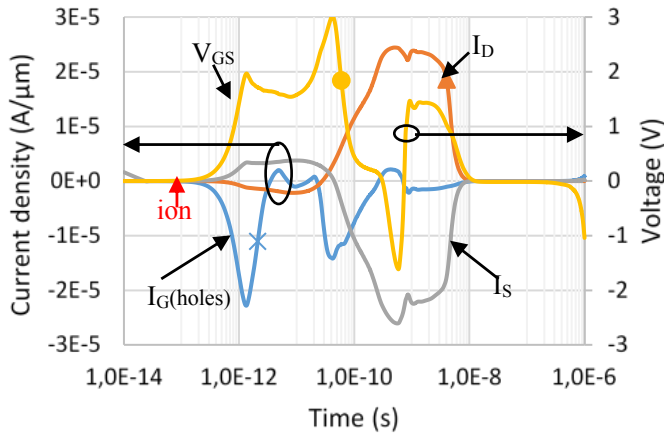


Fig. 6. Evolution of I_D , I_S , I_G and V_{GS} as a function of time after heavy ion impact from the front side at $V_{DS} = 200$ V in blocking state [28]

Dans la fig. 6 : remplacer les virgules par des points

If we compare to MOSFET device behavior under irradiation modeling, the proposed mechanism involves avalanche effect combined to the parasitic bipolar transistor structure, both providing charges to each other [29]. When considering GaN normally-off structure under irradiation, we assume that the transient triggering of parasitic bipolar structure cannot maintain a drain current avalanche thus avoiding burnout failure.

B. Sensitive volume

One can see, from the analysis of Fig. 7, that the transient current is less important when heavy ion is present in the source region, since outside of the space charge region, the tracks require a much larger LET. While there is no significant change in amplitude for all traces generated in the depletion region between the gate and drain, the change in shape is more evident. The tracks which are close to the source and gate have a negative current, just after the impact and the tracks which are close to the drain do not have this negative current (see Fig. 7 zoom). We do not know exactly the origin of this negative current. We think that, when heavy ion is generated close to the gate, excess of holes is close to the source which allows to induce a bipolar mechanism before back-channel effects. However, when heavy ion is generated close to the drain, excess of holes is close to the drain and relatively far from the source: holes need more time to reach the gate or source region and recombine partially. The bipolar mechanism needs high amount of holes unlike the mechanism of the back-channel which can be activated with a small amount of charge. Heavy ion generated close to the drain will activate only the back-channel and all the electrons will pass through the channel, which explains its relative speed triggering compared to the ones generated close to the gate region.

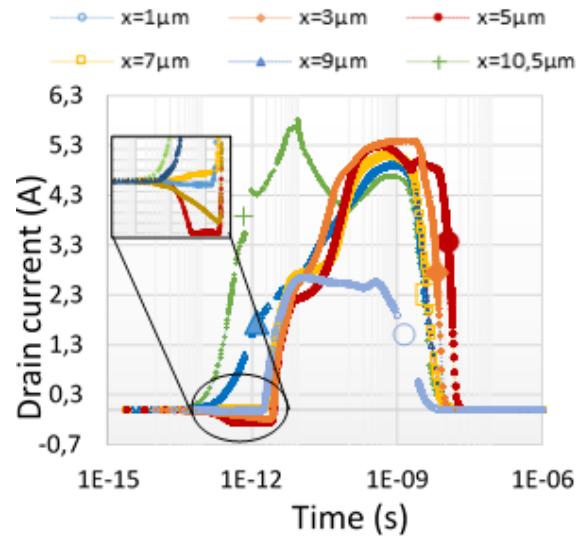


Fig. 7. Evolution of the drain current as a function of time after heavy ion impact for different x positions from the front side at $V_{DS} = 200$ V in the off-state (see Fig. 3 to refer to x position)

Dans la fig. 7 : remplacer les virgules par des points

Fig. 8 and 9 show the evolution of the drain current as a function of time after heavy ion impact for different track lengths from the front side and back side respectively. The transient drain current reaches a saturation value for ranges of $0.2 \mu\text{m}$. These ranges correspond to 20% of the depth of the GaN buffer region at 200 V. From this penetration, the amplitude of transient drain current is constant, whatever the range value. The saturation value depends especially on the bias voltage and not on the energy or range of the ion. Fig. 5 confirms that the amplitude values are strongly related to the increasing drain-source bias voltage for the same charge deposited by the heavy ion, while keeping the same shape.

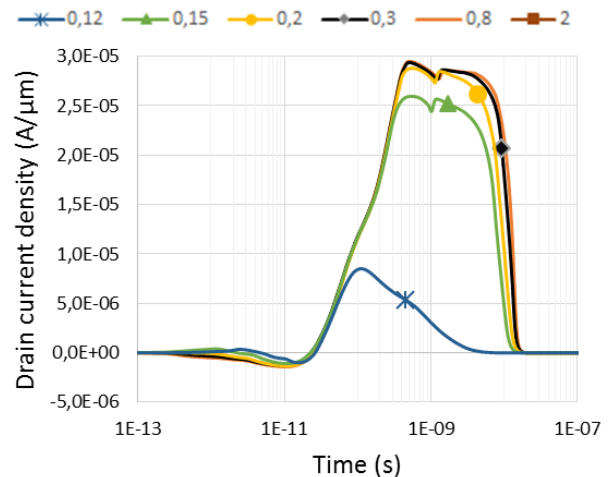


Fig. 8. Evolution of the drain current as a function of time after heavy ion impact for different track lengths (μm) from the front side at $V_{DS} = 200$ V in blocking state

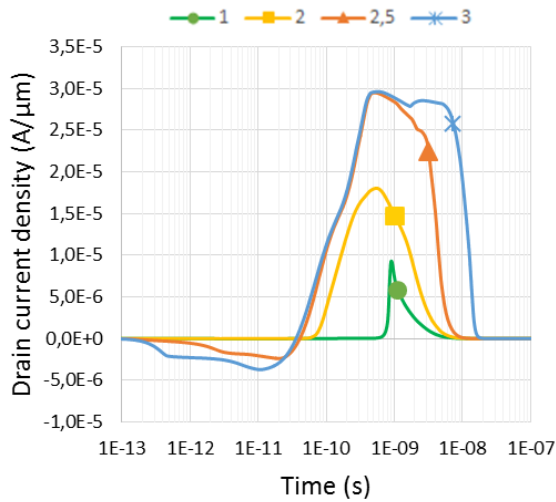


Fig. 9. Evolution of the drain current as a function of time after heavy ion impact for different track lengths (μm) from the back side at $V_{DS} = 200\text{ V}$ in blocking state

Dans les fig. 8 et 9 : remplacer les virgules par des points

The comparison of Fig. 8 (front side) and Fig. 9 (backside) shows that the sensitive case is observed when the heavy ion comes from the front side, especially for the lowest ranges. The tracks, which penetrate toward the channel area (range = 3 μm) from the back side, induce the same transient drain current of the one coming from the front side with a range of 0.2 μm . The first trigger time is slower for small ranges. The transient current does not occur in the same time scale as seen in the case of ion injected on the front side.

C. Effect of radiation on the electric field

The decrease in the electric field before and after the impact of heavy ion has been analyzed. Fig. 10 shows a systematic observation of the electric field in the simulated structures before and after heavy ion irradiation at 300 V. Results shows that the electric field significantly decreases along the structure after radiation.

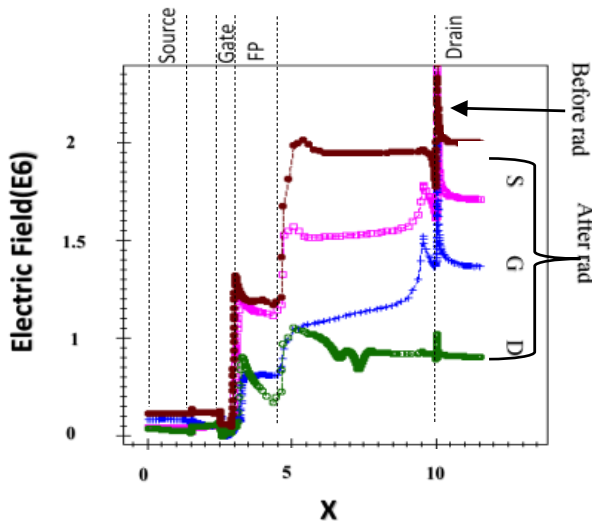


Fig. 10. Electric field decrease after radiation at different track positions (horizontal section at C1 of Fig. 3)

Fig. 11 indicates that the density of traps has a significant effect on the peak of the electric field observed after radiation. Since the detrapping is more important in the ions strike close to the gate electrode, the electric field will be more decreased in this area. This may explain the increase in breakdown voltage observed in [30]. In contrast, for RF HEMT, Erin *et al.* suggest that the trap density in GaN buffer does not have a significant effect on the peak of the electric field observed after radiation [16]. They explain that it could be due to post-radiation traps formed in the AlGaN/Nitride interface, not to post-radiation traps formed in the GaN-buffer layer; a similar explanation was adopted by Travis *et al.* [31] in their radiative tests (2 MeV protons) on AlGaN/GaN HEMT with different substrates (Si, SiC and Al_2O_3). This difference reveals that the trap density in the GaN buffer layer has a more significant effect in power HEMTs than in RF HEMTs.

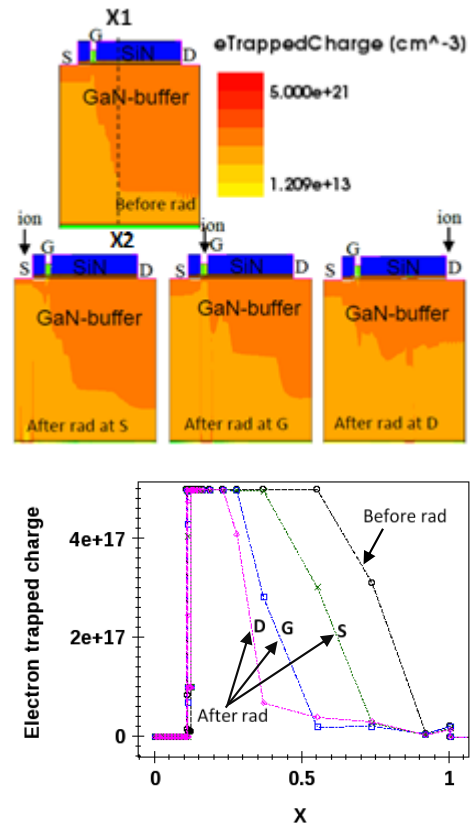


Fig. 11. Electron trapped charge before and after heavy ion radiation (vertical section from x1 to x2)

As in the case of different x positions, the decrease in the electrical field after radiation can better demonstrate the effect of each track length. Fig. 12 shows a systematic observation of the electric field in the simulated structures before and after heavy ion radiation at different depths of penetration for ion coming from the front side. A same large decrease appears around the ion impact position near the gate electrode ($x = 5\ \mu\text{m}$) whatever the track length is. Here, the range has a little effect since the track position is located near the end of

the depletion region with fewer traps; consequently, the detrapping effect on the electric field is the same. However, the decrease on the drain side is very important only when the heavy ion penetrates 40% of the GaN-buffer layer (range = 0.4 μm). The most significant electric field decrease is occurring at 0.8 μm of range, which corresponds to 80% of the depth of GaN-buffer layer and from this range the electric field decrease remains nearly the same.

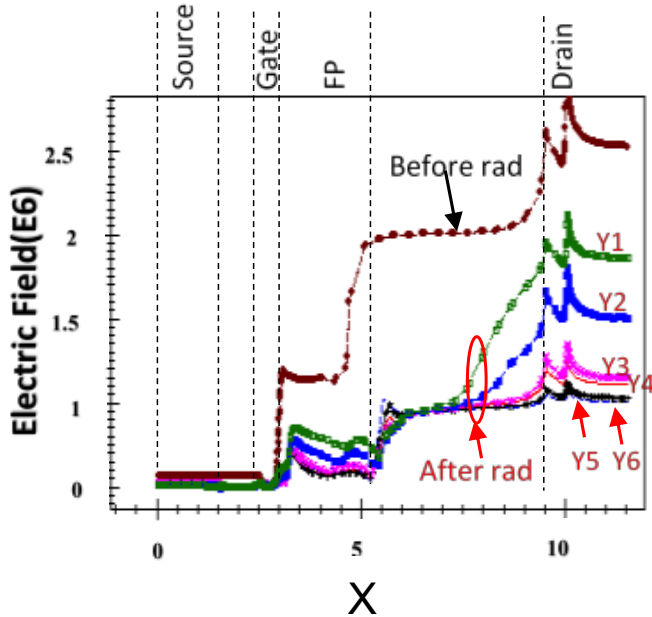


Fig. 12. Electric Field decrease with different track lengths (horizontal section at C1 of Fig. 3) (see Fig. 3 to refer to y position)

Dans la fig. 12 :
 1) remplacer "Electric Field(E6)" par "Electric Field (MV)"
 2) ajouter l'unité après X : "X (μm)"

D. Proposed scenarios of Single Event Effect

First scenario (Burnout)

The plasma generated by a heavy ion can occupy a large part of this small device inducing a big dE/dt which gives a large displacement current. Simulation shows that this current is collected by the electrodes. Fig. 13 and Fig. 14 are showing the evolutions of displacement drain current (I_{DD}) and V_{DS} as a function of time at $V_{DS} = 400$ V in blocking state without and with impact ionization model respectively. These simulated data, both considering the impact ionization model, could provide possible scenarios of SEE in normally-off GaN power transistors under heavy ion. The displacement current, caused by the abrupt change of V_{DS} or V_{DG} immediately after heavy ion impact, is shown in Fig. 13 without impact ionization model and in Fig. 14 with impact ionization model. Concerning the first case (without impact ionization model), the displacement current does not appear immediately after the ion impact: this current increases with the transient drop of V_{DS} and decreases when V_{DS} ascends. On the other side, when the impact ionization model is considered, a very important displacement current (0.1 $\text{A}/\mu\text{m}$) is observed, nearly 1000 times larger than the current simulated without considering the

impact ionization model. This current appears just after the ion hits the front side simultaneously to the V_{DS} increase (see Fig. 14 zoom) and before the drop voltage. Even if this displacement current, caused by the avalanche phenomenon, occurs during a very short time, we assume that this mechanism is probably the origin of SEE in these devices since usually the avalanche phenomenon in the real components is not reversible. We also assume that this mechanism can cause a current filamentation as being responsible of destructive breakdown. This mechanism is observed only in the highest V_{DS} over than 200 V. For V_{DS} less than 200 V, the impact ionization mechanism has no effect. Furthermore, the very high current densities and conductivity of the GaN generated by the avalanche is assumed not to be supported by its limited thermal capacity and thermal conductivity (related to the Si substrate limitation); as a consequence, this increases the risk of thermal runaway [28].

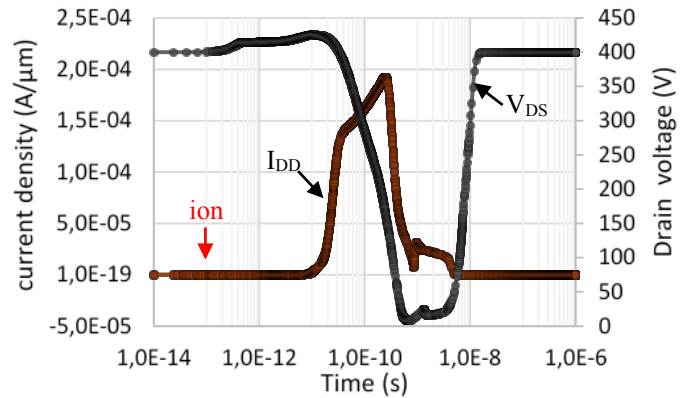


Fig. 13. Evolutions of displacement drain current I_{DD} and V_{DS} as a function of time after heavy ion impact from the front side at $V_{DS} = 400$ V in blocking state (without impact ionization model) [28]

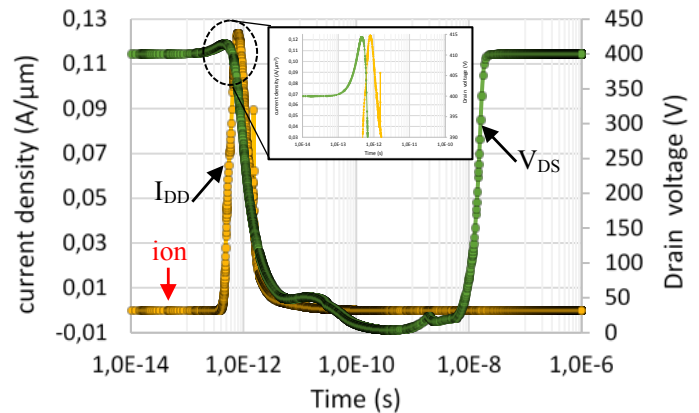


Fig. 14. Evolutions of displacement drain current I_{DD} and V_{DS} as a function of time after heavy ion impact from the front side at $V_{DS} = 400$ V in blocking state (with impact ionization model) [28]

Dans les fig. 13 et 14 : remplacer les virgules par des points

The displacement current in silicon devices was sometimes related to the triggering of the parasitic thyristor as the case of

TRIAC, the combination of the high $[dV/dt]$ and the presence of the stored charge can lead to the undesirable turn-on and to the destructive failure of the thyristor without external gate drive current [32]. In the case of a GaN transistor, this possibility is very unlikely.

Second scenario (dielectric rupture)

Results in Fig. 15 could provide also another possible scenario of SEE in normally-off GaN power transistors under heavy ion. Despite this similarity in drain current behavior between different track positions as shown in Fig. 7, there is an important difference in the gate voltage. Fig. 15 shows that the transient gate voltage is much more important when heavy ion is present in the field plate edge. The gate voltage value could exceed 22 V when heavy ion particles are generated in this region, exactly in the edge of the field plate. This voltage gives a high electric field of 2.2 MV/cm at the thickness of the passivation film (Si_3N_4) between the gate and the field plate (0.1 μm), which is close to the capacitance of this layer, the mean failure electric field for Si_3N_4 being 2.9 MV/cm [33]. Few studies address ion damage in Si_3N_4 , Wrobel suggested that the density of electron-hole plasma along the heavy ion track in the dielectric induces a conductive "pipe" that can be a discharge path of energy stored on the capacitor [33]. We suppose that this hypothesis is possible in this case when heavy ions and this high transient gate voltage are applied together.

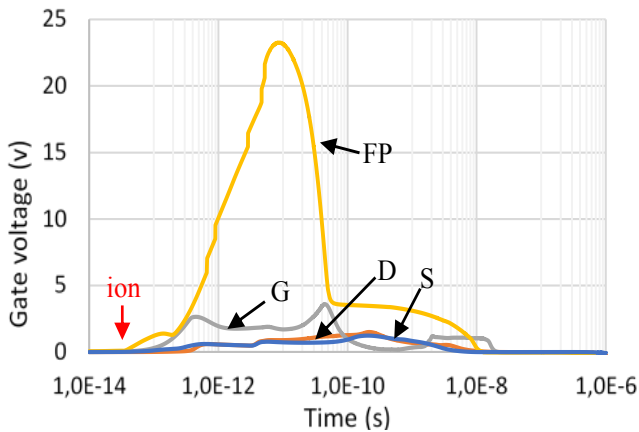


Fig. 15. Evolution of the gate voltage as a function of time after an heavy ion radiation for different x positions (S: source, G: gate, D: drain, FP: field plate) from the front side at $V_{DS} = 200$ V in blocking state

Dans la fig. 15 : remplacer les virgules par des points

Fig. 15 shows a drawing of the evolution of the gate voltage as a function of time after heavy ion impact for different x positions (S: source, G: gate, D: drain, FP: field plate) from the front side at $V_{DS} = 200$ V in blocking state. From these results, we observe that susceptible region which may lead to the dielectric rupture can be located at the field plate edge. This contact is the nearest to the drain contact and creates the most electrical stress which can exceed the edge gate stress on the drain side. Therefore, impact ionization mechanism and related multiplication phenomena are enhanced when a heavy ion strikes under the field plate edge rather than the other track positions. As shown in Fig. 16, we compare the two critical positions, gate and field plate. Several studies of

SEGR (Single Event Gate rupture) in power MOSFETs have shown that the gate leakage current resulting from the ion impact has been increasing rapidly with the exposure time under the beam. This increase can lead to the breakdown of the gate oxide (SiO_2) in most cases [28].

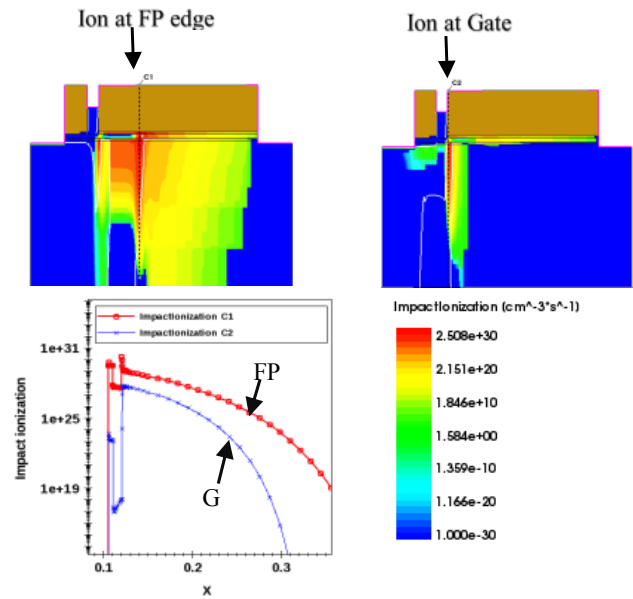


Fig. 16. Impact ionization when a heavy ion strikes at the field plate edge (left) and at the gate (right)

Other studies have shown that the SEGR was mainly affected by pre-existing damage [34] and could also be triggered by ions crossing only the epitaxy without reaching the oxide [35]. Fig. 17 shows a significant increase in electrons density after single heavy ion track, especially in the p-GaN layer, the interface p-GaN/ Si_3N_4 and SiN/AlGaIn layer (green color in Fig. 17). This promotes the trap/defect assisted gate tunneling and increases the leakage current at the gate after irradiation. We assume that the accumulation of these electrons density after irradiation for longer ion exposures can considerably increase the risk of the degradation of Si_3N_4 and its rupture like SEGR in MOSEFT or triggering a burnout initiated by leakage current.

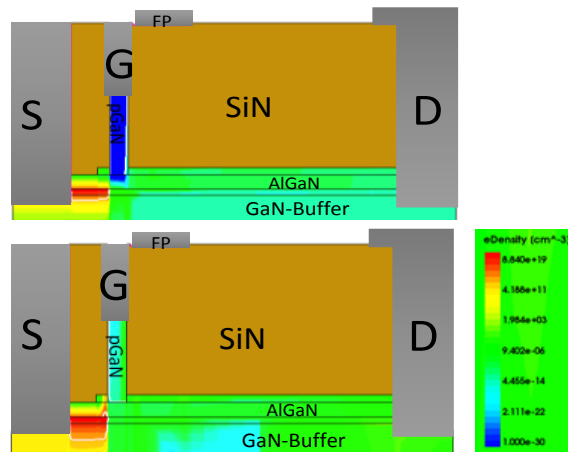


Fig. 17. Leakage current before (top) and after (bottom) radiation

VI. CONCLUSION

Using TCAD simulation, we explain the mechanism of the transient current after the heavy ion strike in normally-off GaN power transistors. The self-polarization of the gate by the holes current coming from ionized plasma leads to transient turn-on the device. We assume that the minor effect of the parasitic bipolar transistor in such devices induces that the triggering is always reversible and avalanche drain current cannot be maintained. The worst case at 200 V in commercial normally-off GaN power transistors is related to an ion coming from the front side, striking next to the field plate edge and crossing more than 20% of the GaN-buffer layer. The most significant electric field decrease observed after radiation is occurring at the drain side. The density of traps in GaN buffer layer has a significant effect on the decrease in the electric field in contrast to RF HEMT devices. This may explain the increase in breakdown voltage observed in the literature.

A possible mechanism of SEE in these devices under heavy ion has been proposed: a heavy ion can induce a huge displacement current (0.1 A/ μm) caused by the avalanche phenomenon in high voltage and the abrupt change of V_{DS} or V_{DG} immediately after heavy ion impact is probably the origin of SEE. Another possible scenario supposes that the origin of SEE in normally-off GaN power transistors is probably the rupture of the dielectric passivation layer (SiN) and this susceptible configuration, which may lead to dielectric rupture, occurs when a heavy ion strikes near the field plate edge.

Acknowledgement: *The paper is a part of the research done at IRT Saint Exupéry, Toulouse, France. The study was conducted in the frame of Electronic Robustness contract Project sponsored by the following funding partners: SERMA technologies, Agence Nationale de la Recherche, Airbus Operations SAS, Airbus Group Innovation, Continental Automotive France, Thales Alenia Space France, Thales Avionics, Laboratoire d'Analyse et d'Architecture des Systèmes — Centre National de la Recherche Scientifique (LAAS-CNRS), Safran Labinal Power Systems, Bordeaux University, Institut National Polytechnique Bordeaux (IMS — UMR 5218), and Hirex engineering.*

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