Degradation and failure mechanisms of P-GaN HEMTs in single and complex radiation environments

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Abstract

In this work, the mechanisms of total ionizing dose effect (TID) and single-event burnout (SEB) failure in P-type gallium nitride gate high electron mobility transistors (P-GaN HEMTs) was investigated based on experiment and simulation. In the TID experiments, three groups of samples with different voltage bias were irradiated up to a maximum of 1 Mrad(Si) using 60Co γ-rays with an average energy of 1.25 MeV, at a dose rate of 100 rad(Si)/s. Positive threshold voltage shifts of different magnitudes are observed, while the gate leakage current increases insignificantly in all of them. We believe that electron and hole trapping at the P-GaN/AlGaN interface and in the AlGaN barrier layer is the main reason for the threshold voltage shift. For the SEB experiments, a tantalum (Ta) ion beam was used for irradiation at an energy of 854.3 MeV and Linear Energy Transfer (LET) value of 86.8 MeV $\cdot$ cm^2/mg in silicon. When the drain-source voltage was 350 V, we observed a significant surge in drain current, while the gate current did not show an uncontrollable increase. The simulation results indicate that the local electric field enhancement due to charge enhancement effect and charge collection phenomenon as well as the intensification of collisional ionization are the main causes of device damage and failure. In addition, we subjected one of the three groups of samples that had undergone TID experiments to Ta ion single-event effect (SEE) experiments once again. The synergistic experimental results show the superposition effect of the two experiments.

Full Text

Degradation and Failure Mechanisms of P-GaN HEMTs in Single and Complex Radiation Environments

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In this work, we investigated the mechanisms of total ionizing dose (TID) effect and single-event burnout (SEB) failure in P-type gallium nitride gate high electron mobility transistors (P-GaN HEMTs) through combined experimental and simulation approaches. For the TID experiments, three groups of samples with different voltage biases were irradiated using ^{60}Co γ-rays with an average energy of 1.25 MeV at a dose rate of 100 rad(Si)/s, reaching a maximum cumulative dose of 1 Mrad(Si). Positive threshold voltage shifts of varying magnitudes were observed in all devices, while the gate leakage current increased only insignificantly. We attribute the threshold voltage shift primarily to electron and hole trapping at the P-GaN/AlGaN interface and within the AlGaN barrier layer. For the SEB experiments, a tantalum (Ta) ion beam was employed at an energy of 854.3 MeV with a linear energy transfer (LET) value of 86.8 MeV · cm^2/mg in silicon. When the drain-source voltage reached 350 V, we observed a significant surge in drain current, whereas the gate current did not exhibit an uncontrollable increase.

Simulation results indicate that local electric field enhancement arising from charge enhancement effects, charge collection phenomena, and intensified collisional ionization constitute the primary causes of device damage and failure. Furthermore, we subjected one of the three sample groups that had undergone TID experiments to additional single-event effect (SEE) testing. The synergistic experimental results demonstrate a clear superposition effect between the two radiation types.

Keywords: High electron mobility transistors, single-event burnout, total ionizing dose effect, synergistic effect.

INTRODUCTION

With the rapid advancement of aerospace and deep-space exploration technologies, the performance demands on spacecraft power systems continue to increase. Compared with conventional silicon-based power devices, gallium nitride (GaN) power devices have emerged as a research focus in this field due to their significant advantages, including high operating voltage, high power density, and high operating frequency [1-5]. GaN material exhibits high critical electric field strength and high atomic displacement threshold, conferring unique advantages for high-power aerospace applications [6-9]. However, limited by the current maturity of fabrication processes, the full performance potential of GaN power devices has not yet been realized. Moreover, in the space radiation environment, irradiation from high-energy particles and rays leads to device performance degradation or even failure, primarily manifested as single-event effects (SEE), total ionizing dose effects (TID), and displacement damage (DD) [10-13]. These factors severely constrain the widespread application of GaN power devices in aerospace systems.

The sensitivity of gallium nitride high electron mobility transistors (GaN HEMTs) to TID effects is influenced by multiple factors, particularly under high-voltage and high-field operating conditions where radiation effects couple with the device' s internal electric field, complicating the radiation damage mechanism. Y. P. Wang et al. [14] conducted γ-ray irradiation experiments on GaN HEMTs under different bias conditions (off-state, on-state, and floating), finding that devices under floating bias exhibited the most stable electrical parameters after irradiation with minimal observable radiation damage. Devices under off-state bias showed moderate degradation, while those under on-state bias suffered the most significant performance degradation. R. Jiang et al. [15] performed X-ray and γ-ray irradiation experiments on depletion-mode GaN HEMTs from various manufacturers, observing negative threshold voltage drift phenomena of varying degrees in different devices. H. Wu et al. [16] carried out TID experiments on P-GaN HEMT devices with different gate voltage biases, finding that the magnitude of negative threshold voltage drift is independent of device breakdown voltage but depends primarily on the applied gate voltage.

Several research groups have investigated single-event effects in GaN power devices. S. J. Cai et al. [17] first studied the degradation behavior of single-particle effects in AlGaN/GaN HEMTs through proton irradiation experiments, reporting significant decreases in transconductance and DC output current. Y. Wang et al. [18] systematically investigated the single-particle-incidence sensitive region and burnout mechanism in GaN MISFET devices, substantially improving the burnout threshold voltage by introducing a Schottky electrode to rapidly discharge irradiation-induced non-equilibrium carriers. Z. X. Zhen et al. [19] further identified the gate edge region as the single-particle-incidence sensitive location in P-GaN HEMT devices and effectively suppressed collisional ionization in high-field regions using a multi-field-plate structure. However, existing studies have focused primarily on exploring and validating device burnout mechanisms and hardening techniques through simulation software, while experimental studies on SEB induced by heavy ions (e.g., Ta ions) remain relatively scarce and require further in-depth investigation.

In this work, we performed γ-ray and Ta ion irradiation experiments on identical samples, observing TID degradation and SEB failure phenomena, respectively. Additionally, we subjected the post-TID samples to SEE experiments, revealing degradation effects arising from synergistic interactions and providing a rational explanation for the observed behaviors.

II. TID EXPERIMENT TEST AND ANALYSIS

1. Device Information and Experimental Setups

The P-GaN HEMT samples used in our experiments feature a multilayer heterostructure as illustrated in [Figure 1: see original paper]. The epitaxial layers, sequentially grown on a sapphire substrate, consist of a 50 nm AlN nucleation layer, a 5.8 µm GaN buffer layer, a 200 nm undoped GaN channel layer, a 15 nm $Al_{0 \cdot 25}Ga_{0 \cdot 75}N$ barrier layer, and a 110 nm Mg-doped P-GaN layer. The devices have a source-drain spacing of 2 µm, a gate-drain spacing of 7 µm, and a field-plate length of 4 µm.

The TID experiment was conducted using a ^{60}Co γ-ray source with a dose rate of 100 rad(Si)/s, as shown in Figure 2: see original paper. Based on the applied voltage bias, the experimental samples were divided into three groups: GND, Semi-ON, and ON, with specific bias conditions detailed in . Samples were irradiated to a maximum dose of 1 Mrad(Si), with intermediate characterization points at 100, 300, 500, and 700 krad(Si). Electrical characterization was performed systematically using a Keithley SCS-4200 Semiconductor Parameter Analyzer, as depicted in Figure 2: see original paper, with all measurements conducted at room temperature.

2. Results and Analysis of TID Experiment

Threshold voltage instability represents one of the inherent reliability issues in semiconductor devices [20, 21]. [Figure 3: see original paper] demonstrates the threshold voltage drift under the three different gate bias conditions. Positive threshold voltage drift was observed in all cases, with the magnitude increasing monotonically with γ-ray irradiation dose. Additionally, the positive gate bias voltage applied during irradiation significantly affects the threshold voltage drift, manifested as larger drift with increasing gate bias. Notably, no saturation of the threshold voltage shift was observed within the dose range investigated.

[Figure 4: see original paper] illustrates the energy band schematic of the P-GaN HEMTs under positive gate bias. Under the influence of the high electric field applied to the gate, channel electrons migrate toward the gate, with some being captured by acceptor traps at the P-GaN/AlGaN interface. These interfacial traps originate from two sources: intrinsic interfacial states introduced by imperfect surface treatment during device fabrication, and additional interfacial states induced by γ-ray irradiation at the P-GaN/AlGaN interface [22]. Simultaneously, irradiation-excited holes and gate-injected holes in the valence band accelerate toward the AlGaN barrier layer, releasing energy into the lattice through phonon emission—a process that may create new defects at the P-GaN/AlGaN interface (Process (4)). These interfacial states serve as effective electron trapping centers (Process (1)).

Furthermore, holes injected from the gate are trapped by both intrinsic and irradiation-induced donor traps in the AlGaN layer (Process (2)) [23]. It is noteworthy that the electron trapping effect in Process (1) leads to positive threshold voltage drift, while the hole trapping effect in Process (2) causes negative threshold voltage drift. These two competing mechanisms collectively determine the threshold voltage drift characteristics of P-GaN HEMTs [24]. The experimentally observed net positive drift indicates that the electron capture process dominates the competition. As gate voltage increases, the high electric field enhances electron drift motion and hole injection, intensifying both Processes (1) and (2) and resulting in larger positive threshold voltage drift.

To evaluate the radiation damage characteristics of the gate stack structure, gate leakage current measurements were performed. The results in [Figure 5: see original paper] show that devices in the GND state exhibited no significant change in gate leakage current after 1 Mrad(Si) irradiation. In contrast, devices in the Semi-ON and ON states displayed distinct leakage characteristics: the gate leakage current increased by approximately one order of magnitude in the gate voltage range of 1–3 V, while remaining essentially unchanged outside this range. This phenomenon suggests that the device operating state significantly affects the extent of radiation damage to the gate stack, with devices under high electric field conditions being more susceptible to radiation-induced damage.

The gate stack structure of P-GaN HEMT devices can be modeled as a combination of a Schottky barrier diode and a p-i-n diode, as shown in [Figure 4: see original paper]. Under negative gate bias, the Schottky barrier diode is forward-biased while the p-i-n diode is reverse-biased, with gate leakage current primarily governed by the p-i-n diode. Conversely, under forward gate bias, the Schottky barrier diode is reverse-biased and the p-i-n diode is forward-biased, with gate leakage current determined by the Schottky barrier diode [25]. Experimental observations show that the reverse gate leakage current does not change significantly, while the forward gate leakage current exhibits a slight increase. This phenomenon can be attributed to electron-hole pairs generated within the P-GaN layer during irradiation. Due to the strong electric field in the space charge region of the Schottky junction, electrons are accelerated to the metal/P-GaN interface and initiate interface damage (Process (3)). This indicates that irradiation primarily degrades the Schottky junction while the p-i-n heterojunction function remains relatively intact.

Irradiation-excited energetic electrons induce defect creation near the metal/P-GaN interface, which may be associated with hole trap states related to nitrogen vacancies. Such defects can introduce a trap-assisted tunneling (TAT) mechanism that enhances hole injection, leading to increased forward gate current [26].

III. SEB EXPERIMENT TEST AND ANALYSIS

1. SEB Experiment and Simulation Setups

The SEB experiment was conducted at the Space Environment Simulation Research Infrastructure at Harbin Institute of Technology, with the experimental environment shown in Figure 6: see original paper. A Ta ion beam with an energy of 854.3 MeV and an LET value of 86.8 MeV · cm^2/mg in silicon was used. The LET value of the Ta ions in GaN material was calculated to be 66.89 MeV · cm^2/mg using SRIM. During the experiment, the ion flux was controlled at 1$×10^{4}$ ions/cm^2/s, with each irradiation stage lasting 100 s to ensure a total fluence of 1$×10^{6}$ ions/cm^2. Throughout the irradiation process, the drain and gate bias voltages were initially set to 0 V. To determine the SEB threshold voltage, the experiment employed a step-up method, gradually increasing the drain voltage at each stage while monitoring drain and gate currents in real time until burnout was observed. The test system is shown in Figure 6: see original paper. When the current exceeds 0.1 A, the overload protection mechanism triggers and automatically disconnects the drain bias voltage. The safe drain voltage under irradiation conditions was recorded as the basis for evaluating the SEB threshold voltage.

The 2-D TCAD simulator has been widely used to study the physical processes of SEBs and hardening methods in power devices [27]. Therefore, we employed Sentaurus TCAD to build a model matching the experimental device dimensions, incorporating Shockley-Read-Hall (SRH) recombination, Fermi statistics, impact ionization, doping dependence, and high-field saturation mobility. The model feasibility has been validated in previous work [28, 29]. Additionally, a heavy-ion model was implemented in the simulation. For carriers induced by irradiation, the generation rate of electron-hole pairs along the ion incidence track is described by the following equation using temporal and spatial Gaussian functions [18, 30]:

$$\text{rate}(x,t) = \left(\frac{\text{LET}}{q\pi\omega_0 T_C}\right) \exp\left[-\frac{(x-x_0)^2}{\omega_0^2}\right] \exp\left[-\frac{(t-T_0)^2}{T_C^2}\right]$$

where LET and x_0 represent the linear energy transfer and incident position of the heavy-ion irradiation, respectively. The initial generation time T_0 is set to 1×10^{-13} s in this work. The spatial and temporal Gaussian function widths ω_0 and T_C are set to 0.05 µm and 2×10^{-12} s, respectively. We selected the most sensitive location—the end of the field plate—as the heavy-ion incidence position [31, 32]. The LET value used in simulations equals 0.635 pC/µm, approximately equivalent to 66.89 MeV · cm^2/mg using a conversion factor of 0.0095 [18, 33].

2. Results and Analysis of SEB Experiment

During Ta ion beam irradiation, samples were subjected to drain voltages ranging from 310 V to 350 V. As shown in Figure 7: see original paper, when the drain voltage was between 310 V and 340 V, the device exhibited small transient drain current fluctuations that increased with drain voltage, but the current overload protection was not triggered. However, when the drain voltage increased from 340 V to 350 V, the drain current rose dramatically. During irradiation at 350 V, at the 24th second the drain current showed an uncontrollable and drastic increase that eventually triggered the current overload protection, signaling the occurrence of SEB.

To determine whether the SEB event originated in the gate region, the transient gate current was also monitored in real time. As shown in Figure 7: see original paper, the transient gate current exhibited small fluctuations that increased with drain voltage. Notably, the gate current amplitude was significantly higher than the drain current under the same drain voltage conditions, yet the overload protection mechanism was not triggered. At a drain voltage of 350 V, the gate current did not increase dramatically at the 24th second. Based on these observations, we infer that the SEB event occurred primarily in the drain region rather than the gate region.

[Figure 8: see original paper] presents a microscopic view of the device surface after SEB, showing significant burnout damage regions concentrated in the drain area. This phenomenon further confirms that the drain region is highly sensitive to the SEB effect and represents the primary failure region. Consequently, the drain region should be prioritized in radiation-hardening device designs to enhance SEB resistance in P-GaN HEMTs.

The simulation results for P-GaN HEMT devices are shown in [Figure 9: see original paper]. During simulation, we observed two significant current density peaks at the source and drain when $t = 1 \times 10^{-13}$ s and $t = 2 \times 10^{-11}$ s, respectively. Subsequently, at $t = 3 \times 10^{-10}$ s, the current density rose sharply, indicating SEB occurrence. Notably, the gate current density remained essentially unchanged throughout the simulation, demonstrating that source-drain punch-through, rather than gate-drain punch-through, is the primary cause of SEB in P-GaN HEMT devices.

To investigate the dynamic carrier behavior following a single-event strike, we analyzed two current peaks and key time points before and after SEB. At $t = 1 \times 10^{-13}$ s, numerous electron-hole pairs are generated near the particle incidence path. These non-equilibrium carriers drift under the device’ s internal electric field, forming the first current peak. At $t = 2 \times 10^{-11}$ s, electrons move toward the drain while holes move toward the gate and source. Simultaneously, we observed significant hot electron injection from the source, forming the second current peak. At this time, a large number of holes migrate to the vicinity of the source and gate, with some holes injected from the drain. The accumulated holes near the source reduce the barrier for electron injection from the source into the buffer layer, leading to more pronounced hot electron injection. This mechanism is known as the back-channel effect [32]. Concurrently, hole accumulation near the gate reduces the potential barrier for electrons crossing the region under the gate from the source, a phenomenon called the bipolar effect [19]. These two charge enhancement effects significantly increase the probability of source-drain punch-through, as shown in Figure 10: see original paper and Figure 10: see original paper.

Non-equilibrium carriers drift under the transverse electric field, and their drift behavior further influences the transverse field distribution. Figure 11: see original paper demonstrates the variation of transverse electric field distribution in the channel region with time. At $t = 1 \times 10^{-13}$ s, the high-field region is concentrated on the drain side of the field plate. Over time, as large numbers of electrons move toward the drain, the high-field center gradually migrates toward the drain. Simultaneously, significant collisional ionization occurs under high-field acceleration, leading to a sharp increase in electron density. At $t = 1 \times 10^{-9}$ s, the high-field and collisional ionization centers have migrated near the drain electrode, where the electric field strength in the channel region significantly exceeds GaN' s critical field strength (3.4 MV/cm). The combined effect of high electric field and high collisional ionization rate leads to material damage, which is the primary cause of the drain leakage and penetration phenomena observed in Figure 7: see original paper.

Figure 11: see original paper shows the variation of transverse electric field distribution in the barrier layer with time. During the transient period, the region near the gate is susceptible to localized high electric fields that may exceed the critical field strength of AlGaN material (5 MV/cm), triggering material damage. This mechanism is the root cause of the gate leakage current increase observed in Figure 7: see original paper.

IV. SYNERGISTIC EFFECT EXPERIMENT TEST AND ANALYSIS

1. Synergistic Experiment Setups

One of the primary challenges for power devices in space applications is the combined radiation effects from multiple types of rays and energetic particles. To investigate the synergistic effect between TID and SEE, we designed a sequential irradiation experiment. In this study, one group of devices was irradiated with γ-rays under Semi-ON bias conditions to a cumulative dose of 1 Mrad(Si). Subsequently, SEE experiments were performed within two hours after completing the TID experiment. The SEE experimental conditions matched those of the SEB experiment, with source and gate bias voltages set to 0 V and drain voltage set to 100 V during irradiation. The transfer characteristics and gate leakage current of the devices were characterized in detail before and after each experiment.

2. Results and Analysis of Synergistic Experiment

The experimental results in [Figure 12: see original paper] show that the device threshold voltage exhibits significant positive drift with increasing γ-ray dose.

However, during subsequent SEE experiments, the threshold voltage undergoes negative drift, similar to the behavior observed at 500 krad(Si) in the TID-only experiment. Notably, the off-state leakage current increases by nearly three orders of magnitude after the synergistic experiment compared to the TID experiment alone. This phenomenon suggests that the synergistic effect of TID and SEE manifests as a superposition of the individual effects. Specifically, SEE triggers material damage in the GaN layer, including atomic displacement and even crack formation, which increases electron leakage paths in the off-state and leads to significantly higher off-state current and negative threshold voltage drift. This interpretation is consistent with the results shown in Figure 11: see original paper.

The gate leakage current behavior is presented in [Figure 13: see original paper]. The TID experiment caused a slight increase in leakage current at low positive voltages, while the reverse gate leakage current remained essentially unchanged. After subsequent SEE experiments, the forward gate current showed no significant change, whereas the reverse gate current increased dramatically by approximately three orders of magnitude. Based on our previous analysis, we conclude that the irradiated p-i-n heterojunction degrades severely while the Schottky junction maintains its functionality. This is related to material damage in the AlGaN barrier layer caused by the high electric field, as shown in Figure 11: see original paper.

V. SUMMARY

In this paper, we performed SEB and TID experiments on our self-developed P-GaN HEMTs. The experimental results demonstrate that the SEB phenomenon manifests as an uncontrollable increase in current between source and drain, but not between gate and drain. Local electric field enhancement due to charge enhancement effects, charge collection phenomena, and intensified collisional ionization are the primary causes of material damage and device failure. In TID experiments, electron and hole trapping at the P-GaN/AlGaN interface and within the AlGaN barrier layer lead to threshold voltage drift, with these two competing mechanisms collectively determining the device' s threshold voltage drift characteristics. The threshold voltage drift becomes more pronounced with increasing gate bias voltage, while the gate leakage current remains relatively stable. Additionally, we conducted experiments on the synergistic effects of Ta ions and ^{60}Co γ-rays, and the results show that the two irradiation effects exhibit superposition in devices, further revealing the reliability degradation mechanisms of P-GaN HEMTs under complex radiation environments.

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Note: Figure translations are in progress. See original paper for figures.