Investigation on the Cumulative Degradation in p-GaN gate HEMTs Under Synergistic Electrical Stress and Heavy Ion Irradiation

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Abstract—In this work, the synergistic effects of electrical stress and heavy-ion irradiation on the cumulative degradation of p-GaN gate AlGaN/GaN HEMTs are systematically investigated. The devices were irradiated with Ta ions (LET = 76.3 MeV·cm²/mg) under the drain bias slightly lower than the single-event burnout threshold voltage (V_{SEB}). The saturated drain current (I_{Dsat}) exhibits a pronounced cumulative degradation with increasing heavy-ion fluence under off-state electrical stress. Electrical characterization results show that neither electrical stress nor irradiation alone induces significant degradation, whereas their synergistic effect leads to severe performance degradation. Further analyses based on low-frequency noise and capacitance deep-level transient spectroscopy reveal a substantial increase in trap density in the p-GaN layer after irradiation. The increased traps within the p-GaN layer degrade carrier transport in the channel, mainly through enhanced Coulomb scattering and mobility reduction, accompanied by a partial reduction in the effective 2DEG density.

***Index Terms*—p-GaN gate, GaN HEMTs, heavy-ion irradiation, cumulative degradation.**

I. Introduction

GaN-based High Electron Mobility Transistors (HEMTs) exhibit advantages of high critical electric field, high frequency, thermal stability, and strong theoretical radiation resistance, making them highly promising for aerospace applications [1], [2], [3], [4], [5]. To ensure the safe industrial operation of power devices, it is generally required to operate in normally-off mode. Among the available approaches to achieve this, p-GaN gates are commercially practical and therefore widely adopted [6], [7], [8]. Although the p-GaN gate AlGaN/GaN HEMTs feature the strong theoretical radiation resistance, some studies have shown that their electrical performance will still be affected during radiation exposure [9], [10], [11]. Therefore, it is essential to investigate the degradation mechanisms of p-GaN gate GaN HEMTs under heavy ion irradiation, as high-energy heavy ions are a primary cause of power device failure in aerospace applications.

Previous studies on heavy ion irradiation in GaN HEMTs have mainly focused on two aspects. The first aspect concerns the degradation of device electrical performance under unbiased heavy ion irradiation. Hu et al. observed positive shift in threshold voltage along with significant decrease in the drain current of AlGaN/GaN HEMTs after irradiation with 1540 MeV Bi ions, which were attributed to defect generation and lattice disorder induced by heavy ion strikes [12]. Lei et al. reported a significant increase in gate leakage current after 800 MeV Bi ions irradiation, attributed to latent tracks along the ion trajectories through the heterojunction [13]. The second aspect focuses on single-event burnout (SEB) induced by heavy-ion irradiation under bias conditions. Two primary SEB mechanisms have been proposed by researchers: enhanced charge collection and high electric-field crowding [14], [15], [16], [17]. Onoda et al. proposed two enhanced charge collection mechanisms, the parasitic bipolar effect and the back-channel effect [14]. Zheng et al. reported that irradiation-induced carrier accumulation near the drain and gate edges can generate strong local electric fields, eventually leading to device burnout [16].

However, most existing studies have focused on the catastrophic failure induced by SEB, while the cumulative degradation of p-GaN gate HEMTs under synergistic conditions without burnout has received little attention, and the underlying mechanisms remain unclear. Therefore, it is of critical importance to systematically investigate the synergistic effects on device electrical degradation, which is essential for evaluating the long-term reliability of p-GaN gate HEMTs in aerospace environments.

In this work, the degradation mechanism of p-GaN gate AlGaN/GaN HEMTs under the combined off-state bias stress and heavy ion irradiation has been studied experimentally. The degradation behavior of the saturated drain current (I_{Dsat}) under heavy ion irradiation was observed. In addition, low-frequency noise (LFN), the capacitance deep-level transient spectroscopy

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(C-DLTS), and technology computer-aided design (TCAD) simulation techniques were further employed to investigate and elucidate the underlying degradation mechanisms in detail.

II. Device Structure and Experimental Setup

Fig. 1 illustrates a 3D schematic of the p-GaN gate AlGaN/GaN HEMT used in this work. A 4 µm GaN buffer layer is grown on Si substrate, followed by a 155 nm undoped GaN channel layer, a 15 nm $Al_{0.2}Ga_{0.8}N$ barrier layer, and an 80 nm Mg-doped p-GaN layer with the concentration of around 3 × 10^{19} cm^{-3}. The 650 V p-GaN gate AlGaN/GaN HEMT features a gate length of 1 µm, a gate-source spacing of 2 µm, a gate-drain spacing of 11 µm, and a source field plate spacing of 5 µm.

The irradiation experiment was carried out at room temperature at the Heavy Ion Research Facility in Lanzhou, Chinese Academy of Sciences. The heavy ion used in the experiment is 1912 MeV Ta with the linear energy transfer (LET) of 76.3 MeV·cm²/mg (in silicon), and the flux is around 1× 10^4 cm^{-2}/s. During the irradiation experiment, the gate bias (V_{GS}) was fixed at 0 V. The drain current (I_D), gate current (I_G), and source current (I_S) were monitored simultaneously.

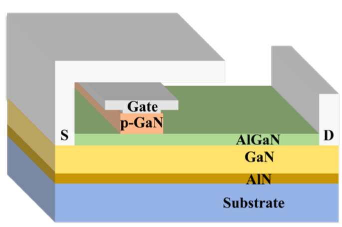

Fig. 1. Schematic illustration of the p-GaN gate AlGaN/GaN HEMTs used in this work.

III. Electrical Degradation Behavior

Fig. 2(a) shows the variation of I_D during irradiation under different V_{D_stress}. It can be observed that the I_D exhibited only slight fluctuations at V_{D_stress} = 360 V and 380 V. However, a sharp rise in I_D occurred when the drain bias was increased to 390 V, which indicates that the device experienced burnout. Hence, we can conclude that the V_{SEB} is around 390 V. To investigate the cumulative degradation induced by the synergistic effect of heavy-ion irradiation and electrical stress, the V_{D_stress} of 360 V was selected in the following. Under this stress condition, catastrophic burnout is avoided, and the electric field is sufficiently high to promote the synergistic effects. It is noteworthy that the total ion fluence during the synergistic effect experiment was 1 × 10^7 ions/cm².

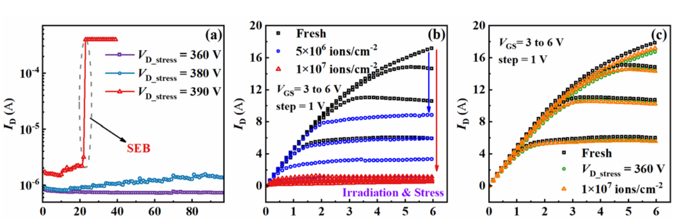

Fig. 2. (a) Real-time monitoring current during irradiation with different drain bias. Output characteristics of p-GaN HEMTs: (b) before and after heavy ion irradiation with 360 V electrical stress combined; (c) Before and after only drain bias stress (V_{D_stress} = 360 V) or heavy-ion irradiation (1 × 10^7 ions/cm²). Electrical stress was performed for 1000 s, corresponding to the irradiation duration required to reach 1 × 10^7 ions/cm².

The output characteristics of the device after heavy ion irradiation under V_{D_stress} = 360 V are shown in Fig. 2(b). A clear reduction in I_{Dsat} was observed with increasing ion fluence. At fluence of 5 × 10^6 ions/cm², the maximum I_{Dsat} decreased from 17.1 A to 8.9 A, corresponding to a reduction of about 47.9 %. With the total fluence of heavy ion increases to 1 × 10^7 ions/cm², the I_{Dsat} further dropped to 1.2 A, corresponding to nearly 92.9 % degradation. This severe reduction indicates that the electrical performance of the device was dramatically degraded.

To distinguish the individual impacts of heavy-ion irradiation and electrical stress on the electrical characteristics of the device, contrast experiments were performed. As shown in Fig. 2(c), the output characteristics remain nearly unchanged with a total fluence of 1 × 10^7 ions/cm². Similarly, the I_{Dsat} of the device exhibits only a slight reduction after electrical stress with the same stress duration. These results indicate that neither electrical stress nor heavy ion irradiation alone causes significant device degradation.

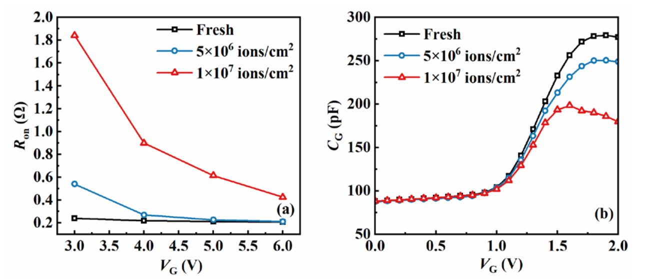

Fig. 3. (a) R_{ON} of p-GaN HEMT at different V_{GS}. (b) C_G-V_G characteristics of p-GaN HEMT.

To further clarify the origin of the degradation observed under the synergistic stress, Fig. 3 (a) compares the variation of on-resistance (R_{ON}) with V_{GS} for the fresh device and the post-irradiation device. For the fresh device, R_{ON} remains nearly constant over the V_{GS} range from 3 to 6 V, indicating that a sufficiently conductive channel is formed at V_{GS} =3V. In contrast, R_{ON} of the post-irradiation device exhibits a significant decrease as V_{GS} increases. Specifically, at a fluence of 5 × 10^6 ions/cm², the R_{ON} decreases from 540.5 mΩ to 210.9 mΩ when the V_{GS} ranges from 3 V to 6 V. With the total fluence increasing to 1 × 10^7 ions/cm², the R_{ON} decreases from 1.84 Ω to 425.5 mΩ over the same V_{GS} range. This behavior indicates that the irradiation-induced degradation is primarily associated with the gate-controlled region.

Furthermore, the variation in C_G is shown in Fig. 3 (b). A pronounced decrease in C_G is observed when the V_G ranges from 1 V to 2 V, and the reduction becomes more significant with increasing total fluence. By integrating the C_G-V_G curves, the effective gate-controlled 2DEG density is estimated. Compared to the fresh device, the reductions are 8.1% and 21.9% for total fluences of 5 × 10^6 and 1 × 10^7 ions/cm², respectively. However, their I_{Dsat} is degraded by 47.9% and 92.9%, respectively. This discrepancy indicates that the severe degradation in I_{Dsat} cannot be explained only by the reduction in 2DEG density. Therefore, it suggests that irradiation-induced defects near the channel may also significantly degrade carrier transport, primarily through enhanced Coulomb scattering and reduced effective mobility.

IV. Trap Characterization and Physical Mechanism Analysis

To investigate the physical origin of the degradation, low-frequency noise (LFN) measurements were performed before and after irradiation, as shown in Fig. 4. The noise measurements were conducted at V_{DS} = 0.1 V, and the normalized noise power spectral density (S_{ID}/I_D^2) was obtained at various frequencies near the threshold voltage. It can be observed that the S_{ID}/I_D^2 increases significantly after irradiation, indicating that a higher trap density occurs near the channel region [18]. Furthermore, both the fresh and post-irradiation devices exhibit a 1/f noise dependence over the frequency range from 1 Hz to 100 kHz. Fig. 4(d) shows the relationship between the S_{ID}/I_D^2 and the I_D at a frequency of 50 Hz. According to the carrier number fluctuation model proposed by McWhorter, a relationship between S_{ID} and the transconductance (g_m) of the device can be established as [19]:

$$\frac{S_{id}}{i_{DS}^2} = \left(\frac{g_m}{I_{DS}}\right)^2 S_{vfb} \tag{1}$$

where S_{vfb} is the flat-band voltage spectral density. The N_T is the trap density primarily attributed to traps located near the p-GaN/AlGaN/GaN heterointerface, and it can be extracted using the following equation [20], [21]:

$$N_T = \frac{fWLC^2}{q^2 KT\lambda} S_{vfb} \tag{2}$$

where C represents the capacitance of the AlGaN barrier layer, λ is the tunneling constant of AlGaN, and L and W denote the gate length and gate width of the device, respectively.

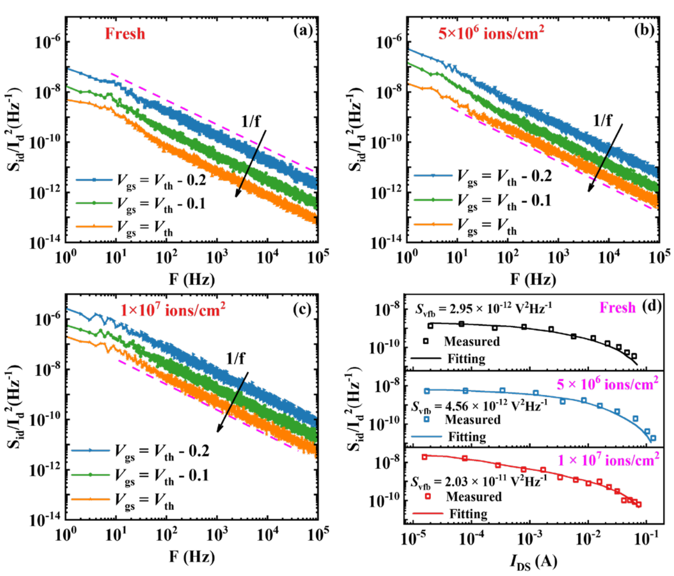

Fig. 4. S_{ID}/I_D^2 vs frequency curves for (a) Fresh and (b) 5 × 10^6 and (c) 1 × 10^7 ions/cm^2 heavy ion-irradiated, respectively. (d) The S_{ID}/I_D^2 obtained at 50 Hz as a function of I_{DS} before and after irradiation.

Based on the equation, the calculated trap densities N_T for the fresh device are 4.15 × 10^{14} cm^{-3}eV^{-1}. However, after irradiation the N_T increases significantly with increasing total fluence, reaching 1.18 × 10^{15} cm^{-3}eV^{-1} at a fluence of 5 × 10^6 ions/cm^2 and further rising to 5.42 × 10^{15} cm^{-3}eV^{-1} at 1 × 10^7 ions/cm^2. Results indicate that the N_T increases by approximately 13 times after irradiation. These radiation-induced defects lead to pronounced degradation in device performance by reducing the 2DEG mobility through Coulomb scattering and decreasing the 2DEG density via carrier removal [22], [23]. In addition, the accumulation of charged traps may introduce local electrostatic perturbations, which can further degrade the effective gate control over the channel [24].

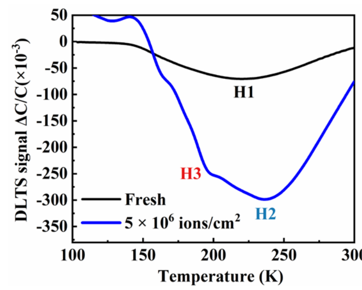

Fig. 5. The DLTS spectra measured before and after irradiation under V_M = 1.8 V, V_F = 2.5 V.

To further localize the radiation-induced defects within the gate stack, the capacitance deep-level transient spectroscopy （C-DLTS） measurements were performed to probe the trap states in the p-GaN layer. The measurement conditions were set to V_M = 1.8 V and V_F = 2.5 V to detect the traps in the p-GaN region. As shown in Fig. 5, for the fresh device, a hole trap peak is observed at approximately 230 K. After synergistic heavy-ion irradiation and electrical stress at a fluence of 5 × 10^6 ions/cm^2, the DLTS signal amplitude in this temperature range increases significantly, indicating a pronounced enhancement of hole trap concentration in the p-GaN layer. In addition, a shoulder feature (H2) becomes more evident after irradiation, suggesting the generation or activation of additional trap states under irradiation conditions. These results indicate that the radiation-induced trap generation in the p-GaN layer is primarily responsible for the observed electrical degradation.

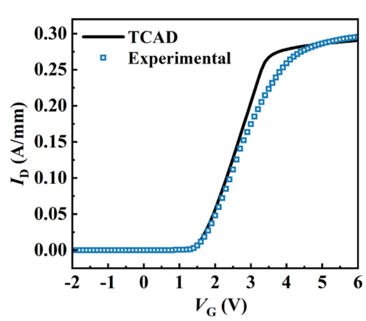

Fig. 6. Transfer characteristics of the fresh p-GaN HEMT.

To explore the mechanism of radiation-induced damage, TCAD simulations were performed in this work, including several typical models for p-GaN HEMT, such as Shockley-Read-Hall (SRH) model, polarization model, High

Field Mobility model, and impact ionization model [25], [26]. The simulated transfer characteristics of the p-GaN HEMT based on these models align well with the measurement results, as shown in Fig. 6, validating the accuracy of the simulation model proposed in this work. The heavy-ion model, impact ionization, and lattice temperature models were then incorporated to simulate the SEB process [25]. Heavy ions are defined as incident vertically on the p-GaN HEMTs, with physical parameters identical to those used in the irradiation experiments. During the simulation, the drain bias voltages were set to 360 V, consistent with the experimental conditions.

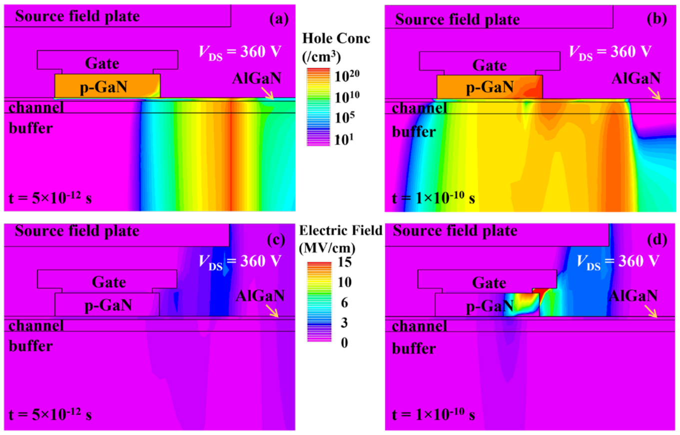

Fig. 7. Hole density distributions of p-GaN HEMT at (a) $t = 5 \times 10^{-12}$ s; (b) $t = 1 \times 10^{-10}$ s. Electric field distribution of the p-GaN layer at (c) $t = 5 \times 10^{-12}$ s; (d) $t = 1 \times 10^{-10}$ s.

TCAD simulation results indicate that SEB is more likely to be triggered by heavy-ion strikes near the edge of the source field plate (SFP) than at other positions between the source and drain. This result is consistent with previous studies, which have shown that heavy-ion strikes originating from vulnerable high electric field regions are more likely to induce catastrophic failure [27], [28]. Therefore, in the simulation of this study, heavy ions are all incident along the edge of the SFP. Fig. 7(a) and (b) depict the hole concentration distribution in p-GaN HEMT following heavy ion strike under V_{DS} = 360 V. The heavy-ion strike generates a dense track of carriers, among which holes drift upward and accumulate beneath the gate. This localized hole accumulation modifies the electrostatic potential and leads to a significant enhancement of the electric field in the p-GaN layer. As shown in Fig. 7(c) and (d), the electric field in the p-GaN layer increases significantly from 5 ps to 100 ps.

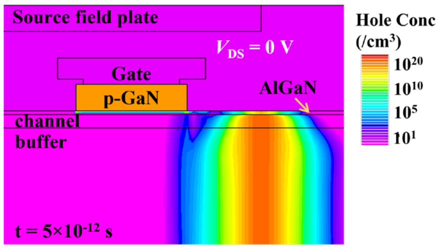

Fig. 8. Hole density distributions at $t = 1 \times 10^{-10}$ s under V_{DS} = 0 V.

In contrast, under V_{DS} = 0 V, the electron-hole pairs generated by a heavy-ion strike are not rapidly extracted or drifted due to the lack of an external electric field, as shown in Fig. 8. Consequently, the majority of these carriers disappear through recombination, resulting in slight degradation of the p-GaN HEMT.

Based on the experiments and simulation results, the schematic illustration of the synergistic effect between electrical stress and heavy ion irradiation in p-GaN HEMT is depicted in Fig. 9. Upon heavy-ion incidence, a large number of electron-hole pairs are generated along the ion track. Driven by the electric field, electrons drift toward and are collected by the drain. while holes move toward the gate. Concurrently, holes accumulate beneath the gate, inducing local high electric field in the p-GaN layer. The local high electric field facilitates the generation and charging of irradiation-induced defects. As a result, irradiation-induced defects, through Coulomb scattering and carrier removal, predominantly degrade the 2DEG mobility and reduce the 2DEG density. These combined effects ultimately lead to a severe deterioration of the electrical performance of the p-GaN HEMT.

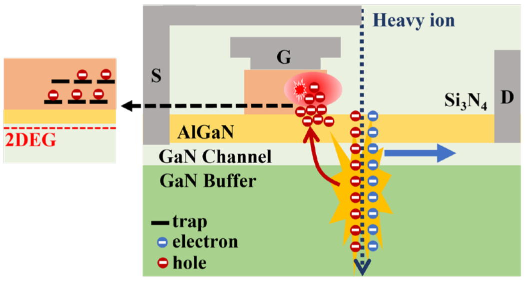

Fig. 9. Schematic diagram of the degradation mechanism of p-GaN HEMT under the synergistic effect of heavy ion irradiation and electrical stress.

V. Conclusion

In conclusion, the cumulative degradation of p-GaN gate HEMTs induced by the synergistic interaction of electrical stress and heavy-ion irradiation has been systematically investigated. It was observed that I_{Dsat} exhibits negligible degradation under electrical stress or irradiation alone. However, a pronounced degradation in I_{Dsat} occurs under their synergistic interaction, and the extent of degradation increases with the heavy-ion fluence. LFN and DLTS measurements reveal that the degradation is mainly associated with a significant increase in trap density within the p-GaN layer. The enhanced trap density leads to stronger Coulomb scattering and carrier removal in the channel, thereby degrading carrier transport. TCAD simulations further indicate that heavy-ion strikes generate a large number of holes that accumulate beneath the gate, intensifying the local electric field in the p-GaN region. The enhanced electric field promotes the activation and charging of irradiation-induced defects, further aggravating the electrical degradation. These results provide valuable insights into the reliability assessment and radiation-hardening design of GaN power devices for aerospace applications.

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