# Low power fluorine plasma effects on electrical reliability of AlGaN/GaN high electron mobility transistor*

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The new electrical degradation phenomenon of the AlGaN/GaN high electron mobility transistor (HEMT) treated by low power fluorine plasma is discovered. The saturated current, on-resistance, threshold voltage, gate leakage and breakdown voltage show that each experiences a significant change in a short time stress, and then keeps unchangeable. The migration phenomenon of fluorine ions is further validated by the electron redistribution and breakdown voltage enhancement after off-state stress. These results suggest that the low power fluorine implant ion stays in an unstable state. It causes the electrical properties of AlGaN/GaN HEMT to present early degradation. A new migration and degradation mechanism of the low power fluorine implant ion under the off-stress electrical stress is proposed. The low power fluorine ions would drift at the beginning of the off-state stress, and then accumulate between gate and drain nearby the gate side. Due to the strong electronegativity of fluorine, the accumulation of the front fluorine ions would prevent the subsequent fluorine ions from drifting, thereby alleviating further the degradation of AlGaN/GaN HEMT electrical properties.

**Keywords:** AlGaN/GaN HEMT, low plasma power, fluorine implant ion, early electrical reliability

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## 1. Introduction

The normally-off operation of AlGaN/GaN transistors has been successfully demonstrated by fluorine implantation.[1–4] Compared with the untreated AlGaN/GaN HEMT structure, the fluorine treated structure has its conduction band minimum above Fermi level, indicating a completely depleted channel and E-mode operation.[5–7] According to deep-level transient spectroscopy (DLTS) observation,[8] the fluorine ions incorporated into the AlGaN barrier introduce a deep level state near the mid-band gap under the high plasma power treatment. Therefore, the fluorine ions are believed to be immobile negatively-charged ions, leading to an additional barrier height. With a high electric field applied continuously (e.g., several hundred hours of off-state electrical stress), electrical stress began to create new defects.[9] After that, the fluorine ions could move along the vacancy-type defects and dislocations. Therefore, the fluorine ions migrate under the gate, leading to a negative shift of threshold voltage. However, so far there have been no reports on the early electrical characteristic degradation of AlGaN/GaN HEMT by low power fluorine ion treatment. In the traditional T-gate field plate process, over-etching is needed to completely remove the SiN layer. Therefore, a small number of low power fluoride ions will be implanted into the AlGaN barrier layer. These implanted fluorine ions will influence stability and reliability of AlGaN/GaN HEMT during the device operation, especially under high electric-field electrical stress. By analyzing the electrical degradation phenomenon under off-state electrical stress, we found that the direct migration of low power implanted fluorine ions was the major reason for the electrical characteristic degradation.

In this paper, a novel degradation mechanism for the low-power fluorine ions implanted into traditional T-gate AlGaN/GaN HEMT is proposed. The saturated current, on-resistance, threshold voltage, gate leakage, and breakdown voltage of low power fluorine treatment AlGaN/GaN HEMT are systematically studied. Finally, the migration phenomenon of fluorine ions is analyzed by the electron redistribution and breakdown voltage enhancement after off-state stress.

## 2. Device fabrication

The undoped AlGaN/GaN hetero-structure layers were grown on a 2-in sapphire substrate by using metal-organic chemical vapor deposition at the University of Xidian. The HEMT hetero-structure comprised 1.5-μm undoped GaN buffer and a 25-nm $Al_{0.25}Ga_{0.75}N$ barrier. Device processing started with the Ti/Al/Ni/Au source and drain electrodes. These were annealed at 850 °C for 30 s in a rapid thermal an-

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neal. Device isolation was achieved by reactive ion etching using $Cl_2$ plasma. SiN passivation was achieved with plasma-enhanced chemical vapor deposition. After gate windows with 0.5 μm length were opened, the samples were treated by $CF_4$ plasma at 50 W for 150 s, 60 W for 150 s and 70 W for 150 s, respectively. Gate patterns were defined by optical lithography with a gate length of 0.5 μm. Then, Ni/Au e-beam evaporation and lift-off were carried out subsequently to form the gate electrodes. Each of all devices in this work had a gate width of 2×50 μm, a gate-source spacing of 0.7 μm, and a gate-drain spacing of 3 μm. A schematic cross section of the structure is shown in Fig. 1.

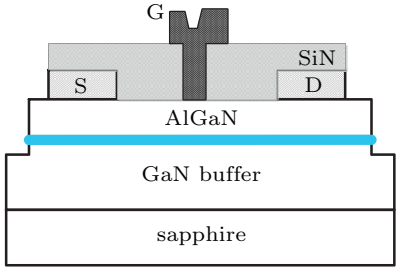



**Fig. 1.** (color online) A schematic cross section of AlGaN/GaN HEMT.

## 3. Results and discussion

The measurement setup is built by using a Keysight B1500A semiconductor device analyzer. A high-resolution source measure unit (SMU) is used for accurate and precise measurement in a range of 1 fA. The high-power SMUs are used for larger voltage/current measurement ranging up to 200 V/1 A. The DC characteristics for different power fluorine treatment AlGaN/GaN HEMTs are shown in Fig. 2(a). At $V_{gate} = 1$ V, the drain current decreases with the increase of fluorine implant ion power. The maximum current changes from 879 mA/mm to 812 mA/mm (Fig. 2(b)). It indicates that the increase of fluorine injection dose will lead to the decrease of maximum current.

Figure 3 shows the transfer characteristics, which are measured at a drain voltage of 10 V. With the increase of fluorine implant ion power, the trans-conductance peak ($G_m$) increases from 160 mS/mm to 189 mS/mm. The threshold voltage varies from −5.15 V to −4.4 V. The shift of transfer curves is partially due to the AlGaN barrier layer etching, but also due to low power fluorine ion implantation. The most significant increase of the $G_m$ occurs at the beginning, and then the increase slows down (Fig. 3(b)). This indicates that the effect of fluorine ion changes from physical etching to ion implant. This is because the implanted fluorine ions can only make the device threshold voltage positively shifted, which does not make the trans-conductance increase.

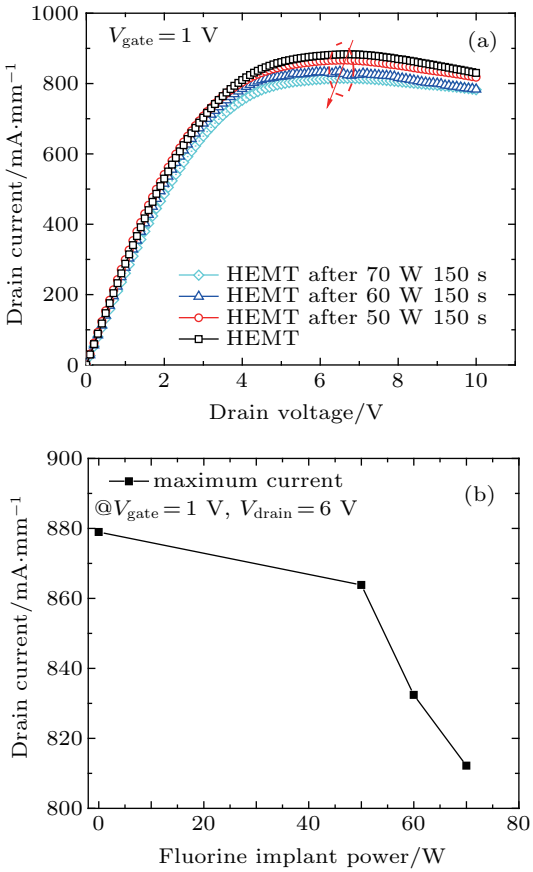



**Fig. 2.** (color online) (a) Output characteristics and (b) drain current under different-power fluorine treatments.

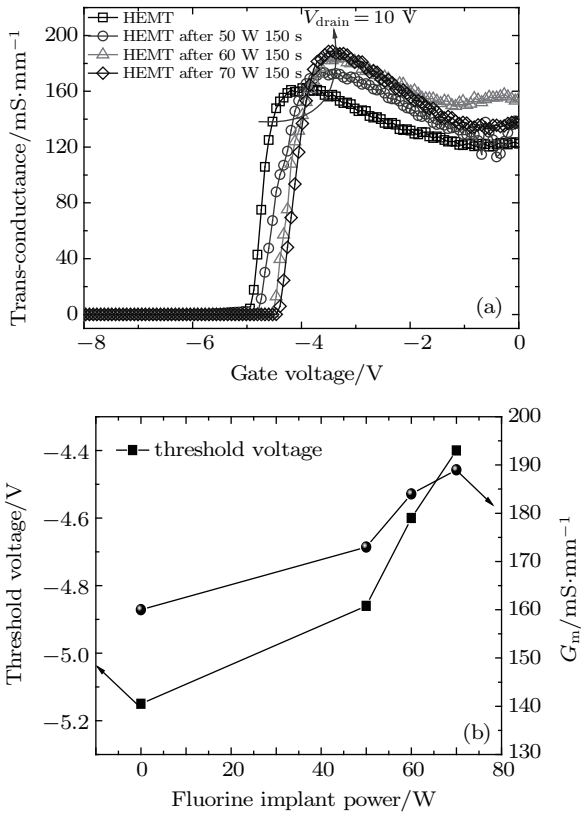



**Fig. 3.** (a) Plots of transfer conductance versus gate voltage for different implant powers and (b) plots of threshold voltage and $G_m$ shift versus fluorine implant power.

Figure 4 shows the *I*–*V* characteristics of AlGaN/GaN Schottky diode after different-low-power fluorine plasma treatments. It is observed that implanted fluorine ions lead to the decrease of the reverse leakage current and the increase of forward voltage ($V_F$). This is because the negative fluorine ion causes the conduction band to bend upward in the AlGaN layer. Further experiments show that fluorine-plasma treatment reduces the gate leakage current, which enables the operation at much higher drain biases.[10,11]

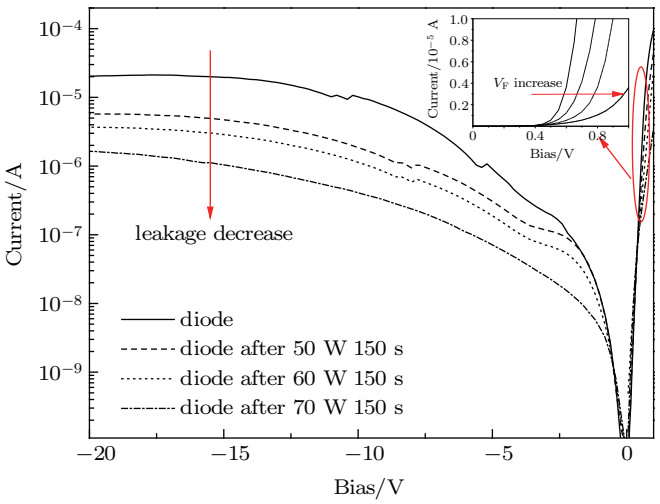



**Fig. 4.** (color online) The *I*–*V* characteristics of AlGaN/GaN Schottky diode after fluorine plasma treatment.

In the following off-state electrical stress experiments, the gate voltage is biased at −30 V and the drain voltage is biased at 20 V. The stress time is then increased from 0 to 3 h. Here, $I_{Dmax}$ is defined as the drain current at $V_{gate} = 1$ V and $V_{drain} = 10$ V, and $R_{ch}$ is defined as the channel resistance that is the slope of curve of drain voltage versus drain current in the linear region. $V_{th}$ is defined as the threshold voltage with the maximum trans-conductance method, and $I_{Goff}$ is defined as the gate current at $V_{gate} = -30$ V and $V_{drain} = 20$ V. Figure 5 shows the time-depenent degradations of drain current and channel resistances at different-fluorinepower treatments under off-state electric stress. In region I, both drain current and channel resistance have more obvious degradations with the increase of fluorine implant ion power. Then, they enter into region II and basically keep unchanged. Compared with the low power fluorine treatment devices, the untreated HEMT shows a stable state.

The stress time dependences of threshold voltage and gate leakage are plotted in Fig. 6. In region I, both threshold voltage and gate leakage have more obvious degradations with the increase of fluorine implant ion power. In region II, the magnitudes of degradation are almost constant. For untreated HEMT, the threshold voltage and gate leakage are independent of off-state stress.

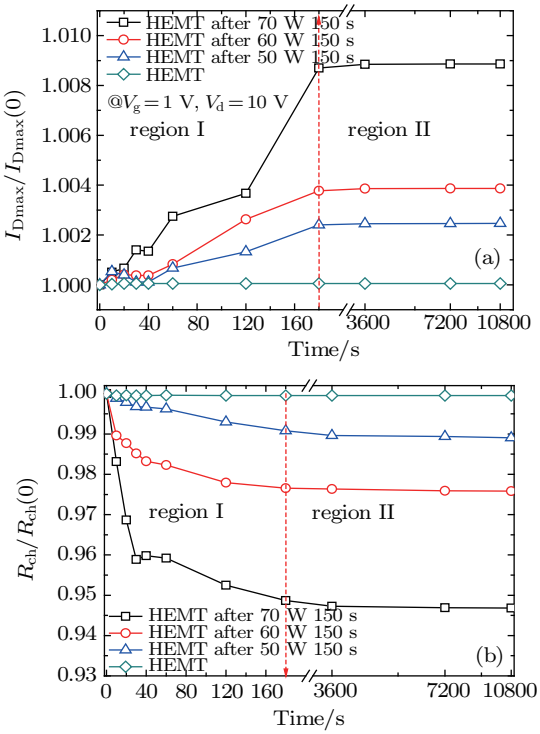



**Fig. 5.** (color online) (a) Time-dependent normalized saturation currents and (b) time-dependent channel resistances at different-fluorine-power treatments under off-state electric stress.

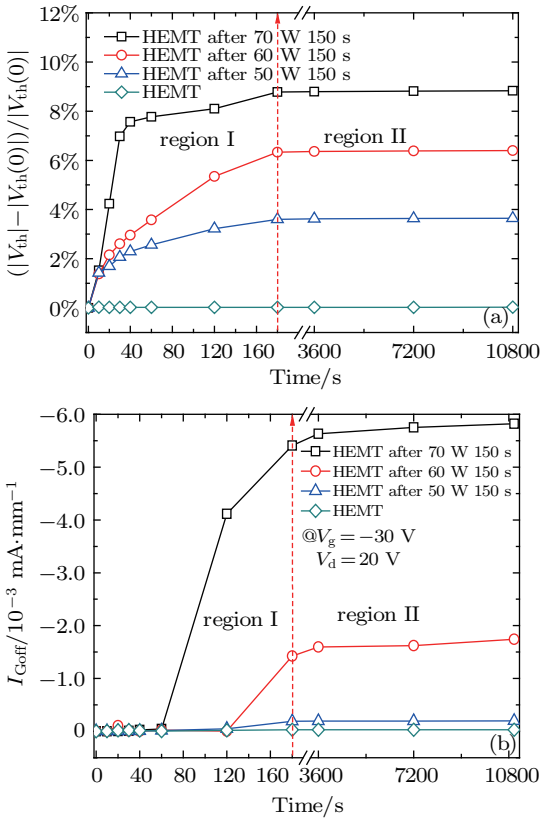



**Fig. 6.** (color online) (a) Time-dependent normalized threshold voltage negative shifts and (b) time-dependent gate leakage increase at different-fluorine-power treatments under off-state electric stress.

The variations of electron redistribution with depth of AlGaN/GaN hetero-structure (70 W for 150 s fluorine treatment)

after off-state stress are displayed in Fig. 7. $N_{CV}$ is defined as volume charge density and measured by the CV profiling technique. In the channel region, there is a significant increase in the electron concentration after off-state stress. This indicates that the migrations of fluorine ions under off-state stress make the 2DEG concentration partially recovered. In the buffer layer, the electron distribution concentration also increases after off-state stress. This indicates that the migrations of fluorine ions make the depletion layer thickness reduced in the GaN layer. When the stress time is longer than 180 s, the increase of electron concentration slows down as off-state stress time increases.

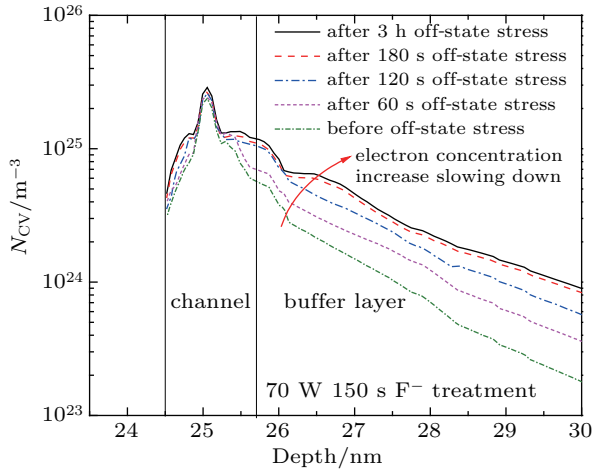



**Fig. 7.** (color online) Electron redistributions of 70 W for 150 s treatment device after off-state stress.

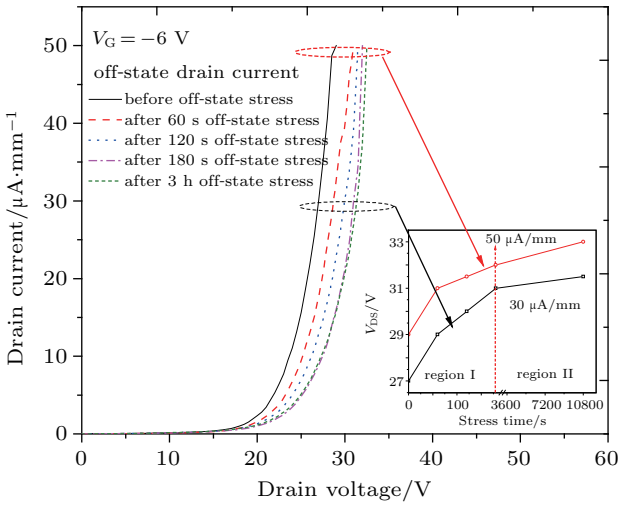



**Fig. 8.** (color online) Off-state $I_{DS}$–$V_{DS}$ characteristic enhancement at 70 W for 150 s treatment device after off-state electrical stress.

Figure 8 shows the off-state $I_{DS}$–$V_{DS}$ characteristic enhancement in 70 W for 150 s treatment device after off-state electrical stress. By applying the off-state stress, a 4 V increase is realized in breakdown voltage. The introduction of fluorine ions which migrate from gate to drain-side gate edge effectively reduce the surface field distribution on the drain side. Therefore, the lower off-state current and higher breakdown voltage are achieved. References [12] and [13] showed that the fluorine plasma treatment on the drain-side gate edge can enhance breakdown voltage. In Fig. 8, the inset shows that the breakdown voltage increases rapidly in region I but slowly in region II. This trend is consistent with the above experimental results.

A schematic diagram demonstrating the proposed fluorine ion degradation mechanism at off-state electric field for low-power fluorine treatment AlGaN/GaN HEMT is drawn in Fig. 9. The degradation tendency mentioned above can be divided into two regions, which show a new degradation mechanism. This new degradation mechanism is different from that for the traditional defect assisted migration.[14–17] In region I, the migrations of fluorine ions are the main reason for the degradation of AlGaN/GaN HEMT. The negatively-charged fluorine ions experience a strong coulomb force during the off-state electrical stress, which could lead to physical migrations of fluorine ions away from the gate. The reductions of the negatively-charged fluorine ions in the gate region could then lead to the rapid degradations of electrical characteristics. In region II, the reduction of electrical parameter degradation indicates that less fluorine ions migrate. Due to SiN passivation, the fluorine ions could not escape from the AlGaN to the air.[18] The migrations of fluorine ions would accumulate at the drain-side gate edge. Due to the strong electronegativity of fluorine, the accumulation of the front fluorine ions would prevent the subsequent fluorine ions from drifting, thereby alleviating further the degradation of AlGaN/GaN HEMT electrical parameter.

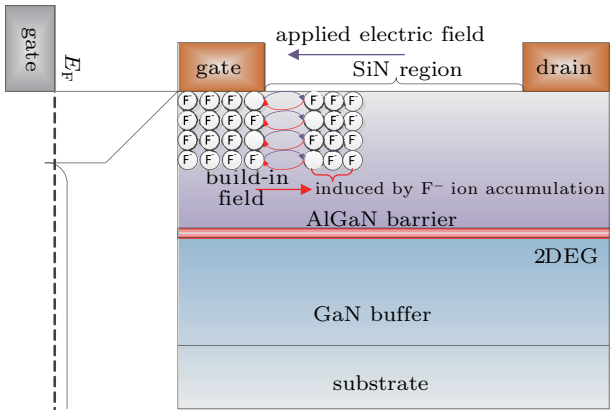



**Fig. 9.** (color online) Schematic diagram showing the proposed migration mechanism of the low-power fluorine ions under the off-state electrical stress.

## 4. Conclusions

In this work, the early reliability of AlGaN/GaN HEMT with low-power fluorine treatment is investigated systematically. Relating to low-power implanted fluorine ions that induce the unique early electrical reliability problem, the electrical degradation mechanism is discussed. Degradation ten-

dency can be divided into two modes. In region I, the migration of fluorine ions is the main reason for rapid degradation. In region II, the build-in electrical field induced by fluorine ion accumulation is the main reason for slow degradation. The new transport hypothesis based on low power implant fluorine ions is further validated by the electron redistribution and breakdown voltage enhancement after off-state stress. Therefore, it should avoid low-power fluorine implanting in the T-gate field plate process, thereby improving the short-term reliability of AlGaN/GaN HEMT.

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