A high-performance enhancement-mode AlGaN/GaN HEMT*

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Abstract: An enhancement-mode AlGaN/GaN HEMT with a threshold voltage of 0.35 V was fabricated by fluorine plasma treatment. The enhancement-mode device demonstrates high-performance DC characteristics with a saturation current density of 667 mA/mm at a gate bias of 4 V and a peak transconductance of 201 mS/mm at a gate bias of 0.8 V. The current-gain cut-off frequency and the maximum oscillation frequency of the enhancement-mode device with a gate length of 1 μm are 10.3 GHz and 12.5 GHz, respectively, which is comparable with the depletion-mode device. A numerical simulation supported by SIMS results was employed to give a reasonable explanation that the fluorine ions act as an acceptor trap center in the barrier layer.

Key words: enhancement-mode; AlGaN/GaN HEMT; fluorine plasma; threshold voltage; numerical simulation
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1. Introduction

High electron mobility transistors (HEMTs) based on AlGaN/GaN heterostructures present excellent candidates for high-power, high-voltage and high-temperature applications[1]. The performance of conventional depletion-mode (D-mode) HEMTs has significantly improved in the last decade, while for digital IC applications and also for RFIC or MMIC design, enhancement-mode (E-mode) devices will play a more important role in the future. For digital IC applications, the simplest circuit configuration can be achieved by using direct-coupled FET logic (DCFL) which features integration of D-mode and E-mode HEMTs[2]. At the same time, for large scale IC design, E-mode devices which do not need a negative voltage supply can greatly reduce the circuit design complexity. Herein, the study of enhancement-mode devices based on the AlGaN/GaN material system is becoming a hot topic nowadays.

Recently, there have been several reports on E-mode GaN HEMTs. Wang *et al*.[3] used a recessed gate with a gate length of 1.2 μm to fabricate enhancement-mode devices with a threshold voltage of 0.57 V, a saturation drain current density of 332 mA/mm at a gate bias of 3 V, and a current-gain cutoff frequency (f_t) of 5.2 GHz. Cai *et al.*[4] used a fluorine-based plasma treatment to fabricate enhancement-mode devices with a saturation drain current density of 310 mA/mm and a peak transconductance of 148 mS/mm.

In this work, a high-performance E-mode AlGaN/GaN HEMT with a threshold voltage of 0.35 V was fabricated by fluorine plasma treatment. Numerical simulation was employed to give a reasonable explanation for the role of fluorine ions in the barrier layer.

2. Experiment

The AlGaN/GaN heterostructure used in this work was grown on n-type SiC substrate by metal organic chemical vapor deposition (MOCVD). The epitaxial structure consisted of a 1.8-μm-thick S.I.-GaN buffer layer, a thin AlN interlayer and a 20-nm-thick AlGaN barrier layer with an Al composition of approximately 21%. Finally, the structural surface was terminated by a 2-nm-thick GaN cap layer.

Device isolation was carried out by mesa etching with chlorine-based plasma in an ICP-RIE system. Source and drain ohmic contacts were prepared using e-beam evaporated Ti/Al/Ni/Au metallization, followed by rapid thermal annealing at 850 ℃ for 30 s. Using on-wafer transfer length method patterns, the ohmic contact resistance was typically measured to be around 0.7 Ω·mm. After the 1 × 100 μm gate windows were opened, the sample was treated by CF4 plasma in an RIE system with an RF plasma power of 150 W for 150 s. Subsequently, the Ni/Au gate was formed by electron-beam evaporation and the lift-off process. Subsequently, PECVD Si_3N_4 dielectric film with a thickness of 200 nm was employed for surface passivation, and then rapid thermal annealing (RTA) was conducted at 400 ℃ for 10 min.

3. Results and discussion

The current–voltage output characteristics of AlGaN/GaN HEMTs with and without fluorine plasma treatment are shown in Figs. 1(a) and 1(b). As shown in Fig. 1(b), the drain current when $V_{gs} = 0$ V is comparable to that of the D-mode HEMT just when $V_{gs} = -4$ V. That is to say, the device shown in Fig. 1(b) can be regarded as pinched-off when the gate voltage is set as 0 V. That means that the device treated by fluorine plasma can be operated at enhancement mode. Compared with the D-mode HEMT, the E-mode device presents a nearly iden-

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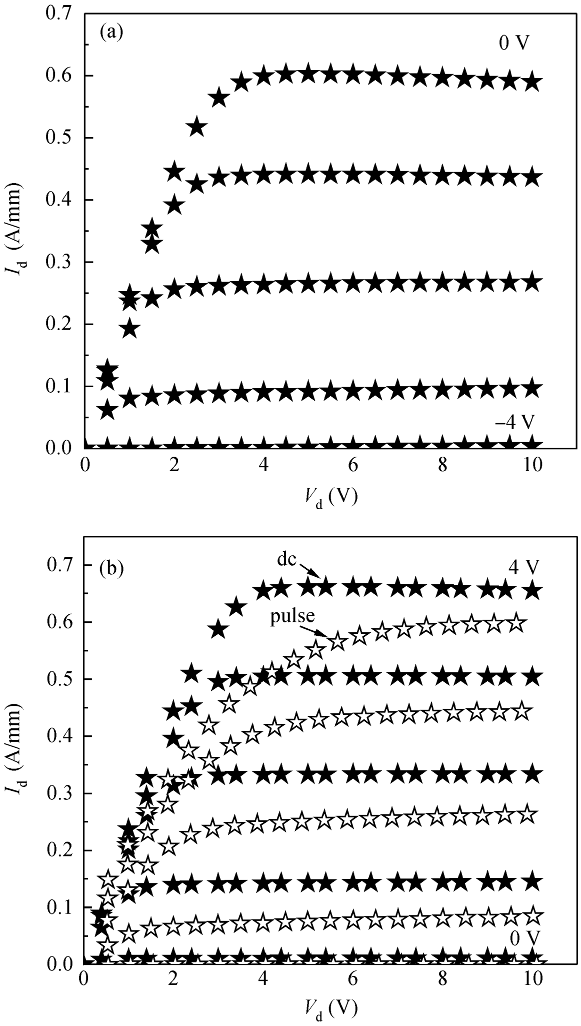

Fig. 1. (a) DC I–V characteristic of a depletion-mode AlGaN/GaN HEMT. (b) DC and pulsed I–V characteristic of an enhancement-mode AlGaN/GaN HEMT.

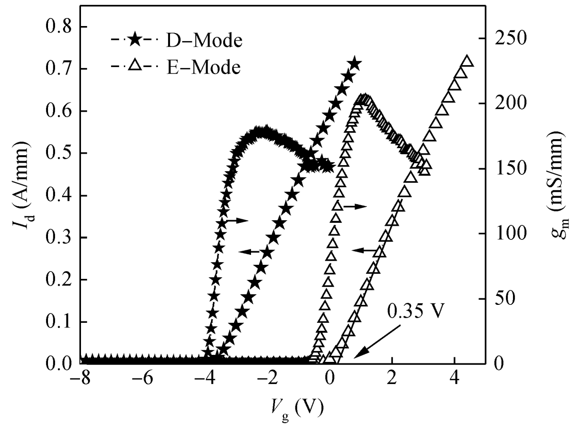

Fig. 2. Transfer and transconductance characteristics of the depletion-mode and enhancement-mode AlGaN/GaN HEMTs.

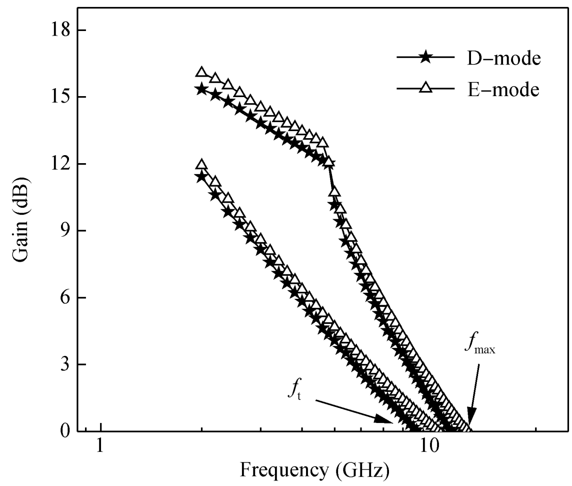

Fig. 3. Small-signal characteristics of the depletion-mode and enhancement-mode AlGaN/GaN HEMTs.

tical current handling ability. The enhancement-mode device exhibits a saturation output current density of 667 mA/mm at V_{gs} = 4 V. The pulsed current–voltage (I–V) characteristics of the E-mode GaN HFET are also plotted in Fig. 1(b). The pulse length and separation time are 0.2 μs and 1 ms with an initial bias point at V_{ds} = 20 V and V_{gs} = –3 V. A low level of current collapse is observed, suggesting no adverse effects associated with the fluorine plasma induced traps.

The transfer curves of D-mode and E-mode devices are shown in Fig. 2. A distinct parallel shift of the transfer curves combined with a threshold voltage is present. Here, the threshold voltage is defined as the gate bias voltage intercept of the linear extrapolation of the drain current. It is obviously that the threshold voltage is approximately 0.35 V for the E-mode device, corresponding to the threshold voltage of –4 V for the D-mode device. As shown in Fig. 2, considering the same non-recessed-gate structure, the transconductance (g_m) of the E-mode device fabricated by fluorine plasma treatment presents a high performance of 201 mS/mm.

The RF characteristics of the D-mode and E-mode devices are characterized at a drain bias of 8 V, as shown in Fig. 3. The current gain ($|h_{21}|$) and the maximum available/stable power gain (MAG/MSG) are extracted from the measured S-parameters and plotted against frequency. The current gain cut-off frequency (f_t) and maximum oscillation frequency (f_{max}) are about 10.3 GHz and 12.5 GHz without de-embedding. Also, it does not show any regression compared with that of the depletion-mode device. The low performance of the maximum oscillation frequency should be due to the high parasitic capacitance from the n-type SiC substrate.

4. Numerical simulation

Li *et al.*[5] have reported that the fluorine-related centers could recapture electrons with an energy barrier of 0.624 meV for AlGaN/GaN heterostructure treated by fluorine plasma. Also, Cai *et al.*[6] observed that fluorine ions incorporated in an AlGaN barrier introduced a negatively charged acceptor-like deep level which was at least 1.8 eV below the conduction-band. Here, the effect of F-related centers is simulated by numerical simulation tools and the F-related centers are treated as acceptor trap centers. The number of F-related centers is simply identified by SIMS results.

The simulation structure is the same as that of samples

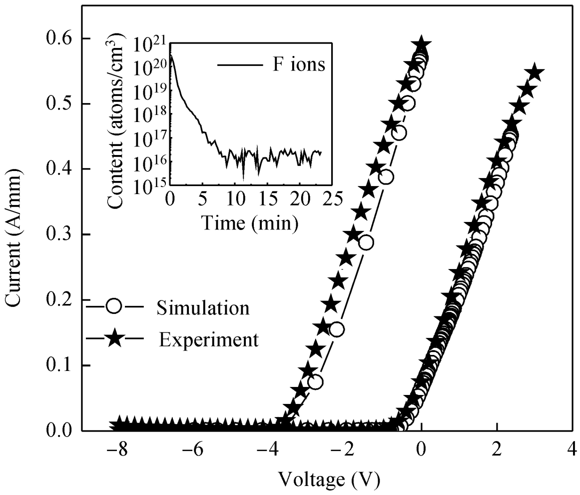

Fig. 4. Comparisons of the simulation and experiment results before and after fluorine plasma treatment of AlGaN/GaN HEMTs. The inset is the SIMS result for the sample treated by fluorine plasma.

treated by fluorine plasma in the previous experiment. The fixed charge concentration of 9.25×10^{12} cm^{-2} is modeled as the 2DEG channel concentration along the AlGaN/GaN interface. The F-related centers are treated as an acceptor trap with an energy barrier of 1.8 eV below the conduction-band.

Figure 4 shows the simulation results. Compared with the transfer characteristic of samples treated by fluorine plasma and simulated by SMIS experiments, the simulation results show a good consistence with that of experiments. In other words, it is a feasibility treatment that the fluorine ions can be treated as acceptor traps in the AlGaN barrier layer.

5. Conclusion

A high-performance enhancement-mode AlGaN/GaN HEMT was fabricated by fluorine plasma treatment. The enhancement-mode device exhibits a saturation current density of 667 mA/mm, a peak transconductance of 201 mS/mm, and a current gain cut-off frequency (f_t) of 10.3 GHz with a gate length of 1 μm, respectively. The numerical simulation results give a reasonable verification that fluorine ions can be treated as acceptor trap centers in the AlGaN barrier layer.

References

[1] Mishra U K, Shen L K, Kazior T E, et al. GaN-based RF power devices and amplifiers. Proc IEEE, 2008, 96(2): 287
[2] Long S, Butner S E. Gallium arsenide digital integrated circuit design. New York: McGraw-Hill, 1990
[3] Wang Chong, Zhang Jinfeng, Quan Si, et al. An enhancement-mode AlGaN/GaN HEMT with recessed-gate. Journal of Semiconductors, 2008, 29(9): 1682
[4] Cai Y, Zhou Y G, Chen K J, et al. High-performance enhancement-mode AlGaN/GaN HEMTs using fluoride-based plasma treatment. IEEE Electron Device Lett, 2005, 26(7): 435
[5] Li B K, Ge W K, Wang J N, et al. Persistent photoconductivity and carrier transport in AlGaN/GaN heterostructures treated by fluorine plasma. Appl Phys Lett, 2008, 92(8): 082105
[6] Cai Y, Zhou Y, Lau K M, et al. Control of threshold voltage of AlGaN/GaN HEMTs by fluoride-based plasma treatment: from depletion mode to enhancement mode. IEEE Trans Electron Devices, 2006, 53(9): 2207