Investigation of AlGaN/GaN fluorine plasma treatment enhancement-mode high electronic mobility transistors by frequency-dependent capacitance and conductance analysis*

Quan Si(全 思)†, Hao Yue(郝 跃), Ma Xiao-Hua(马晓华), and Yu Hui-You(于惠游)
Key Laboratory of Wide Band Gap Semiconductor Materials and Devices, Institute of Microelectronics, Xidian University, Xi'an 710071, *China*

(Received 11 March 2010; revised manuscript received 7 July 2010)

This paper reports fluorine plasma treatment enhancement-mode HEMTs (high electronic mobility transistors) EHEMTs and conventional depletion-mode HEMTs DHEMTs fabricated on one wafer using separate litho-photography technology. It finds that fluorine plasma etches the AlGaN at a slow rate by capacitance–voltage measurement. Using capacitance–frequency measurement, it finds one type of trap in conventional DHEMTs with $\tau_{\rm T} = (0.5-6)$ ms and $D_{\rm T} = (1-5)\times10^{13}$ cm$^{-2}\cdot$ eV^{-1}. Two types of trap are found in fluorine plasma treatment EHEMTs, fast with $\tau_{\rm T(f)} = (0.2-2)$ μs and slow with $\tau_{\rm T(s)} = (0.5-6)$ ms. The density of trap states evaluated on the EHEMTs is $D_{\rm T(f)} = (1-3)\times10^{12}$ cm$^{-2}\cdot$ eV^{-1} and $D_{\rm T(s)} = (2-6)\times10^{12}$ cm$^{-2}\cdot$ eV^{-1} for the fast and slow traps, respectively. The result shows that the fluorine plasma treatment reduces the slow trap density by about one order, but introduces a new type of fast trap. The slow trap is suggested to be a surface trap, related to the gate leakage current.

Keywords: AlGaN/GaN, enhancement-mode high electronic mobility transistors, fluorine plasma treatment, frequency dependent capacitance and conductance

PACS: 81.05.Ea, 85.30.De, 85.50.–n **DOI:** 10.1088/1674-1056/20/1/018101

1. Introduction

Fluorine plasma treatment[1] is a robust approach to controlling the threshold voltage of AlGaN/GaN hige electron mobility transistors (HEMTs).[2−4] This technique has been demonstrated to shift the threshold voltage of AlGaN/GaN HEMTs toward positive bias, thus enabling enhancement-mode operation.[5−8] It has also been reported that exposure of AlGaN/GaN HEMTs to CF_4 plasma prior to gate metallization can significantly suppress gate leakage.[9,10] But the influence of fluorine plasma treatment on AlGaN/GaN HEMTs is not very clear in theory. This paper reports fluorine plasma treatment enhancement-mode HEMTs (high electronic mobility transistors) (EHEMTs) and conventional depletion-mode HEMTs (DHEMTs) fabricated on one wafer using separate litho-photography technology. Capacitance–frequency measurement is used to calculate the trap density of different devices. Using fluorine plasma treatment, the slow surface trap is reduced and a new fast trap is introduced.

2. Device and fabrication

An AlGaN/GaN HEMT layer was grown by metal organic chemical vapour deposition (MOCVD) on a sapphire substrate. The heterostructure consists of a nucleation layer, a 1 μm-thick GaN buffer layer and an un-doped 20 nm-thick AlGaN barrier layer. The AlN mole fraction of the AlGaN was 30%. A step-and-repeat system was used to open the gate regions of AlGaN/GaN DHEMTs and AlGaN/GaN EHEMTs separately on one wafer. These processes were described in detail in our previous paper.[11] The device fabrication started with mesa isolation which was formed by ICP with the etch-depth of 200 nm. Ohmic contacts consisting of Ti/Al/Ni/Au (22 nm/140 nm/55 nm/45 nm) were annealed in nitrogen ambient at 850 °C, yielding a contact resistance typically around 1.0 $\Omega\cdot$mm. The Schottky contacts were formed by Ni/Au. Before the gate deposition of the AlGaN/GaN EHEMTs, the wafer was treated by CF_4 plasma (150 W, 150 s) in a reactive ion etching (RIE) system. Direct current characteristics were measured by an Agilent 1500B semiconductor

*Project supported by the National Natural Science Foundation of China (Grant No. 60736033) and the Fundamental Research Funds for the Central Universities (Grant No. JY10000904009).
†Corresponding author. E-mail: siquan@163.com
© 2011 Chinese Physical Society and IOP Publishing Ltd

parameter analyser, Capacitance–voltage (C–V) and capacitance–frequency were measured by a Keythley 4200 instrument.

3. Measurement and discussion

The threshold voltages are typically 0.57 V and –3.5 V for the AlGaN/GaN EHEMTs and AlGaN/GaN DHEMTs, respectively. The transconductance peak values of AlGaN/GaN EHEMTs and AlGaN/GaN DHEMTs are 201 mS/mm and 234 mS/mm, respectively. The gate leakage current of an AlGaN/GaN EHEMT is about one order of magnitude lower than that of a DHEMT (Fig. 1). The DC characteristics obtained are consistent with previouse reports.[5,6,12]

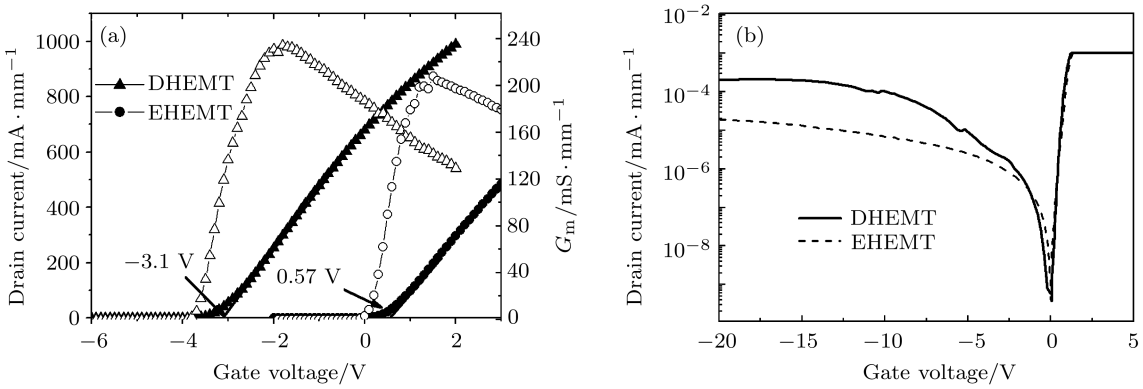


Fig. 1. (a) The DC I–V transfer characteristics of AlGaN/GaN DHEMT and EHEMT (full point is drain current and open point is G_m); (b) Gate leakage characteristics of AlGaN/GaN Schottky gate diodes with and without fluorine plasma treatment.

The C–V characteristics of AlGaN/GaN Schottky gate diodes with and without fluorine plasma treatment are shown in Fig. 2. It can be observed that the accumulation capacitance of diodes with fluorine plasma treatment is larger than that without. We think that the gate-to-channel distance is decreased by the fluorine plasma treatment. In order to prove this, we constructed some graphs on a wafer by lithophotography and then treated the wafer with CF_4 (150 W, 150 s). The etch depth of 4 nm was measured by an atomic force microscope (AFM) shown in Fig. 3. So we conclude that fluorine plasma etches the AlGaN at a slow rate. The reduction of the transconductance peak value is probably due to etching damage.

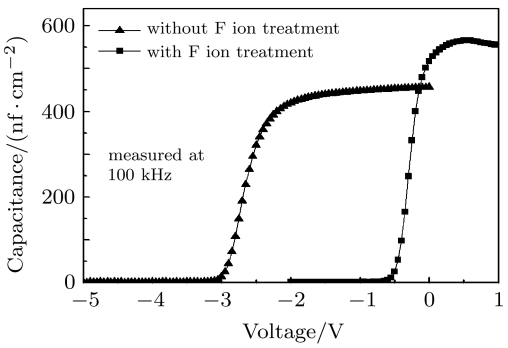


Fig. 2. The C–V characteristics of AlGaN/GaN Schottky gate diodes with and without fluorine plasma treatment.

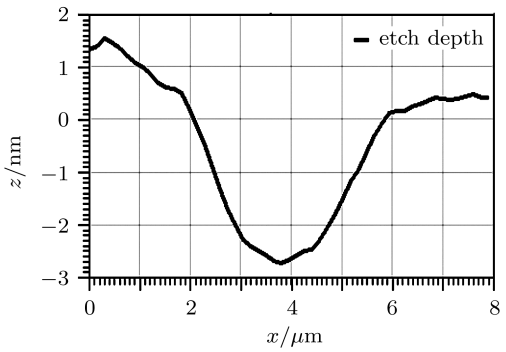


Fig. 3. The AFM image showing 4 nm etching depth of fluorine plasma treatment on the AlGaN layer.

Conductance measurements in the frequency range from 10 kHz to 1 MHz were used to characterize the trapping effects in the prepared DHEMTs and EHEMTs. Assuming a continuum of trap levels, we can express the equivalent parallel capacitance C_P and conductance G_P as functions of frequency as[13]

$$C_p = C_b + \frac{qD_T}{\omega\tau_T \tan(\omega\tau_T)}$$

and

$$\frac{G_p}{\omega} = \frac{qD_T}{2\omega\tau_T} \ln[1 + (\omega\tau_T)^2],$$

where D_T is the trap density, τ_T is the trap state time constant, C_b is the barrier capacitance, and ω is the radial frequency. The D_T and τ_T quantities can be extracted by fitting the experimental $C_P(\omega)$ or

$G_{\rm P}(\omega)$ data. The conductance data were used to calculate the trap density and trap state time constant, as in this case the barrier capacitance $C_{\rm b}$ is not required to be known. Typical $G_{\rm P}/\omega$ versus ω curves for the DHEMT and EHEMT, measured at selected biases near threshold voltage, are shown in Figs. 3 and 4. The data for the DHEMT show one peak, which indicates that onlyt 'slow' traps exist in the DHEMTs. The data for the EHEMT show two peaks. This indicates that two different trap states, 'fast' and 'slow' with different densities and time constants, aree present. So the conductance $\rm G_P$ can be expressed as

$$\frac{G_{\rm p}}{\omega} = \frac{qD_{\rm T(f)}}{2\omega\tau_{\rm T(f)}} \ln\left[1+(\omega\tau_{\rm T(f)})^2\right] + \frac{qD_{\rm T(s)}}{2\omega\tau_{\rm T(s)}} \ln\left[1+(\omega\tau_{\rm T(s)})^2\right].$$

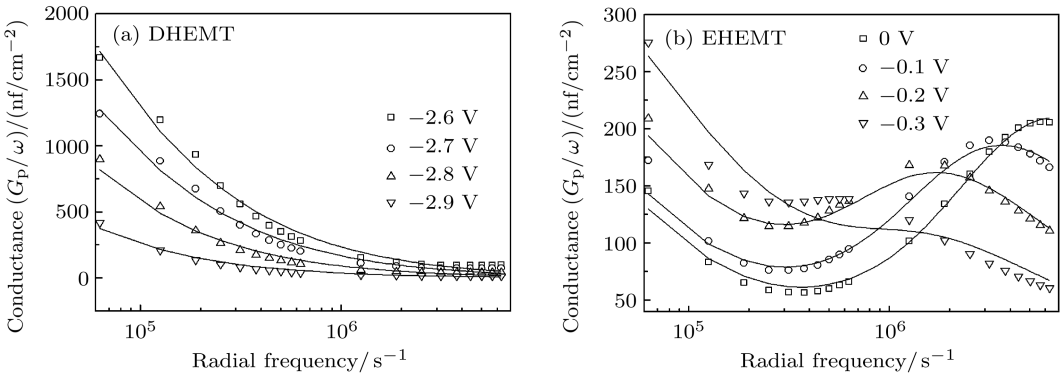


Fig. 4. Conductance as a function of frequency for (a) AlGaN/GaN DHEMT and (b) fluorine plasma treatment EHEMT at the gate voltages near depletion (full lines are fitting curves).

An excellent agreement between the measured data and fitted curves was obtained, assuming two different trap states in the EHEMT and one trap state in the DHEMT. From the fitting resulting parameters of the EHEMT were $D_{\rm T(s)} = (2-6)\times10^{12}$ cm$^{-2}\cdot$ eV^{-1} and $\tau_{\rm T(s)} = (0.5-6)$ ms for the slow trap states and $D_{\rm T(f)} = (1-3)\times10^{12}$ cm$^{-2}\cdot$ eV^{-1} and $\tau_{\rm T(f)} = (0.2-2)$ μs for the fast trap states. On the other hand, fitting of $G_{\rm P}/\omega$ data for the DHEMT yielded the density of slow traps $D_{\rm T(f)} = (1-5)\times10^{13}$ cm$^{-2}\cdot$ eV^{-1} with identical time constants as those for the EHEMT. A comparison of $G_{\rm P}/\omega$ versus ω curves between the DHEMT and EHEMT is shown in Fig. 5.

The density of slow traps in the EHEMT is nearly one order of magnitude lower than that in the DHEMT, and this shows that the fluorine plasma treatment decreases the slow trap density. The slow trap time constant of several ms is consistent with the surface trap obtained in Ref. [13]. The trap assistant tunneling is the dominant source of reverse gate leakage current. The decrease of the surface trap density by fluorine plasma treatment should induce suppression of the reverse gate leakage current. So we conclude that the slow trap is located at the surface of AlGaN and influences the reverse gate leakage current. A new type of trap was introduced into the devices by the fluorine plasma treatment; this trap is 'fast' with a small time constant. This is probably due to the etching damage caused by the fluorine ion treatment, and the reduction of transconductance peak value may be related to this new trap.

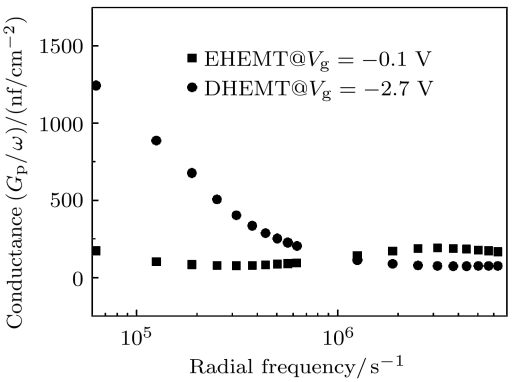


Fig. 5. Comparison of $G_{\rm P}/\omega$ versus ω curves between the DHEMT and EHEMT.

The gate step-stress ($V_{\rm d}$ = 0 V, $V_{\rm g}$; from −1 to −39 V, step: −1 V, each bias for one minute) was applied on both the AlGaN/GaN DHEMT and EHEMT. Figure 6 shows the degradation of the reverse gate leakage currents of the devices with and without the fluorine plasma treatment. The reverse gate leakage currents of diodes without the fluorine plasma treatment increase by nearly one order of magnitude after the gate step-stress. The reverse gate leakage currents

of diodes with the fluorine plasma treatment remain constant during the gate step-stress. The reverse gate leakage current reliability of the diodes with the fluorine plasma treatment remains stable during the gate step-stress while the F ions are unstable under electrical stress,[14] so we can estimate that the reliability of the reverse gate leakage current has no relationship with the F ions in the device. We indicate that the fluorine plasma treatment modifies the surface of the device and decreases the surface state trap, thus improving the reliability of the reverse gate leakage current, and further proving our proposal that the surface slow traps are decreased by the fluorine plasma treatment.

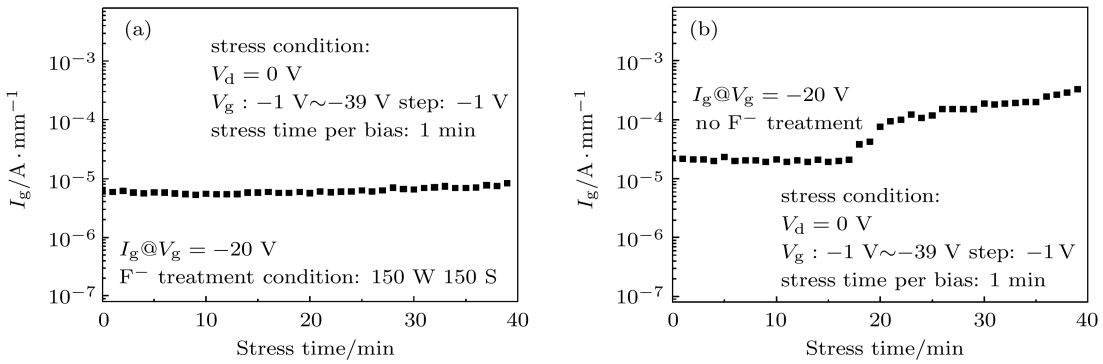


Fig. 6. Degradation of the reverse gate leakage currents of AlGaN/GaN Schottky gate diodes after the gate step-stress for (a) EHEMT and (b) DHEMT.

4. Conclusion

This paper reports fluorine plasma treatment EHEMTs and conventional DMEMTs fabricated on one wafer. It was found that fluorine plasma etches the AlGaN at a slow rate by C–V measurement. Frequency dependent capacitance and conductance analysis were performed on these devices in order to investigate the trapping effects. The results show that one type of trap exists in conventional DHEMTs with $\tau_{\rm T} = (0.5 - 6)$ ms and density of $(1 - 5) \times 10^{13}$ cm$^{-2}\cdot$ eV^{-1}, and two types of trap exist in fluorine plasma treatment EHEMTs, fast with $\tau_{\rm T(f)} = (0.2-2)$ μs and slow with $\tau_{\rm T(s)} = (0.5-6)$ ms. The density of trap states evaluated on the EHEMTs was $D_{\rm T(f)} = (1-3)\times 10^{12}$ and $D_{\rm T(s)} = (2-6)\times 10^{12}$ cm$^{-2}\cdot$ eV^{-1} for the fast and slow traps, respectively. The slow trap is decreased by the fluorine plasma treatment and located at the surface; this explains the suppression of reverse gate leakage current and improved reliability of the reverse gate leakage current. A new trap was introduced into the device by the fluorine plasma treatment; it was assumed to be related to etching damage.

References

[1] Cai Y, Zhou Y G, Lau K M and Chen K J 2006 *IEEE Trans. Electron Devices* **53** 2207

[2] Feng Q, Gu W P, Hao Y, Ma X H, Wang C and Zhang J C 2009 *Acta Phys. Sin.* **58** 511 (in Chinese)

[3] Huang S, Lin F, Liu F, Ma N, Shen B, Wang P, Wang T, Xu F J and Yao J Q 2009 *Acta Phys. Sin.* **18** 1614 (in Chinese)

[4] Duan H T, F Q, Gu W P, Hao Y, Ma X H, Ni J Y and Zhang J C 2009 *Acta Phys. Sin.* **18** 1601 (in Chinese)

[5] Cai Y, Zhou Y G, Chen K J and Lau K M 2005 *IEEE Electron Device Lett.* **26** 435

[6] Cai Y, Zhou Y G, Lau K M and Chen K J 2006 *IEEE Trans. Electron Devices* **53** 2207

[7] Cai Y, Cheng Z Q, Tang W C W, Lau K M and Chen K J 2006 *IEEE Trans. Electron Devices* **53** 2223

[8] Palacios T, Suh C S, Chakraborty A, Keller S, DenBaars S P and Mishra U K 2006 *IEEE Electron Device Lett.* **27** 428

[9] Shen L, Palacios T, Poblenz C, Corrion A, Chakraborty A, Fichtenbaum N, Keller S, Denbaars S P, Speck J S and Mishra U K 2006 *IEEE Electron Device Lett.* **27** 214

[10] Chu R M, Suh C S, Wong H M, Fichtenbaum, Brown D, McCarthy L, Keller S, Wu F, Speck J S and Mishra U K 2007 *IEEE Electron Device Lett.* **28** 781

[11] Quan S, Hao Y, Ma X H, Ma J G and Xie Y B 2009 *Journal of Semiconductors* **30** 40001

[12] Wang C, Quan S, Zhang J F, Hao Y, Feng Q and Chen J F 2009 *Acta Phys. Sin.* **58** 1966 (in Chinese)

[13] Stoklas R, Gregusova D, Novak J, Vescan A and Kordos P 2008 *Appl Phys. Lett.* **93** 124103

[14] Yi C W, Wang R N, and Huang W, Tang W C W, Lau K M and Chen K J 2007 *IEDM* 10-12 Dec. Washington DC, USA p389