Impacts of Fluorine-treatment on E-mode AlGaN/GaN MOS-HEMTs

X. Sun^{1*}, Y. Zhang², K. S. Chang-Liao³, T. Palacios², and T. P. Ma¹

¹Yale Univ., CT, USA ²Massachusetts Institute of Technology (MIT), MA, USA ³National Tsing Hua Univ., Taiwan
Phone: +1 203-980-4789, *E-mail: xiao.sun@yale.edu

Abstract

The impact of fluorine treatment on AlGaN/GaN MOS-HEMTs has been investigated. Fluorine was found to suppress pre-existing traps in MOS-HEMT, which improves the off-state at high temperatures. Fluorine doping and associated etching, however, also generates slow border traps and fast interface states that degrade the MOS-HEMT performance. Multi-faceted mechanisms for drain current degradation due to F-doping and gate-recess-etch have been investigated in enhancement-mode MOS-HEMTs.

Introduction

GaN based MOS-HEMTs are emerging devices for high power and RF applications. Gate-recess etch and fluorine (F) doping are approaches commonly taken to achieve enhancement-mode (E-mode) operation [1, 2]. These technologies, however, tend to result in V_{th} instability and drain current (I_d) degradation in HEMTs [3-7], which could be attributed to F-induced bulk and interfacial traps. In an MOS-HEMT, the related scenario is more complex, because the inserted gate dielectric could weaken the screening effect of gate metal and introduce traps in bulk oxides or at the oxide/barrier-layer interface [8]. In this work, we investigated multifaceted impacts of F-doping and associated etching on E-mode MOS-HEMTs over a wide range of fluorine doses.

Experimental

HEMT structures were fabricated on a commercial GaN-on-silicon wafer (Fig.1). To obtain E-mode behavior, the AlGaN (Al: 26%) barrier in the gated region was treated by CF_4 plasma at an ECR/RF power of 150W/20W for varying intervals of time (TEM in Fig.1). More experimental details can be found in [9]. SIMS study shows the peak of F-concentration at the top AlGaN surface (Fig.2). MOS-HEMT devices were also fabricated by depositing ALD- Al_2O_3 immediately after F-treatment, during which F was driven into Al_2O_3 from the AlGaN underneath. F treatment can effectively increase V_{th} up to ~ 4 V for CF_4 treatments of ~ 120 s, as shown in Fig. 3. In Fig. 4, the gate stack thickness decreases with CF_4 time, indicating that F also etches AlGaN barrier layer during the CF_4 plasma treatment. The resulting thinning of AlGaN, i.e., gate-recess-etch, along with negative charges induced by F ions can effectively increase V_{th} . Additional CF_4 plasma, however, caused serious degradation of on- and off- currents (I_{on} , I_{off}) as shown in Fig. 3 and elsewhere [5, 6].

F-passivation of traps in MOS-HEMT

In MOS-HEMTs, traps exist at the oxide/AlGaN interface and in the gate oxide [8-11]. In this work we have found that these traps appear in the MOS-HEMT with Al_2O_3 as gate

Fig. 1 Schematic and TEM views of MOS-HEMT device studied in this work; The TEM shows a device with 8 nm of AlGaN and 14nm Al_2O_3 on top. treated by CF_4 for 120s.

oxide, and are detrimental to the off-state at high temperatures. Fig.5 shows that, although the hysteresis and I_{off} are small for depletion-mode MOS-HEMTs at 300K, at higher temperatures they increase drastically. The Subthreshold Swing (SS) at different temperatures reveals that while more traps can respond to dc- V_g sweep at higher temperatures, they are positively charged above E_F ,

Fig.2 SIMS indicates that F concentration peaks at the AlGaN upper surface (Al_2O_3 /AlGaN). F diffuses into the Al_2O_3 during the ALD process (after [9]).

Fig. 3 The linear (a) and logarithmic (b) I_d - V_g of MOS-HEMTs with AlGaN treated by CF_4 for time intervals from 0s to 165s. I_{on} and SS degradation is observed after high F doses.

Fig.4 Total gate stack thickness (including Al_2O_3 and AlGaIn layers) after CF_4 plasma treatment of varying intervals of time, as extracted from 1MHz C-V ($\epsilon \sim 10$) and TEM.

resulting in a negative shift of V_{th} and thus a high I_{off} , i.e., difficult turn-off. It is observed that some deep-level traps—“fixed” positive charges commonly found in GaN MOS-HEMT [10, 11]—could also emit/capture electrons in the V_g operation range under high temperatures. For HEMT devices, that has no gate oxides, such degradation does not exist, as shown in the inset of Fig. 5b, proving that the traps are introduced by the Al_2O_3 , including those in Al_2O_3 bulk or at $\text{Al}_2\text{O}_3/\text{AlGaIn}$ interface. Notably, the F-plasma treatment, even with a light dose that is not sufficient to achieve E-mode, is effective in passivating these traps. In Fig. 5b, the MOS-HEMT with 60 s of CF_4 -treated AlGaIn shows little hysteresis and well-behaved I_{off} even at 540 K, in strong contrast to the untreated AlGaIn. Given that F plasma treatment has been reported to be stable in AlGaIn at least up to 800 °C [12], fluorine doping could be a beneficial process for good high-temperature characteristics in GaN MOS-HEMT.

Fig.5 (a) degradation in the log I_d - V_g curves (including hystereses) with increasing temperatures from 300K to 540K in the untreated Al_2O_3 -MOS-HEMT. The inset shows the untreated HEMT device without Al_2O_3 . (b) log I_d - V_g curves (including hystereses) for the untreated- and the 60s- CF_4 treated Al_2O_3 -MOS-HEMTs at 300 K and 540 K.

Slow border traps in AlGaIn

We adapted the ac-transconductance (g_m) method to examine possible slow traps in AlGaIn generated by F-treatment. In the ac - g_m method, under small ac - V_g , the occupation of traps in gate stacks fluctuates due to capture and emission of carriers. By modulating the ac - V_g frequencies, ac - g_m is able to reflect traps with varying time constant (τ). Unlike conventional gate admittance methods involving ac gate currents (such as C-V and G-V), the ac - g_m method probes much larger drain currents with much higher signal-to-noise ratios at low frequencies (down to 10 mHz), and hence is able to probe traps with longer τ (100 μ s – 100 s). More details of the method can be found in [13, 14].

To focus on the traps in F-treated AlGaIn, AlGaIn/GaN HEMTs without gate oxides were tested. The results show that slow traps are introduced by F-treatment in AlGaIn. In Fig. 6, for both the untreated and F-treated devices, ac - g_m shows little frequency dispersion at 300 K. But the F-treated one shows a large *positive* frequency dispersion at 540 K, suggesting F-induced traps capture channel electrons through *inelastic* tunneling. For untreated device, the frequency dispersion is negligible at 540 K (inset of Fig. 6b). Fig. 7 shows the normalized ac - g_m vs. frequency at different temperatures. The corresponding Arrhenius plots show an activation energy $E_a = E_T - E_F$ of 0.3 eV for the as-deposited, and $E_a = 0.75$ eV after 400°C annealing (Fig. 8), consistent with theories that annealing is critical for fluorine to form stable trapping centers [15-17]. Because the traps have an E_a larger than the AlGaIn/GaN conduction band offset, they must not be at the interface, but instead should be in AlGaIn as border traps, as in the band diagram shown in Fig. 9.

F-induced slow traps in AlGaIn also result in trap-assisted-tunneling (TAT) in HEMT devices, as evidenced by the ac - g_m measurements. In Fig. 7c, a *negative* frequency dispersion appears in addition to the positive one, as the traps exchange electrons with the gate in addition to the channel [8] (Fig. 9), resulting in TAT in the gate stack of HEMTs. In MOS-HEMTs, however, the gate oxide suppresses TAT, so this ac - g_m feature is missing. As such, F-induced traps deep in AlGaIn, with higher densities (Fig. 2), result in Fermi-level (FL) pinning by trapping electrons without detrapping them to the gate. For example, in Fig. 10, the dc- I_d degradation after 10 s of additional F-plasma in MOS-HEMTs can be simulated well by considering the FL pinning induced by a trap band (the inset of Fig. 10a).

Fig. 6 AC- g_m vs. V_g at ac- v_g frequencies from 10 mHz to 10k Hz at (a) 300K and (b) 540 K for AlGaIn/GaN HEMT with 120s CF_4 treatment. The inset in (b) shows the ac - g_m for the sample without F-treatment. * In Fig. 6(b), the frequency dependence is not completely monotonic. (see Fig. 7c)

Fig. 7 Normalized $ac-g_m$ vs. $ac-V_g$ frequency for the AlGaIn/GaN HEMT devices after 400°C annealing at (a) 300 K, (b) 450 K, and (c) 540 K. Fig. 7(c) shows that a negative frequency dispersion (the recovery of the positive frequency dispersion) appears in the 540 K-annealed sample below ~1Hz.

Fig. 8 Arrhenius plots of $ac-g_m$ degradation in the form of τ vs. $1/T$ for several different gate overdrives, for the (a) as-deposited and (b) 400°C annealed AlGaIn/GaN HEMT with 120s F treatment. In the y axis, $\tau=1/f$, and f is the frequency where $ac-g_m$ decreases by half of the maximum measured degradation in the frequency scope. Each inset shows E_a vs. dc gate overdrive V_g-V_{th} .

Fig. 9 Conduction band of the AlGaIn/GaN gate stack in a HEMT simulated by SILVACO, resulting from inputting a F doping profile (all ionized) shown in the inset.

Fig. 10 Simulated and experimental I_d-V_g (with hystereses) in (a) linear and (b) log scale for two MOS-HEMTs (5nm Al_2O_3) having 10s difference in CF_4 treatment time interval. The inset of (a) shows the trap profile input to SILVACO: Trap density (contour) vs. Energy ($E-E_c$) and Distance (Z) from the $Al_2O_3/AlGaIn$ (~6nm) interface

Fast interface states at GaN Interface

In addition to slow traps, F plasma also induces fast interface states on GaN in the presence of an AlGaIn blocking layer. C-V and G-V can probe such fast interface states in the subthreshold region when the trap time constants are longer with lower carrier density [18]. In Fig. 11, a large C-V dispersion appears after the MOS-HEMT is turned into E-mode by fluorine, when AlGaIn is still relatively thick, e.g., 8 nm after 120 s of CF_4 , as shown by TEM in Fig. 1. In Fig. 12, the frequency of the G_p/ω peak from the G-V measurements reflects FL movement under V_g , and the value thereof reflects the interface state density (D_{it}). A 60 s F plasma treatment can reduce D_{it} from 10^{11} to $10^{10}/cm^2/eV$, indicating that light-dose F could passivate the pre-existing traps at/near the GaN interface. However, further treatment to 120 s increases D_{it} to $10^{11}/cm^2/eV$, possibly due to fluorine accumulation at the AlGaIn/GaN interface. Finally, 165 s increases D_{it} to $10^{12}/cm^2/eV$, consistent with the D_{it} level of the Al_2O_3/GaN interface in GaN MOSFETs [19]. Indeed, TEM reveals that at 165 s, F treatment has etched all the AlGaIn and reached the GaN, yielding an Al_2O_3/GaN interface (Fig. 13). Plasma over-etch can also damage the GaN surface [20].

I_d degradation mechanism in F-treated MOS-HEMTs

I_d degradation in F-treated MOS-HEMTs (Fig. 3) results from both mobility (μ) drop and FL pinning. In Fig. 14, I_d can be mostly recovered by 50-ns pulsed I_d-V_g measurement for medium F-dose (120 s), but can only be partly mitigated for heavy F-dose (165 s), partially because the time constants of generated interfaces states in the later are much shorter than 50 ns.

Fig. 11(left) C-V dispersions from 10kHz to 1MHz of MOS-HEMTs w/~15 nm Al₂O₃ that received F-treatment with time intervals from 0s to 165s

Fig. 12(right) G_p/ω contour vs. gate frequency and dc- V_g for MOS-HEMTs w/~15 nm Al₂O₃ that received CF₄ for different time intervals. The peaks of G_p/ω in subthreshold region are traced by white lines. The value of G_p/ω is transformed to D_{it} based on the Nicollian-Brews model [18].

Fig. 13 A cross sectional view of 165s-CF₄ treated MOS-HEMT by TEM. The frame on the right shows an enlarged view of the resulting Al₂O₃/GaN interface by F-plasma over-etch.

On the other hand, Fig. 15 shows the measured μ and V_{th} as functions of F plasma time for HEMTs and MOS-HEMTs. Unlike HEMTs, μ degrades dramatically in MOS-HEMTs with ~15 nm Al₂O₃, especially for the E-mode. The mechanisms of I_d degradation after F treatment are summarized below, in the order from low-dose to high-dose: (1) the thinning of AlGaIn by F etching reduces 2DEG density and μ ; (2) F generates border traps in AlGaIn, resulting in FL pinning; (3) with a few nm of AlGaIn left, F can generate interface states at AlGaIn/GaN, resulting in stronger FL pinning and μ drop; (4) after AlGaIn being completely etched out, plasma damage and a high-concentration of F in the GaN channel could degrade μ significantly by scattering (Fig. 15). Compared to MOS-HEMTs, HEMTs show little degradation in μ after 120 s F plasma treatment, due to TAT and gate screening of trapped charges, but at the cost of low V_{th} . A tradeoff therefore exists between V_{th} and I_{on} for these devices that use F implantation and/or gate-recess to achieve E-mode.

Fig. 15 V_{th} and measured peak mobility vs. CF₄ treatment time interval for HEMT and MOS-HEMTs with ~5 nm and ~15 nm Al₂O₃.

Fig. 14 DC and pulsed I_d - V_g (50 ns) for MOS-HEMTs w/~15 nm Al₂O₃ that received different CF₄ treatment time intervals

Summary

In summary, fluorine treatment enhanced SS and I_{off} of MOS-HEMT at high temperatures, by passivating traps contained in gate stacks of GaN MOS-HEMT devices. More Fluorine treatment, however, results in border traps in AlGaIn with $E_a \sim 0.75$ eV, and interface states at AlGaIn/GaN, degrading I_{on} through pinning FL and reducing mobility. Extremely low mobility can occur due to over-etch-induced GaN surface damage and high fluorine impurity concentrations within the channel.

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