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

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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_{2}O_{3} immediately after F-treatment, during which F was driven into Al_{2}O_{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_{2}O_{3} as gate 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. 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_{2}O_{3} on top. treated by CF_{4} for 120s.](image)

![Fig. 2 SIMS indicates that F concentration peaks at the AlGaN upper surface (Al_{2}O_{3}/AlGaN). F diffuses into the Al_{2}O_{3} during the ALD process (after [9]).](image)

![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.](image)
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
device, 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$_2$O$_3$, including those in Al$_2$O$_3$ bulk or
at Al$_2$O$_3$/AlGaN 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 AlGaN shows little
hysteresis and well-behaved $I_{off}$ even at 540 K, in strong
contrast to the untreated AlGaN. Given that F plasma
treatment has been reported to be stable in AlGaN at least up
to 800 °C [12], fluorine doping could be a beneficial process
for good high-temperature characteristics in GaN
MOS-HEMT.

Slow border traps in AlGaN

We adapted the ac-transconductance ($g_m$) method to
examine possible slow traps in AlGaN 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 ($\tau$). 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 $\tau$ (100 $\mu$s – 100 s).
More details of the method can be found in [13, 14].

To focus on the traps in F-treated AlGaN, AlGaN/GaN
HEMTs without gate oxides were tested. The results show
that slow traps are introduced by F-treatment in AlGaN. 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 $E_a = E_F - E_T$ 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 AlGaN/GaN conduction band offset, they
must not be at the interface, but instead should be in AlGaN
as border traps, as in the band diagram shown in Fig. 9.

F-induced slow traps in AlGaN 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 AlGaN, 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-$I_g$ 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. 7 Normalized $ac-g_m$ vs. $ac-v_g$ frequency for the AlGaN/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 ~1 Hz.

Fig. 8 Arrhenious plots of $ac-g_m$ degradation in the form of $\tau$ vs. $1/T$ for several different gate overdrives, for the (a) as-deposited and (b) 400°C annealed AlGaN/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 $E_t$ vs. dc gate overdrive $V_g-V_{th}$.

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

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 AlGaN 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 AlGaN 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 $G_m/\omega$ 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 AlGaN/GaN interface. Finally, 165 s increases $D_{it}$ to $10^{12}$/cm$^2$/eV, consistent with the $D_{it}$ level of the Al$_2$O$_3$/GaN interface in GaN MOSFETs [19]. Indeed, TEM reveals that at 165 s, F treatment has etched all the AlGaN and reached the GaN, yielding an Al$_2$O$_3$/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 ($\mu$) drop and FL pinning. In Fig. 14, $I_d$ can be mostly recovered by 50-nps pulsed $I_{ds}-V_g$ 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 with ~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-Vg for MOS-HEMTs with ~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].

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 AlGaN by F etching reduces 2DEG density and μ; (2) F generates border traps in AlGaN, resulting in FL pinning; (3) with a few nm of AlGaN left, F can generate interface states at AlGaN/GaN, resulting in stronger FL pinning and μ drop; (4) after AlGaN 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.

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 AlGaN with E_a ~0.75eV, and interface states at AlGaN/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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Reference
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