Student Paper

Impact of CF_4 Plasma Treatment on DC Performance of Al_2O_3/InAlN/GaN MOS-HEMTs

Zongyang Hu[1,*], Yuanzheng Yue[1], Mingda Zhu[1], Bo Song[1], Satyaki Ganguly[1], Josh Bergman[2], Debdeep Jena[1] and Huili Grace Xing[1]

[1]*Department of Electrical Engineering, University of Notre Dame, Notre Dame, IN 46556, USA*

[2]*Teledyne Scientific & Imaging, LLC, Thousand Oaks, CA 91360, USA* *Email: zhu1@nd.edu

GaN HEMTs with lattice matched $In_{0.17}Al_{0.83}N$ barrier have been extensively studied for high power and high speed applications in recent years. In principle, enhancement mode (E-mode) operation is more challenging for InAlN barrier HEMTs than AlGaN barrier HEMTs due to the high 2DEG concentration, large spontaneous polarization charge and thin barrier thicknesses in InAlN HEMTs. As a means to reduce the gate leakage, ALD Al_2O_3 is usually inserted as gate dielectric; however, it has been also reported to induce a positive sheet charge at the interface with the III-nitrides [1], whose magnitude is comparable to the net polarization charge at the HEMT barrier-channel interface thus making it even more challenging to realize E-mode. On the other hand, negative charges can be introduced by fluorine containing plasma treatments [2] [3], and E-mode operation can be potentially obtained even with thick gate dielectric layers. For thin InAlN barrier MOS-HEMTs, there have been very few reports on the performance of E-mode operation due to the challenges mentioned above. In this work, a detailed study on threshold voltage control and electron transport properties using F-plasma treatments is presented.

The HEMT layer structure (Fig. 1) consists of 5 nm $In_{0.17}Al_{0.83}N$ barrier, 1 nm AlN interlayer, GaN channel and 1.8 µm semi-insulating GaN buffer on SiC substrate grown by metal organic chemical vapor deposition. Alloyed ohmic contacts were formed first, followed by isolation of devices using ion implantation. The devices have 25 nm SiN_x passivation in the access regions. The CF_4 plasma at a low power in a reactive ion etching (RIE) system is used to define the gate regions through SiN_x, followed by various CF_4 plasma treatments at different plasma power for the same duration of 3 min. Al_2O_3 gate dielectric of 16 nm was subsequently deposited in an atomic layer deposition (ALD) system. The devices were finally annealed at 400 ºC for 5 min after gate metallization.

In Fig. 2, family I-Vs and transfer I-Vs for the MOSHEMTs without and with F plasma treatments are plotted. By linear extrapolation of I_d near peak g_m, the threshold voltages are determined as -2.8 V and 0.8 V, respectively. The off-state leakage currents are below $1x10^{-10}$ A/mm. Both types of devices show very small hysteresis (0.02 V and 0.15 V). Representative pulsed I_d-V_{ds} curves using 300 ns pulse widths for both devices are plotted in Fig. 3, where negligible dispersion is seen, indicating adequate passivation of the access regions and dielectric/barrier interfaces. V_{th} of MOSHEMTs treated under different plasma powers is plotted in Fig. 4a as a function of ALD Al_2O_3 thickness t_{ox}, which shows a linear dependence on t_{ox} after post gate annealing while the slope depends on the plasma power. The dependence of V_{th} on t_{ox} is explained by the schematic energy band diagram shown in Fig. 4b. The total shift in V_{th} can be lumped into two contributions: the band bending in the gate oxide (depending on $Q_{it}+Q_F$ thus on the fitted slope in Fig.4a) and the band bending in InAlN due to F treatment (independent of t_{ox} but dependent on the intercept of the fitted lines in Fig.4a). These two contributions are extracted and shown in Fig. 5a. With a high plasma power of 100 W, the equivalent interface charge density $Q_{it}+Q_F$ is reduced from $2.84x10^{13}$ cm^{-2} to $2.11x10^{13}$ cm^{-2}, approaching the spontaneous polarization charge density of GaN (Q_{GaN}), when the flat band condition is expected in the oxide. However, with the $Q_{it}+Q_F$ higher than Q_{GaN}, the reversal of the electric field direction in the oxide is not observed in this experiment, which is necessary to achieve E-mode operation with increasing oxide thickness. The field-effect mobility as a function of 2DEG density and plasma power is extracted using the split C-V technique (Fig. 5b). The electron mobility for the D-mode MOSHEMT has a peak value of 1180 cm^2/Vs near $7x10^{12}$ cm^{-2} and decreases with increasing 2DEG density due to electron-electron scattering. For the higher power plasma treatments, the maximum mobility decreases and is ~540 cm^2/Vs near $8x10^{12}$ cm^{-2} for the E-mode MOSHEMT. This, together with the higher hysteresis in the E-mode MOSHEMT compared with that of the D-mode, suggests that further increase of plasma powers may not be desirable for improved device performance.

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References

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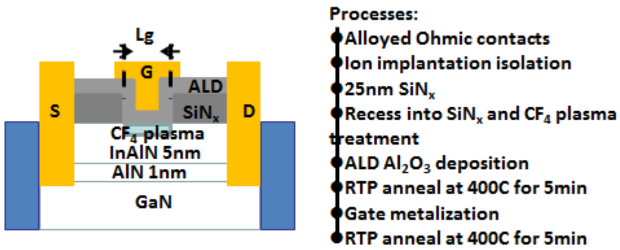

Figure 1: Cross section schematic and process flow of the Al_2O_3/InAlN/GaN MOSHEMTs.

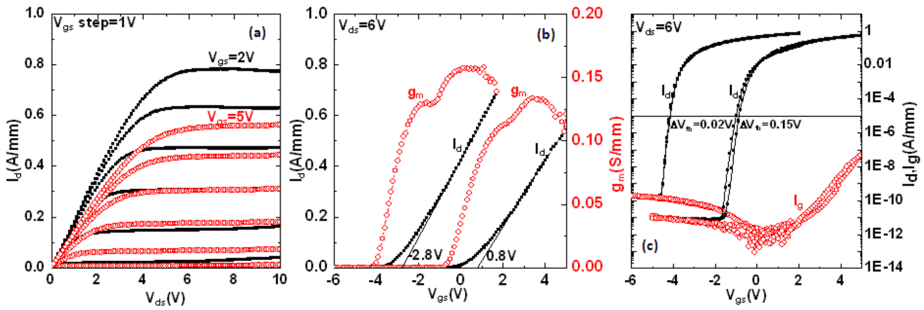

Figure 2: (a) I_d-V_{ds} and transfer I-Vs in linear (b) and semi-log(c) scale of MOSHEMTs without and with F treatment (at 100 W for 3 min). Both devices have a gate length of 2μm gate lengths and a S-D distance of 5μm.

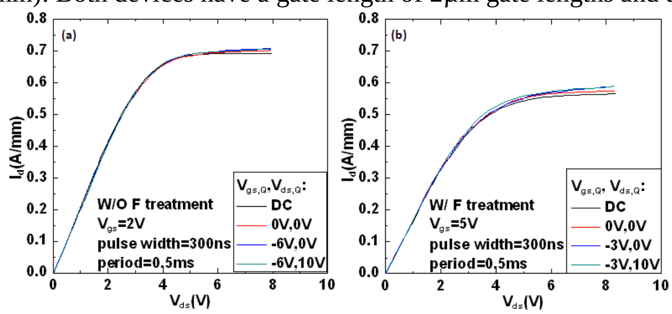

Figure 3: Pulsed I_d-V_{ds} behavior of MOSHEMTs without (a) and with (b) F treatment.

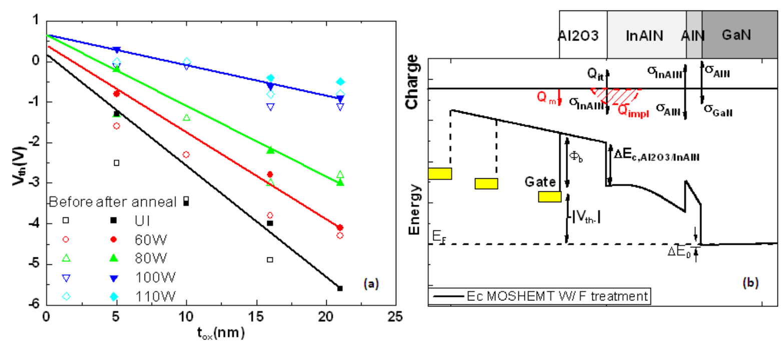

Figure 4: (a) Threshold voltages V_{th} of MOSHEMTs versus the gate oxide thickness and CF_4 plasma power before and after post-gate annealing. (b) Band diagrams illustrating the more negative V_{th} with increasing oxide thickness.

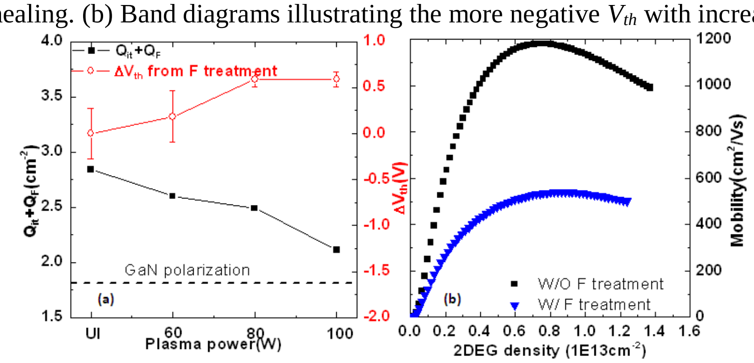

Figure 5: (a) Total equivalent interface charge Q_{it}+Q_F and V_{th} shift due to F treatment extracted from Fig. 4. (b) Field-effect mobility of electrons extracted by the split C-V method from MOSHEMTs with 20 μm gate lengths.