In situ plasma enhanced atomic layer deposition half cycle study of Al_2O_3 on AlGaN/GaN high electron mobility transistors

(Supplementary Materials)

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(1) Device Fabrication and Structures

Fig. S1 shows a cross section of MISHEMTs and images of MOSCAPs and MOSHEMTs fabricated in this study. The diode fabrication flow for C-V measurements has been described previously.[1,2] For the transistor fabrication, a mesa isolation using 500 s BCl_3 (15 sccm)/Ar (5 sccm) reactive ion etching (RIE) was first processed. The etching depth was ~ 150 nm. Then, ohmic source/drain regions (see Fig. S1 (b) and (c)) defined by a standard photolithography were opened by 20 s BCl_3/Ar reactive ion etching (removing the Al_2O_3 layer). The ohmic contacts were then formed by e-beam evaporation deposition (base pressure ~1×10^{6} mbar) of Ti/Al/Ti/Au (20 nm/ 40nm/ 20nm/ 100 nm) flowed by rapid thermal annealing at 850 °C for 60 s with 2000 sccm N_2 after patterning by lift off. Gate electrodes defined by the photolithography were finally fabricated using e-beam deposition of Ni/Au (50 nm/100 nm thickness) and lift off.

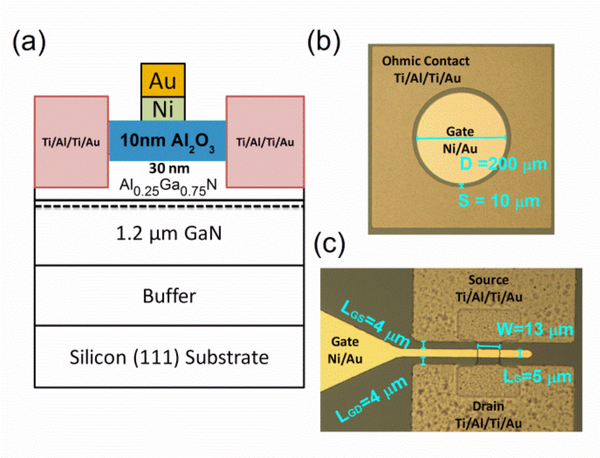

Fig. S1 (a) Schematic cross section of MISHEMTs. Optical images of (b) the diode structure for C-V and gate leakage characterizations and, and (c) the transistor structure for I-V characterizations.

(2) Al 2*p* and O 1*s* of 100 cycles Al_2O_3 and Band Offsets at ALD Al_2O_3/AlGaN and PEALD Al_2O_3/AlGaN

As Fig. S2 shows, Al 2*p* and O 1*s* core lever spectra from 100 cycles of ALD Al_2O_3 and 100 cycles of PEALD Al_2O_3 overlap together indicating the same stoichiometry. Fig. S3 (a) and (d) show the O 1*s* core level spectra along with the onset of the O loss features upon 100 cycles of Al_2O_3 on AlGaN. The band gap of the Al_2O_3 films can be extracted from the separation between the O 1*s* core level feature and the onset of its loss feature originated from the excitation of electrons from the valence band to the conduction band.[3,4] As Fig. S3 (a) and (d) show, the extracted ALD and PEALD Al_2O_3 band gap values are both 6.9±0.1 eV. The valence band spectra offset (VBO) values between the AlGaN surface and then after 100 cycles of ALD and 100 cycles of PEALD Al_2O_3 are determined to be 1.2±0.1 and 1.1±0.1 eV, respectively. The deduced conduction band offset (CBO) values for ALD Al_2O_3/AlGaN and PEALD Al_2O_3/AlGaN are 1.8 and 1.9 eV, respectively.

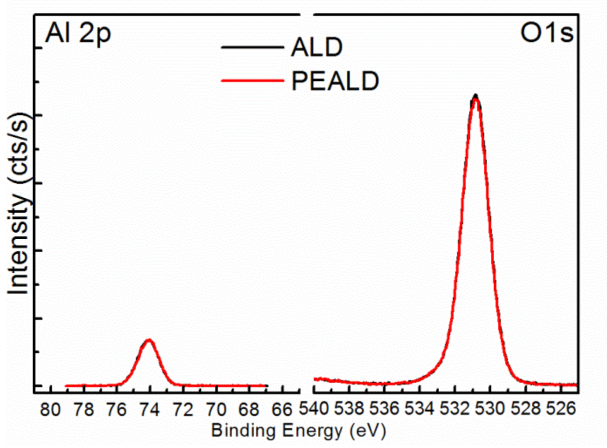

Fig. S2 XPS of Al 2p and O 1s core level spectra from 100 cycles of ALD Al_2O_3 and 100 cycles of PEALD Al_2O_3, respectively.

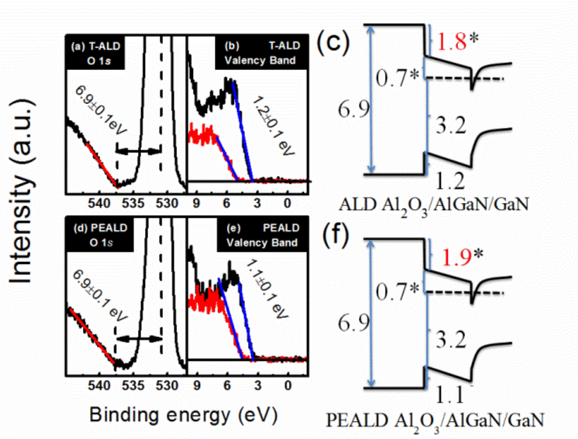

Fig. S3 XPS of O 1*s* core level spectra showing the onset of O loss features for 100 cycles of (a) ALD Al_2O_3/AlGaN and (d) PEALD Al_2O_3/AlGaN, XPS valence band spectra for AlGaN and 100 cycles of (b) ALD Al_2O_3/AlGaN and (e) PEALD Al_2O_3/AlGaN, and energy band diagram for (c) ALD Al_2O_3/AlGaN/GaN and (f) PEALD Al_2O_3/AlGaN/GaN interfaces.

(3) The Extraction of Threshold Voltage

In general, the mathematic model is similar to metal-oxide-semiconductor field-effect-transistors (MOSFETs).[5]

(1) Linear Extraction

With the gate voltage larger than threshold voltage (V_{TH}), the charge sheet induced by the gate is given by:

$$Q_n = C_o(V_G - V_{TH}) \quad (1)$$

where C_o is the insulator (Al_2O_3 and AlGaN) capacitance, and V_G is the gate bias voltage.

When a drain bias is applied, the channel has a variable potential with distance. Therefore, the channel charges as a function of position could be described by equation (2), and the channel current is given by equation (3):

$$Q_{n(x)} = C_o(V_G - V_{TH} - V_x) \quad (2)$$

$$I_D = \frac{Z}{L}\left(\int_0^L Q_{n(x)}\, v(x)dx\right) \quad (3)$$

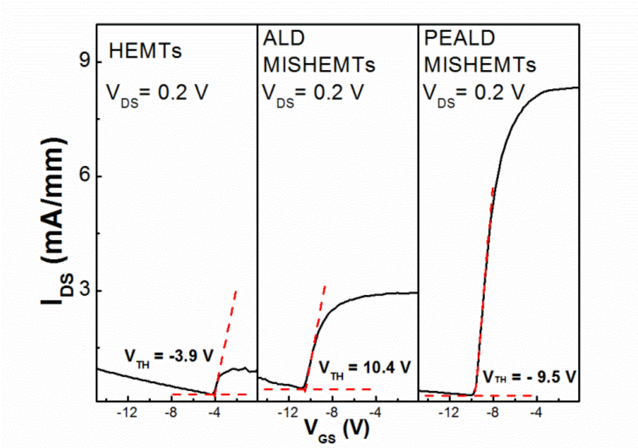

Fig. S4 DC I_{DS}-V_{GS} characteristics of HEMTs, ALD-MISHEMTs, and PEALD-MISHEMTs at VDS = 0.2 V

Assuming that the mobility is constant, the drift velocity is given by equation (4) and the drain current as a function of gate voltage at a low drain voltage is given by equation (5).

$$v(x) = \mu_n E(x) = \mu_n \frac{dV_x}{dx} \quad (4)$$

$$I_{DS} = \frac{Z\mu_n C_o}{L}\left[(V_G - V_{TH})V_D - \frac{V_D^2}{2}\right] \quad (5)$$

In the linear region, (VD « (V_G-V_{TH})), equation (5) is reduced to equation (6)

$$I_{DS} = \frac{Z\mu_n C_o}{L}\left[(V_G - V_{TH})V_D\right] \quad (6)$$

Therefore, a linear extraction could be performed from Fig. S4 (V_{DS} = 0.2 V) and the V_{TH} values are -3.9, 10.4 and -9.5 V for HEMTs, ALD-MISHEMTs, and PEALD-MISHEMTs, respectively.

(2) Saturation Current Method

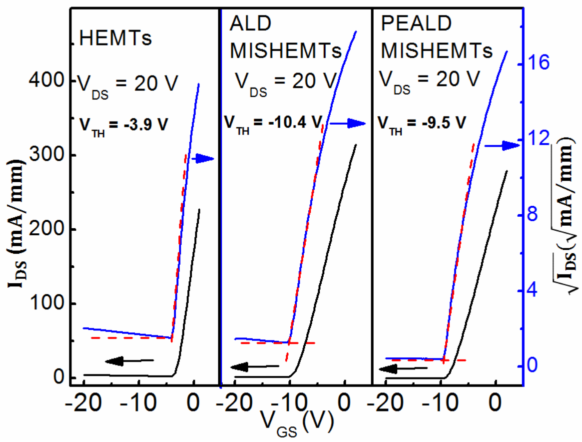

Fig. S5 DC I_{DS}-V_{GS} characteristics of HEMTs, ALD-MISHEMTs and PEALD-MISHEMTs at V_{DS} = 20 V.

At a high V_{DS}, corresponding to the pinch-off condition, the current saturates are depicted by equation (7)

$$I_{DS} = \frac{Z\mu_n C_o}{L}\left[(V_G - V_{TH})^2\right] \quad (7)$$

Therefore, $\sqrt{I_{DS}}$ is linear to V_G, and V_{TH} could be extracted at the onset of I_{DS}-V_{DS} plots as shown in Fig. S5. The values are consistent with the values using the linear extraction method.

Reference

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