Gate Recessed Quasi-Normally OFF Al_2O_3/AlGaN/GaN MIS-HEMT With Low Threshold Voltage Hysteresis Using PEALD AlN Interfacial Passivation Layer

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***Abstract*— In this letter, a gate recessed normally OFF AlGaN/GaN MIS-HEMT with low threshold voltage hysteresis using Al_2O_3/AlN stack gate insulator is presented. The trapping effect of Al_2O_3/GaN interface was effectively reduced with the insertion of 2-nm AlN thin interfacial passivation layer grown by plasma enhanced atomic layer deposition. The device exhibits a threshold voltage of +1.5 V, with current density of 420 mA/mm, an OFF-state breakdown voltage of 600 V, and high ON/OFF drain current ratio of $\sim 10^9$.**

***Index Terms*— GaN, metal-insulator-semiconductor high electron-mobility transistor (MIS-HEMT), normally-OFF, gate recessed, gate insulator, threshold voltage hysteresis, Al_2O_3 and AlN, plasma enhanced atomic layer deposition (PE-ALD), interfacial passivation layer (IPL).**

I. INTRODUCTION

FOR THE AlGaN/GaN high-electron-mobility transistor (HEMT) power devices to be used for the electrical vehicle applications, it is indispensable to have the normally-OFF operation from the fail-safe point of view. For gate recessed metal-insulator-semiconductor (MIS)-HEMT, gate insulator can be used to suppress gate leakage current and increase on-state operation swing. Several gate insulators, such as SiO_2 [1], Si_3N_4 [2], Al_2O_3 [3] have been experimented.

However, for the GaN normally-OFF MIS-HEMTs to be used for power switching application, high positive gate voltage can easily induce the electrons in the 2DEG channel to enter the high density deep states at the oxide/III-nitride interface, resulting in the threshold voltage (V_{th}) hysteresis [4]. Therefore, how to resolve V_{th} instability is an important issue for normally-OFF MIS-HEMT with oxide insulator.

Recent study shows that the nitride-based insulators, such as AlN, grown by plasma enhanced ALD (PE-ALD), emerge as compelling candidates for passivation with low interface trapping states for GaN-based devices. AlN is of special interest because it has smaller lattice mismatch with GaN, wide band-gap, and with high thermal conductivity [5], [6]. These benefits make PE-ALD AlN a good candidate as the interfacial passivation layer (IPL) for the normally-OFF MIS-HEMT power devices with improved interface quality between Al_2O_3 and GaN.

In this letter, we fabricated a gate recessed GaN MIS-HEMT with Al_2O_3/AlN stack as the gate insulator. The very low threshold voltage hysteresis was achieved by inserting the PE-ALD AlN IPL between Al_2O_3 and GaN. The capacitance-voltage (C-V), dc, and pulsed I-V measurements demonstrate this approach can effectively improve the V_{th} instability for the normally-off GaN MIS-HEMTs.

II. DEVICE FABRICATION

The AlGaN/GaN HEMT structure was grown on (111) silicon substrate by metal-organic chemical vapor deposition (MOCVD). The epitaxial structure consisted of 2-nm GaN cap layer, 25-nm $Al_{0.23}Ga_{0.77}N$ barrier layer, 4-um i-GaN layer and the buffer layer consisted of GaN/AlGaN/AlN with total thickness of 1um. The electron mobility and sheet resistance were 1500 cm^2/V and 380 ohm/sq., respectively, by Hall measurement. Fabrication steps of this device started with ohmic-contact formation. Ti/Al/Ni/Au metal stack was deposited by e-beam evaporator and subsequently annealed in N_2 ambient at 800 °C for 60 seconds to form ohmic contacts. Mesa isolation was performed by ICP-RIE system with Cl_2 as the etching gas. The contact resistance was measured to be 0.7 Ωmm using transfer length method (TLM). The gate region was recessed with low power BCl_3/Cl_2 plasma dry etching. The 2nm AlN IPL was deposited by PE-ALD system at 250 °C with $Al(CH_3)_3$ (TMA) and NH_3 gases as precursors. Then, 8nm Al_2O_3 was subsequently deposited using the same ALD chamber. Afterward, a post–deposition annealing (PDA) was carried out at 500 °C in N_2 ambient

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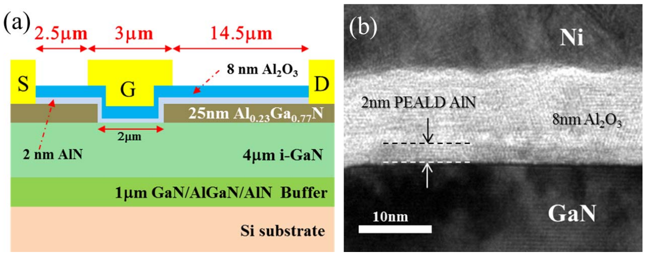

Fig. 1. (a) Schematic cross section of a recessed normally-OFF GaN MIS-HEMT with Al_2O_3/AlN stacks as gate insulator. (b) Cross sectional HRTEM image of 2nm PE-ALD AlN in the gate recess region.

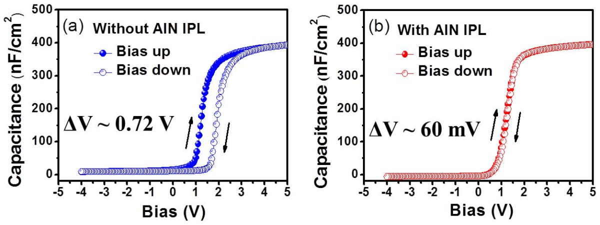

Fig. 2. C-V characteristics of Al_2O_3/GaN MIS-diode (a) without and (b) with PE-ALD AlN IPL as measured at 100 kHz.

to improve the gate insulator quality. The ohmic contact windows were etched by ICP-RIE. Finally, Ni/Au was deposited by electron beam evaporation as the gate metal and the T shaped gate was formed by lift-off process. Fig. 1(a) shows the schematic cross-sectional view of the Al_2O_3/AlN stack insulator on normally-OFF MIS-HEMT. The device characterization was performed on devices with L_{GD} = 14.5um, L_{GS} = 2.5um, gate length = 2um and gate width = 50um. Fig. 1(b) shows the high resolution transmission electron microscopy (HRTEM) image of the cross section of the recessed gate region. The AlGaN barrier layer was fully recessed. AlGaN/GaN normally-OFF MIS-HEMT without PEALD AlN IPL was also fabricated at the same time on the same epitaxial wafer as the reference device.

III. RESULT AND DISCUSSION

To investigate the Al_2O_3/AlN/GaN interface quality, the capacitance-voltage (C–V) measurements were performed on the recessed Al_2O_3/GaN and Al_2O_3/AlN/GaN MIS diodes at 100 kHz. These circular capacitors with a diameter of 50 μm went through the same device process steps. Fig. 2(a) shows the V_{th} hysteresis with a shift of 0.72 V when the bias swept from −4V to 5 V and 5 V to −4 V for the Al_2O_3/GaN MIS diode. The phenomenon was also observed in other recessed Al_2O_3/GaN MIS-diodes in literature [7]. The possible reason of the positive threshold voltage shift was due to the acceptor-like states existing at the Al_2O_3/GaN interface [8]. Compared to the Al_2O_3/GaN MIS diodes without AlN IPL, the Al_2O_3/AlN/GaN MIS diodes with PE-ALD AlN IPL exhibited much smaller hysteresis voltage (60mV) under the same sweep conditions as shown in Fig. 2(b), indicating that the insertion of the PE-ALD AlN IPL could effectively reduce the interface states of the Al_2O_3/GaN MIS diode.

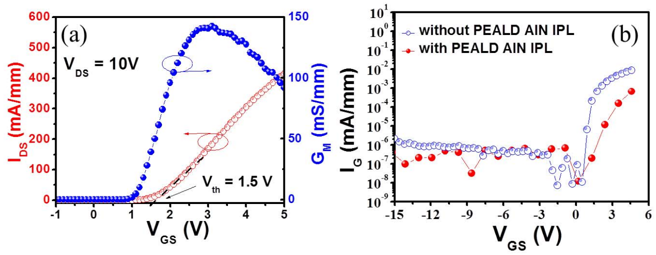

Fig. 3. (a) Normally-OFF GaN MIS-HEMT with PE-ALD AlN IPL transfer curve (I_D-V_{GS}) measured at VGS from −1V to 5 V. (b) Gate leakage current characteristics of the MIS-HEMT without and with PE-ALD AlN IPL.

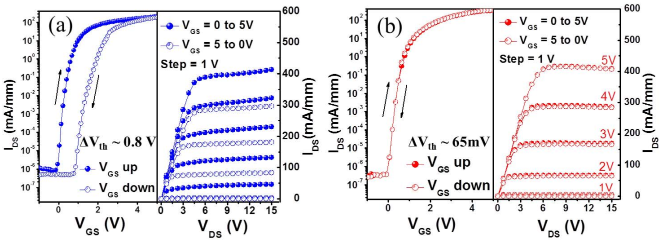

Fig. 4. DC output and transfer characteristics in semi-log scale by up and down sweep measurements (a) without PE-ALD AlN IPL (b) with PE-ALD AlN IPL for normally-OFF GaN MIS-HEMT.

Fig. 3(a) shows the transfer characteristics of the GaN MIS-HEMT with PE-ALD AlN IPL. As shown in the figure, peak transconductance of G_M = 140 mS/mm was achieved and the completely normally-OFF HEMT was achieved with V_{th} of +1.5 V as determined by linear extrapolation of the transfer curve at the point of peak transconductance. The gate leakage current of E-mode GaN MIS-HEMT without and with PE-ALD AlN IPL are shown in Fig. 3(b). When the applied forward gate bias was +5 V, the gate leakage current I_G of the device with AlN IPL gradually increased to 9×10^{-4} mA/mm. With PE-ALD AlN IPL, the gate leakage current was reduces more than one order.

Output I–V and transfer characteristics of the devices with and without AlN IPL were measured with the sweep measurement. As shown in Fig. 4(b), very small V_{th} hysteresis (60 mV) was observed when the gate was swept from −1V to 5 V and from 5V to −1 V for the device with AlN IPL layer. The MIS-HEMT with AlN IPL also exhibited high I_{ON}/I_{OFF} ratio in the order of $\sim 10^9$. In additional, the I–V curve has no obvious current slump with step-up and step-down measurements. The R_{ON} measured at I_{DS} = 250mA and V_{GS} = 5V was $10\Omega \cdot$mm, and the drain current was 420mA/mm at V_{GS} = 5 V. The well-behaved transfer and output I–V characteristics were achieved by the Al_2O_3/AlN/GaN MIS-HEMT device. However, the MIS-HEMT without AlN IPL shows larger than 0.8 V clockwise hysteresis and serious current slump, as shown in Fig. 4(a).

To further investigate the V_{th} hysteresis, the sweep transfer characteristics were measured by pulsed I_D-V_{GS} measurement with various drain biases in the linear region during the MIS-HEMT operation. The measurement technique consisting of high-based (up-sweep) and low-based (down-sweep) has been shown to be able to reveal fast trapping effects on the normally-OFF AlGaN/GaN MIS-HEMT [9]. The pulse

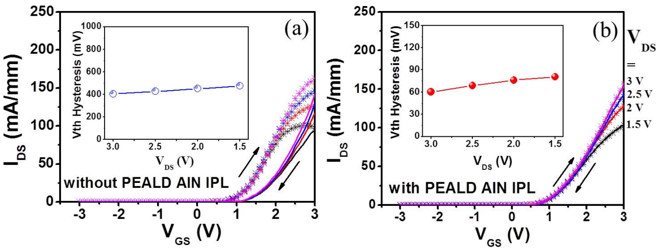

Fig. 5. Transfer sweep measured with different V_{DS} from 3 V to 1.5 V by pulse mode of normally-OFF MIS-HEMT with (a) Al_2O_3 only and with (b) Al_2O_3 and PE-ALD AlN IPL. (inset) V_{th} hysteresis varied with different applied V_{DS}.

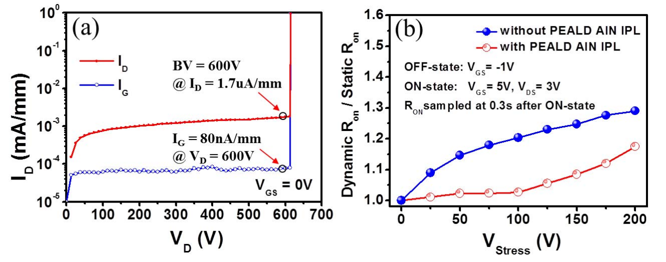

Fig. 6. (a) Three terminal OFF state breakdown characteristics of GaN MIS-HEMT with PE-ALD AlN IPL (b) Dynamic R_{on} and static R_{on} ratio with drain bias stress voltage (V_{stress}) for normally-OFF MIS-HEMT devices.

width and period were 2 ms and 20 ms, respectively, in this letter. In Fig. 5(b), the MIS-HEMT with AlN IPL shows very small V_{th} (60mV) shift with gate bias voltage sweep from at −3V and 3 V. In addition, when the lower V_{DS} was applied to the devices, because the field assisted de-trapping effect was reduced, the V_{th} hysteresis would become more serious as reported in the literature [10]. In the inset of Fig. 5(b), the ΔV_{th} only slightly increased from 60mV to 80mV for MIS-HEMT with AlN IPL when the V_{DS} were decreased from 3V to 1.5V. The density of traps could be estimated by equation $D_{it} = C_{oxide} \cdot \Delta V_{th}/q$ [7]. The D_{it} value was calculated to be 1.608×10^{11} cm^{-2} and 1.732×10^{12} cm^{-2} for samples with and without PE-ALD AlN IPL respectively in this letter. The density of traps observed was more than one order lower for the MIS-HEMT with AlN IPL, indicating the insertion of PE-ALD IPL layer between Al_2O_3 and GaN can effectively reduce the interface trapping density of the MIS-HEMT. The obvious discrepancy of V_{th} stability can be attributed to the prevention of the Ga-O bonding formation during ALD Al_2O_3 deposition by inserting the PE-ALD AlN IPL. The ALN IPL acts an oxygen diffusion barrier between Al_2O_3 and GaN to reduce the hysteresis effect of the GaN MIS-HEMTs [11].

The three terminal breakdown characteristics of the device with PE-ALD AlN IPL are shown in Fig. 6(a). When the drain bias was increased to 600V, the drain leakage current and gate leakage current were measured to be 1.7uA/mm and 80nA/mm, respectively, at V_{GS} = 0V. The breakdown voltage is defined as the drain bias voltage at a drain leakage current of 2uA/mm. In additional, the hard breakdown occurred at gate to drain voltage (V_{GD}) = 620V. To investigate the dynamic switching characteristics of the normally-OFF MIS-HEMT devices with high drain voltage, the Agilent B1505A power device analyzer system was used. The detailed measurement steps are as follows. First, the device was turned OFF with 3s hold time at stress voltage (V_{stress}), while the gate bias was set at $V_G = -1$ V. Then, the device was turned ON at V_{GS} = 5V and V_{DS} = 3V. The ON state resistance was sampled at the end of 0.3 s to calculate the dynamic R_{ON}. The switching time was 20 us by Agilent High Voltage/High Current Switch component. As shown in Fig. 6(b), current collapse phenomena were less severe for the GaN MIS-HEMT with PE-ALD AlN IPL.

IV. CONCLUSION

Gate recessed normally-OFF GaN MIS-HEMT with Al_2O_3/AlN stack insulator was fabricated in this study. The normally-OFF device shows a threshold Voltage of +1.5 V, a current density of 420mA/mm and an OFF-state breakdown of 600V with low drain leakage of 1.7uA/mm. The MIS-HEMT exhibited very low threshold voltage hysteresis and low current collapse due to the insertion of PE-ALD AlN layer with greatly reduces the interface trapping density at the Al_2O_3/GaN interface. The PE-ALD AlN IPL is therefore a very promising approach to achieve high performance normally-OFF GaN MIS-HEMT for power application.

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