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AlGaN/GaN MIS-HEMTs With High Quality ALD-Al_2O_3 Gate Dielectric Using Water and Remote Oxygen Plasma As Oxidants

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ABSTRACT We demonstrate the electrical performances of AlGaN/GaN metal–insulator–semiconductor-high electron mobility transistors (MIS-HEMTs) with high quality Al_2O_3 gate dielectric deposited by plasma enhanced atomic layer deposition using both H_2O and remote O_2 plasma as oxygen sources. Excellent gate-dielectric/GaN interface and Al_2O_3 film quality were obtained, resulting in a very small threshold voltage hysteresis and a low interface trap density. The MIS-HEMT device exhibited high on/off current ratio of $\sim 10^{10}$, steep subthreshold slope, small gate leakage current, low dynamic on-resistance degradation, and effectively current collapse suppression. These results indicate that incorporating remote O_2 plasma in the ALD-Al_2O_3 deposition process is an effective and simple way to provide high quality gate dielectric for the GaN MIS-HEMTs production.

INDEX TERMS AlGaN/GaN, MIS-HEMT, Al_2O_3, PEALD, oxygen plasma.

I. INTRODUCTION

AlGaN/GaN high electron mobility transistors (HEMTs) show potential to be economically viable alternatives to silicon- or SiC-based power devices because of its inherent material properties. However, conventional Schottky gate HEMTs suffer from high gate-source leakage current, which limits the efficiency of the GaN-based power device. To overcome this problem, a typical method is using an insulator layer inserted between the gate metal and AlGaN, forming a metal–insulator–semiconductor (MIS)- HEMTs structure [1]–[4]. Among the various high-*k* gate dielectrics used for GaN MIS-HEMTs, Al_2O_3 is the most commonly used so far and is one of the most attractive candidates owing to its large bandgap, high dielectric constant, and high breakdown field [5].

For the deposition of Al_2O_3 film by atomic layer deposition (ALD), trimethylaluminum (TMA) and water (H_2O) are usually used as the precursors for aluminum and oxygen. However, there are significant amount of defective states such as Al–Al and Al–O–H bonds observed in the H_2O-sourced ALD-Al_2O_3 film. These defective bonds are believed to be the origins of positive fixed charges and acceptor-like border traps [6]. Recently, several groups have reported that using ozone (O_3) as oxygen precursor to suppress these defective bonds in the ALD-Al_2O_3 film, high performance GaN MIS-HEMTs can be achieved [7], [8]. Kubo *et al.* [9], [10] demonstrated that both H and C concentrations in the ALD-Al_2O_3 were reduced by using both water and ozone as oxidants, and the main function of the O_3 pulse following the H_2O pulse is to break the O–H bonds and remove the –OH group impurities. In addition, some studies reported that using O_2 plasma as oxidant resulted in good film quality. Malmros *et al.* [11] reported the InAlN/AlN/GaN HEMTs with plasma enhanced ALD (PEALD) Al_2O_3 passivation layer exhibited better performance as compared with thermal ALD Al_2O_3. Qin and Wallace [12] demonstrated the remote O_2 plasma oxidized AlGaN surface can passivate the surface and reduce the OFF-state leakage.

In previous work, we have presented Al_2O_3/AlGaN/GaN MIS-HEMT with low threshold voltage hysteresis using PEALD-AlN interfacial passivation layer (IPL) [13]. Besides, the high-*k*/III-V interface quality was greatly improved and the bulk oxide traps at the insulator layer were reduced by utilizing PEALD-AlN IPL and post remote-plasma (PRP) gas treatment [14], [15]. In this work, we fabricated GaN MIS-HEMTs with Al_2O_3/AlN stack gate dielectric, in which the quality of the Al_2O_3 film was improved by utilizing H_2O and remote O_2 plasma as oxidants. Significant reduction of the defect bonds in ALD-Al_2O_3 film was observed by X-ray photoelectron spectroscopy (XPS) analysis. The influence of incorporating remote O_2 plasma in the ALD-Al_2O_3 process on the device performance was characterized by capacitance-voltage (*C-V*), DC, and pulsed *I-V* measurements.

II. DEVICE FABRICATION

The AlGaN/GaN HEMT heterostructure structure was grown on 6-in. p-type Si (111) substrate by metal organic chemical vapor deposition (MOCVD) method. The epitaxial structure from top to bottom consisted of 1-nm GaN cap layer, 25-nm $Al_{0.2}Ga_{0.8}N$ barrier layer, 1.3-µm i-GaN layer and 2-µm GaN/AlGaN/AlN buffer layer. The device fabrication started with mesa isolation of the active areas by inductively coupled plasma (ICP) etching using Cl_2 gases. Ti/Al/Ni/Au ohmic contact was deposited by electron beam evaporator and lift-off, followed by RTA at 800 °C for 1 min in N_2 ambient. The contact resistance was 0.35 Ω·mm extracted from the transfer length method (TLM). Prior to the gate dielectric deposition, the samples were dipped in dilute HF (1:10) for native oxide removal and subsequently loaded into the chamber of Cambridge Fiji PEALD system at a substrate temperature of 250 °C. The ALD deposited films include an 1-nm AlN IPL [13], [16] and a 10-nm Al_2O_3 as gate dielectric. Afterward, post deposition annealing (PDA) was carried out at 450 °C in oxygen ambient to improve the gate insulator quality [17]. Finally, the gate metal of Ni/Au was deposited by electron beam evaporator. Fig. 1(a) shows the schematic cross-sectional view of the fabricated MIS-HEMT. The gate-to-drain spacing L_{GD}, gate-to-source spacing L_{GS}, gate length L_G and gate width W_G were 15 µm, 3 µm, 2 µm, and 25 µm, respectively.

To compare the effect of ALD-Al_2O_3 film formed using different oxidants on device performance, the wafer was diced into 2 cm × 2 cm square pieces after mesa etch and ohmic contact formation to ensure the same starting characteristics; one group of samples used TMA and H_2O as precursors in each cycle, another group of samples used TMA and H_2O plus O_2 plasma (at a power of 50 W for 6 sec; $O_2/Ar = 20/25$ sccm flow rate) as precursors in each cycle, as shown in Fig. 1(b), and the other group of samples used for the conventional Schottky-gate GaN HEMTs fabrication.

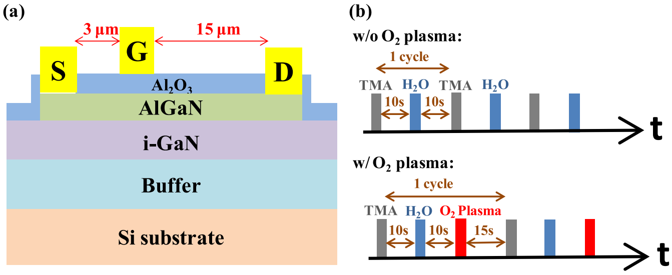

FIGURE 1. **(a) Schematic cross-sectional view of the GaN MIS-HEMT with 10 nm Al_2O_3 as gate insulator. (b) Schematic diagram of the gas flow sequences in the PEALD-Al_2O_3 process for the sample without and with O_2 plasma.**

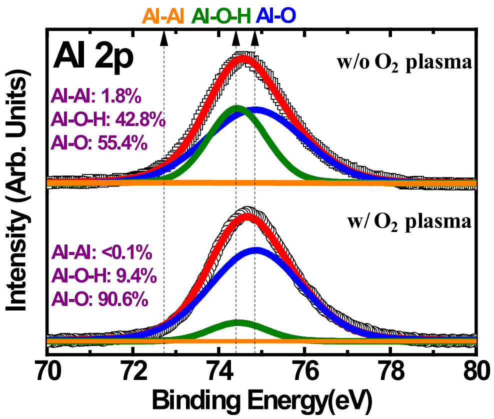

FIGURE 2. **Al 2p XPS spectra of 10-nm PEALD-Al_2O_3 for the sample without and with O_2 plasma.**

III. RESULT AND DISCUSSION

The material properties of 10-nm-thick ALD-Al_2O_3 films deposited using different oxidants were performed by XPS analysis. Fig. 2 shows the Al 2p core level spectra for the sample without and with O_2 plasma. From the XPS results, by incorporating remote O_2 plasma after TMA and H_2O precursors, the Al–Al bond could be effectively suppressed and the Al–O–H dangling bonds were significantly reduced, indicating a better ALD-Al_2O_3 film quality [7], [9].

The *C-V* measurements were performed on the MIS diodes at 100 kHz. These circular-shaped gate diodes with a diameter of 50 µm went through the same device process steps. As shown in Fig. 3, the bias of *C-V* curve was initially swept from −12 V to 2 V and then reversely biased back to −12 V. A very small hysteresis (~50 mV) was observed for the sample with O_2 plasma, indicating fewer bulk traps at the gate insulator and the high quality of the gate-dielectric/GaN interface. The threshold voltage (V_{TH}) shifted from −7.8 V to −5.8 V by incorporating O_2 plasma in the ALD-Al_2O_3 process. The V_{TH} shifted in the positive direction was due to the reduced number of positive interface fixed charges [8], [18]. In addition, the dielectric constant

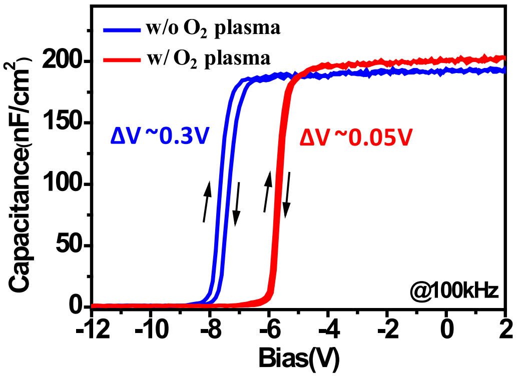

FIGURE 3. *C-V* characteristics of the Al$_2$O$_3$/GaN MIS-diode as measured at 100 kHz.

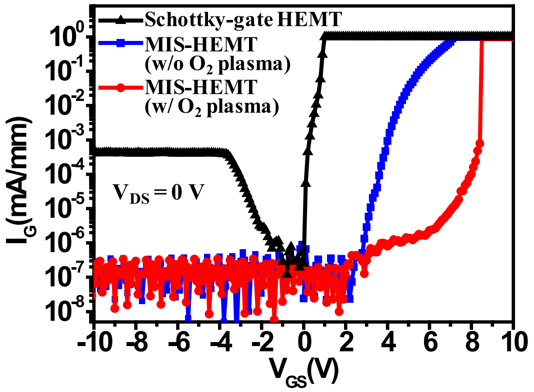

FIGURE 4. Gate leakage current characteristics of the Schottky-gate GaN HEMT and GaN MIS-HEMTs.

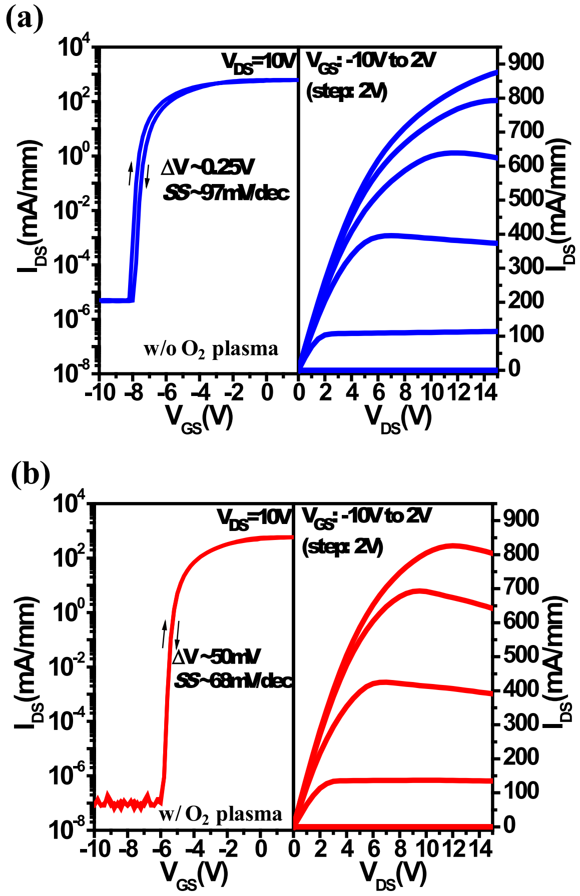

FIGURE 5. Transfer (left) and DC output (right) characteristics of the ALD-Al$_2$O$_3$ GaN MIS-HEMTs: (a) the sample without O$_2$ plasma. (b) the sample with O$_2$ plasma.

(ε) of the sample without and with O$_2$ plasma were about 7.8 and 8.5, respectively.

Fig. 4 shows the gate leakage under both reverse and forward gate biases for the conventional Schottky-gate GaN HEMT and the ALD-Al$_2$O$_3$ GaN MIS-HEMTs with V$_{DS}$ = 0 V. There is an obvious reduction in the gate leakage current at both reverse and forward bias regions for MIS-HEMT devices owing to using high bandgap Al$_2$O$_3$ as the gate dielectric. However, the MIS-HEMT with O$_2$ plasma sample showed well-suppressed gate leakage up to a forward bias of 7 V, indicating that H$_2$O+O$_2$ plasma based ALD-Al$_2$O$_3$ was a high quality gate insulator.

The transfer characteristics and output *I-V* of the ALD-Al$_2$O$_3$ GaN MIS-HEMT were measured using Agilent B1505A digital curve tracer. As shown in Fig. 5, transfer characteristics of the fabricated devices were measured with the gate voltage up-sweep from −10 V to 2 V and down-sweep from 2 V to −10 V. The V$_{TH}$ were −7.8 V and −5.8 V for the sample without and with O$_2$ plasma, respectively, defined at an I$_D$ of 1 μA/mm in the up-sweep measurement. The sample with O$_2$ plasma exhibits the well-behaved transfer characteristics with small hysteresis (ΔV$_{TH}$) of ~50 mV, low subthreshold slope (*SS*) of ~68 mV/dec and high I_{ON}/I_{OFF} ratio in the order of ~10^{10}. By contrast, the sample without O$_2$ plasma shows a larger ΔV$_{TH}$ of ~0.25 V, *SS* of ~97 mV/dec, and a lower I_{ON}/I_{OFF} ratio in the order of ~10^8. Similar to the ΔV$_{TH}$ observed in the *C-V* characteristics, the down-sweep transfer curves shift to the positive side after V$_{GS}$ exceeds +1 V. The clockwise hysteresis was due to the acceptor-like trap states at gate-dielectric/GaN interface under the gate bias sweep [19]. The density of traps can be estimated by using a pulse-mode ΔV$_{TH}$ characterization method with the equation $D_{it} = C_{oxide} \cdot \Delta V_{TH}/q$ [20]. The D$_{it}$ value of the sample without and with O$_2$ plasma were extracted to be ~9.8×10^{11} cm^{-2} and ~ 2.2 × 10^{11} cm^{-2}, respectively, indicating the sample with O$_2$ plasma exhibited the lower near interfacial bulk traps and border traps [21], [22].

To further investigate the gate dielectric film property, pulsed *I-V* measurement with a 500 μs pulse width and 1% duty cycle were performed on the fabricated GaN MIS-HEMTs. Fig. 6 shows the current collapse behaviors of GaN MIS-HEMTs with different quiescent biases (V$_{GSQ}$, V$_{DSQ}$). There were almost no current slump in both devices under the gate-lag (V$_{GSQ}$ = off-state bias, V$_{DSQ}$ = 0 V) measurements. Regarding the drain lag (V$_{GSQ}$ = off-state bias, V$_{DSQ}$ = 20 V) measurements, the current collapse suppression was observed for the sample with O$_2$ plasma, suggesting

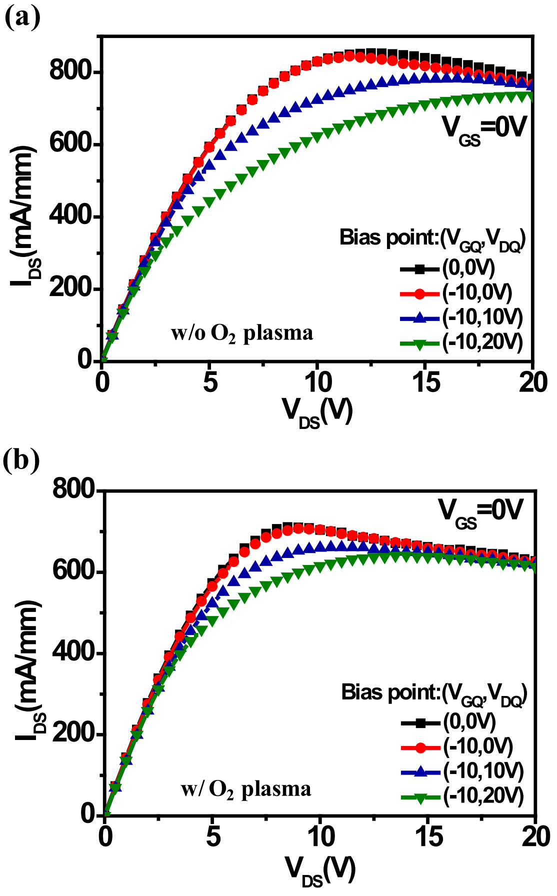

FIGURE 6. Pulsed *I-V* data measured with 500 μs pulse width and 1% duty cycle of the ALD-Al_2O_3GaN MIS-HEMTs: (a) the sample without O_2 plasma. (b) the sample with O_2 plasma.

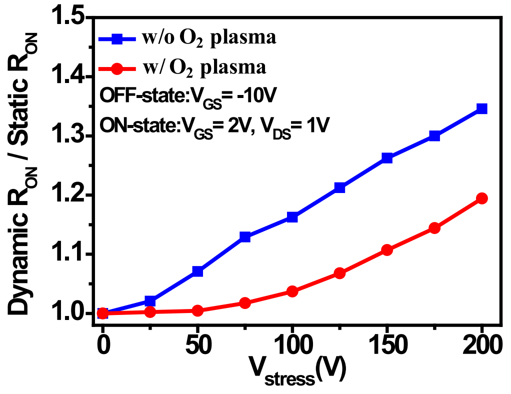

FIGURE 7. The normalized dynamic on-resistance (dynamic R_{on}/static R_{on}) with off-state drain bias stress voltage (V_{stress}) up to 200 V.

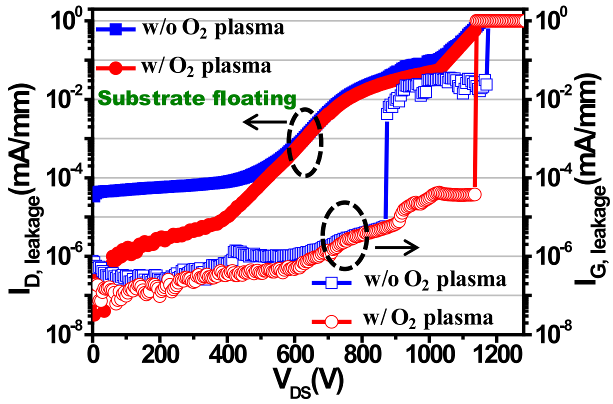

FIGURE 8. OFF-state breakdown characteristics of the GaN MIS-HEMTs for the sample without and with O_2 plasma.

that the number of traps at the bulk and the interface for the H_2O+O_2 plasma based ALD-Al_2O_3 film were reduced. Thus, the GaN MIS-HEMT performance was improved by using the proposed ALD precursors.

The Agilent B1505A power device analyzer system was used to investigate the dynamic switching characteristics of the ALD-Al_2O_3GaN MIS-HEMT devices with high drain voltage. The measurement setup is similar to the previous report [13]. The dynamic on-resistance characterization was carried out by calculating the on-state resistance. The device was switched from different off-state conditions (V_{GS} = −10 V and V_{DS} stress from 0 V to 200 V) to on-state (V_{GS} = 2 V and V_{DS} = 1 V) for the measurement. The switching time interval was set to be 20 μs. As shown in Fig. 7, the dynamic R_{ON} is only 18% larger than the static R_{ON} at the off-state V_{DS} stress of 200 V for the sample with O_2 plasma, indicating that the current collapse was effectively suppressed by the proposed deposition method.

The three-terminal off-state breakdown characteristics of the GaNMIS-HEMTs with the floating substrate are shown in Fig. 8. Both the samples without and with O_2 plasma exhibited about 640 V breakdown voltage at drain leakage current ($I_{D,leakage}$) of 1 μA/mm. It is noted that the sample with O_2 plasma showed lower drain leakage current when V_{DS} < 600 V, and the gate leakage current ($I_{G,leakage}$) was less than 1 μA/mm even when V_{DS} exceeds 1000 V.

IV. CONCLUSION

In this study, high quality Al_2O_3 film deposited by PEALD using both H_2O and remote O_2 plasma as oxygen precursors for GaN MIS-HEMT gate dielectric is investigated. Excellent bulk and interface properties of the Al_2O_3 film were obtained, resulting in low trap density in the film and a very small threshold voltage hysteresis. The MIS-HEMTs exhibited improvements in on/off current ratio, subthreshold slope, off-state leakage current, dynamic R_{ON}, and current collapse suppression. These results demonstrate that the proposed ALD-Al_2O_3 film deposition method can be a simple approach to achieve high performance GaN MIS-HEMTs for future power electronic production.

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