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Impact of post metallization annealing (PMA) on the off-state drain leakage (I_{off}) for $\text{Al}_2\text{O}_3/\text{GaN}/\text{AlGaIn}/\text{GaN}$ metal-oxide-semiconductor high electron mobility transistors (MOSHEMTs) on Si has been investigated. After implementation of PMA at 500 °C for 10 min in N_2 ambient, the I_{off} can be reduced by three orders of magnitude compared to that without PMA. In consequence, a high on/off current ratio of 10^8 and a steep subthreshold slope of 71 mV/dec are achieved for the MOSHEMTs. The reduction of I_{off} results from the suppression of source-drain surface leakage through the interface between Al_2O_3 and GaN. The decrease of

accumulation capacitance of the MOS capacitors (MOSCAPs) after 500 °C PMA suggests an oxidation process at the GaN surface during the high temperature annealing, which was confirmed by the increase of oxide layer thickness measured by transmission electron microscopy (TEM), and also the increase of Ga–O/Ga–N bond ratio at the $\text{Al}_2\text{O}_3/\text{GaN}$ interface revealed by X-ray photoelectron spectroscopy (XPS). These results suggest that the significant reduction of I_{off} after 500 °C PMA can be attributed to partial surface oxidation of the GaN cap, which suppresses the conduction path at the $\text{Al}_2\text{O}_3/\text{GaN}$ interface.

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1 Introduction GaN-based high electron mobility transistors (HEMTs) have demonstrated great potential for power switching and high frequency power amplifier applications [1–3]. The conventional HEMT with Schottky gate structure usually suffers from high gate leakage, which would increase the standby power loss and also limit the gate forward bias. In order to block the gate leakage current and suppress the drain current collapse, the Al_2O_3 gate dielectric by atomic layer deposition (ALD) has been adopted to form metal-oxide-semiconductor HEMTs (MOSHEMTs) [4–7]. However, adding an insulator between the gate metal and barrier layer creates an extra dielectric/(Al)GaN interface, which could introduce high density donor-like interface traps [8, 9]. These trap states can assist the two-dimensional variable range hopping (2D-VRH) conduction, resulting in serious surface leakage

current through the interface [10, 11]. Consequently, a high off-state drain leakage current (I_{off}) can be a serious issue for the MOSHEMTs. Post metallization annealing (PMA) has been studied to improve the gate contact with dielectric and also to reduce the fixed charges at the dielectric/semiconductor interface or within the dielectric bulk [12–16]. Most of these studies mainly focus on the influence of PMA on the threshold voltage of MOSHEMTs.

In this work, we investigated the effects of PMA on the I_{off} for $\text{Al}_2\text{O}_3/\text{GaN}/\text{AlGaIn}/\text{GaN}$ MOSHEMTs on Si. It was found that PMA at 500 °C in N_2 for 10 min can reduce the I_{off} by three orders of magnitude, resulting in a high on/off current ratio of 10^8 and a steep subthreshold slope (SS) of 71 mV/dec. The reduction of accumulation capacitance of the MOS capacitors (MOSCAPs) after 500 °C PMA revealed a partial oxidation of the GaN surface.

Transmission electron microscopy (TEM) and X-ray photoelectron spectroscopy (XPS) techniques were performed to identify the oxidation process at the $\text{Al}_2\text{O}_3/\text{GaN}$ interface during the high temperature annealing.

2 Experimental The $\text{GaN}/\text{AlGaN}/\text{GaN}$ heterostructure used in this work was grown on a 6-inch n-type Si substrate by metal-organic chemical vapor deposition (MOCVD). As shown in Fig. 1(a), the epilayer, from bottom to top, consists of a 200-nm AlN nucleation layer, an 800-nm step-graded AlGaN layer, a 2- μm unintentionally doped GaN layer, a 1-nm AlN spacer, a 30-nm $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ barrier, and a 2-nm GaN cap. Hall measurements showed a sheet carrier density of $7 \times 10^{12} \text{ cm}^{-2}$ and mobility of $1800 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$, resulting in an average sheet resistance of $500 \Omega/\text{sq}$. Atomic force microscope (AFM) observation of the as-grown HEMT epi on Si showed a smooth surface morphology with root mean square (RMS) roughness of 0.5 nm across a $5 \times 5 \mu\text{m}^2$ scanned area.

The MOSHEMT fabrication started from device isolation by BCl_3/Cl_2 -based inductively coupled plasma (ICP) etching. The mesa depth was around 150 nm. Then the source/drain metal stack $\text{Ti}/\text{Al}/\text{Ni}/\text{Au}$ (20/150/50/80 nm) was deposited by e-beam evaporation and annealed at 850°C in N_2 ambient for 30 s to form Ohmic contact. After that, the sample was cleaned by an oxygen plasma treatment with a power of 100 W for 1 min and a $\text{HCl}:\text{H}_2\text{O}$ (1:3) solution immersion for 2 min. Then a 10-nm Al_2O_3 gate

dielectric was deposited immediately in an Oxford Instruments atomic layer deposition (ALD) system at 300°C using trimethylaluminum (TMA) and H_2O vapor as precursors. Finally the Ni/Au (20/200 nm) gate metal was deposited by e-beam evaporation. After device fabrication, the sample was separated into four pieces, three of which were annealed at 300, 400, and 500°C , respectively, by rapid thermal annealing (RTA) process in N_2 ambient for 10 min. The MOSHEMTs used in the following characterization are with 2 μm gate length, gate-source and gate-drain distance of 1 μm , and gate width of 10 μm . Circular MOSCAPs with 200 μm in diameter were also fabricated on the same sample for capacitance–voltage (CV) characterization.

3 Results and discussion Figure 2 shows the drain current and gate leakage current versus gate bias for the fabricated MOSHEMTs. For all the devices without and with various PMAs, the gate leakage currents remain below $10^{-6} \text{ mA mm}^{-1}$. The devices without PMA show a high I_{off} of $10^{-2} \text{ mA mm}^{-1}$ at V_{GS} of -8 V and V_{DS} of 6 V. The large difference between the gate leakage current and the I_{off} indicates that the I_{off} is dominated by the drain-to-source leakage. No obvious change in the I_{off} is observed for the devices with PMA at 300°C and 400°C , while the I_{off} is reduced by three orders of magnitude for the devices with PMA at 500°C . Consequently, a high $I_{\text{on}}/I_{\text{off}}$ ratio of $\sim 10^8$ and a sharp SS of 71 mV/dec are achieved for the MOSHEMTs with 500°C PMA. The positive shift of threshold voltage for samples with PMA was attributed to the reduction of fixed positive charges at the $\text{Al}_2\text{O}_3/\text{GaN}$ interface or within Al_2O_3 bulk [12, 13].

In order to find out the impact of PMA on the effectiveness of the Al_2O_3 passivation in the access region, DC-pulsed IV dispersion of output characteristics for the MOSHEMTs without PMA and with various PMA conditions were characterized, as compared in Fig. 3. For the DC output characteristics, the maximum drain current at the gate bias of +

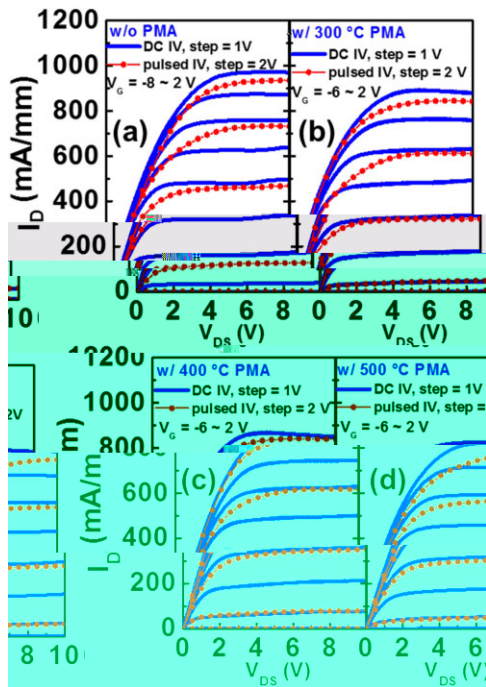


Figure 3 DC/gate pulsed output characteristics of the MOSHEMTs (a) without PMA, (b) with 300 °C PMA, (c) with 400 °C PMA, and (d) with 500 °C PMA. The pulse period is 1 s and pulse width is 500 μ s. Gate pulse base voltage V_{GS0} is -8 V.

the sheet resistance (R_{sh}) and Ohmic contact resistance (R_c), measured 387 Ω /sq and 1.1 $\Omega \cdot \text{mm}$ without PMA, slightly increase to 400 Ω /sq and 1.2 $\Omega \cdot \text{mm}$ after 500 °C PMA. The slight increase of R_{sh} and R_c may have contributed to the decrease of maximum drain current. For the pulsed IV characterization, a pulsed voltage with duty/period of 500 μ s/1 s was applied to the gate with the base voltage at -8 V (quiescent bias at pinch-off condition). On-state resistance (R_{on}) was extracted in the linear region with gate bias of +2 V and compared between DC and gate pulsed IV. The ratio of $R_{on,pulse}/R_{on,DC}$ is 1.13, 1.03, 1.02, and 1.09 for the device without PMA, with 300, 400, and 500 °C PMA, respectively. The little increase of the $R_{on,pulse}$ compared to the $R_{on,DC}$ indicates good surface passivation effect of the Al_2O_3 , and the negligible difference between the ratio of $R_{on,pulse}/R_{on,DC}$ without PMA and that with various PMA conditions suggests good thermal stability of the effective Al_2O_3 passivation.

Figure 4 shows the buffer leakage between two individual Ohmic pads with both width and gap of 100 μm for samples without and with various PMA temperatures. The buffer leakage of a HEMT sample fabricated using the same epi wafer was added for comparison with the same PMA conditions. It can be seen that the buffer leakage currents for the MOSHEMT samples without PMA and with 300 and 400 °C PMA are three orders of magnitude higher than that of the HEMT sample with/without PMA. The significantly increased buffer

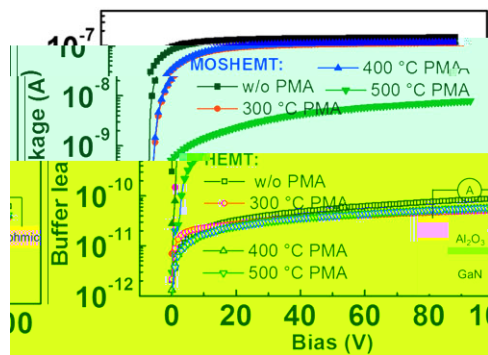


Figure 4 Buffer leakage comparison of MOSHEMT and HEMT samples without and with various PMAs. The pad width and gap both are 100 μm .

leakage mainly results from the surface leakage at the $\text{Al}_2\text{O}_3/\text{GaN}$ interface. With PMA at 500 °C, the surface leakage can be reduced by more than one order of magnitude.

Double-sweep mode CV characteristics of the MOSCAPs on samples without PMA, with 300 °C PMA and with 500 °C PMA were shown in Fig. 5. The accumulation capacitance for the MOSCAP with 500 °C PMA is $\sim 10\%$ lower than those without PMA and with 300 °C PMA. The reduction of the accumulation capacitance indicates the increase of equivalent oxide thickness (EOT). Moreover, the hysteresis in the CV of MOSCAPs can be reduced from ~ 0.2 V without PMA to ~ 0.1 V with 300 and 500 °C PMA, suggesting an improved interface after PMA. The reduction of the accumulation capacitance is also part of the reasons for the decrease of maximum drain current of MOSHEMTs with 500 °C PMA. It was suspected that the GaN surface had been oxidized during the high temperature annealing.

To compare the oxide thicknesses for samples without and with 500 °C PMA, two samples were prepared with 10 nm Al_2O_3 and 20 nm Ni on top for TEM observation. PMA at 500 °C was performed for one of them. The cross-sectional TEM images for the two samples are shown in

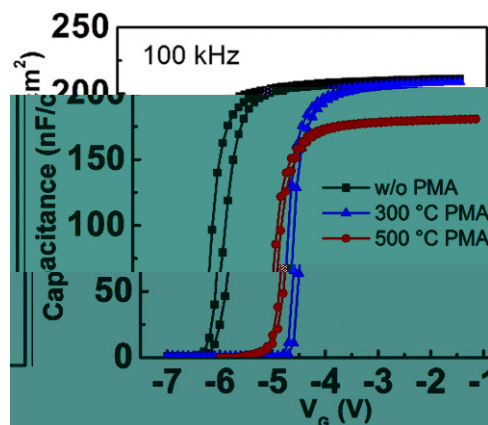


Figure 5 Capacitance-voltage characteristics of circular MOSCAPs without and with various PMAs.

Fig. 6. The oxide layer thickness increases slightly from 8.9 to 9.4 nm and the interface of $\text{Al}_2\text{O}_3/\text{GaN}$ is more abrupt after 500 °C PMA.

To further verify the oxidation process during the 500 °C PMA, the chemical bonding composition at the $\text{Al}_2\text{O}_3/\text{GaN}$ interfaces was revealed by XPS, using a monochromatic Al K

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