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Device Performances Related to Gate Leakage Current in Al_2O_3/AlGaN/GaN MISHFETs

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***Abstract*—In this paper, we have characterized the electrical properties related to gate leakage current in AlGaN/GaN MISHFETs with varying the thickness (0 to 10 nm) of Al_2O_3 gate insulator which also serves as a surface protection layer during high-temperature RTP. The sheet resistance of the unprotected TLM pattern after RTP was rapidly increased to 1323 Ω/□ from the value of 400 Ω/□ of the as-grown sample due to thermal damage during high temperature RTP. On the other hand, the sheet resistances of the TLM pattern protected with thin Al_2O_3 layer (when its thickness is larger than 5 nm) were slightly decreased after high-temperature RTP since the deposited Al_2O_3 layer effectively neutralizes the acceptor-like states on the surface of AlGaN layer which in turn increases the 2DEG density. AlGaN/GaN MISHFET with 8 nm-thick Al_2O_3 gate insulator exhibited extremely low gate leakage current of 10^{-9} A/mm, which led to superior device performances such as a very low subthreshold swing (SS) of 80 mV/dec and high I_{on}/I_{off} ratio of ~ 10^{10}. The PF emission and FN tunneling models were used to characterize the gate leakage currents of the devices. The device with 5 nm-thick Al_2O_3 layer exhibited both PF emission and FN tunneling at relatively lower gate voltages compared to that with 8 nm-thick Al_2O_3 layer due to thinner Al_2O_3 layer, as expected. The device with 10 nm-thick Al_2O_3 layer, however, showed very high gate leakage current of 5.5×10^{-4} A/mm due to poly-crystallization of the Al_2O_3 layer during the high-temperature RTP, which led to very poor performances.**

***Index Terms*—Gallium nitride, HFET, thin Al_2O_3 layer, ALD, sheet resistance, gate leakage current**

I. INTRODUCTION

AlGaN/GaN heterojunction field-effect transistors (HFETs) have been widely investigated as a very promising device for high-power/frequency applications due to the high two-dimensional electron gas (2DEG) density along with the high electron mobility [1-3]. For better device performance, a thin AlGaN barrier is usually required to suppress the short channel effect and to increase the transconductance of the device, which results in high cutoff frequency (f_T) and maximum oscillation (f_{max}) frequency [4]. In general, however, the device with thin AlGaN barrier suffers from a large gate leakage current due to various surface damage during subsequent fabrication steps such as plasma or high temperature thermal process. The large gate leakage current of HFET can cause severe device degradation such as high subthreshold swing (SS), low I_{on}/I_{off} ratio, and current dispersion [5, 6]. AlGaN/GaN metal-insulator-semiconductor HFETs (MISHFETs) with appropriate thin gate insulator such as Al_2O_3, SiO_2, or Si_3N_4 layer were therefore investigated to reduce the gate leakage current. The use of thin gate insulator is also required to achieve the high frequency operation (f_T,

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f_{max}) for RF devices [7-9]. The Al_2O_3 layer, usually deposited by atomic layer deposition (ALD), has been widely used as a gate dielectric layer among other insulators because it offers high gate capacitance due to relatively high dielectric constant (9.1 eV), high breakdown field (10 MV·cm^{-1}), and large conduction band offset of 2.1 eV with AlGaN layer which ensures low gate leakage current [10-13].

In this work, we have optimized the thickness of the thin Al_2O_3 layer, which can serve as an effective surface protection layer during high-temperature RTP as well as an excellent gate dielectric layer in AlGaN/GaN MISHFETs. The utilization of the thin Al_2O_3 layer simplifies the fabrication of the AlGaN/GaN MISHFET because it does not require removal of the Al_2O_3 protection layer after RTP and re-deposition of the gate dielectric layer.

II. EXPERIMENT

Fig. 1 shows the cross-sectional schematic of the fabricated AlGaN/GaN MISHFET with Al_2O_3 gate dielectric. A 17 nm-thick AlGaN/GaN heterostructure with an electron mobility of 1900 cm^2/Vs, sheet electron concentration of 8×10^{12}/cm^2, and the sheet resistance of 400 Ω/□ was grown on sapphire (0001) substrate by metal organic chemical vapor deposition (MOCVD).

Firstly, the device isolation was carried out by transformer-coupled-plasma reactive ion etching (TCP-RIE) using a BCl_3/Cl_2 gas mixture. A thin amorphous Al_2O_3 layers, with different thickness of 5, 8, and 10 nm were then deposited with a deposition rate of 0.7 Å/cycle at 450°C using plasma-enhanced atomic layer deposition (PEALD), which serves as both the surface protection layer during RTP and as gate insulator of the device. The Al_2O_3 layer was patterned to define the source/drain regions and then Si/Ti/Al/Ni/Au (1/25/160/40/100 nm) layers were deposited, followed by two-step RTP at low temperature of 500°C for 20 sec and subsequently at higher temperature of 800°C for 30 sec in N_2 ambient. Finally, Ni/Au (50/50 nm) gate metal was deposited. The gate length and width of the fabricated AlGaN/GaN MISHFETs were 3 and 100 µm, respectively. After the fabrication of the devices, the electrical properties and device parameters were characterized according to the variation of the thickness of Al_2O_3 layer.

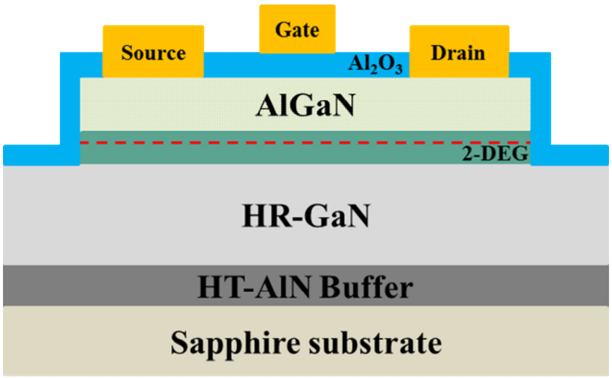
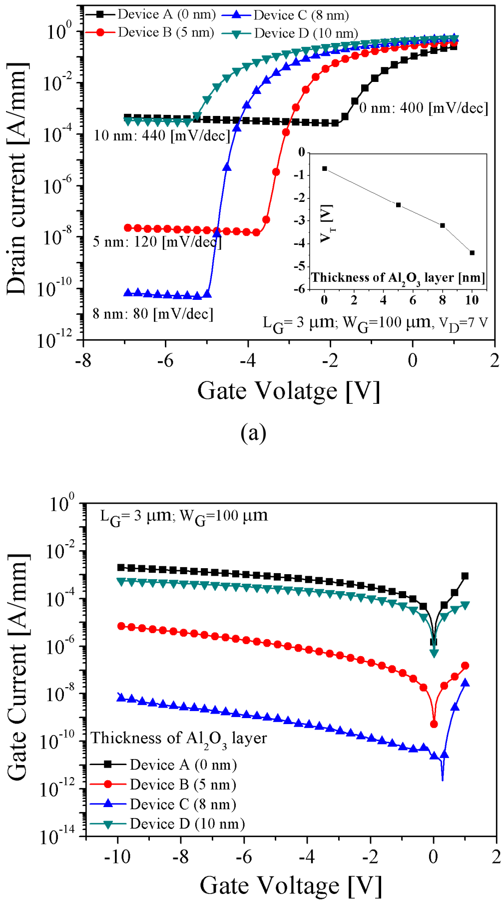


Fig. 1. Schematic structure of AlGaN/GaN MISHFET fabricated with thin Al_2O_3 layer.

III. RESULTS AND DISCUSSION

The resistance parameters for ohmic contact were extracted by using transmission line method (TLM). The sheet resistance of the device with unprotected AlGaN surface was increased to 1323 Ω/□ from the value of 400 Ω/□, obtained by hall measurement for the as-grown AlGaN/GaN heterostructure. This clearly indicates that the surface of the thin AlGaN layer becomes thermally damaged due to the high temperature exposure during RTP [14, 15], which would create many acceptor-like states on the AlGaN surface and thus decrease the electron density in the 2DEG channel underneath. On the contrary, the sheet resistances of the surface protected devices were not degraded, but rather decreased after high temperature RTP. This is because the thin Al_2O_3 layer not only protects the AlGaN surface during the RTP, but also effectively compensates the acceptor-like states on the surface of AlGaN layer which increases the electron density in the 2DEG channel.

Fig. 2 shows the semi-log transfer characteristics for AlGaN/GaN MISHFETs with different Al_2O_3 thicknesses. The curve with black squares represents the characteristics for the AlGaN/GaN HFET without Al_2O_3 gate insulator, which is reference device. It is noticed that the threshold voltage (V_T) of the device negatively shifts with increasing the thickness of Al_2O_3 layer. The extracted threshold voltages for the devices were also shown in the inset of Fig. 2. The device with 8 nm-thick Al_2O_3 layer clearly demonstrates excellent performances such as very low off-state leakage current (I_{off}) of 6.4×10^{-11} A/mm, very low subthreshold swing (SS) of 80



(a)

(b)

Fig. 2. (a) Log-scale I_D-V_G characteristics according to the thickness of Al_2O_3 layer. The inset shows the threshold voltages with varying the thickness of Al_2O_3 layer, (b) Gate leakage current as functions of gate bias.

mV/dec, and high I_{on}/I_{off} ratio of ~ 10^{10}, which indicates that 8 nm-thick Al_2O_3 layer is very effective in decreasing both the gate leakage current and the surface leakage current between the gate and the drain which also results in suppressing the off-state surface leakage current. In contrast, the device with 10 nm-thick Al_2O_3 layer exhibits the highest on-state current due to large negative V_T of – 4.4 V, but the other performances are very poor such as very low I_{on}/I_{off} ratio of ~ 10^3, very high SS of 440 mV/dec, and high off-state leakage current of 3.4 × 10^{-4} A/mm owing to the high gate leakage current of the device.

It was found the device performances observed in Fig. 2(a) were strongly related to the gate leakage currents The device with lower gate leakage current exhibited better device performances as shown in Fig. 2(b). The reference HFET device without Al_2O_3 layer showed high gate leakage current of ~ 2 × 10^{-3} A/mm at V_G = - 10 V, due to typical schottky gate leakage current (I_{SG}) through thin AlGaN barrier and the surface leakage current (I_{SL}) by the surface defect charge [16-18]. The leakage current greatly decreased to ~ 7 × 10^{-6} A/mm at V_G = - 10 V as the thickness of the Al_2O_3 layer was increased to 5 nm and the current was further decreased to 6.1× 10^{-9} A/mm at same gate voltage for the device with 8 nm-thick Al_2O_3 layer. However, the device with 10 nm-thick Al_2O_3 layer showed very high gate leakage current of 5.5 × 10^{-4} A/mm, similar to the value for the reference HFET device. It is generally known that the ALD Al_2O_3 layer becomes poly-crystallized when the annealing temperature reaches at ~ 850°C [19]. Furthermore, premature poly-crystallization of the layer can be observed even at lower annealing temperature as the thickness of the layer increases. Thus, the unexpected result for the device with 10 nm-thick Al_2O_3 layer is probably due to the poly-crystallization of the Al_2O_3 layer during the RTP which causes large current flow through the grain boundaries of the Al_2O_3 layer to make the layer very leaky. The extracted parameters of all the devices are summarized in Table 1.

Table 1. The parameters extracted from devices

	Device A	Device B	Device C	Device D
Al_2O_3 thickness [nm]	0	5	8	10
V_T [V]	- 0.7	- 2.3	- 3.2	- 4.4
$I_{D,max}$ at V_D= 7V [mA/mm]	248.6	355.8	513.5	533.7
$g_{m,max}$ [mS/mm]	155	127	129	110
SS [mV/dec]	400.0	120.0	80.0	440.0
I_{on}/I_{off} ratio	10^3	10^7	10^{10}	10^3
$I_{D,off}$ at V_G= - 7 V [A/mm]	4.30E-04	2.20E-08	6.40E-11	3.40E-04
I_G at V_G= - 10 V [A/mm]	1.90E-03	6.90E-06	6.10E-09	5.50E-04

Two models, Poole-Frankel (PF) emission, $\ln(I/V) = \sqrt{V}$ and Fowler-Nordheim (FN) tunneling, $\ln(I/V^2) = -(1/V)$, were employed to characterize the gate leakage current of the Al_2O_3 gate insulator with different thickness. Fig. 3(a) shows PF emission plots from the gate leakage currents of the devices with 5 and 8 nm-thick Al_2O_3 layer. PF emission of the device with relatively thin 5 nm-thick Al_2O_3 layer begins from very low gate voltage. This indicates that the electrons emitted from the gate easily tunnel through the thin Al_2O_3 layer to be captured into the interface trap between the Al_2O_3

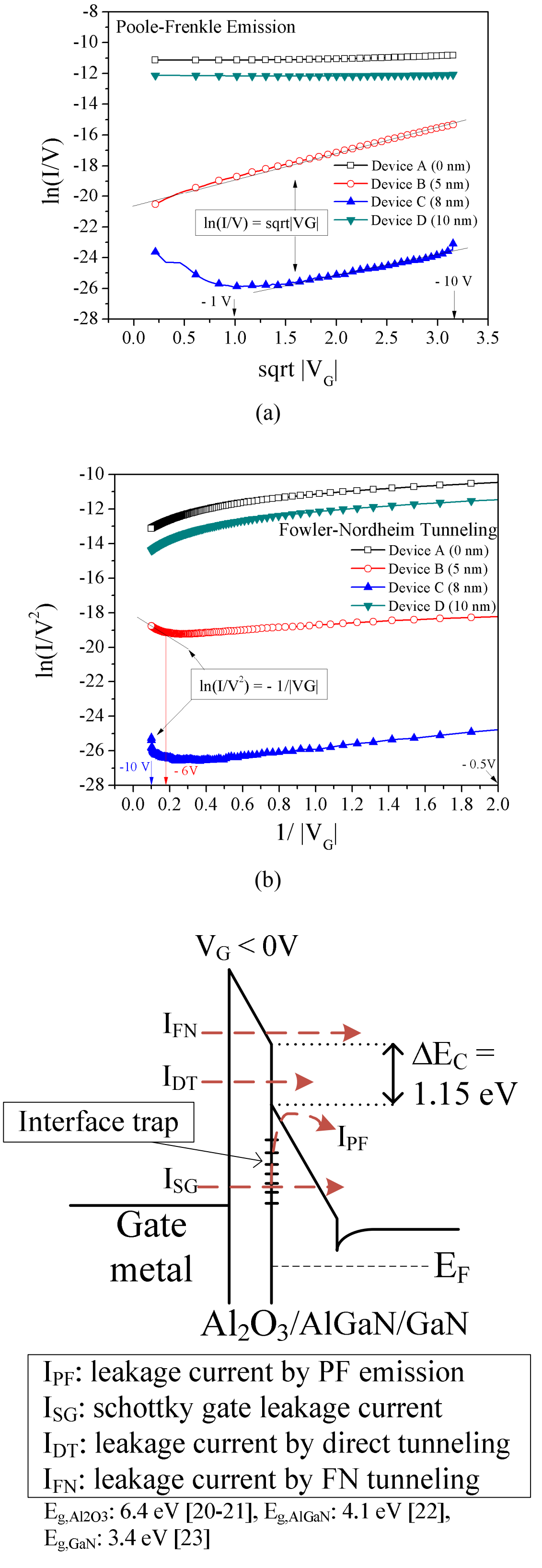


Fig. 3. (a) Poole-Frankel emission plots, (b) Fowler-Nordheim plots with varying the thickness of Al_2O_3 layer, (c) The schematic model of the gate leakage current of the device.

layer and AlGaN layer, and then the trapped electrons escape from the trap toward the channel to form the gate leakage current (I_{PF}) as a simple band diagram modeled in Fig. 3(c). On the other hand, the device with relatively thick 8 nm-thick Al_2O_3 layer exhibited the PF emission at higher gate voltage larger than - 1 V, which is expected because the thicker gate oxide requires higher gate voltage to supply tunneling electrons to the interface traps. Fig. 3(b) shows FN tunneling plots extracted from the gate leakage currents (I_{FN}) of the devices. The plot may cover the voltage related to the direct tunneling (I_{DT}), which occurs prior to the FN tunneling. The FN tunneling for the device with 5 nm-thick Al_2O_3 layer begins at the gate voltage of - 6 V. For the device with 8 nm-thick Al_2O_3 layer, the tunneling becomes significant when the gate voltage is larger than - 10 V and the current level is three orders lower in magnitude compared to the value observed in the device with 5 nm-thick Al_2O_3 layer, which is also expected from the band diagram in Fig. 3(c), because the thicker oxide needs higher tunneling voltage. Finally, the device with 10 nm-thick Al_2O_3 layer showed neither the FN tunneling nor the PF emission since the 10 nm-thick Al_2O_3 layer became poly-crystallized during the high-temperature RTP and the layer lost the insulating properties, which resulted in very similar poor leakage characteristics with the reference device without the Al_2O_3 layer.

IV. CONCLUSIONS

In this work, we have investigated the device performances related to gate leakage current in Al_2O_3/AlGaN/GaN MISHFETs with varying Al_2O_3 gate insulator thickness. Thin Al_2O_3 layer serves as excellent gate dielectric and the effective surface protection layer during the fabrication of the AlGaN/GaN MISHFET. Models for the PF emission and the FN tunneling were employed to characterize the gate leakage current of the Al_2O_3 gate insulator with different thickness. The devices with 5 and 8-nm Al_2O_3 gate insulator exhibited both the PF emission and the FN tunneling. The device with 8 nm-thick Al_2O_3 gate insulator showed very low gate leakage current of 6.1×10^{-9} A/mm which led to excellent device performances such as SS of 80 mV/dec and I_{on}/I_{off} ratio of ~ 10^{10}. However, the device with 10 nm-thick Al_2O_3 layer showed neither the PF emission nor the FN tunneling, but instead exhibited very large gate leakage current because the Al_2O_3 layer became poly-crystallized during the high-temperature RTP, which led to very poor device performances.

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