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Threshold voltages of Al_2O_3/AlGaN/GaN and AlTiO/AlGaN/GaN metal-insulator-semiconductor devices

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Abstract – We systematically investigated threshold voltages of Al_2O_3/AlGaN/GaN and AlTiO/AlGaN/GaN metal-insulator-semiconductor devices, where Al_2O_3 and AlTiO insulators are obtained by atomic layer deposition. Analyzing the insulator thickness dependence of the threshold voltages, we obtained positive insulator-semiconductor interface fixed charges, whose density is lower for AlTiO/AlGaN/GaN than for Al_2O_3/AlGaN/GaN.

1 Introduction

GaN-based metal-insulator-semiconductor (MIS) devices have been extensively developed owing to the merits of gate leakage reduction and passivation effects. As a gate insulator, high-dielectric-constant (high-k) materials, such as Al_2O_3 [1], HfO_2 [2], TiO_2 [3], AlN [4], BN [5], TaON [6], and AlTiO [7], were employed. AlTiO, an alloy of TiO_2 and Al_2O_3, is useful to balance the dielectric constant k and the bandgap E_g, with intermediate properties between TiO_2 ($k \sim 60$, $E_g \sim 3$ eV) and Al_2O_3 ($k \sim 9$, $E_g \sim 7$ eV) [8]. When an insulator is formed on AlGaN with a negative polarization charge, in many cases, a positive interface fixed charge occurs to almost cancel the polarization charge [9, 10], although the physical origin of the interface fixed charge is not fully elucidated. The interface fixed charge affects device characteristics, in particular, the threshold voltage. In this work, we fabricated and characterized Al_2O_3/AlGaN/GaN and AlTiO/AlGaN/GaN MIS devices, where Al_2O_3 and AlTiO insulators are obtained by atomic layer deposition (ALD). From a systematic investigation of threshold voltages of the MIS devices, we evaluated insulator-semiconductor interface fixed charges.

2 Device fabrication

Using an $Al_{0.27}Ga_{0.73}N$(30 nm)/GaN(3000 nm) heterostructure obtained by metal-organic vapor phase epitaxy on sapphire(0001), we fabricated Al_2O_3/AlGaN/GaN and AlTiO/AlGaN/GaN MIS devices shown in Fig. 1. On the heterostructure, Ti/Al/Ti/Au Ohmic electrodes were formed. The Al_2O_3 gate insulator ($k \simeq 9$, $E_g \simeq 6.8$ eV) was deposited on the AlGaN surface by ALD using trimethylaluminum (TMA) and H_2O as precursors, followed by post-deposition annealing in H_2-mixed Ar at 350 °C. Also we deposited the Al_xTi_yO gate insulator ($x : y = 0.73 : 0.27$, $k \simeq 15$, $E_g \simeq 6.0$ eV) by ALD using TMA, tetrakis-dimethylamino titanium (TDMAT), and H_2O, followed by the same post-deposition annealing. Ni/Au gate electrodes were formed on the gate insulator, completing the device fabrication.

3 Device characterization

We measured capacitance-voltage characteristics of the MIS devices with several insulator thicknesses $d_{\rm ins}$. Figure 2 shows the capacitance C between the gate electrode and the grounded Ohmic electrode, and the sheet electron concentration $n_{\rm s}$ calculated by integration of C, as functions of the gate voltage $V_{\rm G}$. The measurements were carried out at 1 MHz and under a voltage sweep $V_{\rm G} = 0 \rightarrow -12$ V. The measured capacitance C_0 at $V_{\rm G} = 0$ should be given by $1/C_0 = d_{\rm ins}/(k_{\rm ins}\varepsilon_0) + d_{\rm AlGaN}/(k_{\rm AlGaN}\varepsilon_0)$ (with obvious notations). From the $d_{\rm ins}$ dependence of C_0, we obtain $k_{\rm AlGaN} = 9.3$, and also $k_{\rm ins} = 9.2$ and 15.4 for Al_2O_3 and AlTiO, respectively. From the $n_{\rm s}$-$V_{\rm G}$ relation in Fig. 2, threshold voltages $V_{\rm th}$ as functions of $d_{\rm ins}$ are determined as shown in Fig. 3, where we can confirm linear dependences. Figure 4 shows the schematic band diagram of the MIS devices, from which we obtain

$$V_{\rm th} \simeq -\frac{\Delta\sigma_{\rm ins}}{k_{\rm ins}\varepsilon_0}d_{\rm ins} - \frac{\Delta\sigma_{\rm AlGaN}}{k_{\rm AlGaN}\varepsilon_0}d_{\rm AlGaN} + \frac{\psi_{\rm m}}{q}, \qquad (1)$$

where $\Delta\sigma_{\rm ins} = \sigma_{\rm ins} - \sigma_{\rm GaN}$ and $\Delta\sigma_{\rm AlGaN} = \sigma_{\rm AlGaN} - \sigma_{\rm GaN}$, with the insulator-semiconductor interface fixed charge density $\sigma_{\rm ins}$, the polarization charges $\sigma_{\rm AlGaN}$ for AlGaN and $\sigma_{\rm GaN}$ for GaN, and $\psi_{\rm m} = \phi - \varphi - \Delta E_{\rm C}$ defined in Fig. 4. By fitting the $d_{\rm ins}$ dependence of $V_{\rm th}$ using Eq. (1), we obtain $\Delta\sigma_{\rm ins}/q = 1.5 \times 10^{13}$ cm^{-2} and 1.1×10^{13} cm^{-2} for Al_2O_3/AlGaN/GaN and AlTiO/AlGaN/GaN, respectively, as shown in Table I. Assuming $\sigma_{\rm GaN}/q = 2.1 \times 10^{13}$ cm^{-2} and $\sigma_{\rm AlGaN}/q = 3.4 \times 10^{13}$ cm^{-2}, we also estimated $\sigma_{\rm ins}$ and $\psi_{\rm m} = \phi - \varphi - \Delta E_{\rm C}$ given in Table I. We find a lower $\sigma_{\rm ins}$ for AlTiO/AlGaN/GaN than for Al_2O_3/AlGaN/GaN.

From the above results, we can estimate the band diagrams of the MIS devices by Poisson-Schrödinger calculation as shown in Fig. 5. It should be noted that, for AlTiO/AlGaN/GaN MIS devices, the AlTiO/AlGaN interface is negatively charged owing to the lower $\sigma_{\rm ins}$. As a result, the electric field in AlTiO almost vanishes, while that in Al_2O_3 is rather high. For AlTiO/AlGaN/GaN MIS devices, this fact and the high dielectric constant lead to shallow threshold voltages in comparison with Al_2O_3/AlGaN/GaN.

4 Summary

We fabricated and investigated Al_2O_3/AlGaN/GaN and AlTiO/AlGaN/GaN MIS devices with Al_2O_3 and AlTiO gate insulators deposited by ALD. From the insulator thickness dependence of threshold voltages, we obtained the insulator-semiconductor interface fixed charges, whose density is lower for AlTiO/AlGaN/GaN than for Al_2O_3/AlGaN/GaN. This fact and the high dielectric constant lead to shallow threshold voltages for AlTiO/AlGaN/GaN MIS devices.

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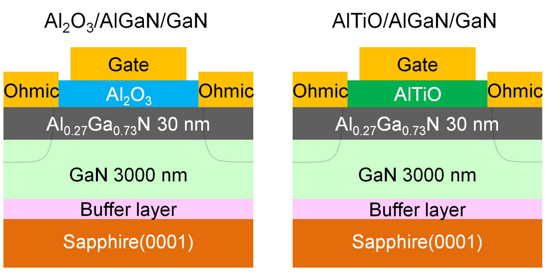

Fig. 1: The schematic cross sections of Al_2O_3/AlGaN/GaN and AlTiO/AlGaN/GaN MIS devices.

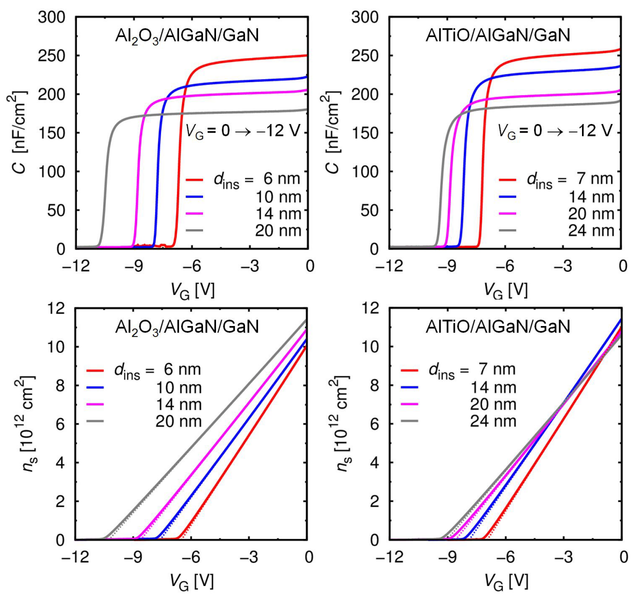

Fig. 2: The capacitance C and the sheet electron concentration n_s as functions of the gate voltage V_G. The measurements were carried out at 1 MHz and under a voltage sweep $V_G = 0 \to -12$ V.

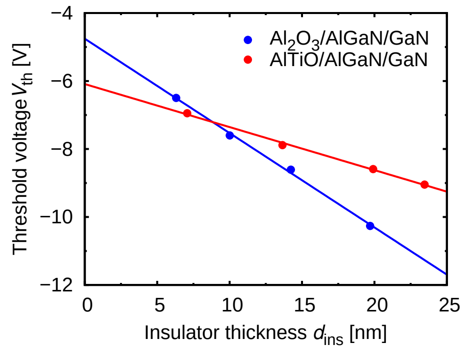

Fig. 3: The threshold voltage V_{th} as functions of the insulator thickness d_{ins}.

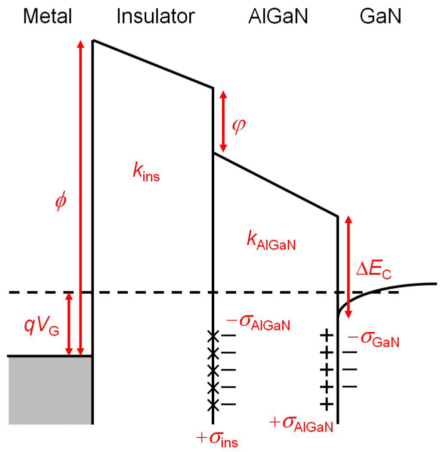

Fig. 4: The schematic band diagram of the MIS devices.

Table I: $\Delta\sigma_{ins}$, σ_{ins}, and $\psi_m = \phi - \varphi - \Delta E_C$ for (a) Al_2O_3/AlGaN/GaN and (b) AlTiO/AlGaN/GaN MIS devices.

	$\Delta\sigma_{ins}/q$ [cm^{-2}]	σ_{ins}/q [cm^{-2}]	ψ_m [eV]
(a)	1.5×10^{13}	3.6×10^{13}	2.0
(b)	1.1×10^{13}	3.2×10^{13}	0.7

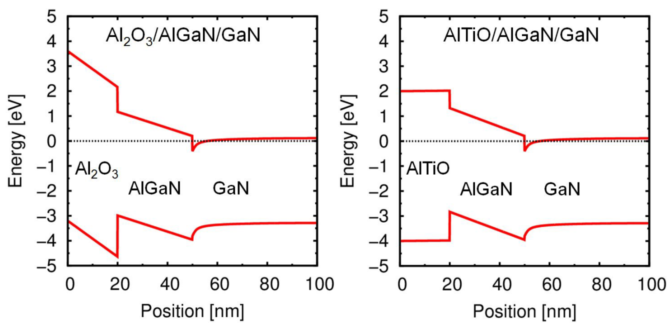

Fig. 5: The band diagrams of the MIS devices, obtained by Poisson-Schrödinger calculation.