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Impacts of nitrogen plasma surface cleaning on threshold voltages of AlTiO/AlGaN/GaN MIS devices

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Abstract – For AlTiO/AlGaN/GaN metal-insulator-semiconductor (MIS) devices with different AlTiO gate insulator thicknesses and compositions, we investigated impacts of nitrogen plasma surface cleaning of AlGaN on the threshold voltages. The slope of the thickness-dependence of the threshold voltages is increased by the surface cleaning, indicating that the AlTiO/AlGaN interface fixed charges are suppressed. The intercept of the dependence is also increased by the surface cleaning, indicating that the AlTiO/AlGaN band offset is decreased. Theses effects are more pronounced for AlTiO with a higher Ti composition.

1 Introduction

As a gate insulator for GaN-based metal-insulator-semiconductor (MIS) devices, high-k dielectrics, such as Al_2O_3 [1], HfO_2 [2], TiO_2 [3], AlN [4], BN [5], TaON [6], and AlTiO [7], have been investigated. AlTiO, an alloy of Al_2O_3 and TiO_2, is a useful gate insulator due to its controllable properties to balance the dielectric constant k and the bandgap E_g according to its composition [8]. At the interface between a gate insulator and a negatively polarized semiconductor surface, such as Ga-face (Al)GaN, positive fixed charges tend to be generated and to cancel the negative polarization charges, although the existence of the interface fixed charges is not a necessity [9–11]. The interface fixed charges strongly affect the threshold voltage; if the positive interface fixed charge density is sufficiently suppressed, a normally-off operation can be achieved [12]. Previously, we observed that, for AlTiO/AlGaN/GaN MIS devices, the interface fixed charges are suppressed as the Ti composition increases [13], although the suppression is not enough for normally-off operation. In this work, employing nitrogen plasma surface cleaning of AlGaN in AlTiO/AlGaN/GaN MIS device process, we investigated the threshold voltages, where we expect that the cleaning can suppress oxygen-related donors and/or nitrogen vacancies at the interface, which can be origins of the interface fixed charges.

2 Device fabrication

We fabricated AlGaN/GaN MIS devices with Al_xTi_yO gate insulators, 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). The process flow of the device fabrication is shown in Fig. 1. After formation of a Ti/Al/Ti/Au Ohmic electrode, surface cleaning of the AlGaN was carried out using electron-cyclotron-resonance nitrogen plasma. After the surface cleaning, within 5 minutes, the Al_xTi_yO gate insulators with several thicknesses and two compositions, $x/(x+y) = 0.73$ ($k \simeq 14$, $E_g \simeq 6.0$ eV) and $x/(x+y) = 0.47$ ($k \simeq 20$, $E_g \simeq 5.0$ eV), were formed by atomic layer deposition (ALD), followed by post-deposition annealing. A Ni/Au gate electrode surrounded by the Ohmic electrode was formed on the gate insulator, completing the device fabrication. In addition to the devices with the cleaning, devices without the cleaning were also fabricated for comparison.

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. The measurements were carried out under a voltage sweep $V_{\rm G} = 0 \to -12$ V at 1 MHz. We can obtain the capacitances C_0 at $V_{\rm G} = 0$ V and the threshold voltages $V_{\rm th}$.

Figure 3 shows $1/C_0$ as functions of $d_{\rm ins}$, with fitting lines given by $1/C_0 = d_{\rm ins}/(k_{\rm ins}\varepsilon_0) + d_{\rm AlGaN}/(k_{\rm AlGaN}\varepsilon_0)$. From the fitting, we can estimate the dielectric constants $k_{\rm AlGaN} \simeq 11$, and also $k_{\rm ins} \simeq 13.7$ and 19.8 for $x/(x+y) = 0.73$ and 0.47, respectively.

Figure 4 shows $V_{\rm th}$ as functions of $d_{\rm ins}$, showing liner dependence given by

$$V_{\rm th} \simeq -\frac{\Delta\sigma_{\rm ins}}{k_{\rm ins}\varepsilon_0} d_{\rm ins} + \text{const.}, \tag{1}$$

where $\Delta\sigma_{\rm ins} = \sigma_{\rm ins} + \sigma_{\rm D} - \sigma_{\rm GaN}$, with the insulator-semiconductor interface fixed charge density $\sigma_{\rm ins}$, the sheet ionized donor charge density $\sigma_{\rm D}$ in AlGaN, and the GaN polarization charge density $\sigma_{\rm GaN}$. For both compositions, the slope of the linear dependence is increased (positively shifted) by the nitrogen plasma surface cleaning. The intercept of the linear dependence is also increased (positively shifted) by the surface cleaning. From the slope, we obtain $\Delta\sigma_{\rm ins}$ as shown in Fig. 5(a). We find that $\Delta\sigma_{\rm ins}$ is decreased by the nitrogen plasma surface cleaning. We consider that the cleaning can decrease the interface fixed charges by suppressing oxygen-related donors and/or nitrogen vacancies at the interface, which can be origins of the interface fixed charges; surface-absorbed oxygen-related molecules and near-surface nitrogen vacancies can be removed by the nitrogen plasma. The interface fixed charge density $\sigma_{\rm ins}$ is plotted in Fig. 5(b) in comparison with the AlGaN polarization charge density $\sigma_{\rm AlGaN}$, where the diagonal line corresponds to neutral AlTiO-AlGaN interfaces. We find that $\sigma_{\rm ins}/q$ is decreased by 1.4 and 2.3×10^{12} cm^{-2} for $x/(x+y) = 0.73$ and 0.47, respectively. Moreover, the increased (positively shifted) intercept of the linear dependence indicates that the AlTiO/AlGaN band offset is decreased by the nitrogen plasma surface cleaning, where the band offset decrease is 0.4 eV and 0.7 eV for $x/(x+y) = 0.73$ and 0.47, respectively. The effects of decreasing the interface fixed charge and the band offset are more pronounced for AlTiO with a higher Ti composition.

4 Summary

For AlTiO/AlGaN/GaN MIS devices, we investigated impacts of nitrogen plasma surface cleaning of AlGaN on the threshold voltages. From the behavior of the threshold voltages, we find that the AlTiO/AlGaN interface fixed charges are suppressed by the cleaning. Also the AlTiO/AlGaN band offset is decreased by the cleaning. Theses effects are more pronounced for AlTiO with a higher Ti composition.

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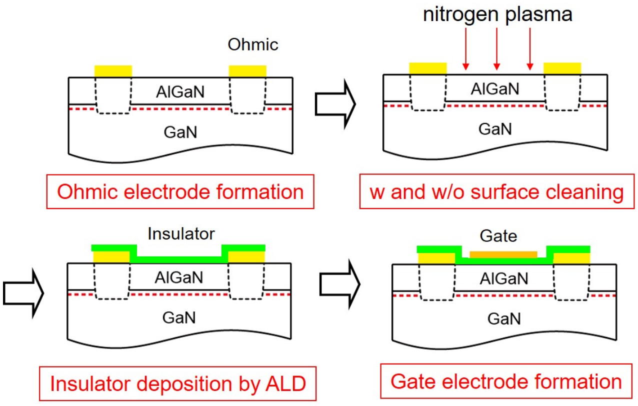

Fig. 1: Process flow of the device fabrication.

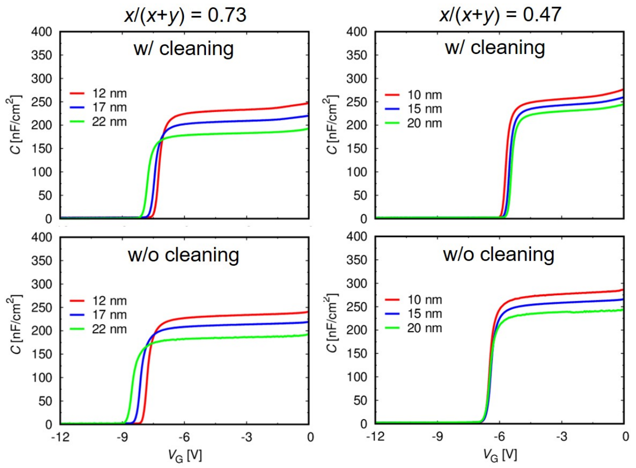

Fig. 2: The capacitance C as functions of the gate voltage V_{G}.

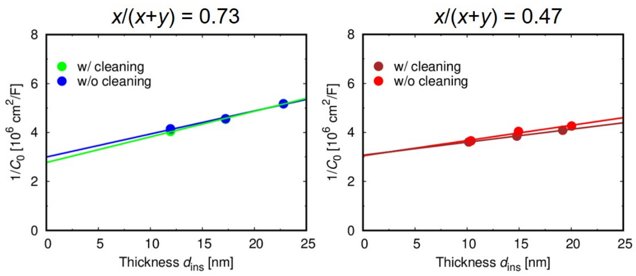

Fig. 3: $1/C_0$ at $V_{\mathrm{G}} = 0$ V as functions of d_{ins} .

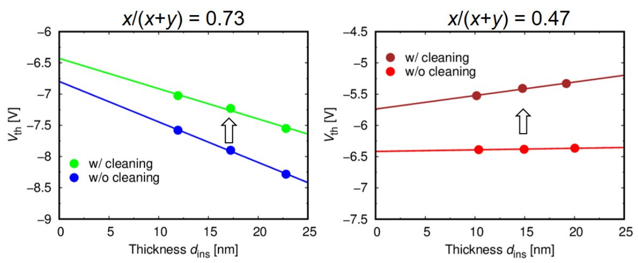

Fig. 4: The threshold voltage V_{th} as functions d_{ins}.

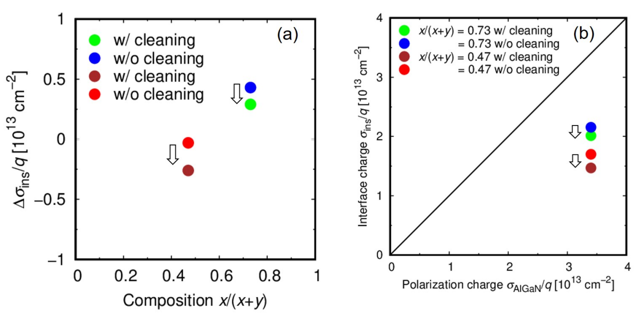

Fig. 5: (a) $\Delta\sigma_{\mathrm{ins}}$ as functions of the composition $x/(x+y)$. (b) σ_{ins} in comparison with the σ_{AlGaN}.