Extended Abstracts of the 2018 International Conference on Solid State Devices and Materials, Tokyo, 2018, pp241-242

Threshold voltages of AlGaN/GaN metal-insulator-semiconductor devices depending on Al_xTi_yO gate insulator compositions

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Abstract – We systematically investigated threshold voltages of AlGaN/GaN metal-insulator-semiconductor devices, where Al_xTi_yO gate insulators with different compositions were employed. We elucidated the behavior of the threshold voltage dominated by the insulator-semiconductor fixed charges depending on the gate insulator composition.

1 Introduction

As a gate insulator for GaN-based metal-insulator-semiconductor (MIS) devices, 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] have been investigated, where AlTiO, an alloy of TiO_2 and Al_2O_3, is useful to balance the dielectric constant k and the bandgap E_g [8]. In GaN-based MIS device processing, when an insulator is deposited on a negatively polarized semiconductor surface, such as Ga-face (Al)GaN, positive insulator-semiconductor interface fixed charges tend to be generated and to cancel the negative polarization charges in many cases, although the existence of the interface fixed charges is not a necessity [9–11]. Since the interface fixed charges have significant impacts on threshold voltages, we can expect threshold voltage control by the interface fixed charges. In particular, if the positive interface fixed charge density is sufficiently suppressed, a normally-off operation can be expected [12, 13]. Previously, we observed that, for AlGaN/GaN MIS devices, an AlTiO gate insulator leads to a lower positive interface fixed charge density in comparison with Al_2O_3; incorporation of Ti to Al_2O_3 gate insulators can suppress the positive interface fixed charges [14]. In this work, AlGaN/GaN MIS devices with AlTiO gate insulators were fabricated and characterized, where AlTiO with different compositions were obtained by atomic layer deposition (ALD). We systematically investigated threshold voltages of the MIS devices depending on the compositions, and evaluated the interface fixed charge density.

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 AlGaN/GaN MIS devices with Al_xTi_yO gate insulators shown in Fig. 1. On the heterostructure, Ti/Al/Ti/Au Ohmic electrodes were formed. The Al_xTi_yO gate insulators with three Al compositions, $x/(x+y) = 1$ (Al_2O_3, $k \simeq 9$, $E_g \simeq 6.8$ eV), $x/(x+y) = 0.73$ ($k \simeq 14$, $E_g \simeq 6.0$ eV), and $x/(x+y) = 0.47$ ($k \simeq 20$, $E_g \simeq 5.0$ eV), were deposited by ALD using trimethyl aluminum (TMA), tetrakis-dimethylamino titanium (TDMAT), and H_2O as precursors, followed by post-deposition annealing in H_2-mixed Ar at 350 °C. 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 $d_{\rm ins}$ ranging from 10 nm to 30 nm. 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 integrating C, as functions of the gate voltage $V_{\rm G}$. The measurements were carried out under a voltage sweep $V_{\rm G} = 0 \to -15$ V at 1 MHz. We can obtain the capacitances C_0 at $V_{\rm G} = 0$ V from the C-$V_{\rm G}$ characteristics. Also, from the $n_{\rm s}$-$V_{\rm G}$ characteristics, we can obtain the threshold voltages $V_{\rm th}$ and the sheet electron concentrations $n_{\rm s0}$ at $V_{\rm G} = 0$ V.

Figure 3(a) shows $1/C_0$ at $V_{\rm G} = 0$ V as functions of $d_{\rm ins}$, with fitting lines given by $1/C_0 = d_{\rm ins}/(k_{\rm ins}\varepsilon_0) + d_{\rm AlGaN}/(k_{\rm AlGaN}\varepsilon_0)$ (with obvious notations). From the fitting, we can estimate the dielectric constants $k_{\rm AlGaN} \simeq 9.6$, and also $k_{\rm ins} = 9.4$, 13.7, and 19.8 for $x/(x+y) = 1$, 0.73, and 0.47, respectively, as summarized in Fig. 3(b). Since the dielectric constant of TiO_2 is higher than that of Al_2O_3, $k_{\rm ins}$ increases with decrease in the Al composition $x/(x+y)$.

Figure 4(a) shows $d_{\rm ins}$ dependence of $V_{\rm th}$, which indicates liner relations. Interestingly, in the case of $x/(x+y) = 0.47$, $V_{\rm th}$ is almost constant, independent of $d_{\rm ins}$. The linear relations should be given by

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

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 $\sigma_{\rm GaN}$. By fitting using Eq. (1), we obtain $\Delta\sigma_{\rm ins}$ as summarized in Fig. 4(b). We find that $\Delta\sigma_{\rm ins}$ decreases with decrease in the Al composition $x/(x+y)$; the insulator-semiconductor interface fixed charges are suppressed for high Ti compositions.

In Fig. 5(a), $n_{\rm s0}$ at $V_{\rm G}$= 0 V is plotted as functions of $d_{\rm ins}$, showing nonlinear relations. We obtain

$$\frac{\partial n_{\rm s0}}{\partial d_{\rm ins}} \simeq \frac{C_0}{k_{\rm ins}\varepsilon_0}(\Delta\sigma_{\rm ins}/q - n_{\rm s0}), \qquad (2)$$

which implies that $\Delta\sigma_{\rm ins}/q > n_{\rm s0}$ leads to increasing $n_{\rm s0}$ with $d_{\rm ins}$ and $\Delta\sigma_{\rm ins}/q < n_{\rm s0}$ leads to decreasing $n_{\rm s0}$. We find that $n_{\rm s0}$ is an increasing function for $x/(x+y) = 1$, whereas being decreasing function for $x/(x+y) = 0.73$ and 0.47. In particular, for $x/(x+y) = 0.47$, $n_{\rm s0}$ strongly decreases with increase in $d_{\rm ins}$, owing to the low interface fixed charge density. By using Poisson-Schrödinger calculation, we estimated the band diagram of the MIS devices in the case of Al_xTi_yO with $x/(x+y) = 0.47$, as shown in Fig. 5(b). We can confirm that the AlTiO-AlGaN interface is negatively charged and the electric field inside

AlTiO insulator is rather high, leading to n_{s0} strongly decreasing with increase in d_{ins}.

4 Summary

For AlGaN/GaN MIS devices with Al_xTi_yO gate insulators having different compositions, we systematically investigated threshold voltages depending on the compositions. The behavior of the threshold voltage is elucidated; it is found that the insulator-semiconductor interface fixed charges are suppressed for high Ti compositions.

Acknowledgment

This work was supported by JSPS KAKENHI Grant Number 26249046, 15K13348.

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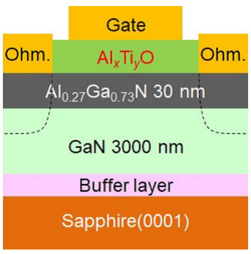

Fig. 1: The schematic cross section of AlGaN/GaN MIS devices with Al_xTi_yO gate insulators.

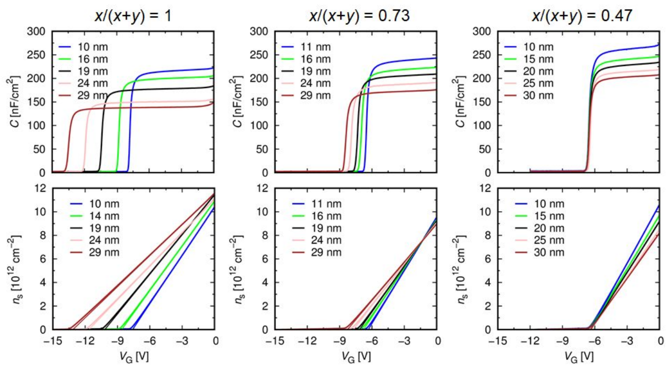

Fig. 2: The capacitance C and the sheet electron concentration n_s as functions of the gate voltage V_G.

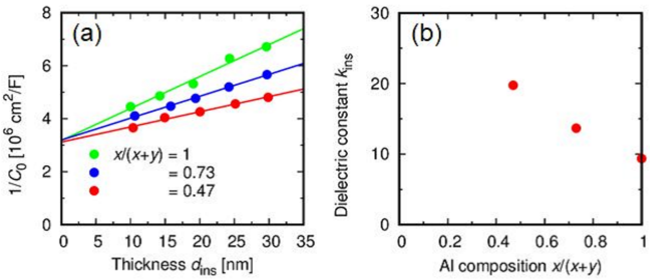

Fig. 3: (a) $1/C_0$ at $V_G = 0$ V as functions of d_{ins} with fitting lines. (b) The insulator dielectric constant k_{ins} depending on the Al composition $x/(x+y)$.

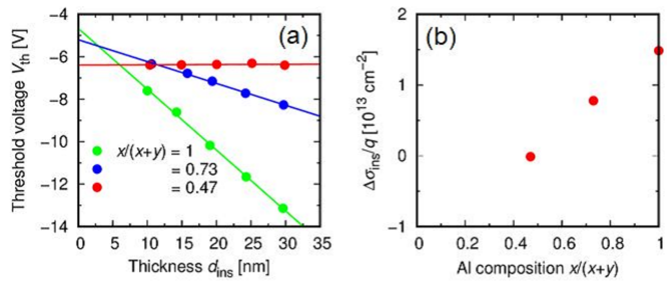

Fig. 4: (a) The threshold voltage V_{th} as functions of the insulator thickness d_{ins}. (b) $\Delta\sigma_{ins}$ depending on the Al composition $x/(x+y)$.

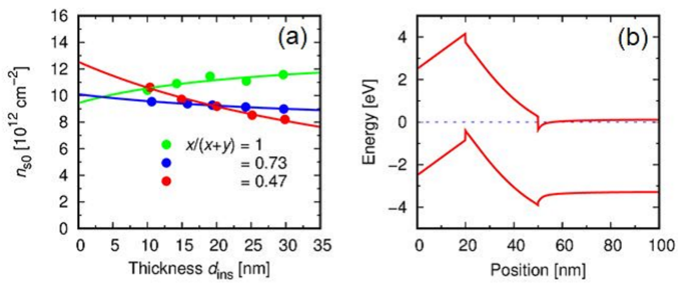

Fig. 5: (a) n_{s0} at $V_G = 0$ V as functions of d_{ins} with fitting curves. (b) An estimated band diagram of the MIS devices for Al_xTi_yO with $x/(x+y) = 0.47$ obtained by Poisson-Schrödinger calculation.