Extended Abstracts of the 2013 International Conference on Solid State Devices and Materials, Fukuoka, 2013, pp920-921

Application of AlTiO thin films to AlTiO/AlGaN/GaN metal-insulator-semiconductor heterojunction field-effect transistors

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Abstract — We investigated properties of AlTiO thin films obtained by atomic layer deposition. We observed increase in the bandgap and decrease in the dielectric constant, with increase in the Al composition of AlTiO. Based on the results, $Al_{0.73}Ti_{0.27}O$ is applied to fabrication of AlTiO/AlGaN/GaN metal-insulator-semiconductor heterojunction field-effect transistors (MIS-HFETs). The MIS-HFET exhibits a low gate leakage current, a high drain current, and a transconductance with good linearity.

1 Introduction

AlGaN/GaN metal-insulator-semiconductor heterojunction field-effect transistors (MIS-HFETs) have attracted much attention for their potential uses in high-frequency and high-power applications. As a gate insulator of the MIS-HFETs, high-dielectric-constant (high-k) materials, such as Al_2O_3 [1], HfO_2 [2], and AlN [3–5] were studied. Owing to a very high k of TiO_2 (~ 60), TiO_2/AlGaN/GaN MIS-HFETs were investigated [6] as a candidate of high-performance devices. However, the small band gap of TiO_2 (~ 3 eV) is a drawback, as shown by large gate leakage currents. Although the usage of AlTiO, alloys of TiO_2 and Al_2O_3, is one of effective solutions to overcome the drawback as shown in AlTiO/GaAs systems [7], there is no report on AlTiO/AlGaN/GaN MIS-HFETs. In this work, we investigated properties of AlTiO thin films obtained by atomic layer deposition (ALD), and fabricated and characterized $Al_{0.73}Ti_{0.27}O$/AlGaN/GaN MIS-HFETs.

2 AlTiO thin films obtained by atomic layer deposition

We investigated properties of AlTiO thin films obtained by ALD. Using trimethylaluminum (TMA), tetrakis-dimethylamino titanium (TDMAT), and H_2O as precursors, $\sim$ 25-nm-thick AlTiO films were deposited on n-GaAs(001) at substrate temperatures of 130-150°C. In order to control the compositions of AlTiO, we employed alternative combinations of l-cycles Al_2O_3 and m-cycles TiO_2. Figure 1 shows global X-ray photoelectron spectroscopy (XPS) spectra of the AlTiO thin films, including Ti2p1, Ti2p3, Al2s, Al2p, Ti3s, and Ti3p peaks, which give the atomic composition, $x : y$ of Al_xTi_yO. We found that $(l, m) = (0, 1)$, $(1, 3)$, $(1, 2)$, $(1, 1)$, $(2, 1)$, and $(1, 0)$ give $x : y = 0 : 1$, $0.47 : 0.53$, $0.57 : 0.43$, $0.73 : 0.27$, $0.84 : 0.16$, and $1 : 0$, respectively. In addition, using the O1s electron energy loss spectra, we obtained bandgap of the AlTiO thin films.

In order to investigate electrical properties of AlTiO thin films, we measured temperature-dependent I-V characteristics of AlTiO/n-GaAs(001) MIS structures. We obtain low leakage currents exhibiting the Pooler-Frenkel (PF) conduction mechanism, from which we can estimate the dielectric constant of AlTiO thin films.

Figure 2 summarizes the bandgap and the dielectric constant as functions of the Al composition $x/(x + y)$ of Al_xTi_yO. We observed increase in the bandgap and decrease in the dielectric constant, with increase in the Al composition. Based on the results, we decided to apply $Al_{0.73}Ti_{0.27}O$ to fabrication of AlTiO/AlGaN/GaN MIS-HFETs, considering the trade-off between the bandgap and the dielectric constant.

3 Fabrication and characterization of AlTiO/AlGaN/GaN MIS-HFETs

The device fabrication processing was started with Ohmic-electrode formation (Ti/Al/Ti/Au = 10/200/100/50 nm), followed by annealing in N_2 ambience at 600 °C for 5 minutes. After surface treatment using organic solvents, oxygen plasma ashing, and ammonium-based solution, the 29-nm-thick $Al_{0.73}Ti_{0.27}O$ film was deposited by ALD. Finally, gate electrode formation (Ni/Au = 5/35 nm) completed the device fabrication processing. The MIS-HFETs (shown in the inset of Fig. 3) have a gate length of 260 nm, a source-gate spacing of 2 μm, a gate-drain spacing of 3 μm, and a gate width of 50 μm.

For improving electrical properties, we carried out post-gate-annealing at 350 °C for 30 minutes in H_2-mixed (10 %) Ar ambience. We obtain large decreases ($\sim$ 2 orders) of gate leakage currents for both reverse and forward biases, as shown in Fig. 3. From PF plots at forward biases shown in Fig. 4, we estimate the dielectric constant $k \sim$ 23-29 for the $Al_{0.73}Ti_{0.27}O$.

Figure 5 shows the output characteristics of the MIS-HFETs after the annealing, with a high drain current of $\sim$ 800 mA/mm. The transfer characteristics is shown in Fig. 6, with a good linearity of the transconductance, suggesting a good gate control in comparison with the AlN/AlGaN/GaN MIS-HFETs [4, 5].

4 Summary

We investigated properties of AlTiO thin films obtained by ALD. We observed increase in the bandgap and decrease in the dielectric constant, with increase in the Al composition of AlTiO. Based on the results, we fabricated and characterized $Al_{0.73}Ti_{0.27}O$/AlGaN/GaN MIS-HFETs. The MIS-HFET exhibits a low gate leakage current, a high drain current, and a transconductance with good linearity, indicating a possibility of the AlTiO gate insulator.

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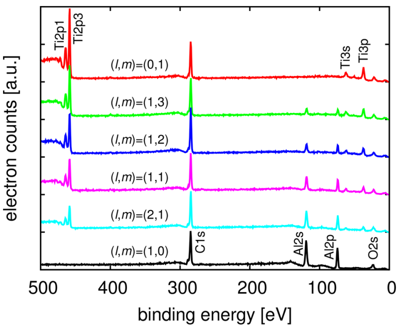

Fig. 1: Global XPS spectra for ∼ 25-nm-thick AlTiO thin films on n-GaAs(001), including Ti2p1, Ti2p3, Al2s, Al2p, Ti3s, and Ti3p peaks, giving the atomic compositions.

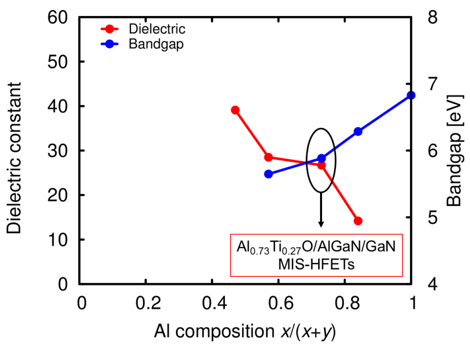

Fig. 2: The bandgap and the dielectric constant as functions of the Al composition in the Al_xTi_yO thin films.

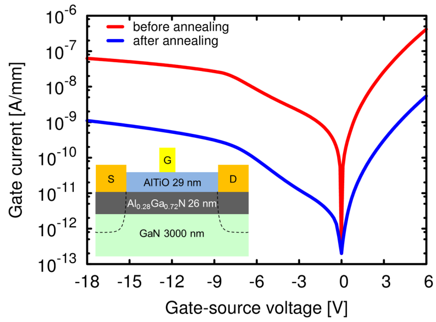

Fig. 3: Gate-source (drain open) I-V characteristics of the AlTiO/AlGaN/GaN MIS-HFET before and after annealing.

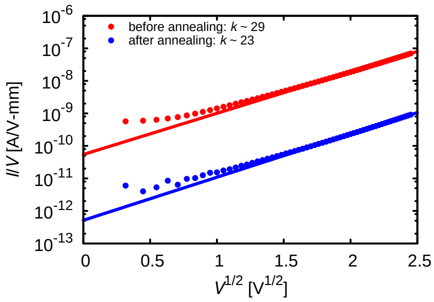

Fig. 4: Poole-Frenkel plot for gate leakage currents (drain open) at forward biases of the AlTiO/AlGaN/GaN MIS-HFET before and after annealing.

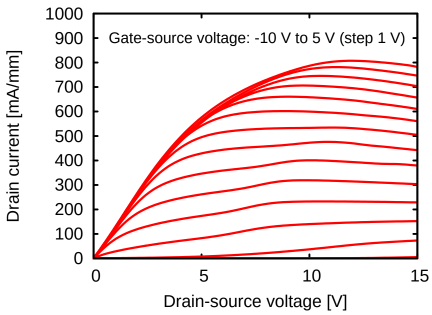

Fig. 5: Output characteristics of the AlTiO/AlGaN/GaN MIS-HFETs after the annealing.

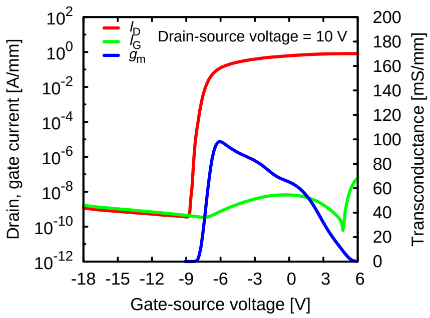

Fig. 6: Transfer characteristics of the AlTiO/AlGaN/GaN MIS-HFETs after the annealing. Drain current I_D, gate current I_G, and transconductance g_m were obtained under the gate-source voltage sweep of -18 V $\rightarrow$ $+6$ V at drain-source voltage of $+10$ V.