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Chemical and electronic properties of ALD-Al_2O_3/AlGaN interfaces

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1. Introduction

AlGaN/GaN heterostructure field effect transistor is very attractive for high-temperature and high-power applications because of its superior interface properties including high density of two-dimensional electron gas (2DEG). An insulated-gate structure can reduce gate leakage current and enhance the dynamic range of device operation. Moreover, the controlled insulator/AlGaN interface can passivate the surface and contribute to operational stability.

An aluminum oxide (Al_2O_3) layer is promising as a gate insulator because of its large band gap against AlGaN, high breakdown field and large dielectric constant. The purpose of this study is to investigate Al_2O_3/AlGaN interfaces prepared by atomic layer deposition (ALD), focusing on the chemical analysis using x-ray photoelectron spectroscopy (XPS) and the electronic evaluation of metal/insulator/semiconductor (MIS) structures.

2. Atomic layer deposition

ALD is one of the chemical vapor deposition techniques. In ALD process, gas-phase precursors, H_2O as O source and trimethylaluminum (TMA) as Al source, are introduced into the reactor chamber in alternate pulse forms, resulting in the formation of Al_2O_3 in the layer-by-layer fashion. **Figure 1** schematically shows the sequence of the precursor supply in ALD process. The N_2 carrier gas continuously flows into the reactor, and the base pressure in the reactor is approximately 40 Pa. Each precursor was injected into the reactor for 15ms, and the purging time was set to 5 s. The following reaction is expected in a cycle:

$$Al(CH_3)_3 + 3/2\,H_2O \rightarrow 1/2\,Al_2O_3 + 3CH_4$$

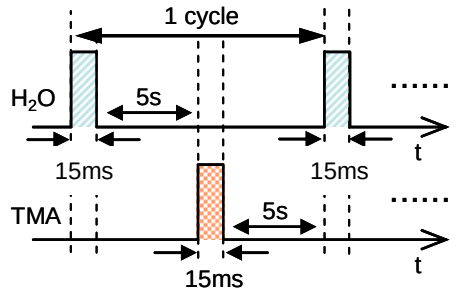


Fig.1 Schematics of the sequence of the precursor supply in ALD process.

In our case, the growth rate is estimated to be 0.10 nm/cycle. The deposition was carried out at 300 °C. Before deposition, the GaN surface was treated in 30%-HF solution for 5 min.

3. Result and discussion

Figure 2 (a) shows the XPS O 1s spectra obtained from ALD-Al_2O_3 with thicknesses of 1nm and 30nm. The peak position of Al_2O_3 with a thickness of 30nm is very close to that of crystalline Al_2O_3 (sapphire). This indicates that the Al-O bond is dominant in atomic configuration. In comparison, the spectrum of the 1nm-Al_2O_3 layer had the higher peak energy position and the broader linewidth. There is a possibility that some kinds of C-O bonds originating from methyl group are incorporated into Al_2O_3 at an initial stage of the ALD process. The Ga 3d spectra of the n-GaN surface with and without the 1nm-Al_2O_3 layer are shown in **Fig.2 (b)**. Both spectra are almost the same, indicating that the ALD process did not cause significant degradation on the chemical bonding structure of n-GaN surface.

The Al 2p spectrum of ALD-Al_2O_3 with a thickness of 30nm is compared with that of crystalline Al_2O_3 in **Fig. 3 (a)**. Again, the peak position is very close in both spectra. The linewidth of ALD-Al_2O_3 is slightly wider than that of the reference sapphire, probably arising from amorphous phase of ALD-Al_2O_3. The band gap, E_G, of the ALD-Al_2O_3 layer can be estimated from the energy-loss peak in the O1s spectrum [1]. As shown in **Fig. 3 (b)**, the onset of the loss-peak line gave E_G = 6.7eV that is close to data reported

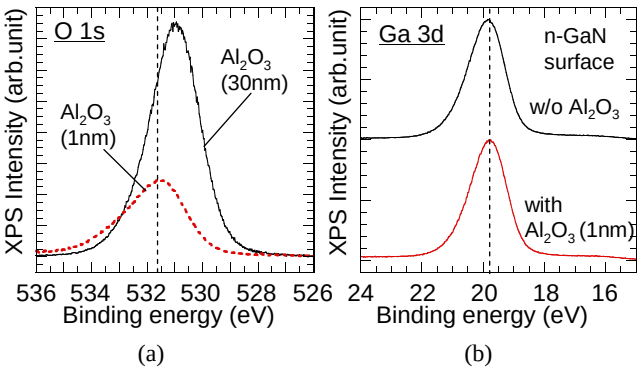
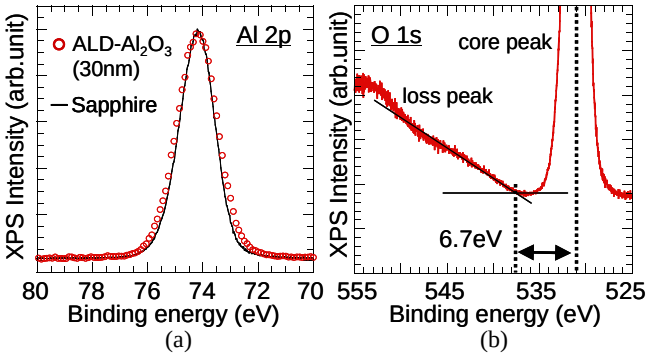


Fig.2 (a) XPS O 1s spectra obtained from ALD-Al_2O_3 with thicknesses of 1nm and 30nm, (b) Ga 3d spectra of the n-GaN surface with and without 1nm-Al_2O_3 layer.



(a) (b)

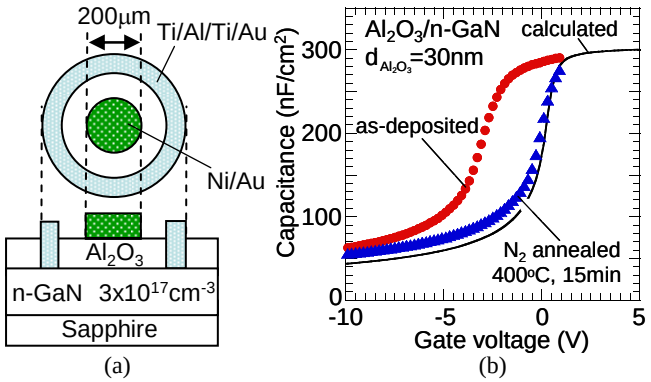
Fig.3 (a) XPS Al 2p spectra obtained from ALD-Al_2O_3 and reference sapphire, (b) O 1s spectrum including an energy-loss peak.

for thin Al_2O_3 layers fabricated by thermal or plasma oxidation of metallic Al [1, 2].

Then, we investigated interface properties between ALD-Al_2O_3 and GaN. **Figure 4 (a)** schematically shows the fabricated MIS capacitor. After deposition of the Al_2O_3 film with a thickness of 30nm, a Ti/Al/Ti/Au multi-layer structure was deposited on n-GaN surface as a ring-shape ohmic contact, followed by an annealing at 800°C for 1min in N_2 ambience. A Ni/Au gate electrode with a diameter of 200μm was deposited on the Al_2O_3 surface.

Figure 4 (b) shows capacitance-voltage (C-V) characteristics of the fabricated MIS capacitor. From the maximum capacitance value, the dielectric constant, ε_{ox}, of Al_2O_3 was estimated to be 9.7, being in agreement with a typical value for Al_2O_3. The flat-band voltage shift toward negative bias direction was observed for the as-deposited sample. After annealing process at 400°C for 15min in N_2 ambience, we obtained the C-V curve very close to the calculated one, as shown in Fig. 4 (b). Although the reason for this change is not clear yet, it is likely that the C-O components shown in the XPS spectra [Fig.2 (a)] at the interface can be decomposed during the annealing process. The calculation taking account of interface states showed the minimum interface state density (D_{it0}) for the annealed sample was $1x10^{12}cm^{-2}eV^{-1}$ or less.

Next, we deposited Al_2O_3 films with various thicknesses by ALD on $Al_{0.25}Ga_{0.75}N$/GaN structure. The thickness of AlGaN layer is 30nm. Typical values of the electron mobility and concentration of 2DEG at RT were



(a) (b)

Fig.4 (a) Schematics of Al_2O_3/n-GaN MIS capacitor, (b) C-V characteristics of Al_2O_3/n-GaN MIS capacitor.

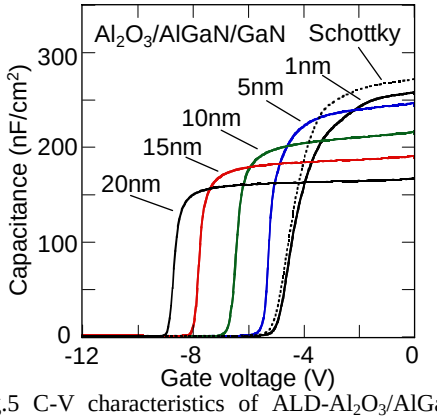


Fig.5 C-V characteristics of ALD-Al_2O_3/AlGaN/GaN MIS capacitors with various Al_2O_3 thicknesses.

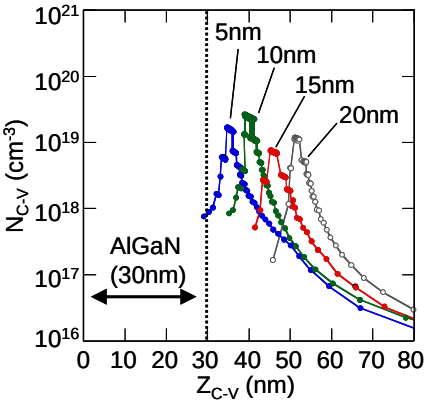


Fig.6 Carrier concentrations as a function of depth estimated from $1/C^2$-V characteristics.

$1350cm^2/Vs$ and 9.0 x $10^{12}cm^{-2}$, respectively. After annealing at 400°C for 15min in N_2 ambience, we fabricated MIS capacitors, as indicated in Fig. 4 (a).

Figure 5 shows C-V characteristics of Al_2O_3/AlGan/GaN structures as well as the Schottky sample. A systematic change in C-V curve was observed with the thickness of the Al_2O_3 layer. From the zero-bias capacitance values, we confirmed that the insulator thicknesses were in good agreement with the designed ones from the deposition rate. In addition, the threshold voltages for the depletion of 2DEG were nearly consistent with the calculated results without assuming electronic states at the Al_2O_3/AlGaN interface. **Figure 6** shows the carrier concentrations (N_{C-V}) as a function of depth estimated from $1/C^2$-V characteristics [3]. The peak depth positions of N_{C-V} corresponded to each increase in the Al_2O_3 film thickness, and peak values of the N_{C-V} profiles were almost the same, showing the ALD deposition of Al_2O_3 did not affect the 2DEG properties at the AlGaN/GaN interface.

The results obtained here indicate that the present ALD process is promising for fabricating a stable Al_2O_3/AlGaN structure with a relatively low interface state density.

References

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