Chemical and electronic properties of ALD-Al2O3/AlGaN interfaces

Yujin Hori¹, Chihoko Mizue¹, Kimihito Ooyama¹, Marcin Miczek² and Tamotsu Hashizume¹

¹Research Center for Integrated Quantum Electronics (RCIQE), Hokkaido University,
N13, W8, Kita-ku, Sapporo, 060-8628, Japan
Phone: +81-11-706-7174, E-mail: (hori, hashi)@rciqe.hokudai.ac.jp

²Institute of Physics, Silesian University of Technology
Krzywoustego 2, 44-100 Gliwice, Poland
Phone: +48-32-237-2736, E-mail: Marcin.Miczek@polsl.pl

1. Introduction

AlGaN/GaN heterostructure field effect transistor is very attractive for high-temperature and high-power applications because of its superior surface 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 (Al2O3) 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 Al2O3/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, H2O as an O source and trimethylaluminum (TMA) as Al source, are introduced into the reactor chamber in alternate pulse forms, resulting in the formation of Al2O3 in the layer-by-layer fashion. Figure 1 schematically shows the sequence of the precursor supply in ALD process. The N2 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:

\[
\text{Al(CH}_3\text{)}_3 + 3/2 \text{H}_2\text{O} \rightarrow 1/2 \text{Al}_2\text{O}_3 + 3\text{CH}_4
\]

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-Al2O3 with thicknesses of 1nm and 30nm. The peak position of Al2O3 with a thickness of 30nm is very close to that of crystalline Al2O3 (sapphire). This indicates that the Al-O bond is dominant in atomic configuration. In comparison, the spectrum of the 1nm-Al2O3 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 Al2O3 at an initial stage of the ALD process. The Ga 3d spectra of the n-GaN surface with and without the 1nm-Al2O3 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-Al2O3 with a thickness of 30nm is compared with that of crystalline Al2O3 in Fig. 3 (a). Again, the peak position is very close in both spectra. The linewidth of ALD-Al2O3 is slightly wider than that of the reference sapphire, probably arising from amorphous phase of ALD-Al2O3. The band gap, Eg, of the ALD-Al2O3 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 Eg = 6.7eV that is close to data reported extended...
for thin Al₂O₃ layers fabricated by thermal or plasma oxidation of metallic Al [1, 2].

Then, we investigated interface properties between ALD-Al₂O₃ and GaN. Figure 4 (a) schematically shows the fabricated MIS capacitor. After deposition of the Al₂O₃ 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 N₂ ambience. A Ni/Au gate electrode with a diameter of 200μm was deposited on the Al₂O₃ surface.

Figure 4 (b) shows capacitance-voltage (C-V) characteristics of the fabricated MIS capacitor. From the maximum capacitance value, the dielectric constant, ε₀ε₅, of Al₂O₃ was estimated to be 9.7, being in agreement with a 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 (Dₓ₀) for the annealed sample was 1x10¹⁰/cm²•eV⁻¹ or less.

Next, we deposited Al₂O₃ films with various thicknesses by ALD on Al₀.₃₂Ga₀.₆₈N/GaN structure. The thickness of AlGaN layer is 30nm. Typical values of the electron mobility and concentration of 2DEG at RT were 1350cm²/Vs and 9.0 x 10¹⁷cm⁻², respectively. After annealing at 400°C for 15min in N₂ ambience, we fabricated MIS capacitors, as indicated in Fig. 4 (a).

Figure 5 shows C-V characteristics of Al₂O₃/AlGaN/GaN structures as well as the Schottky sample. A systematic change in C-V curve was observed with the thickness of the Al₂O₃ 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 Al₂O₃/AlGaN interface. Figure 6 shows the carrier concentrations (NₓCV) as a function of depth estimated from 1/C²-V characteristics [3]. The peak depth positions of NₓCV corresponded to each increase in the Al₂O₃ film thickness, and peak values of the NₓCV profiles were almost the same, showing the ALD deposition of Al₂O₃ 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 Al₂O₃/AlGaN structure with a relatively low interface state density.

References

Fig.3 (a) XPS Al 2p spectra obtained from ALD-Al₂O₃ and reference sapphire, (b) O 1s spectrum including an energy-loss peak.

Fig.4 (a) Schematics of Al₂O₃/n-GaN MIS capacitor, (b) C-V characteristics of Al₂O₃/n-GaN MIS capacitor.

Fig.5 C-V characteristics of ALD-Al₂O₃/AlGaN/GaN MIS capacitors with various Al₂O₃ thicknesses.

Fig.6 Carrier concentrations as a function of depth estimated from 1/C²-V characteristics.