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Analysis of post-deposition annealing effects on insulator/semiconductor interface of Al_2O_3/AlGaN/GaN high-electron-mobility transistors on Si substrates

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Abstract

Post-deposition annealing (PDA) effects on Al_2O_3 deposited by atomic layer deposition (ALD) and Al_2O_3/AlGaN interface were studied by electrical measurements, X-ray photoelectron spectroscopy (XPS), and X-ray reflectivity (XRR). Both water (H_2O) and ozone (O_3) were used as oxidants in the ALD process, and XPS and XRR were performed in Aichi synchrotron radiation center. The initial threshold voltage shift (ΔV_{th}) of ALD-Al_2O_3/AlGaN/GaN metal-insulator-semiconductor high-electron-mobility transistors (MIS-HEMTs) on Si substrates was reduced from 5 to 0.5 V with increasing the PDA temperature up to 750°C, while the gate leakage current (I_g) increased from 1×10^{-7} to 1×10^{-4} mA/mm. Furthermore, the oxygen diffusion from Al_2O_3 to AlGaN was clarified from XPS and XRR analysis. The results of this study indicate that the PDA is effective to reduce ΔV_{th} which is caused by oxide traps in the Al_2O_3 layer.

1. Introduction

For high-power and high-frequency switching device applications, AlGaN/GaN high-electron-mobility transistors (HEMTs) with metal-insulator-semiconductor (MIS) structures have been studied by many groups, which is effective for gate leakage reduction and large gate voltage swings. For the insulator of MIS-HEMTs, Al_2O_3 deposited by atomic layer deposition (ALD) is useful because Al_2O_3 has both relatively large band gap and high dielectric constant, and ALD is a layer-by-layer process that can produce an oxide layer that is pinhole free and uniform in thickness. In contrast, post-deposition annealing (PDA) of ALD-Al_2O_3 is needed to improve the *I-V* characteristics of MIS-HEMTs.

In our previous study, it was reported that MIS-HEMTs with Al_2O_3 deposited by ALD using both water (H_2O) and ozone (O_3) as the oxidants showed good *I-V* characteristics [1,2]. However, the effects of PDA on H_2O+O_3-based Al_2O_3/AlGaN/GaN HEMTs have not been clarified enough. Therefore, we investigated the effets of the PDA temperature on the initial threshold voltage shift (ΔV_{th}) and the gate leakage current (I_g) of MIS-HEMTs. Furthermore, the effects of PDA on chemical characteristics around Al_2O_3/AlGaN interfaces with thick Al_2O_3 layers were studied by X-ray photoelectron spectroscopy (XPS) and X-ray reflectivity (XRR) in Aichi synchrotron radiation center.

2. Experimental Procedure

Al_2O_3/AlGaN/GaN MIS-HEMTs were fabricated by the same process as that in the previous papers [2]. AlGaN/GaN heterostructures were grown on 4-in. p-type Si (111) substrates using a MOCVD system. 20 nm thick Al_2O_3 layers were deposited by ALD at 300°C. Both H_2O and O_3 were used as oxygen precursors, and trimethylaluminum (TMA) was used as the aluminum precursor. Post-deposition annealing was performed at 500, 550, 600, 650, 700, 750°C for 1 min in nitrogen ambient. A schematic cross-sectional view of the MIS-HEMT is shown in Fig. 1. The dimensions of the fabricated HEMTs were as follows: source-gate spacing (L_{sg}) = 4 µm, gate width (W_g) = 15 µm, gate length (L_g) = 1.5 µm, and gate-drain spacing (L_{gd}) = 4 µm. To investigate the electrical properties, the drain current-voltage (I_d-V_d) and the transfer characteristics were measured using an Agilent B1505A power device analyzer.

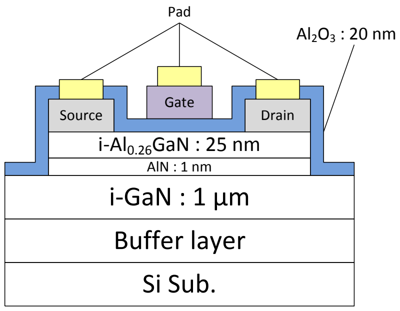

Fig. 1 Schematic cross-sectional view of the Al_2O_3/AlGaN/GaN MIS-HEMT.

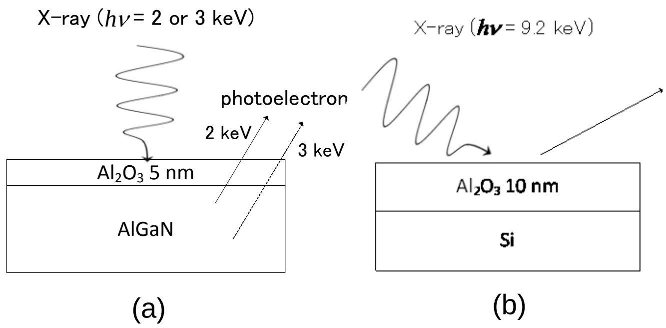

Fig. 2 Schematic diagrams of XPS and XRR measurements in Aichi synchrotron radiation center: (a) XPS (b) XRR.

For the XPS measurements, 5 nm thick Al_2O_3 layers were deposited on AlGaN layers by the same process for MIS-HEMTs. The X-ray energies were 2 keV and 3keV to obtain the information of the chemical characteristics near the Al_2O_3/AlGaN interface and inside the AlGaN layer, respectively. For the XRR measurements, 10 nm thick Al_2O_3 layers were deposited on Si substrates by the same process for MIS-HEMTs. The X-ray energy was 9.2 keV. Schematic diagrams of XPS and XRR measurements are shown in Fig. 2. In both XPS and XRR measurements, we investigated as-deposited samples and PDA samples annealed at 700°C.

3. Results and Discussion

Figure 3 shows dependences of the ΔV_{th} and the I_g at a V_g of 8V on the PDA temperature. As shown in Fig. 3, by increasing the PDA temperature, the ΔV_{th} was reduced from 5 to 0.5 V, and the I_g increased from 1×10^{-7} to 1×10^{-4} mA/mm. The reduction of the ΔV_{th} seems to be caused by the reduction of oxide traps inside the ALD-Al_2O_3 layer. As for the I_g increase, it may be caused by the microcrystallization in the ALD-Al_2O_3 by the PDA, whose grain boundaries can serve as high-leakage paths. From Fig. 3, it was found that the crystal structure of ALD-Al_2O_3 changed largely at a temperature between 650 and 700°C.

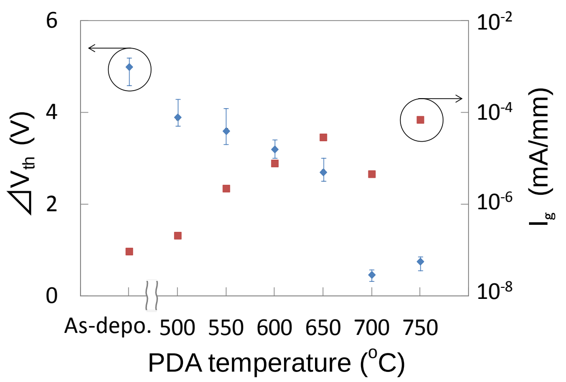

Fig. 3 Dependence of the initial threshold voltage shift (ΔV_{th}) and the gate leakage current (I_g) at a gate bias voltage of 8 V on the post-deposition annealing temperature of H_2O+O_3-based Al_2O_3.

Ga 2p $_{3/2}$ and Al 1s XPS spectra obtained from Al_2O_3/AlGaN layers were shown in Fig. 4. From Ga 2p spectra obtained from as-deposited samples, it was found that the Ga at Al_2O_3/AlGaN interface was slightly oxidized in comparison with the Ga inside the AlGaN layer, which may be caused during the ALD process. Furthermore, from Ga 2p spectra obtained from as-deposited and PDA samples, it was found that Ga at Al_2O_3/AlGaN interface was more oxidized after PDA at 700°C, and the oxidation spread towards the AlGaN layer by the PDA. As for the Al 1s spectra, they indicate that the Al-Al metallic bonding in the Al_2O_3 layer was reduced after PDA at 700°C, and the oxidation spread towards the AlGaN layer by the PDA, which was the same information obtained from Ga 2p spectra. The schematic diagram of the effects of PDA at 700°C on oxide traps and oxygen atoms in Al_2O_3 and AlGaN layers is shown in Fig. 5. The similar results were also obtained from XRR measurements.

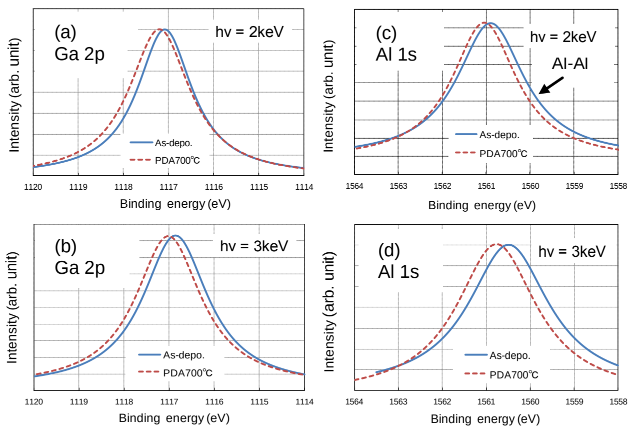

Fig. 4 XPS spectra obtained from Al_2O_3/AlGaN layers: (a) and (b) Ga 2p $_{3/2}$ (c) and (d) Al 1s.

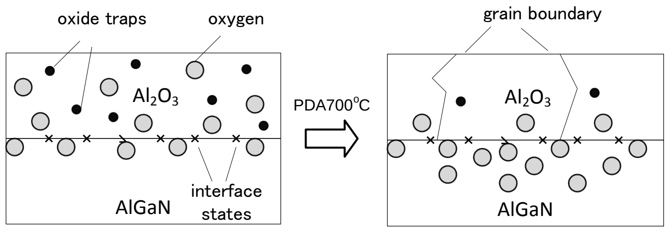

Fig. 5 Schematic diagram of the effects of PDA at 700°C on oxide traps and oxygen atoms in Al_2O_3 and AlGaN layers.

4. Conclusions

ALD-Al_2O_3/AlGaN/GaN MIS-HEMTs were fabricated using both H_2O and O_3 as oxidants with the PDA of the ALD-Al_2O_3 at 500, 550, 600, 650, 700, 750°C, and their ΔV_{th} and I_g were investigated. Furthermore, XPS and XRR analysis were performed in Aichi synchrotron radiation center to clarify the chemical characteristics near Al_2O_3/AlGaN interface. As the results, by increasing the PDA temperature up to 750°C, the ΔV_{th} was reduced from 5 to 0.5 V, and the I_g increased from 1×10^{-7} to 1×10^{-4} mA/mm. XPS and XRR analysis indicate that oxygen atoms diffused from the Al_2O_3 layer to the AlGaN layer by the PDA at 700°C. These results suggest that the PDA was effective to reduce oxide traps inside the H_2O+O_3-based Al_2O_3 layer, and the crystallization of the Al_2O_3 and the behavior of oxygen atoms should be studied in detail to decrease the I_g of MIS-HEMTs

Acknowledgements

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