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Estimation of post-deposition annealing effects on electrical properties of ALD-SiO_2/AlGaN/GaN MIS-HEMTs

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Abstract

Post-deposition annealing (PDA) effects on SiO_2/AlGaN/GaN metal-insulator-semiconductor high-electron-mobility transistors (MIS-HEMTs) were studied by *I-V* measurements, X-ray photoelectron spectroscopy (XPS) using synchrotron radiation, and secondary ion mass spectroscopy (SIMS). Tris(dimethylamino)silane (DTMAS) and ozone (O_3) were used as the silicon and oxygen precursors in the atomic layer deposition (ALD) process. The PDA was performed in nitrogen ambient, and the PDA temperature ranged from 400 to 800°C. The dynamical threshold voltage shift (ΔV_{th}) of MIS-HEMTs was less than 1 V, and the I_g decreased with increasing the PDA temperature. XPS and SIMS analysis indicate that *I-V* characteristics is affected by the oxidation of Si atoms in the SiO_2 layer and the diffusion of Ga atoms. The results of this study indicate that N_2-PDA temperatures between 400 and 600°C are appropriate for ALD-SiO_2 on AlGaN/GaN heterostructures.

1. Introduction

GaN-based semiconductor devices are expected for next generation high-power and high-frequency switching device applications. Especially, metal–insulator–semiconductor (MIS)-type high electron mobility transistors (HEMTs) have been studied. MIS structures are effective at reducing the gate leakage current (I_g) and enhancing the gate voltage swing. As the insulator, some oxides that have a large band gap, such as Al_2O_3 and SiO_2, are appropriate, and many results were reported [1]. For the deposition method of the insulator, atomic layer deposition (ALD) is promising. This layer-by-layer process can produce an oxide layer that is pinhole free and uniform in thickness. Compared to ALD-Al_2O_3, the study of ALD-SiO_2 for GaN-based power devices has been hardly reported. SiO_2 has a relatively large band gap of approximately 9eV. Therefore, large suppression of I_g is expected, especially for the gate stack structure such as Al_2O_3/SiO_2. In order to fabricate MIS-HEMTs with good current–voltage (*I–V*) characteristics, post- deposition annealing (PDA) is known to be effective. However, the effects of PDA on ALD-SiO_2/AlGaN/GaN heterostructures are not clarified enough. Therefore, in this study, we investigate the dependences of electrical characteristics and chemical properties of ALD-SiO_2/AlGaN/GaN MIS-HEMTs on PDA temperature by *I-V* measurements and X-ray photoelectron spectroscopy (XPS) using synchrotron radiation and secondary ion mass spectroscopy (SIMS).

2. Experimental procedure

ALD-SiO_2/AlGaN/GaN MIS-HEMTs for *I-V* measurements were fabricated by a similar procedure to that in a previous study [2]. AlGaN/GaN heterostructures were grown on 4-in. p-type Si (111) substrates using an MOCVD system. After the source/drain ohmic contacts were formed with annealing, the samples were prepared with HCl solution, and 8.5 nm-thick SiO_2 layers were deposited by the O_3-based ALD at 300°C. Tris(dimethylamino)silane (DTMAS) was used as the silicon precursor. The PDA was performed at 400, 600, 800°C for 1 min in nitrogen ambient. Finally, the gate contacts and the contact pads were formed. A schematic cross-sectional view of the MIS-HEMT is shown in Fig. 1. The dimensions of the MIS-HEMTs were as follows: source-gate spacing (L_{sg}) = 4μm, gate width (W_g) = 15μm, gate length (L_g) = 2μm, and gate-drain spacing (L_{gd}) = 4μm. The *I-V* characteristics were measured by using an Keysight B1505A power device analyzer under dark conditions at room temperature.

SiO_2/AlGaN/GaN samples for XPS and SIMS measurements were also fabricated using the same AlGaN/GaN hetero-structures. After soaking in HCl solution, SiO_2 layers with thicknesses of 5 (for XPS) and 15 (for SIMS) nm were deposited by the O_3-based ALD at 300°C, and PDA was performed at 500°C and 700°C for 1 min in a nitrogen atmosphere. The XPS measurements were conducted at the Aichi Synchrotron Radiation Center. X-ray energies of 2 keV was used, and the Si 1s and the Ga $2p_{3/2}$ core-level spectra were investigated. For Ga $2p_{3/2}$ spectra, the information on the chemical characteristics of the ALD-SiO_2/AlGaN interfaces were obtained. As for the SIMS, the measurements were per-formed using a Cs+ ion sputter source operated at 2 keV. The analysis was carried out in negative polarity, and an electron flood gun was used to compensate for sample charging.

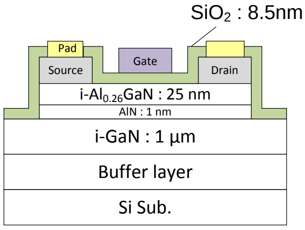

Fig. 1 Schematic cross-sectional view of the SiO_2/AlGaN/GaN MIS-HEMT.

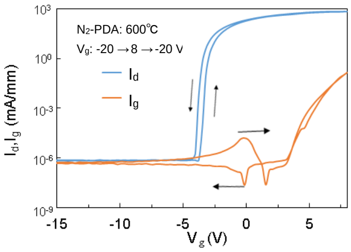

Fig. 2 Typical result of the transfer curve measurements. The PDA temperature was 600°C.

3. Results and Discussion

A typical result of the transfer curve measurements is shown in Fig. 2. The PDA temperature was 600°C. The gate voltage (V_g) was swept from −20 to 8V and from 8 to −20V, with a drain voltage of 10V. The maximum drain current was 720mA/mm, I_g at 8V was 0.14mA/mm, and ΔV_{th} was 0.3V. As shown in Fig. 2, the V_{th} shifted toward the negative bias direction. All of the V_{th} showed the same behavior. Therefore, the cause of ΔV_{th} in ALD-SiO_2/AlGaN/GaN MIS-HEMTs is considered to be the movement of oxide charges near the SiO_2/AlGaN interface. Figure 3 shows the dependences of ΔV_{th} and I_g at a V_g of 4.7V on the PDA temperature. The SiO_2 thickness of 8.5nm is relatively low. Therefore, we estimated the I_g at a V_g of 4.7V, which is equal to the I_g at a V_g of 8 V with a 20-nm-thick SiO_2 layer. As shown in Fig. 3, ΔV_{th} was less than 1V, and I_g decreased from 6.7×10^{-3} to 1.7×10^{-6} mA/mm by PDA at 800°C. In our previous study, the I_g of ALD-Al_2O_3/AlGaN/GaN MIS-HEMTs increased with increasing the PDA temperature due to the crystallization of the Al_2O_3 layer [2]. As for the I_g of MIS-HEMTs with ALD-SiO_2, the crystallization temperature of SiO_2 is considered to be approximately 1000°C. Therefore, the I_g did not increase. Moreover, the decrease of I_g seems to be caused by the oxidation of Si in SiO_2 layers. The slight increase of ΔV_{th} at 800°C can be caused by the Ga diffusion from the AlGaN layer to the SiO_2 layer. Considering both of ΔV_{th} and I_g, PDA temperatures between 400°C and 600°C are appropriate.

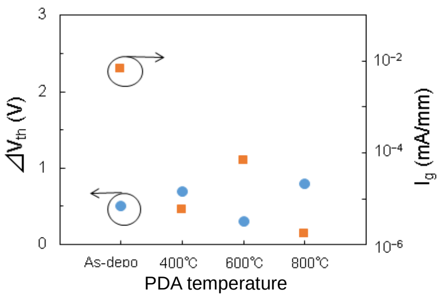

Fig. 3 Dependences of the $\varDelta V_{th}$ and the I_g at a V_g of 4.7V on the PDA temperature.

Figures 4(a) and (b) show Si 1s and Ga $2p_{3/2}$ XPS core-level spectra obtained from SiO_2/AlGaN layers. The peak positions were calibrated against C1s peak positions set at 285.0eV. As shown in Fig. 4(a), the peak position shifted from 1843.0 to 1843.3eV upon annealing at 500°C, and shifted to 1843.1eV at 700°C. The peak shift toward a higher binding energy at 500°C indicates that Si atoms in the SiO_2 layer were oxidized by PDA at 500°C. Furthermore, the peak shift at 700°C might be caused by the Ga diffusion to the SiO_2 layer. As for the Ga $2p_{3/2}$ spectra, the peak position shifted from 1117.4 to 1117.9eV upon annealing at 500°C, and shifted to 1117.6 eV at 700°C. The peak shift at 500°C indicates that the Ga atoms around SiO_2/AlGaN interface were oxidized, and the peak shift at 700°C also can be related to the Ga diffusion.

Figures 5(a) and (b) show H and C depth profiles measured by SIMS. As shown in Fig. 5, the concentration of H is higher than that of C, which means that H atoms are not bonded to only C atoms. Furthermore, H atoms slightly diffused from the SiO_2 layer to the AlGaN layer by PDA at 500°C, and the concentration of H was reduced by PDA at 700°C. The de- crease of H and C impurities in ALD-Al_2O_3

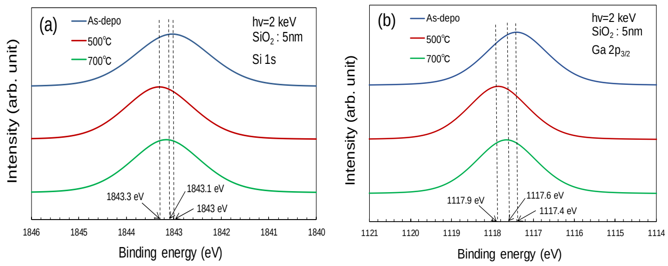

Fig. 4 XPS core-level spectra obtained from SiO_2/AlGaN (5/25 nm) layers, (a) Si 1s, (b) Ga $2p_{3/2}$.

layers by PDA at approximately 600°C have been reported by several groups, while the concentration of C in ALD-SiO_2 hardly changed as shown in Fig. 5(b). Compared to the dependences of ΔV_{th} and I_g on PDA temperature, it was found that the change of H and C concentrations hardly affect the *I-V* characteristics. *I-V* characteristics can be related to the oxidation of Si atoms and the diffusion of Ga atoms. From this study, for ALD-SiO_2, N_2-PDA temperatures between 400°C and 600°C are considered to be appropriate.

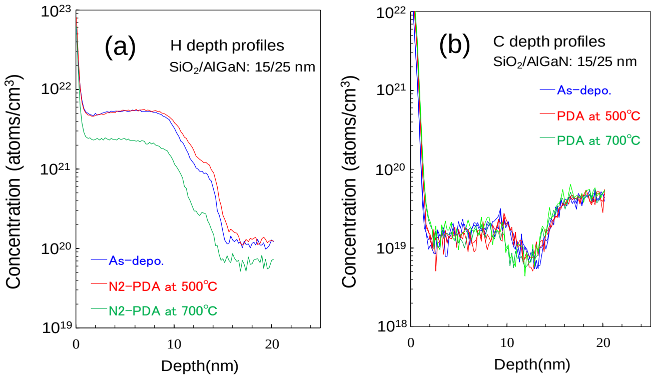

Fig. 5 SIMS depth profiles for ALD-SiO_2/AlGaN (15/25 nm) layers, (a) H, (b) C.

4. Conclusions

ALD-SiO_2/AlGaN/GaN MIS-HEMTs were fabricated with N_2-PDA at 400, 600, 800°C, and ΔV_{th} and I_g were investigated. Furthermore, XPS and SIMS analysis were performed to clarify the chemical characteristics around the SiO_2/AlGaN interfaces. From the results, it was found that the ΔV_{th} is less than 1 V, and the I_g decreased with increasing the PDA temperature. XPS and SIMS analysis indicate that *I-V* characteristics is affected by the oxidation of Si atoms and the diffusion of Ga atoms. The results of this study indicate that N_2-PDA temperatures between 400°C and 600°C are appropriate for ALD-SiO_2 on AlGaN.

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