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Reduction of initial threshold voltage shift in ALD-Al_2O_3/AlGaN/GaN MIS-HEMTs on Si substrates by post-deposition annealing

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Abstract

Post-deposition annealing (PDA) was performed on Al_2O_3 deposited by atomic layer deposition (ALD) using both water (H_2O) and ozone (O_3) as oxidants to reduce 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, and the dependence of the ΔV_{th} on the PDA temperature was investigated. As the result, ΔV_{th} was reduced from 4.2 to 2.6 V with increasing the PDA temperature up to 650°C, while the gate leakage current increased from 3.5×10^{-8} to 2.9×10^{-5} mA/mm. The results of this study indicate that the PDA is effective to reduce ΔV_{th} which is caused by deep traps inside the H_2O+O_3-based Al_2O_3 layer.

1. Introduction

GaN-based high-electron-mobility transistors (HEMTs) with metal-insulator-semiconductor (MIS) structures have been investigated for high-power and high-frequency switching device applications, which is effective for gate leakage reduction and large gate voltage swings. Al_2O_3 is a promising material for the insulator owing to its relatively large band gap and high dielectric constant. Among fabrication methods of Al_2O_3, atomic layer deposition (ALD) is superior, as it is a layer-by-layer process that can produce an oxide layer that is pinhole free and uniform in thickness.

In our previous study, the authors found 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 without post-deposition annealing of the ALD-Al_2O_3. Furthermore, the MIS-HEMTs showed normally-off behavior with initial threshold voltage (V_{th}) shifts due to deeply trapped electrons [1,2]. Recently, however, MIS-HEMTs with the H_2O+O_3-based Al_2O_3 which did not show the V_{th} shift were fabricated by post-deposition annealing (PDA) of the Al_2O_3 at 600°C [3]. Therefore, the effect of the PDA temperature on the initial V_{th} shift of MIS-HEMTs with the H_2O+O_3-based Al_2O_3 was investigated.

2. Experimental Procedure

Al_2O_3/AlGaN/GaN MIS-HEMTs were fabricated by the same process as that in the previous papers. AlGaN/GaN heterostructures were grown on 4-in. p-type Si (111) substrates using a MOCVD system. The structure consists of a 25-nm $Al_{0.26}GaN$ layer, a 1-nm AlN layer, a 1-μm GaN layer, and a 2.5 μm buffer layer. After mesa isolation by BCl_3 plasma-based reactive ion etching, source/drain ohmic contacts (Ti/Al/Ni/Au: 15/80/12/40 nm) were formed on the devices and annealed at 850°C for 30 s under a flow of nitrogen gas. 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, and 650°C for 1 min. After gate lithography, Pd/Ni/Au (40/20/60 nm) was deposited as the gate contact. 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.

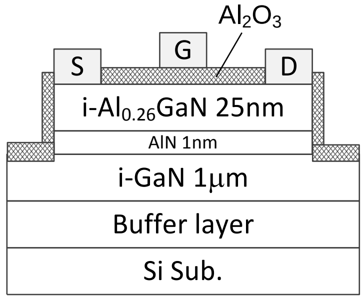

Fig. 1 Schematic cross-sectional view of the Al_2O_3/AlGaN/GaN MIS-HEMT.

3. Results and Discussion

Figure 2 shows the DC I_d-V_d characteristics of the MIS-HEMT with the H_2O+O_3-based Al_2O_3 annealed at 500°C. As shown in Fig. 2, good pinch-off characteristics were obtained, which are indicative of all cases of PDA temperatures in this study. The maximum I_d (I_{dmax}) was 570 mA/mm at a gate voltage of 8 V, and the maximum transconductance was 88 mS/mm. Figures 3(a) and 3(b) show the dependence of I_d and the gate leakage current (I_g) on the gate bias voltage (V_g) for the MIS-HEMTs with the H_2O+O_3-based Al_2O_3 annealed at 500°C and 650°C, respectively. As shown in Fig. 3, initial V_{th} shifts (ΔV_{th}s) caused by deeply trapped electrons, which showed quasi-fixed charge characteristics, were observed in all cases, and the amount of the $\varDelta V_{th}$ was reduced with increasing the PDA temperature. On the other hand, the I_g increased with increasing the PDA temperature, 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.

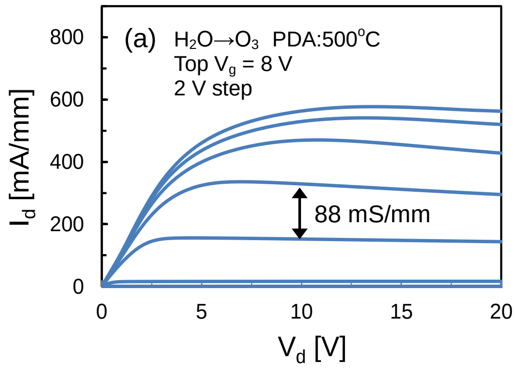

Fig. 2 DC drain current-voltage (I_d-V_d) characteristics of MIS-HEMT built with H_2O+O_3-based Al_2O_3 annealed at 500°C.

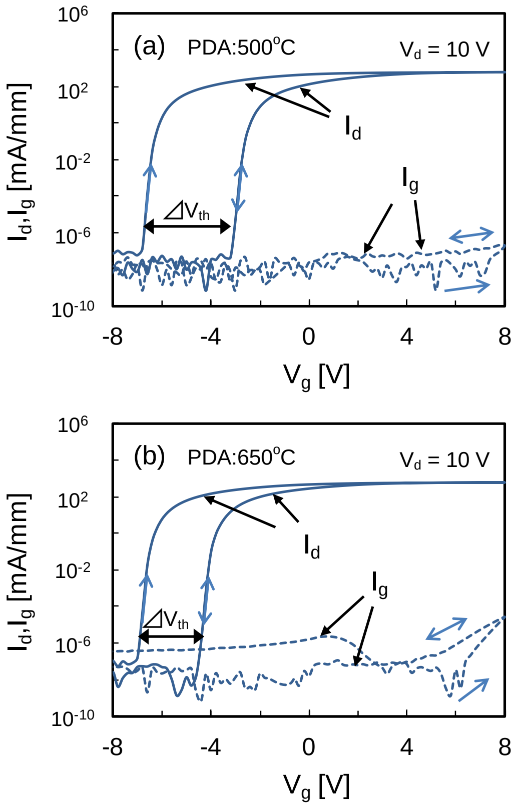

Fig. 3 Dependence of the drain current (I_d) and the gate leakage current (I_g) on the gate bias voltage (V_g) for MIS-HEMTs built with H_2O+O_3-based Al_2O_3 annealed at (a) 500°C, (b) 650°C.

Figure 4 shows dependences of the $\varDelta V_{th}$ and the I_g at a V_g of 8V on the PDA temperature of the H_2O+O_3-based Al_2O_3. As shown in Fig. 4, by increasing the PDA temperature, the $\varDelta V_{th}$ was reduced from 4.2 to 2.6 V, and the I_g increased from 3.5×10^{-8} to 2.9×10^{-5} mA/mm. The reduction of the $\varDelta V_{th}$ seems to be caused by the reduction of deep traps inside the ALD-Al_2O_3 layer rather than the reduction of interface states at the Al_2O_3/AlGaN interface. For further study, we investigated the pulsed I_d-V_d characteristics of MIS-HEMTs and the interface state density (D_{it}) at the Al_2O_3/AlGaN interface by the photo-assisted *C-V* shift [4,5]. As the result, the I_d degradation in the pulsed mode and the D_{it} did not show the PDA temperature dependence. It indicates that the PDA is effective to reduce deep traps inside the H_2O+O_3-based Al_2O_3.

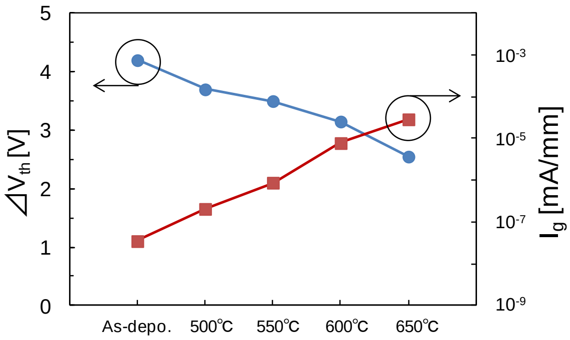

Fig. 4 Dependence of the initial threshold voltage shift ($\varDelta V_{th}$) and the gate leakage current (I_g) at a gate bias voltage of 8 V on the post-deposition annealing temperature of H_2O+O_3-based Al_2O_3.

4. Conclusions

ALD-Al_2O_3/AlGaN/GaN MIS-HEMTs were fabricated using both H_2O and O_3 as oxygen precursors with the PDA of the ALD-Al_2O_3 at 500, 550, 600, and 650°C, and their *I-V* characteristics, especially $\varDelta V_{th}$, were investigated. As the results, by increasing the PDA temperature, the $\varDelta V_{th}$ was reduced from 4.2 to 2.6 V, and the I_g increased from 3.5×10^{-8} to 2.9×10^{-5} mA/mm. Furthermore, the I_d degradation in the pulsed mode and the D_{it} at Al_2O_3/AlGaN interface did not show the PDA temperature dependence. These results suggest that the PDA was effective to reduce deep traps inside the ALD-Al_2O_3 layer deposited using both H_2O and O_3 as oxygen precursors.

Acknowledgement

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