Effect of Oxidant Source on Threshold Voltage Shift of AlGaN/GaN MIS-HEMTs Using ALD-Al_2O_3 Gate Insulator films

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Abstract

We have investigated the threshold voltage (V_{th}) shift of AlGaN/GaN metal-insulator-semiconductor (MIS) high electron mobility transistors (HEMTs) when using atomic layer deposited (ALD)-Al_2O_3 for the gate insulator films. As an oxidant source for ALD-Al_2O_3, H_2O vapor and O_2 plasma were compared, focusing on the V_{th} shift, which was evaluated by capacitance-voltage (C-V) hysteresis. As a result, we found that both $Al(OH)_x$ residues in ALD-Al_2O_3 and GaN oxidation layer at the GaN/ Al_2O_3 interface affected the V_{th} shift. By increasing rapid thermal annealing (RTA) temperature, the $Al(OH)_x$ concentration could be decreased, suppressing the V_{th} shift. GaN oxidation layer at the GaN/Al_2O_3 interface was promoted by O_2 plasma and the V_{th} shift of O_2 plasma-Al_2O_3 was larger than that of H_2O vapor-Al_2O_3. From the drain-current v.s. gate-voltage (I_{ds}-V_{gs}) characteristics, we confirmed that AlGaN/GaN MIS-HEMT with H_2O vapor-Al_2O_3, which was annealed at high temperature, showed the smallest V_{th} shift.

INTRODUCTION

AlGaN/GaN high electron mobility transistors (HEMTs) have demonstrated good performance in high power applications, such as power amplifiers in wireless base stations [1]. The primary requirement for high power devices is a low gate leakage current for high power operation and high reliability. Over the past few years, several groups have attempted to suppress the gate leakage using the metal-insulator-semiconductor (MIS) structure. Among the various insulator films that have been employed in AlGaN/GaN MIS-HEMTs, Al_2O_3 is one of the most attractive ones because of its high band gap (~7.0 eV), high dielectric constant (~9.0), and high breakdown voltage (10–30 MV/cm) [2]. Furthermore, among these films, atomic layer deposited (ALD)-Al_2O_3 have the advantages of nanometer scalability, and normally-off characteristics were reported by using ALD-Al_2O_3 [3]. Recently, threshold voltage (V_{th}) shift was reported when using ALD-Al_2O_3 [4, 5]. However, the mechanism has not been confirmed yet. Possible origin of the V_{th} shift is OH residues ($Al(OH)_x$) that are attributed to the oxidant source remaining in ALD-Al_2O_3, and they may function as electron traps which cause the V_{th} shift. On the other hand, several studies have reported that gallium oxide (GaO_x) functions as electron traps at the GaN/Al_2O_3 interface [6].

In this paper, we have investigated the effect of $Al(OH)_x$ and GaN oxidation on the V_{th} shift by using two different oxidant sources for ALD-Al_2O_3.

EXPERIMENTAL

Al_2O_3 films were deposited on AlGaN/GaN HEMT epitaxial structure (n-GaN/n-AlGaN/GaN/Buffer/Substrate) by using the ALD method at 350°C. Trimethylaluminum (TMA) was used as the source of aluminum, and H_2O vapor or O_2 plasma was used as the oxidant source. Al_2O_3 films were formed by following reaction [7, 8]:

$$2Al(CH_3)_3 + 3H_2O \rightarrow Al_2O_3 + 6CH_4 \quad (1)$$

$$2Al(CH_3)_3 + 4O_2 \rightarrow Al_2O_3 + 2CO_2 + 4CH_4 + H_2O \quad (2)$$

After deposition, rapid thermal annealing (RTA) in N_2 atmosphere was performed to decrease the amount of $Al(OH)_x$ for 1 min at 700°C and 800°C. Annealing temperatures were determined by H_2O thermal desorption spectroscopy (TDS) of the as-deposited ALD-Al_2O_3 due to following $Al(OH)_x$ dehydration [9].

$$2AlOH \rightarrow Al_2O_3 + H_2O \quad (3)$$

$Al(OH)_x$ and GaO_x concentrations were analyzed by X-ray photoelectron spectroscopy (XPS). The V_{th} shift was evaluated by capacitance-voltage (C-V) measurement at 100 kHz using a mercury-probe. The gate bias was swept from forward (-20 to 10 V) to reverse (10 to -20 V) in the dark, and the V_{th} shift was estimated from the hysteresis width.

After that, we have fabricated two kinds of AlGaN/GaN normally-on type MIS-HEMTs using H_2O vapor and O_2 plasma-Al_2O_3 for the gate insulator films, as shown in Fig. 1.

The drain-current v.s. gate-voltage (I_{ds}-V_{gs}) characteristics were measured at the drain-source voltage (V_{ds}) of 10 V, and the V_{th} shift was estimated from the hysteresis of I_{ds}-V_{gs} curves. The gate bias was swept from forward (-20 to 10 V) to reverse (10 to -20 V) in the dark. Furthermore, to investigate the effect of captured electrons on V_{th}, we have applied negative V_{gs} stress of -20 V for 10 min under halogen lamp irradiation, and compared V_{th} before and after negative V_{gs} stress.

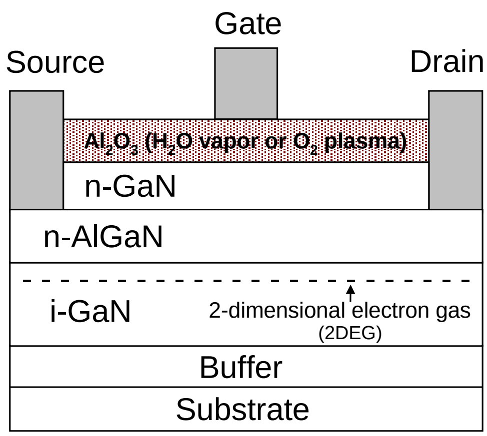

Fig. 1 Schematic cross-sectional view of normally-on type AlGaN/GaN MIS-HEMTs structure used in this work.

Results and Discussions

The relationship between the oxidant source and the V_{th} shift is shown in Fig. 2. The V_{th} shift of O_2 plasma-Al_2O_3 was larger than that of H_2O vapor-Al_2O_3. By increasing RTA temperature, the V_{th} shift could be reduced for both oxidant sources.

To investigate the mechanism of the V_{th} shift, we measured the $Al(OH)_x$ concentration in ALD-Al_2O_3 by XPS. Figure 3 shows the O 1s spectrum of the as-deposited Al_2O_3. Sapphire was used as a standard reference sample. The O 1s spectrum of ALD-Al_2O_3 was different from an ideal Al_2O_3 spectrum due to $Al(OH)_x$ residues. Furthermore, H_2O thermal desorption due to $Al(OH)_x$ dehydration was observed in ALD-Al_2O_3 as shown in Fig. 4. Thus, Figures 3 and 4 indicate that $Al(OH)_x$ was formed in ALD-Al_2O_3 for both oxidant source cases.

Figure 5 shows the effect of RTA on the V_{th} shift and the $Al(OH)_x$ concentration, which was calculated by waveform analysis of separating the O 1s spectrum into Al_2O_3 (530.7 eV) and $Al(OH)_x$ (531.33 eV) [10]. We found that the $Al(OH)_x$ concentration was decreased by increasing RTA temperature. It was confirmed that the V_{th} shift was reduced corresponding to decreasing the $Al(OH)_x$ concentration, suggesting that the V_{th} shift was attributed to $Al(OH)_x$ in ALD-Al_2O_3.

On the other hand, the V_{th} shift of O_2 plasma-Al_2O_3 was larger than that of H_2O vapor-Al_2O_3 at the same $Al(OH)_x$ concentration. Moreover, the difference in the V_{th} shift was remarkable at low $Al(OH)_x$ concentrations when RTA was applied at 800°C. Therefore, another origin of the V_{th} shift, in addition to $Al(OH)_x$ effect, should be considered, focusing on the effect of the oxidant source. A possible hypothesis is that GaN oxidation at the GaN/Al_2O_3 interface was promoted by O_2 plasma because of its high reactivity.

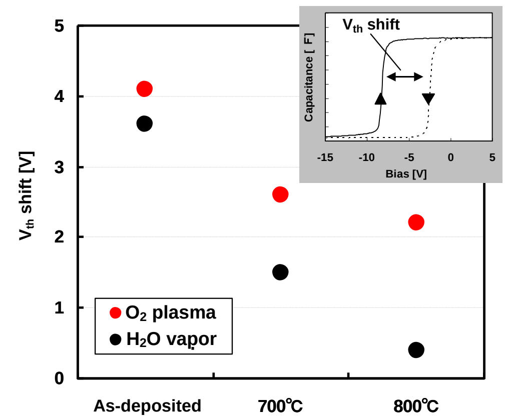

Fig. 2 Variation in V_{th} shift with oxidant source and RTA temperature. Upper right inset shows the C-V profile to estimate V_{th} shift.

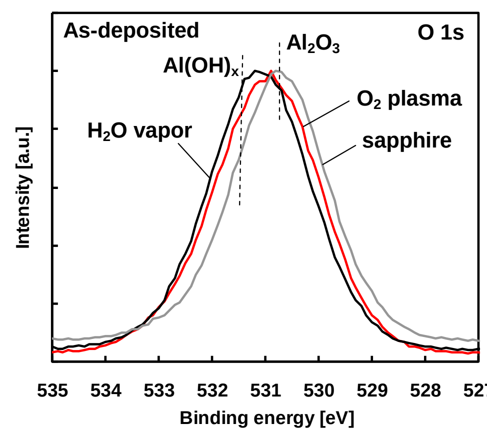

Fig. 3 O 1s spectrum of as-deposited H_2O vapor and O_2 plasma-Al_2O_3 measured by XPS.

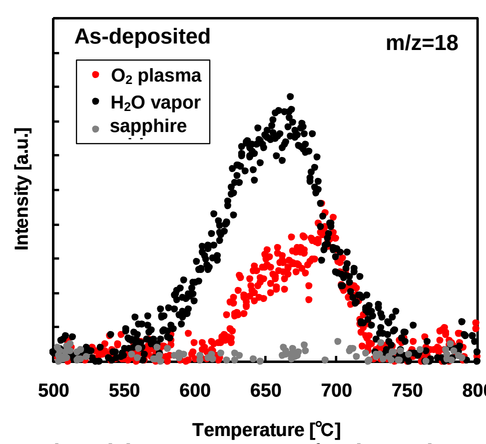

Fig. 4 H_2O thermal desorption spectrum of as-deposited H_2O vapor and O_2 plasma-Al_2O_3 measured by TDS.

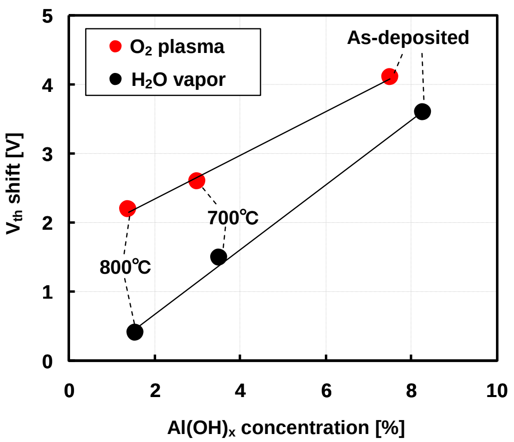

Fig. 5 Al(OH)$_x$ concentration dependence on V_{th} shift for H_2O vapor and O_2 plasma-Al_2O_3. RTA temperature was varied.

To verify the effect of the oxidant source on GaN oxidation at the GaN/Al_2O_3 interface, we measured Ga 3d spectrum on very thin 2-nm-thick ALD-Al_2O_3 deposited on GaN. 800°C RTA was applied after Al_2O_3 deposition. GaO_x concentration was calculated by waveform analysis of separating the Ga 3d spectrum into GaN (19.7 eV) and GaO_x (20.8 eV) [11].

Figure 6 shows the Ga 3d spectrum at the GaN/Al_2O_3 interface. The Ga 3d spectrum of O_2 plasma-Al_2O_3 was shifted to higher binding energy relative to H_2O vapor-Al_2O_3. Figure 7 shows the GaO_x concentrations for H_2O vapor and O_2 plasma, respectively. From these results, it was confirmed that the GaO_x concentration of O_2 plasma-Al_2O_3 was higher than that of H_2O vapor-Al_2O_3, as we had expected. These results indicate that GaN oxidation at the GaN/Al_2O_3 interface also caused the V_{th} shift, in addition to Al(OH)$_x$ in ALD-Al_2O_3.

To investigate the effect of GaN oxidation at the GaN/Al_2O_3 interface on the I_{ds}-V_{gs} characteristics, we have fabricated two kinds of AlGaN/GaN normally-on type MIS-HEMTs using H_2O vapor and O_2 plasma-Al_2O_3 for the gate insulator films as shown in Fig. 1.

Figure 8 shows the I_{ds}-V_{gs} curves, which were measured at the V_{ds} of 10 V. 800°C RTA was applied in this case. The gate bias was swept from forward (-20 to 10 V) to reverse (10 to -20 V) in the dark, and the V_{th} shift was estimated from the hysteresis of I_{ds}-V_{gs} curves. When RTA temperature was varied, it was confirmed that AlGaN/GaN MIS-HEMT with H_2O vapor-Al_2O_3, which was applied 800°C RTA showed the smallest V_{th} shift. This trend was in agreement with the results of C-V measurement as shown in Fig. 5. On the other hand, as shown in Fig. 8, V_{th} which was defined from the forward sweep curve of O_2 plasma-Al_2O_3 was larger than that of H_2O vapor-Al_2O_3. We have already reported that the reversible change in V_{th} was caused by the captured electrons in the deep level, which might exist at the GaN/Al_2O_3 interface, and the captured electrons could be released to the 2DEG due to negative gate bias stress [5]. Therefore, if electrons were captured in GaO_x at the GaN/Al_2O_3 interface, it was concerned that V_{th} shifted positive value from the veritable V_{th}.

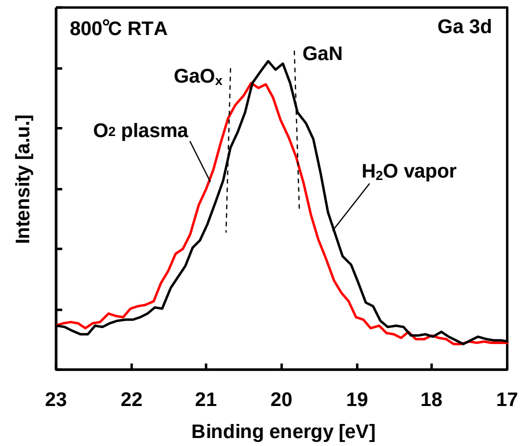

Fig. 6 Ga 3d spectrum at GaN/Al_2O_3 interface for H_2O vapor and O_2 plasma-Al_2O_3 measured by XPS. 800°C RTA was applied in this figure case.

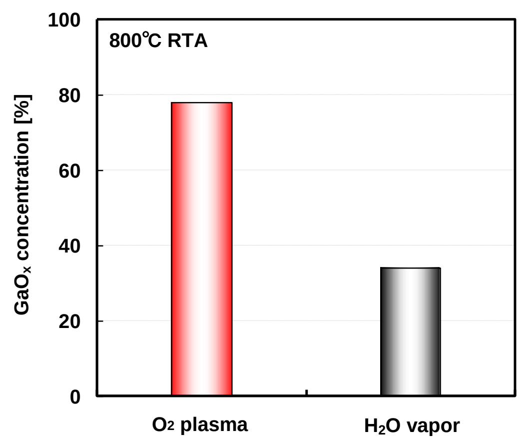

Fig. 7 Comparison of GaO_x concentration between O_2 plasma and H_2O vapor-Al_2O_3. 800°C RTA was applied in this figure case.

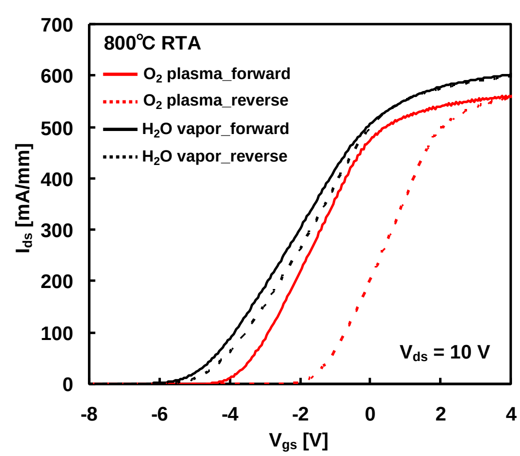

Fig. 8 I_{ds}-V_{gs} curves for AlGaN/GaN normally-on type MIS-HEMTs using H_2O vapor and O_2 plasma-Al_2O_3 for gate insulator films. 800°C RTA was applied in this figure case.

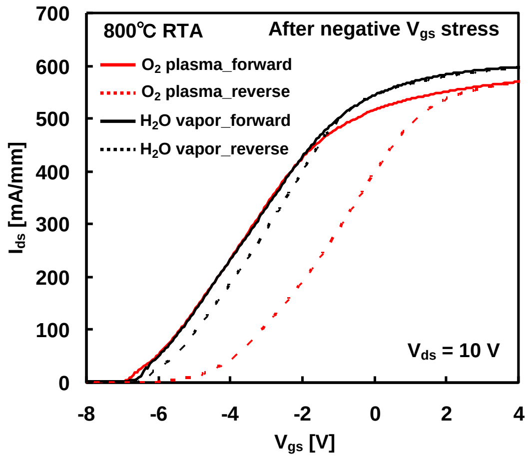

Fig. 9 I_{ds}-V_{gs} curves after negative V_{gs} stress under halogen lamp irradiation for AlGaN/GaN normally-on type MIS-HEMTs using H_2O vapor and O_2 plasma-Al_2O_3 for gate insulator films. 800°C RTA was applied in this figure case.

To investigate the effect of the captured electrons on V_{th}, we have applied negative V_{gs} stress of -20 V for 10 min under halogen lamp irradiation. Figure 9 shows the I_{ds}-V_{gs} curves after negative V_{gs} stress. The negative shift of V_{th} was confirmed with both samples. However, the V_{th} shift of O_2 plasma-Al_2O_3 was larger than that of H_2O vapor-Al_2O_3, and there was no difference between O_2 plasma and H_2O vapor-Al_2O_3 in V_{th} which was defined from the forward sweep curve after negative V_{gs} stress under light irradiation.
From these results, it was considered that V_{th}, when no electron was captured at the deep level by light illumination at negative V_{gs}, was inherently same value between O_2 plasma and H_2O vapor-Al_2O_3. The difference of V_{th} from forward sweep curve in Fig. 8 was caused by captured electrons in GaO_x at the GaN/Al_2O_3 interface as shown in Fig. 10.

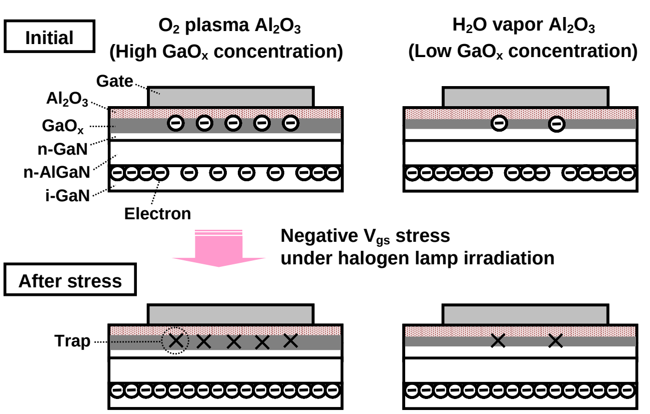

Fig. 10 Schematic cross-sectional view of the proposed mechanism for the phenomena during negative V_{gs} stress under halogen lamp irradiation for AlGaN/GaN normally-on type MIS-HEMTs using H_2O vapor and O_2 plasma-Al_2O_3 for the gate insulator films.

CONCLUSIONS

The V_{th} shift phenomena of AlGaN/GaN normally-on type MIS-HEMT were investigated by focusing on the effect of oxidant sources for ALD-Al_2O_3. We confirmed that both $Al(OH)_x$ residues in ALD-Al_2O_3 and GaN oxidation layer at the GaN/Al_2O_3 interface affected the V_{th} shift. By increasing RTA temperature, the $Al(OH)_x$ concentration could be decreased, suppressing the V_{th} shift. GaN oxidation at the GaN/Al_2O_3 interface was promoted by O_2 plasma, and the V_{th} shift of O_2 plasma-Al_2O_3 was larger than that of H_2O vapor-Al_2O_3. Thus, AlGaN/GaN MIS-HEMTs with H_2O vapor-Al_2O_3, which was annealed at high temperature, showed the smallest V_{th} shift. We conclude that reducing GaO_x at the GaN/Al_2O_3 interface has a key role in suppressing the V_{th} shift for AlGaN/GaN MIS-HEMTs.

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ACRONYMS

HEMT: High Electron Mobility Transistor
MIS: Metal-Insulator-Semiconductor
ALD: Atomic Layer Deposition
RTA: Rapid Thermal Annealing
TDS: Thermal Desorption Spectroscopy
XPS: X-ray Photoelectron Spectroscopy