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

Shiro Ozaki, Toshihiro Ohki, Masahito Kanamura,
Norikazu Nakamura, Naoya Okamoto, Toyoo Miyajima and Toshihide Kikkawa

Fujitsu Laboratories Ltd.
10-1 Morinosato-Wakamiya, Atsugi, Kanagawa, 243-0197, Japan
ozaki.shirou@jp.fujitsu.com
Phone: +81-46-250-8242

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Abstract

We have investigated the threshold voltage (Vth) 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 film. As an oxidant source for ALD-Al_2O_3, H_2O vapor and O_2 plasma were compared, focusing on Vth shift which was evaluated by C-V hysteresis. As a result, we found that both Al(OH)x residues in Al_2O_3 and GaN oxidation layer at the GaN/ Al_2O_3 interface affected Vth shift. By increasing RTA temperature, Al(OH)x concentration could be decreased, suppressing Vth shit. GaN oxidation layer at the GaN/Al_2O_3 interface was promoted by O_2 plasma and the Vth shift of O_2 plasma-Al_2O_3 was larger than that of H_2O vapor-Al_2O_3. We confirmed that GaN MIS-HEMT with H_2O vapor-Al_2O_3, which was annealed at high temperature, showed most small Vth 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 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 films have the advantages of nanometer scalability and high uniformity. Recently, threshold voltage (Vth) shift was reported when using Al_2O_3 [3, 4]. However, mechanism has not been confirmed yet. Possible origin of Vth shift is OH residues (Al(OH)x) that are attributed to the oxidant source remain in ALD-Al_2O_3 films, and may function as electron traps that cause a threshold voltage (Vth) shift. On the other hand, several studies have reported that gallium oxide (GaOx) functions as an electron trap at the GaN/Al_2O_3 interface [5].

In this paper, we have investigated the effect of Al(OH)x and GaN oxidation on Vth shift by using two different oxidant sources for Al_2O_3.

Experimental

Al_2O_3 films were deposited on AlGaN/GaN HEMT epitaxial structure (n-GaN/n-AlGaN/GaN on S.I. SiC sub.) by using the ALD method at 350°C. Trimethylaluminum (TMA) was used as a source of aluminum, and H_2O vapor or O_2 plasma was used as an oxidant source. After deposition, rapid thermal annealing (RTA) in N_2 atmosphere was performed to decrease Al(OH)x for 1 minute at 700°C and 800°C. Al(OH)x and GaOx concentrations were analyzed by X-ray photoelectron spectroscopy (XPS). The Vth shift was evaluated by C-V measurement at 100 kHz using a mercury-probe. The gate bias was switched from forward (-20 to 10 V) to reverse (10 to -20 V) in the dark, and the Vth shift was estimated from the hysteresis width.

Results and Discussions

The relationship between the oxidant source and the Vth shift is shown in Fig. 1. The Vth shift of O_2 plasma-Al_2O_3 was larger than that of H_2O vapor-Al_2O_3. When increasing RTA temperature, the Vth shift could be reduced for both oxidant sources.

To investigate the mechanism of the Vth shift, we measured Al(OH)x concentration in the Al_2O_3 films by XPS. Figure 2 shows the O 1s spectrum of ALD-Al_2O_3 films without RTA and sapphire that was used as a standard reference sample. The O 1s spectrum of Al_2O_3 films was different from an ideal Al_2O_3 spectrum due to Al(OH)x residues. Thus, Figure 2 indicates that Al(OH)x was formed in Al_2O_3 for both oxidant source cases.

Figure 3 shows the effect of RTA on Vth shift and Al(OH)x concentration. We found that Al(OH)x concentration was decreased by increasing RTA temperature. It was confirmed that the Vth shift was reduced corresponding to decreasing Al(OH)x concentration, suggesting that Vth shift was attributed to Al(OH)x.

On the other hand, the Vth 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 Vth shift was remarkable at low Al(OH)x concentrations. Therefore, additional origin of Vth shift, when Al(OH)x concentration was low, should be considered, focusing on the effect of oxidant source. Possible hypnosis is that GaN oxidation at the GaN/Al_2O_3 interface was promoted by O_2 plasma because of its high reactivity. To verify the effect of the oxidant source on GaN oxidation at the GaN/Al_2O_3 interface, we measured Ga 3d spectra on 2-nm-thick Al_2O_3 films. Figures 4 and 5 show the Ga 3d spectra and GaOx concentrations for H_2O vapor and O_2 plasma, respectively. As shown in Fig. 5, GaOx 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 Vth shift, in addition to Al(OH)x in Al_2O_3 films.

Conclusions

The Vth shift phenomena of GaN 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 Al_2O_3 and GaN oxidation layer at the GaN/Al_2O_3 interface affected Vth shift. By increasing RTA temperature, Al(OH)x concentration could be decreased, suppressing Vth shift. GaN oxidation at the GaN/Al_2O_3 interface was promoted by O_2 plasma, and the Vth shift of O_2 plasma-Al_2O_3 was larger than that of H_2O vapor-Al_2O_3. Thus, GaN MIS-HEMT with H_2O vapor-Al_2O_3, which was annealed at high temperature, showed most small Vth shift.

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References

[1] T. Kikkawa *et al.*, IEDM Tech. Digest, pp.585-588 (2001).
[2] Z. H. Liu *et al.*, Proceedings of EuMA, pp.41-44 (2010).
[3] C. Mizue *et al.*, J. Appl. Phys. 50 (2011) 021001.
[4] T. Imada *et al.*, Proceedings of IIRW, 4.1 (2011).
[5] N. Nepal *et al.*, Appl. Phys. Express 4 (2011) 055802.

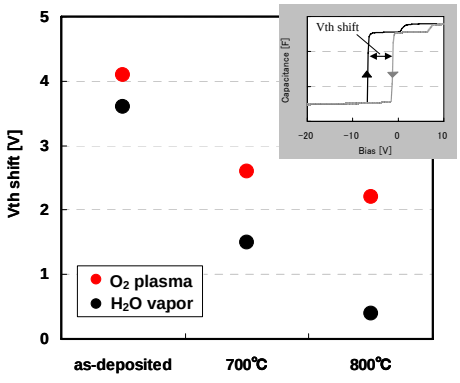

Fig. 1 Variation in Vth shift with oxidant source and RTA temperature. Upper right inset shows the C-V profile to estimate Vth shift.

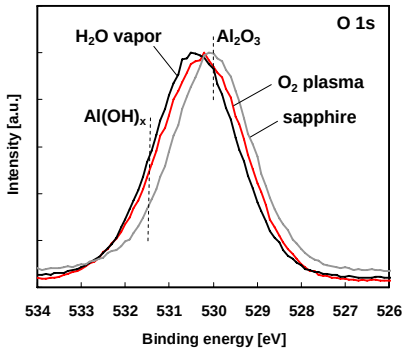

Fig. 2 O 1s spectrum of H_2O vapor and O_2 plasma-Al_2O_3 measured by XPS. RTA was not applied in this figure case.

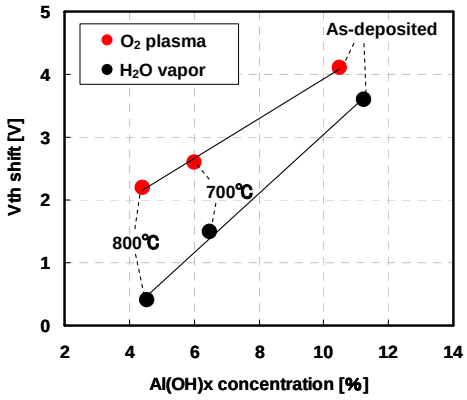

Fig. 3 Al(OH)x concentration dependence on Vth shift for H_2O vapor and O_2 plasma-Al_2O_3. RTA temperature was varied.

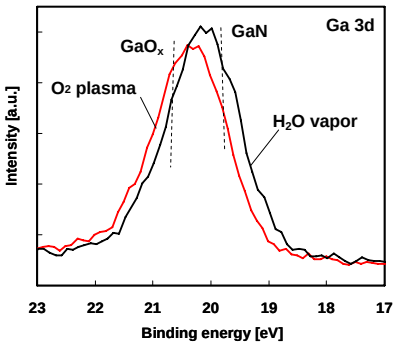

Fig. 4 Ga 3d spectra at GaN/Al_2O_3 interface for H_2O vapor and O_2 plasma-Al_2O_3.

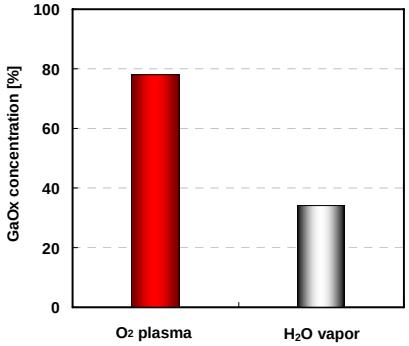

Fig. 5 Comparison of GaOx concentration between O_2 plasma and H_2O vapor-Al_2O_3.