Investigation of Thermal Stability of TiN/O_3-Al_2O_3/GaN Metal-Oxide-Semiconductor Diodes with 2 nm H_2O-Al_2O_3 as Oxide/III-Nitride Interfacial Layer

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Abstract

Interface property of O_3-sourced ALD grown Al_2O_3 is systematically investigated with various thermal processing temperature. It is revealed that TiN/Al_2O_3/GaN MOS diodes exhibit good insulating behavior with post-metal-annealing (PMA) from 400 ˚C to 700 ˚C, while its leakage current becomes larger at higher PMA temperature (800 ˚C). Temperature dependent ac-conductance measurement detects a relatively low density (1-3×10^{12} $cm^{-2}eV^{-1}$) of shallow interface traps (0.28 eV<E_C-E_T<0.6 eV) at the Al_2O_3/GaN interface, while an increased density of deep traps (E_C-E_T>0.6 eV), which are suspected to be border traps, are created at high PMA temperature (>700 ˚C). High-resolution TEM analyses reveal the Al_2O_3 layer in the MOS diodes would crystalize at high PMA temperature. It could be the probable cause for the increased leakage current and formation of border traps.

INTRODUCTION

GaN-based MIS/MOS-HEMTs have become increasingly attractive in power switching applications thanks to the lower gate leakage current and larger gate swing compared with conventional Schottky gate HEMTs [1-3]. It is highly desirable to adopt a gate dielectric which features large conduction-band offset to GaN, and moreover, low interface states in the MOS gate for enhanced reliability of GaN-based power switches [4]. Oxide-based materials have been widely used and studied as the gate dielectric, including SiO_2 [5], Al_2O_3 [6, 7], HfO_2 [8], among which Al_2O_3 is commonly used in GaN-based MOS-HEMTs because of its high breakdown electric field and wide bandgap. Typically, the Al_2O_3 is grown by ALD with precursors TMAl as aluminum source and H_2O as oxygen source. However, significant amount of defective bonds such as Al–Al and Al–O–H are observed in the ALD-Al_2O_3 films, which are proposed to be the source of positive fixed charges [9]. Therefore, ozone (O_3), a hydrogen-free ALD precursor have attracted much attention recently in the growth of Al_2O_3 films [10, 11]. It offers the advantage of suppressing Al dangling bonds and H-related bonds. However, limited research has been performed regarding the thermal stability and interface property of TiN/O_3-Al_2O_3/GaN MOS diodes with 2 nm H_2O-Al_2O_3 as the oxide/III-nitride interfacial layer.

In this work, the effect of high temperature PMA on the electrical properties of TiN/O_3-Al_2O_3/GaN MOS diodes is investigated with *I-V*, temperature dependent ac-conductance and high-resolution TEM characterizations. It is found that the O_3-sourced Al_2O_3 features good thermal stability up to 700 ˚C PMA. However, creation of deep border traps occurs at high PMA temperature, which is probably due to the crystallization of the ALD-Al_2O_3 film.

DEVICE STRUCTURE AND FABRICATION

The GaN wafer used in this work was grown by MOCVD on a 4 inch sapphire substrate by Advanced Micro-Fabrication Equipment (AMEC) Inc. The buffer layers consist of a LT-GaN buffer layer and a 4 μm-thick silicon doped GaN layer. A standard RCA cleaning process of the wafer was performed. Afterward, the ohmic contact was formed by high temperature annealing of a sputtered Ti/Al/Ti/TiN (20/120/40/60 nm) Au-free metal stack in N_2 ambient at 850 ˚C for 60 s. The contact resistance is measured to be 1.04 Ω·mm using circular TLM patterns. Then the GaN surface was treated in a diluted NH_4OH solution (10%) at 50 ˚C for 15 min. A 20 nm-thick Al_2O_3 gate dielectric layer was grown by ALD at 300 ˚C with the first 2 nm using TMAl and

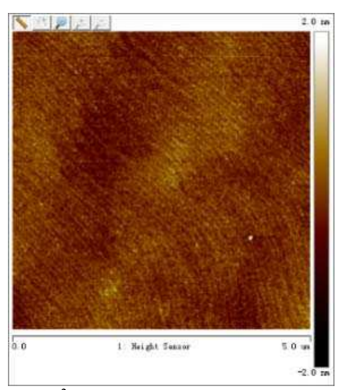

Fig. 1 5×5 $μm^2$ AFM image of O_3-Al_2O_3, Rq: 0.275 nm

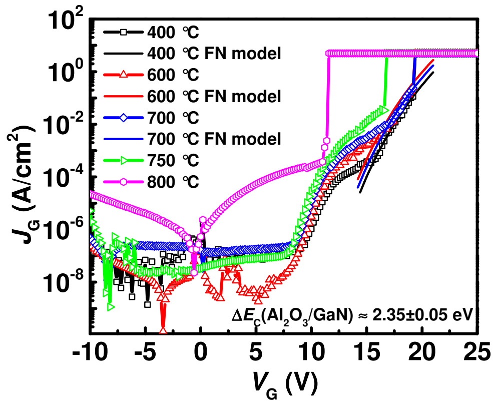

Fig. 2 *I-V* characterization of TiN/Al_2O_3/GaN MOS diodes at different PMA temperature.

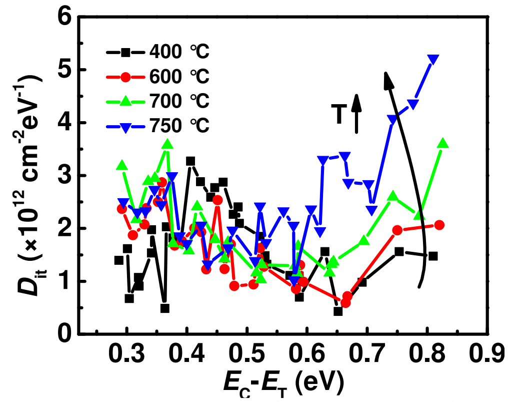

Fig. 4. Distribution of states at Al_2O_3/GaN interface for different PMA temperature, which is extracted by temperature dependent ac-conductance characterization.

H_2O as precursors, while the remaining 18 nm Al_2O_3 was deposited using O_3 instead of H_2O. The purpose of inserting a 2-nm H_2O-Al_2O_3 layer is to suppress the oxidation of GaN surface (O_3 is a strong oxidant) [11]. Then the dielectric was annealed at 500 ˚C for 60 s in N_2 ambient. A 150 nm-thick TiN layer was sputtered and patterned as a circle shaped Schottky gate with a diameter of 160 µm. The spacing between the Schottky contact and the ohmic contact ring was 20 µm. Finally, the whole wafer was cut into small pieces and PMA under a range of conditions was performed (400-800 ˚C).

Results And Discussion

Fig. 1 shows the AFM result of the O_3-Al_2O_3 surface after the 500 ˚C post deposition annealing. The surface roughness of a 5×5 µm^2 area is 0.275 nm. Distinct atomic steps can be observed, indicating the growth of Al_2O_3 is conformal with

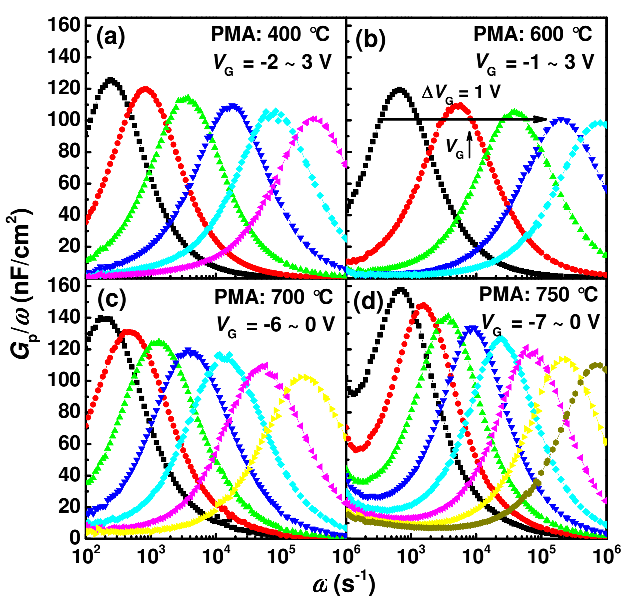

Fig.3 Temperature dependent ac-conductance characterization of samples with PMA at (a)400 ˚C, (b)600 ˚C, (c)700 ˚C and (d)750 ˚C. Results measured at 200 ˚C are shown here.

the morphology of GaN surface. The *I-V* characteristics of TiN/Al_2O_3/GaN MOS diodes with PMA of 400 ˚C, 600 ˚C, 700 ˚C, 750 ˚C and 800 ˚C are plotted in Fig. 2. The gate leakage at $V_G < +7$ V for samples with PMA from 400 ˚C to 700 ˚C is lower than 1×10^{-6} A/cm^2, showing good thermal stability and insulating behavior of the gate dielectric. Hard breakdown of the MOS diodes with PMA from 400 ˚C to 700 ˚C occurs at $V_G \sim +19$V, corresponding to a breakdown *E*-field of ~8.7 MV/cm after taking account of the band bending in the GaN layer. However, as the PMA temperature increases to 750 ˚C, the breakdown voltage decreases to ~ +16 V and further drops to ~ +11 V with PMA at 800 ˚C. On the other hand, the leakage current is increased about two orders of magnitude, similar to behavior in a Schottky diode. It is possibly caused by the crystallization of the ALD-Al_2O_3 layer at high temperature [12, 13]. The *I-V* characteristics of samples with PMA from 400 ˚C to 700 ˚C at high gate bias (> 15 V) are well fitted by Fowler-Nordheim tunneling model. The conduction band offsets between GaN and Al_2O_3 are extracted to be ~2.35±0.05 eV, which are in good consistent with previous reports [4].

Temperature dependent ac-conductance measurement is conducted (-50 to 200 ˚C) to quantify the interface trap distribution. The evolution of G_p/ω vs. ω curves measured at 200 ˚C (PMA at 400 ˚C, 600 ˚C, 700 ˚C, and 750 ˚C) is shown in Fig. 3 as representative. The measured biases were set from -6 to +3 V with a step of 1 V. The corresponding Al_2O_3/GaN interface trap density is extracted and plotted in Fig. 4. It is found that the density of deep traps at E_C-E_T > 0.6 eV slightly increases with increasing PMA temperature, while almost no significant difference in density for shallow interface traps (1-3×10^{12} cm^{-2}eV^{-1}) is observed (E_C-E_T < 0.6 eV). It is worth noting that another peak seems to appear at low ω in each curve for the 750 ˚C PMA sample, as shown in Fig. 3(d), indicating presence of deep border traps beyond the measurement limit [14]. The signal of these border traps would contribute to the evolution of G_p/ω vs. ω curves and enhance the detected signal density of deep interface traps, resulting in the significant increase of deep traps at E_C-E_T > 0.6 eV [Fig. 4].

Microstructure of the Al_2O_3/GaN interfaces with various PMA of 400 ˚C, 700 ˚C and 800 ˚C is analyzed by high-resolution TEM, as shown in Fig. 5. An amorphous Al_2O_3 layer is observed in the 400 ˚C PMA sample [Fig. 5(a)]. As the PMA temperature is increased to 700 ˚C, the Al_2O_3 layer becomes partially crystallized, as indicated by red arrow in Fig. 5(b). Moreover, the crystallized region becomes larger as the PMA temperature is further increased to 800 ˚C [Fig. 5(c)]. The observation confirms our hypothesis that the increase of leakage current in TiN/Al_2O_3/GaN MOS diodes is mainly caused by dielectric crystallization. Meanwhile, the crystallization would also introduce defects, i.e., grain boundaries, and therefore, border traps with long emission time constant in the vicinity of the Al_2O_3/GaN interface. This process would be enhanced by higher PMA temperature.

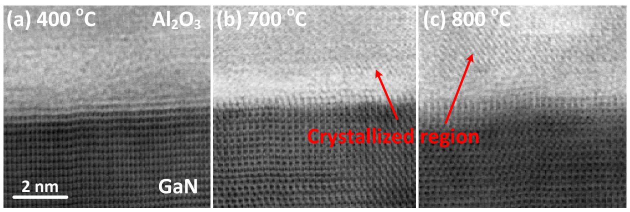

Fig. 5. High resolution TEM cross section view of the Al_2O_3/GaN interface for the samples with PMA at 400 ˚C, 700 ˚C and 800 ˚C, respectively.

CONCLUSIONS

We have investigated the interface property of TiN/O_3-Al_2O_3/GaN MOS diodes under different thermal processing temperature. It is revealed that the O_3-Al_2O_3 shows good insulating behavior as PMA temperature varies from 400 ˚C to 700 ˚C, while its leakage-blocking behavior degrades at higher PMA temperature (800 ˚C). Temperature dependent ac-conductance measurement detects a relatively low density ($1\text{-}3\times10^{12}$ $cm^{-2}eV^{-1}$) of shallow interface traps ($0.28\ eV<E_C-E_T<0.6\ eV$) but increased deep traps ($E_C-E_T>0.6\ eV$). The increase of these deep traps is likely due to the formation of border traps induced by high PMA temperature (>700 ˚C). High-resolution TEM analyses of the Al_2O_3/GaN interface reveal the Al_2O_3 film would crystalize with the increase of PMA temperature, which may be responsible for the increased leakage current and formation of border traps.

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REFERENCES

[1] Z. K. Tang, Q. M. Jiang, Y. Y. Lu, S. Huang, S. Yang, X. Tang, *et al.*, "600-V Normally Off SiNx/AlGaN/GaN MIS-HEMT With Large Gate Swing and Low Current Collapse," *IEEE Electron Device Lett.*, vol. 34, pp. 1373-1375, Nov 2013.

[2] M. Van Hove, S. Boulay, S. R. Bahl, S. Stoffels, X. W. Kang, D. Wellekens, *et al.*, "CMOS Process-Compatible High-Power Low-Leakage AlGaN/GaN MISHEMT on Silicon," *IEEE Electron Device Lett.*, vol. 33, pp. 667-669, May 2012.

[3] M. Kanamura, T. Ohki, T. Kikkawa, K. Imanishi, T. Imada, A. Yamada, *et al.*, "Enhancement-Mode GaN MIS-HEMTs With n-GaN/i-AlN/n-GaN Triple Cap Layer and High-k Gate Dielectrics," *Electron Device Letters, IEEE,* vol. 31, pp. 189-191, 2010.

[4] Z. Zhang, C. M. Jackson, A. R. Arehart, B. Mcskimming, J. S. Speck, and S. A. Ringel, "Direct Determination of Energy Band Alignments of Ni/Al2O3/GaN MOS Structures Using Internal Photoemission Spectroscopy," *J. Electron. Mater.,* vol. 43, pp. 828-832, Apr 2014.

[5] C. J. Kirkpatrick, B. Lee, R. Suri, X. Y. Yang, and V. Misra, "Atomic Layer Deposition of SiO2 for AlGaN/GaN MOS-HFETs," *IEEE Electron Device Lett.,* vol. 33, pp. 1240-1242, Sep 2012.

[6] D. H. Kim, V. Kumar, G. Chen, A. M. Dabiran, A. M. Wowchak, A. Osinsky, *et al.*, "ALD Al2O3 passivated MBE-grown AlGaN/GaN HEMTs on 6H-SiC," *Electron. Lett.,* vol. 43, p. 127, 2007.

[7] T. Hashizume, S. Ootomo, and H. Hasegawa, "Suppression of current collapse in insulated gate AlGaN/GaN heterostructure field-effect transistors using ultrathin Al2O3 dielectric," *Appl. Phys. Lett.,* vol. 83, p. 2952, 2003.

[8] J. X. Shi, L. F. Eastman, X. B. Xin, and M. Pophristic, "High performance AlGaN/GaN power switch with HfO2 insulation," *Appl. Phys. Lett.,* vol. 95, p. 042103, 2009.

[9] B. Shin, J. R. Weber, R. D. Long, P. K. Hurley, C. G. Van de Walle, and P. C. McIntyre, "Origin and passivation of fixed charge in atomic layer deposited aluminum oxide gate insulators on chemically treated InGaAs substrates," *Appl. Phys. Lett.,* vol. 96, p. 152908, 2010.

[10] T. Kubo, J. J. Freedsman, Y. Iwata, and T. Egawa, "Electrical properties of GaN-based metal–insulator–semiconductor structures with Al2O3deposited by atomic layer deposition using water and ozone as the oxygen precursors," *Semicond. Sci. Technol.,* vol. 29, p. 045004, 2014.

[11] S. Huang, X. Y. Liu, K. Wei, G. G. Liu, X. H. Wang, B. Sun, *et al.*, "O-3-sourced atomic layer deposition of high quality Al2O3 gate dielectric for normally-off GaN metal-insulator-semiconductor high-electron-mobility transistors," *Appl. Phys. Lett.,* vol. 106, Jan 19 2015.

[12] Y. Hori, C. Mizue, and T. Hashizume, "Process Conditions for Improvement of Electrical Properties of Al2O3/n-GaN Structures Prepared by Atomic Layer Deposition," *Jpn. J. Appl. Phys.,* vol. 49, p. 080201, 2010.

[13] Y. Q. Wu, T. Shen, P. D. Ye, and G. D. Wilk, "Photo-assisted capacitance-voltage characterization of high-quality atomic-layer-deposited Al2O3/GaN metal-oxide-semiconductor structures," *Appl. Phys. Lett.,* vol. 90, Apr 2 2007.

[14] S. H. Liu, S. Yang, Z. K. Tang, Q. M. Jiang, C. Liu, M. J. Wang, *et al.*, "Interface/border trap characterization of Al2O3/AlN/GaN metal-oxide-semiconductor structures with an AlN interfacial layer," *Appl. Phys. Lett.,* vol. 106, Feb 2 2015.

ACRONYMS

MIS/MOS HEMTs: Metal-Insulator/Oxide-Semiconductor High-Electron-Mobility Transistors
TMA: Trimethylaluminum
ALD: Atomic Layer Deposition
MOCVD: Metal-Organic Chemical Vapor Deposition
TLM: Transfer Length Method
AFM: Atomic Force Microscope
TEM: Transmission Electron Microscope