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GaN MOS-HEMT USING ATOMIC LAYER DEPOSITION Al_2O_3 AS GATE DIELECTRIC AND SURFACE PASSIVATION

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We report on a GaN metal-oxide-semiconductor high electron mobility transistor (MOS-HEMT) using atomic layer deposition (ALD) Al_2O_3 film as a gate dielectric and for surface passivation simultaneously. Compared to the conventional AlGaN/GaN HEMT of the same design, six order of magnitude smaller gate leakage current and tripled drain current at forward gate bias demonstrate the effectiveness of ALD Al_2O_3 as a gate dielectric. The high transconductance and high effective two-dimensional electron mobility verify the high-quality of Al_2O_3/AlGaN interface with low interface trap density. The Al_2O_3 passivation effect is also studied by sheet resistance measurement and short pulse drain characterization.

1 Introduction

GaN-based high-power microwave electronic device as an emerging compound semiconductor technology attracts tremendous interest in both industry and academia. However, two key problems still remain. First, the gate leakage current for GaN metal-semiconductor field-effect-transistor (MESFET) and GaN high electron mobility transistor (HEMT) is too high due to the surface defects and finite barrier height. The high gate leakage directly impacts the drain breakdown voltage, rf performance, noise figure, and reliability of the device. Second, without proper passivation, GaN devices exhibit current collapse with a high rf-input drive on the gate, which significantly reduces rf output power and degrades the device performance. In the past years, several groups have attempted to suppress the gate leakage using the metal-insulator-semiconductor

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field-effect-transistor (MISFET) [1-2] or metal-oxide-semiconductor field-effect-transistor (MOSFET) [3] approaches. These devices perform quite poorly. More recently, significant progress has been made on metal-insulator-semiconductor high electron mobility transistor (MIS-HEMT) or metal-oxide-semiconductor high electron mobility transistor (MOS-HEMT) using SiO_2 [4-8], Si_3N_4 [9-10], and other exotic oxides [11-12].

In this paper, we report, for the first time, AlGaN/GaN MOS-HEMTs with atomic layer deposition (ALD) Al_2O_3 as gate dielectric and surface passivation. Similar to SiO_2 [4-8], Si_3N_4 [9-10], and Sc_2O_3 [11], Al_2O_3 can significantly reduce the gate leakage current of AlGaN/GaN HEMTs thereby improve their performance and reliability. Al_2O_3 offers additional advantages of large bandgap (9 eV), high dielectric constant (k ~ 10), high breakdown field (10^7 V/cm), thermal stability (amorphous up to at least 1000°C), and chemical stability against AlGaN (without interdiffusion and interaction of Si and Al). Further, Al_2O_3 formed by ALD has become one of the leading candidates to replace SiO_2 in future-generation Si CMOS digital ICs [13]. The ALD Al_2O_3 has demonstrated low defect density, high uniformity, and nm scalability. The ALD Al_2O_3 process is robust and highly manufacturable. We have already demonstrated excellent performance in GaAs and InGaAs MOSFETs with ALD Al_2O_3 [14-16].

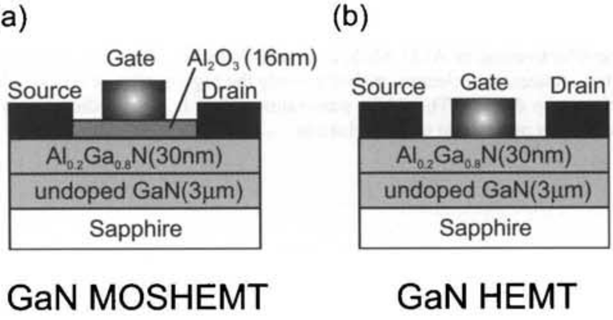

Figure 1. Schematic illustration of (a) AlGaN/GaN MOS-HEMT with ALD-grown Al_2O_3 as gate dielectric and (b) AlGaN/GaN HEMT as a baseline.

2 Device Fabrication

For the present MOS-HEMTs as shown in Fig. 1, after the AlGaN/GaN heterostructure was formed on 2-inch sapphire wafers by MOCVD, 16-nm-thick Al_2O_3 was deposited by ALD in an ASM Pulsar2000™ module, using the TMA/H_2O process. The wafers were conveniently transferred in air before and after ALD. Device isolation was achieved by nitrogen implantation. Source-drain and gate contacts were formed by Ti/Al/Ni/Au and Ni/Au, respectively. Conventional HEMTs of similar structures were processed together with the MOS-HEMTs. The gate lengths of the measured devices are 0.65, 1, 5, and 10 μm. The gate width is 100 μm. The source-to-gate and the gate-to drain spacings are ~ 2 μm. Their characteristics are compared below.

3 Device Characterization

Fig. 2(a) shows the C-V measurements at 1 MHz for 8000 μm^2 gate capacitors on the MOS-HEMT and HEMT devices. The comparable sharp rise from depletion to accumulation in CV curves for both MOS-HEMT and HEMT demonstrates the high-quality interface of Al_2O_3 to AlGaN. Fig. 2(b) shows GaN MOS-HEMT devices exhibit extremely low gate leakage currents of 10^{-6} A/cm^2, more than six orders of magnitudes lower at positive gate bias, compared to the conventional GaN HEMTs. The forward two-terminal breakdown voltage is ~ 12 V. The low gate leakage for MOS-HEMT increases the breakdown voltage and the power-added efficiency while decreasing the noise figure.

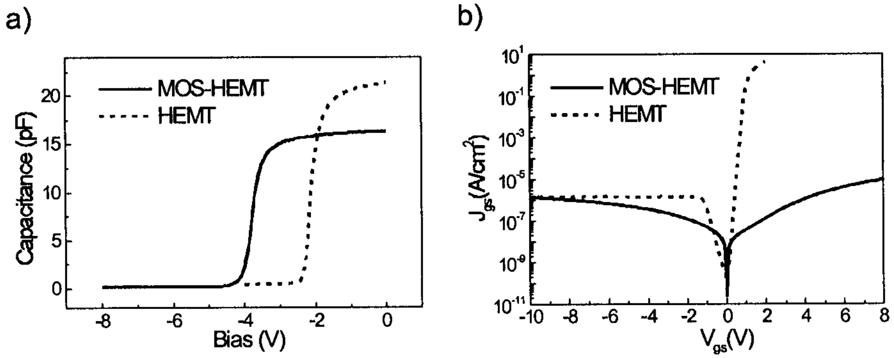

Figure 2. (a) Measured C-V characteristics of a GaN MOS-HEMT (solid line) and a HEMT (dashed line) for equal area of ~8000 μm2. (b) Gate leakage current for the MOS-HEMT (solid lines) and the baseline HEMT (dashed lines).

Fig. 3 shows well-behaved I-V characteristics of GaN MOS-HEMT operating at V_{ds}=10 V with a pinch-off voltage of -3 V. The off-state drain-source three-terminal breakdown voltage with 2 μm drain-gate spacing is around 145 V. The results indicate that ALD Al_2O_3 is an effective gate dielectric for AlGaN/GaN devices. Fig. 4(a) shows the gate-voltage dependence of the drain current for the identical geometry HEMTs and MOS-HEMTs. The drain current is ~150% higher for the MOS-HEMTs, reaching a maximum value of ~ 0.45 A/mm. Using $I_{ds}=e \cdot n_s \cdot v_{sat} \cdot W$, we estimate the maximum sheet carrier density $n_s = 6\times10^{12}/cm^2$ as expected for undoped AlGaN/GaN two-dimensional channel density. Here, v_{sat} $=6\times10^6$ cm/s for GaN. Fig. 4(b) shows that the intrinsic peak g_m for MOS-HEMT is ~100 mS/mm and for HEMT is ~120 mS/mm. The decrease of g_m corresponds to the added Al_2O_3 thickness. The high g_m for MOS-HEMT indicates that the Al_2O_3/AlGaN interface has low interface-trap density. The drain current and g_m can be improved by employing doped AlGaN layer or SiC substrates.

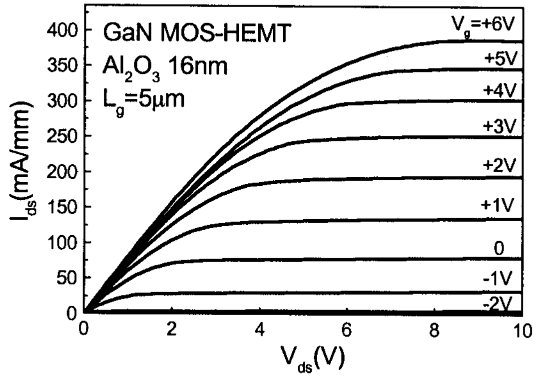

Figure 3. I-V characteristics for a MOS-HEMT.

In order to quantitatively characterize the AlGaN/GaN interface with ALD Al_2O_3 on top, we study the transverse field effect on 2D electron mobility, which is directly related to interface properties. By measuring I_{ds} vs. V_{gs} at V_{ds}=0.1 V (mobility region) of 5 and 10 μm long channel devices, we are able to extract the series resistance of the devices with a relative error of less than 5%. Fig. 5 is the summary plot of the effective 2D electron mobility vs. effective electric field. The mobility of 1200 cm^2/Vs at low transverse field is consistent with the value obtained from the Hall measurements. The effective 2D electron mobility of 640 cm^2/Vs at the high transverse field of 0.6 MV/cm is much higher than 400 cm^2/Vs, the universal surface mobility of Si MOSFETs at the same transverse field. It is also higher than the surface mobility on GaAs and InGaAs surface obtained from ALD Al_2O_3 GaAs and InGaAs MOSFETs [16]. It's mainly beneficial from the epitaxially grown AlGaN/GaN heterojunction, which has much less interface traps compared to oxide-semiconductor interfaces. Because of the high-quality ALD Al_2O_3 as gate dielectric on AlGaN (i.e., low gate leakage current and low interface trap density at Al_2O_3/AlGaN interface), it enables us to measure the effective 2D electron mobility at high electron density and high transverse field for the first time.

To study the passivation effect of ALD Al_2O_3 on AlGaN, we measure the sheet resistances of AlGaN/GaN with and without ALD Al_2O_3 on top. The lack of Al_2O_3 passivation at drain-gate and source-gate regions for the baseline HEMT could lead to increased parasitic resistance, thus degrades intrinsic g_m. The parasite resistance is determined from the transmission line model (TLM) method fabricated on the same chip. The sheet resistance measured from TLM for MOS-HEMT with ALD Al_2O_3 passivation is ~700 Ω/sq. and for HEMTs without any passivation is ~950 Ω/sq., which indicates the effectiveness of the ALD Al_2O_3 passivation on AlGaN. The preliminary study of the pulsed drain characteristics also shows interesting results. For example, after up to 80 V drain voltage stress, DC drain characteristics (solid lines in Fig. 6) show the well-known current collapse effect on drain current at $V_{ds} < 15$ V. It is mainly due to hot carrier injections at the oxide/semiconductor interface or even in the bulk oxide at the drain side

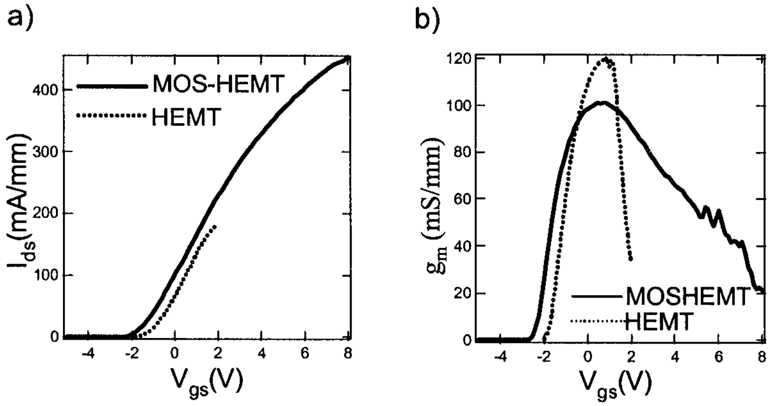

Fig. 4. (a) The drain-current Ids verses gate bias Vgs in the saturation region (Vds=10V) for the MOS-HEMT (solid line) and the baseline HEMT (dashed line) with Lg=5 μm. (b) The intrinsic transconductance gm verses gate bias Vgs at the same drain bias Vds=10V for the MOS-HEMT (solid line) and baseline HEMT (dashed line) of the same device.

under high voltage drain stress. The dashed lines in Fig. 6 show that the short pulse (1-μs) drain characteristics are fully recovered from DC characteristics at V_{gs}=4V quiescent conditions. The short pulse drain measurements at different quiescent points could be an effective method to study Al_2O_3 surface passivation. More device evaluation in terms of CW and pulsed, small- and large-signal characteristics is in progress.

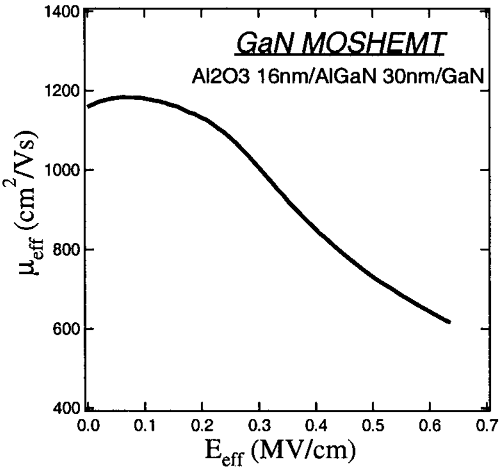

Fig. 5. Effective two-dimensional electron mobility μeff verses effective electron field Eeff. The data are obtained from 5 μm and 10 μm-gate-length devices.

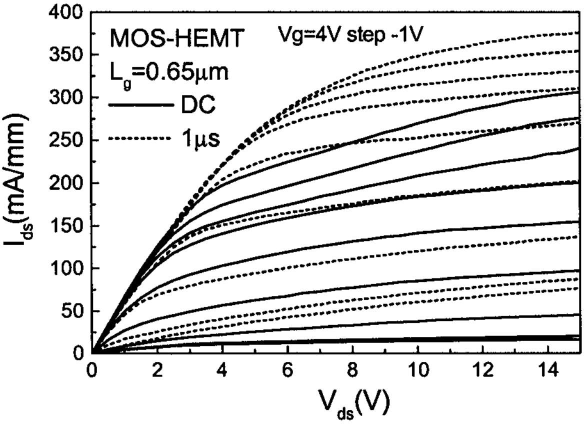

Fig. 6. Output I-V characteristics of MOS-HEMT under DC (solid line) and 1μs pulsed-gate bias (dashed line).

4 Summary

In summary, ALD Al_2O_3 process provides high-quality gate dielectric and surface passivation for AlGaN/GaN HEMTs. The resulted MOS-HEMT shows favorable characteristics when compared to MOS-HEMTs with other gate insulators such as those of [1]-[12]. This indicates excellent potential of Al_2O_3/AlGaN/GaN MOS-HEMTs for high-speed and high-power applications.

References

1. M. Asif Khan, et al., Electron. Lett., vol. 30, pp. 2175, Dec. 1994.
2. S.C. Binari, et al., International Symp. Compound Semiconductor, pp. 459, 1995.
3. F. Ren, et al., Appl. Phys. Lett., vol. 73, no. 26, pp. 3893-3895, Dec. 1998.
4. M. Asif Khan, et al., IEEE Electron Device Lett., vol. 21, no. 2, pp. 63-65, Feb. 2000.
5. M. Asif Khan, et al., Appl. Phys. Lett., vol. 77, no. 9, pp. 1339-1341, Aug. 2000.
6. G. Simon, et al., Electronics Lett., vol. 36, no. 24, pp. 2043-2044, Nov. 2000.
7. Koudymov, et al., IEEE Electron Device Lett., vol. 23, no. 8, pp. 449-451, Aug. 2002.
8. G. Simon, et al., IEEE Electron Device Lett., vol. 23, no. 8, pp. 458-460, Aug. 2002.
9. G. Simon, et al., IEEE Electron Device Lett., vol. 22, no. 2, pp. 53-55, Feb. 2001.
10. X. Hu, et al., Appl. Phys. Lett., vol. 79, no. 17, pp. 2832-2834, Oct. 2000.
11. R. Mehandru, et al., Appl. Phys. Lett., vol. 82, no. 15, pp. 2530-2532, Apr. 2003.
12. T. Hashizume et al., Appl. Phys. Lett., vol 83, no. 14, pp. 2952-2954, Oct. 2003.
13. G. D. Wilk, et al., J. Appl. Phys., vol. 89, pp. 5243-5275, 2001.
14. P. D. Ye, et al., IEEE Electron Device Lett. vol. 24, no. 4, pp. 209, Apr. 2003.
15. P. D. Ye, et al., Appl. Phys. Lett., vol. 83, no. 1, pp. 180-183, July 2003.
16. P. D. Ye, et al., Appl. Phys. Lett., vol. 84, no. 3, pp. 434-436, 2004.