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GaN metal-oxide-semiconductor field-effect-transistor with atomic layer deposited Al_2O_3 as gate dielectric

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Abstract

We report on a GaN metal-oxide-semiconductor field-effect-transistor (MOSFET) using atomic-layer-deposited (ALD) Al_2O_3 as the gate dielectric. Compared to a GaN metal-semiconductor field-effect-transistor (MESFET) of similar design, the MOSFET exhibits several orders of magnitude lower gate leakage and near three times higher channel current. This implies that the ALD Al_2O_3/GaN interface is of high quality and the ALD Al_2O_3/GaN MOSFET is of interest and potential for high-power RF and digital applications. In addition, the channel mobility of *n*-GaN layer is ~414 cm^2/V s, which has not been degraded by ALD Al_2O_3 growth and device fabrication.

Keywords: Aluminium oxide; Gallium nitride; Metal-oxide-semiconductor structures

1. Introduction

GaN is a promising semiconductor electronic material for applications in high-temperature, high-speed and high-power electronics due to its fundamental physical properties such as a wide bandgap and high saturation velocity. Recently, there is a growing interest in exploring GaN metal-oxide-semiconductor field-effect-transistors (MOSFETs) for very large scale integrated circuit (VLSI) or digital applications because GaN devices could provide low off drain currents, excellent transport properties, high-quality epi-layers on Si and material compatibility for Si process temperatures. Forthmore, GaN based electronic devices could find wide applications by integrating with GaN optoelectronic devices. From literatures, there are few works on studying formation of high-quality gate dielectrics on GaN and making high-performance GaN MOSFETs, though significant progress has been made on GaN metal-insulator-semiconductor high-electron-mobility-transistors (MIS-HEMTs) and GaN metal-oxide-semiconductor high-electron-mobility-transistors (MOS-HEMTs) using SiO_2 [1–5], Si_3N_4 [6,7], Al_2O_3 [8–10], and other oxides [11,12]. The major motivation on GaN MOSFET research is to realize high-performance enhancement mode or even inversion-type devices with scalable gate dielectrics. Atomic layer deposition (ALD) is a surface controlled layer-by-layer process for the deposition of thin films with atomic layer accuracy. Each atomic layer formed in the sequential process is a result of saturated surface controlled chemical reactions. The thickness control of the ALD films thus scalability is much superior than those of the plasma-enhanced-chemical-vapor-deposition (PECVD) grown SiO_2 and Si_3N_4. The quality of the ALD Al_2O_3 is also much higher than those deposited by other methods, i.e., sputtering and electron-beam deposition, in terms of uniformity, defect density and stoichiometric ratio of the films. Al_2O_3 offers additional advantages of a large bandgap (9 eV), high dielectric constant (k~8.6–10), high breakdown field (10–30 MV/cm), thermal stability, and chemical stability against GaN. Furthermore, ALD is the most promising approach to high-k dielectrics (i.e., HfSiON) and given Si industry's familiarity with ALD for frontend processes, the transition to ALD GaN MOSFETs integrated on Si must be easier. The ALD equipment for Al_2O_3 has demonstrated low defect density, high uniformity, and nanometer scalability. The ALD Al_2O_3 process is *ex situ*, robust and highly manufacturable. We reported earlier excellent performance of GaAs and InGaAs MOSFETs with ALD Al_2O_3 [13–15]. We now report similar performance advantages of a depletion-mode Al_2O_3/GaN MOSFET.

2. Experiments

Fig. 1(a) shows the cross sections of an ALD Al_2O_3/GaN MOSFET. A 40 nm undoped AlN buffer layer, a 3 μm undoped

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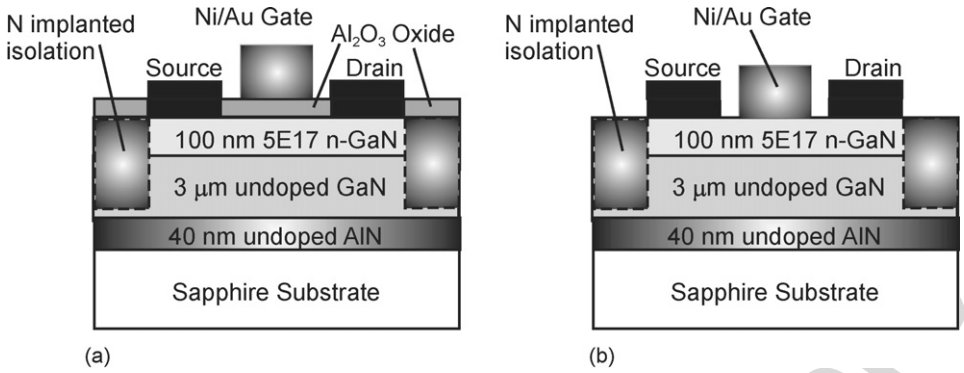

Fig. 1. Cross sections of (a) an ALD Al_2O_3/GaN MOSFET and (b) a conventional GaN MESFET of similar design.

GaN layer, and a 100 nm $5 \times 10^{17}/cm^3$ Si-doped GaN layer were sequentially grown by metal-organic chemical vapor deposition on a 2 in. sapphire substrate. After these layers were grown, the wafer was transferred via room ambient to an ASM Pulsar2000^{TM} ALD module. A 8 nm-thick Al_2O_3 layer was deposited at 300 °C then followed by annealing at 600 °C for 60 s in oxygen ambient. Device isolation was achieved by nitrogen implantation. Using a wet etch in diluted HF, the oxide on the source and drain regions was removed while the gate region was protected by photoresist. Ohmic contacts were formed by electron-beam deposition of Ti/Al/Ni/Au and a lift-off process, followed by an 850 °C rapid thermal annealing (RTA) in a nitrogen ambient, which also activated the previously implanted nitrogen. Finally, Ni/Au metals were e-beam evaporated and lifted off to form the gate electrodes. All four levels of lithography (alignment, isolation, ohmic, and gate) were done by using a contact aligner. The sheet resistance of the source/drain regions of MOSFET and MESFET were measured to be 5300 and 7500 Ω/sq, respectively. The gate lengths, L_g, of the measured devices are 1, 2, 4, 8 and 20 μm. The gate width, W_g, is 100 μm. The relatively long gate length (i.e., 8 and 20 μm) is necessary for accurate characterization of the channel mobility, in order to reduce the error in extracting the series resistance. The source-to-gate and the gate-to-drain spacings are 1–2 μm. GaN metal-semiconductor field-effect-transistors (MESFETs) of similar design were also fabricated without ALD insulator formation as shown in Fig. 1(b).

3. Results and discussions

Fig. 2 shows the well-behaved *I–V* characteristics of a typical GaN MOSFET with a drain bias V_{ds} of 0–20 V and a gate bias V_{gs} of −10 to 4 V. The oxide is as thin as 8 nm with the equivalent oxide thickness (EOT) of 3.6 nm. The pinch-off voltage is around −10 V. The maximum drain current density I_{ds}/W_g at $V_{gs} = 4$ V is approximately 180 mA/mm, which is about one order of magnitude higher than previously reported Gd_2O_3/GaN MOSFET. [12] The results indicate that ALD Al_2O_3 is an effective gate dielectric for GaN MOSFET. The typical leakage current density for an 8 nm thick ALD Al_2O_3 is less than 10^{-6} A/cm^2 under gate bias less than 4 V. The process, in particular, the high temperature ohmic contact annealing at 850 °C, degrades the insulator quality. For a 1×100 μm^2 device, the typical gate leakage current is less than 1 μA. It is about four orders of magnitude smaller than drain current and unobservable in the *I–V* characteristic as shown in Fig. 2. Using Mo/Al/Mo/Au ohmic contacts with annealing temperature of 500 °C [16] or deposition of ALD insulating films after Ti/Al/Ni/Au ohmic contact formation, it is possible to achieve much less gate leakage current.

Fig. 3 illustrates the saturated ($V_{ds} = 16$ V) drain current density and extrinsic transconductance g_m as a function of gate bias for the GaN MOSFET and the GaN MESFET of similar design. The drain current density of the GaN MESFET (grey line) is limited to 70 mA/mm at $V_{gs} = 1$ V. The gate leakage current of GaN MESFET becomes unmanageable once the gate bias sweeps above 1 V due to low Ni/*n*-GaN Schottky barrier. By contrast, the drain current density of the GaN MOSFET (black squares) is 180 mA/mm at $V_{gs} = 5$ V and can be further increased under higher V_{gs}. The combination of higher breakdown voltage due to the wide bandgap of GaN and higher drain current by employing gate oxide implies that the output power of the MOSFET can be much higher than that

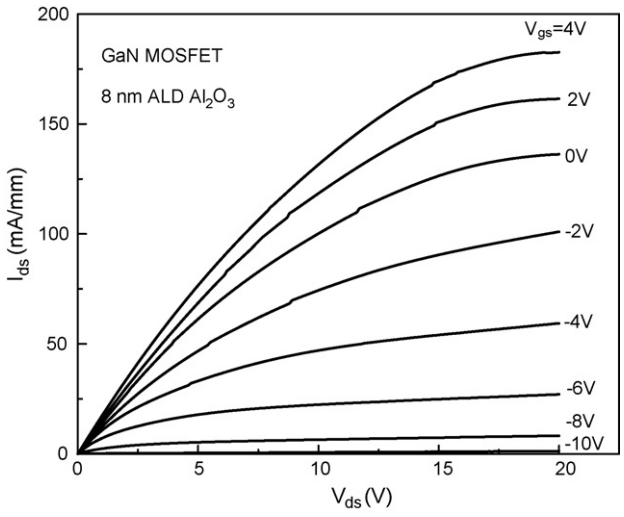

Fig. 2. Measured *I–V* characteristics of the GaN MOSFET with 8 nm ALD Al_2O_3 as the gate dielectric. The gate length $L_g = 1$ μm and the gate width $W_g = 100$ μm.

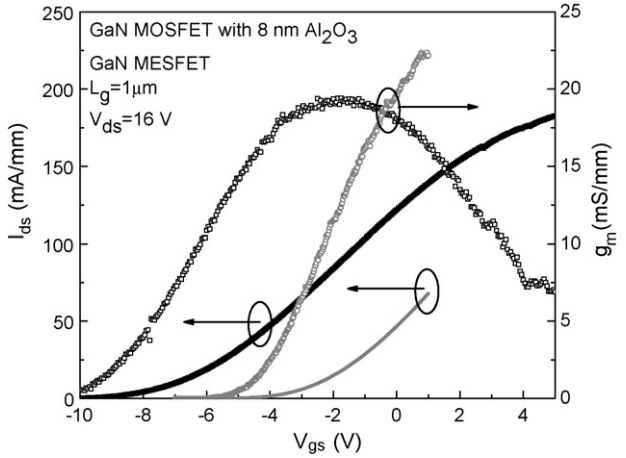

Fig. 3. The transfer and transconductance characteristics measured with the GaN MOSFET (I_{ds}: solid squares; g_m: empty squares) and GaN MESFET (I_{ds}: grey line; g_m: grey empty circles) in saturation ($V_{ds} = 16$ V).

of the MESFET. Using $I_{ds}/W_g = en_s\upsilon_{sat} = 200$ mA/mm and the sheet carrier density n_s of 5×10^{12}/cm^2, we obtain the saturated velocity $\upsilon_{sat} = 2.5 \times 10^6$ cm/s, which is within the range of values commonly observed for doped GaN bulk channel. Fig. 3 shows that the extrinsic peak g_m is 20 and 22.5 mS/mm for the MOSFET and the MESFET, respectively. The intrinsic peak g_m could be calculated from the measured extrinsic transconductance by accounting for the parasitic source resistance R_s of 33 and 20 Ω mm for the MOSFET and the MESFET, respectively. The R_s values were measured on test structures fabricated alongside the MOSFET and the MESFET according to the transmission line method (TLM) or the mobility region of *I–V* characteristics of these devices. The peak intrinsic g_m is about 59 mS/mm for MOSFET and 52 mS/mm for MESFET. The g_m value for MOSFET is in agreement with theoretical estimation according to $g_m = \upsilon_{sat}C_{MOSFET}$. Using $\upsilon_{sat} = 2.5 \times 10^6$ cm/s, $C_{MOSFET} = 18$ pF, g_m was estimated to be 58 mS/mm for the MOSFET, which is very near the measured value of 59 mS/mm. This also indicates that the interface trap capacitance C_{it} is very small or near negligible. ALD process enables us to grow high-quality Al_2O_3 on GaN with excellent interface quality or low interface trap density D_{it}. *C*–V measurements at 1 MHz on MOS capacitors further confirm the above statement, which shows negligible hysteresis in the loop as the gate bias sweeps between −15 and 0 V. Only small hysteresis, less than 150 mV, exhibits when the gate bias sweeps near the flat-band condition (not shown).

Maximum intrinsic g_m for the long-channel depletion mode MOSFET is given by $g_m = (W_g/L_g)\mu_n N_d t$, where N_d and t are the doping and thickness of the channel layer, μ_n is the channel mobility. For the long-channel devices, i.e., 8 μm-gate-length and 100 μm-gate-width device, the maximum intrinsic g_m is obtained to be 4.1 mS. The calculated channel mobility μ_n is ∼414 cm^2/V s, which is consistent with the recommended value from the GaN epi-vendor. No any significant mobility degradation is observed by ALD Al_2O_3 growth and device fabrication.

4. Conclusions

In conclusion, ALD Al_2O_3 was proven to be an excellent gate dielectric for GaN MOSFET. The present depletion-mode GaN MOSFET exhibits favorable characteristics when compared to GaN MESFET. The present MOSFET shows low leakage current, high drain current density, high intrinsic transconductance and high channel mobility, compared to previous work reported in literatures. These characteristics imply that ALD is an enabler for high-quality dielectrics on GaN wide-bandgap material and it has excellent potential for high-power RF applications. By realizing enhancement-mode GaN MOSFET using ALD dielectrics, it could open up the new opportunity to explore GaN MOSFETs integrated on Si for digital applications.

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