A study of GaN MOSFETs with atomic-layer-deposited Al_2O_3 as the gate dielectric

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Accumulation-type GaN metal-oxide-semiconductor field-effect transistors (MOSFETs) with atomic-layer-deposited Al_2O_3 gate dielectrics are fabricated. The device, with atomic-layer-deposited Al_2O_3 as the gate dielectric, presents a drain current of 260 mA/mm and a broad maximum transconductance of 34 mS/mm, which are better than those reported previously with Al_2O_3 as the gate dielectric. Furthermore, the device shows negligible current collapse in a wide range of bias voltages, owing to the effective passivation of the GaN surface by the Al_2O_3 film. The gate drain breakdown voltage is found to be about 59.5 V, and in addition the channel mobility of the n-GaN layer is about 380 cm^2/Vs, which is consistent with the Hall result, and it is not degraded by atomic-layer-deposition Al_2O_3 growth and device fabrication.

Keywords: gallium nitride, metal-oxide-semiconductor field-effect transistor, atomic-layer deposition, aluminium oxide

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1. Introduction

GaN, with a high saturation velocity at a high electrical field ($v_{sat} \sim 3\times10^7$ cm/s at 150 kV/cm),[1,2] a high critical electrical field (up to 3 MV/cm), a good thermal conductivity,[3] and epilayers grown on Si,[4,5] has been widely studied for applications in high-power and high-temperature devices, such as heterojunction field-effect transistors (HFETs). Compared with the conventional radio frequency (RF) AlGaN/GaN HFETs,[6−11] GaN metal-oxide-semiconductor field-effect transistors (MOSFETs) feature a large voltage sweep range, low gate leakage currents and circuit simplicity, hence they have attracted much attention lately.[12,13]

Since the discovery of Ga_2O_3 (Gd_2O_3) as a gate dielectric, which leads to the advent of the first depletion-mode GaN MOSFETs, much research effort has been devoted to alternative high-k dielectrics on GaN, including HfO_2,[14,15] Al_2O_3,[16,17] Gd_2O_3,[18,19] and MgO.[20] Recently, atomic layer deposition (ALD) has been employed to grow ultrathin and high-k dielectrics on the GaN substrate due to its advantages over other deposition methods, such as excellent thickness uniformity over a large substrate area, conformability, low processing temperature, low impurity content, and very precise thickness control.[21] Al_2O_3 offers the additional advantages of a large bandgap (9 eV), a high dielectric constant ($k \sim$ 8.6–10), a high breakdown field (10–30 MV/cm), thermal stability, and chemical stability against GaN.

In this paper, we report a high-performance accumulation-type GaN MOSFET with ALD-Al_2O_3 as the gate dielectric. Compared with the previously reported GaN-based MOSFET with Al_2O_3 as the gate dielectric, the device demonstrates excellent direct-current (DC) output, as well as transfer characteristics, such as a high drain current (I_d), a high transconductance (G), and a low gate leakage current.

2. Device and fabrication

A schematic cross section of the fabricated GaN MOSFETs is shown in Fig. 1(a). The 2 μm unintentionally doped GaN and the 0.2 μm n-GaN epilayer were grown on a 5 cm c-face sapphire substrate using the metal organic chemical vapor deposition (MOCVD) technique. According to the Hall measurement, the electron concentration was 3×10^{17} cm^{-3},

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and the electron mobility was about 390 cm^2/Vs at 300 K.

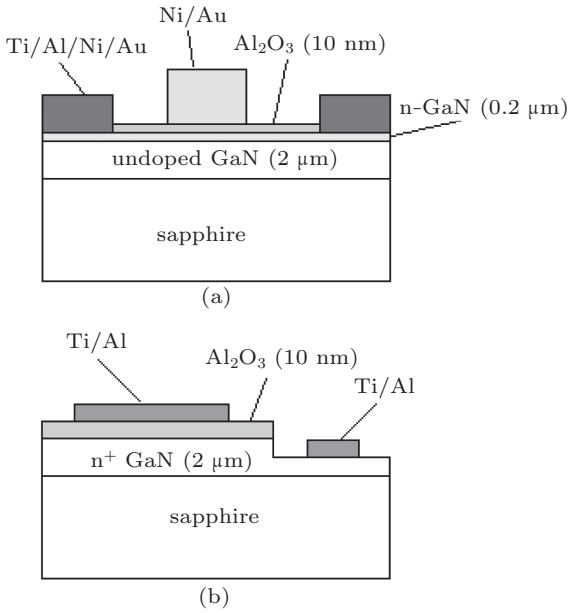


Fig. 1. (colour online) (a) A schematic of the device structure of a fabricated GaN MOSFET, and (b) a Ti/Al-Al_2O_3-GaN MOS structure.

The electrical isolation was performed by forming the mesa structure using an inductively coupled plasma etching system with the chlorine gas. In order to form the source and the drain ohmic electrodes, the Ti/Al/Ni/Au was deposited by electron beam evaporation and annealed by rapid thermal annealing in nitrogen gas at 830 °C for 30 s. The thicknesses of the ohmic contact stacks were 20, 120, 55 and 45 nm. A 10 nm thick Al_2O_3 layer was deposited on the wafer by using the ALD at 300 °C, and then followed by annealing at 600 °C for 60 s in ambient oxygen. Using Ni/Au (20/200 nm) as the gate electrode material, the device had a gate length L_g of 2 μm and a gate width W_g of 100 μm. On the other hand, in order to extract the channel mobility, the relative long gate devices were fabricated on the wafers ($L_g = 8$ μm and $W_g = 100$ μm), and the source-to-gate and gate-to-drain spacings were both 2 μm.

3. Results and discussion

For dielectric measurements, the metal-oxide-semiconductor (MOS) structures were fabricated on the heavily Si-doped (n^+) GaN epilayer, which was grown on the sapphire substrate as shown in Fig. 1(b). The current–voltage characteristics of the MOS structure at room temperature were measured using an HP4156B semiconductor parameter analyzer. As the voltage increases to 6.4 V, a steep increase is observed, as shown in Fig. 2, which is characteristic of Fowler-Nordheim (FN) tunneling. After FN tunneling, the breakdown of the Al_2O_3 thin film occurs. If we define the breakdown voltage as the voltage at which the current density is larger than 10^{-7} A/cm^2, the breakdown field is approximately 6 MV/cm, which is consistent with the value given in Ref. [22].

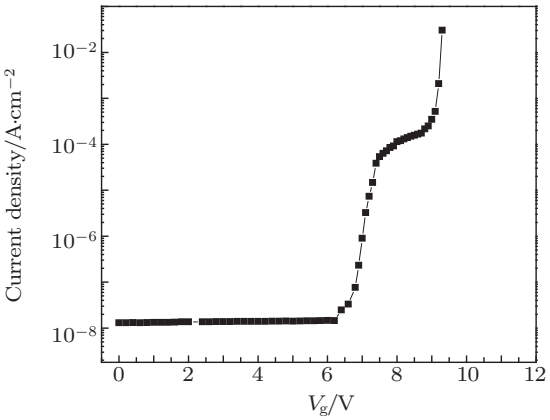


Fig. 2. The current-voltage characteristics of the Al_2O_3 thin film.

Figure 3(a) shows the output characteristics of the fabricated GaN MOSFET, which behaves well in the gate bias V_g ranging from −8 to 6 V for a drain bias V_d ranging from 0 to 16 V. The oxide is as thin as 10 nm, with an equivalent oxide thickness of 4.5 nm. The pinch-off voltage of the device is around −7 V. The maximum drain current density at $V_g = 6$ V is about 260 mA/mm, which is about one order of magnitude higher than that of the previously reported Gd_2O_3/GaN MOSFET. The results indicate that ALD-Al_2O_3 is an effective gate dielectric for the GaN MOSFET, so the efficient gate modulation is achieved, and more carriers accumulate in the channel layer, thus giving a higher accumulated current at +6 V. Compared with the Schottky-gated GaN devices, this device demonstrates a large positive gate voltage (+6 V) with a low gate leakage current, which results from the high conduction-band offset (> 2 eV) of Al_2O_3/GaN.[23] Using $I_{ds}/W_g = en_s\upsilon_{sat} = 260$ mA/mm and sheet carrier density $n_s = 6 \times 10^{12}$ cm^{-2}, we obtain the saturated velocity $\upsilon_{sat} = 2.7 \times 10^6$ cm/s, which is within the range of values commonly observed for the doped GaN bulk channel. Furthermore, gate pulsed I–V measurements with a pulse width of 200 μs are performed to analyse the current collapse as shown in

Fig. 3(b), where neither a significant current collapse in the pulsed curves, nor an I_d reduction in the pulsed curves in the saturation region is observed. However an increased I_d of the pulsed curves is observed, which is due to the self-heating effect occurring under the high drain bias. In Fig. 3(c), if we remove the Al_2O_3 passivation layers between the source and the gate and between the gate and the drain, the current collapse phenomenon is noticeable and leads to a reduction in I_{ds}, which we believe is due to the fact that the dangling and the reconstructed bonds on the surface of the GaN epilayer act as donor-like traps. In the gate pulse measurement process, the device is in a deep depletion state, lots of electrons flow from the gate to the drain electrode and are trapped by the surface states, and then the net negative charge exists on the GaN surface. Thus the surface potential turns negative, depleting the channel of electrons and leading to a decrease in the drain current. After passivation, the surface state density is greatly reduced, and the electron trapping and the depletion of channel electrons are suppressed, which again strongly indicates the effective surface passivation of GaN using Al_2O_3.

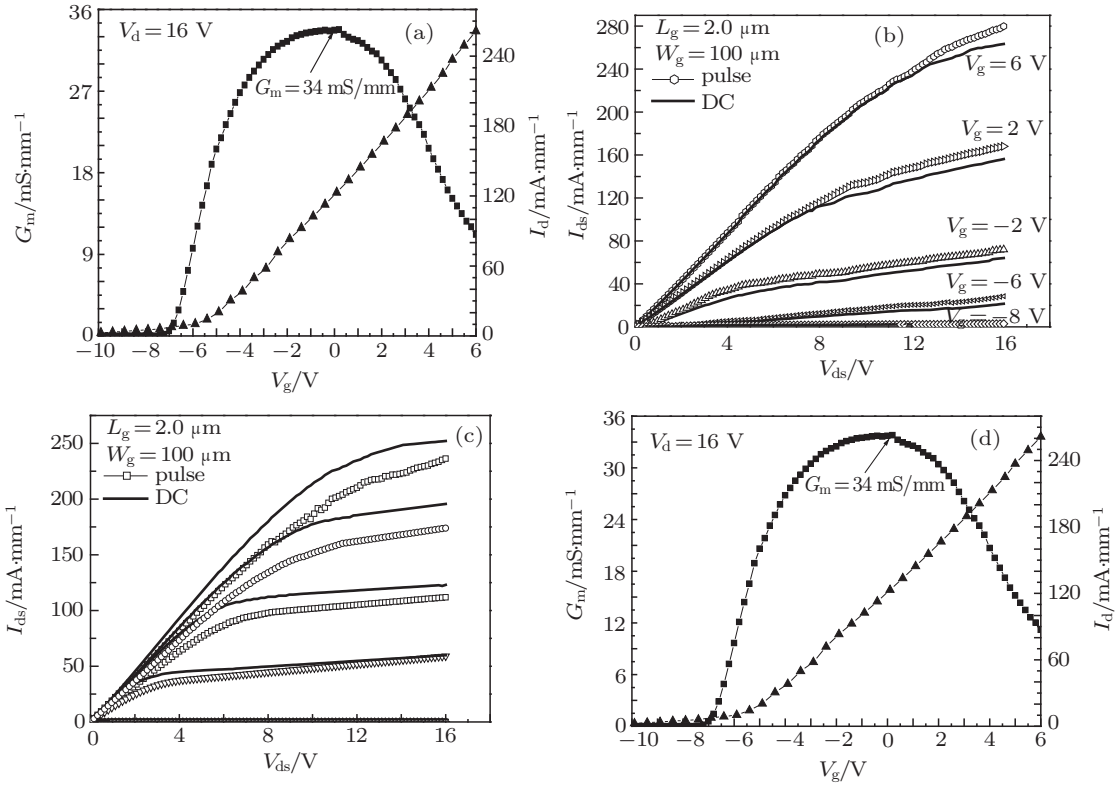


Fig. 3. (a) The current-voltage characteristics of the device at a drain voltage of 16 V, (b) the pulsed I–V characteristics with a pulse width of 200 μs with Al_2O_3 passivation, (c) the pulsed I–V characteristics with a pulse width of 200 μs without Al_2O_3 passivation, and (d) the drain current and transconductance of the device at $V_d = 16$ V.

The transfer characteristics of the device are shown in Fig. 3(d) in the case of a drain voltage of 16 V. The G curve is wide and has a maximum transconductance of about 34 mS/mm. The maximum intrinsic transconductance G_{in} for the long channel depletion mode MOSFET is given by $G_{in} = (W_g/L_g)\mu_n N_d t q$, where N_d and t are the doping concentration and the thickness of the channel layer, respectively, μ_n is the channel mobility, and q is the elementary charge. For the long channel device with $L_g = 8$ μm and $W_g = 100$ μm, the measured maximum transconductance is 21.4 mS/mm (not shown here) according to formula $G_m = G_{in}/(1 + R_s G_{in})$, where G_{in} is the intrinsic transconductance, G_m is the measured transconductance, and R_s is the parasitic source resistance. In order to obtain the R_s value, we first measure the resistance versus the contact spacing data using the transmission line model (TLM) method, and the results are shown in Fig. 4. The TLM pads have dimensions of 80 ×40 μm and seven separations (5, 10, 15, 20, 30, 40 and 50 μm). If we assume that the resistance beneath the Ohmic contact is equal

to the sheet resistance of the GaN epilayer, we find that the sheet resistance is 5520 Ω/sq and the Ohmic contact resistance is 14 Ω·mm. With a source-contact-to-gate separation of 2 μm, the contribution of this region to the source resistance is 11 Ω·mm. By adding the contact resistance of 14 Ω·mm obtained from the TLM measurement, the parasitic source resistance is calculated to be 25 Ω·mm, and we obtain an intrinsic transconductance of about 4.6 mS. So the calculated channel mobility is about 383 cm^2/Vs, which is consistent with the Hall measurement results. No significant mobility degradation is observed in the ALD-Al_2O_3 growth and the device fabrication.

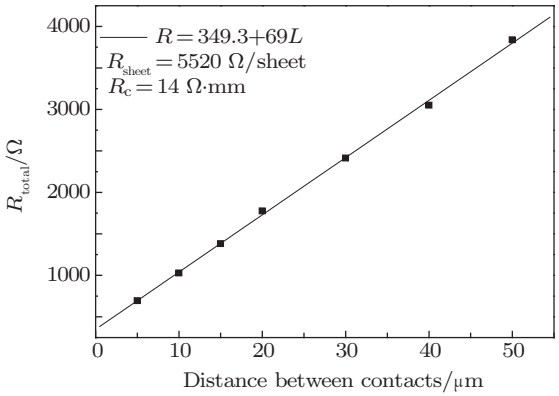


Fig. 4. Measured resistance vs contact spacing.

Figure 5 shows that for the GaN MOSFET, the gate leakage current varies with the gate voltage in the range from −10 to +9 V. Specifically, the gate leakage current is as low as 10^{-8} A/cm^2 for the gate voltage ranging from −10 to +4 V. Even when the gate voltage increases to +9 V, the gate leakage current is only 10^{-1} A/cm^2, which is much lower than that of the GaN MESFET device.[12] Furthermore,

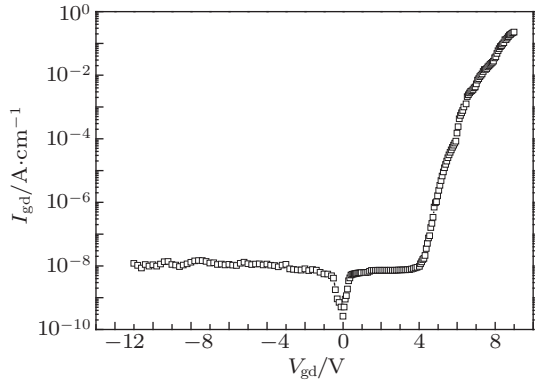


Fig. 5. The gate leakage current of the GaN MOSFET.

if we define the voltage at which the I_g is equal to 1 mA/mm as the breakdown voltage, the gate drain breakdown voltage is about 59.5 V, as shown in Fig. 6. The high breakdown voltage value is also evidence for the high-quality Al_2O_3-GaN interface that sustains the high electrical field.

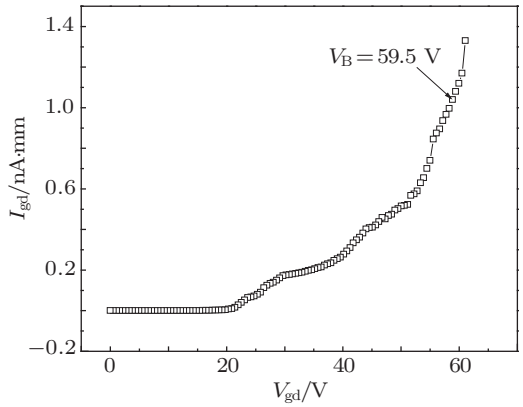


Fig. 6. The gate-drain breakdown characteristics.

In the representative GaN-based depletion mode MOSFETs, the following parameters have been reached: I_d = 25 mA/mm at V_g = +7 V and V_d = 20 V;[24] I_d = 180 mA/mm at V_g = +4 V and V_d = 20 V, G_m = 22.5 mS/mm at V_d = 16 V;[25] I_d = 230 mA/mm at V_g = +6 V and V_d = 20 V, G_m = 31 mS/mm at V_d = 15 V.[26] In this work, the following parameters have been achieved: I_d = 260 mA/mm and G_m = 34 mS/mm, which are higher than the previous results. Nevertheless, the simply designed Al_2O_3/GaN MOSFETs provide extremely low leakage current and negligible current collapse.

4. Conclusion

We fabricated a GaN MOSFET with ALD-Al_2O_3 as the gate dielectric. The device presents a high drain current of 260 mA/mm, a high transconductance of 34 mS/mm and negligible current collapse in a wide range of bias voltages. These results imply that ALD-Al_2O_3/GaN MOSFETs are excellent for high-power RF applications.

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