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A study on Al_2O_3 passivation in GaN MOS-HEMT by pulsed stress*

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This paper studies systematically the drain current collapse in AlGaN/GaN metal–oxide–semiconductor high electron mobility transistors (MOS-HEMTs) by applying pulsed stress to the device. Low-temperature layer of $A1_2O_3$ ultrathin film used as both gate dielectric and surface passivation layer was deposited by atomic layer deposition (ALD). For HEMT, gate turn-on pulses induced large current collapse. However, for MOS-HEMT, no significant current collapse was found in the gate turn-on pulsing mode with different pulse widths, indicating the good passivation effect of ALD $A1_2O_3$. A small increase in I_d in the drain pulsing mode is due to the relieving of self-heating effect. The comparison of synchronously dynamic pulsed $I_d - V_{ds}$ characteristics of HEMT and MOS-HEMT further demonstrated the good passivation effect of ALD $A1_2O_3$.

Keywords: AlGaN/GaN MOS-HEMT, Al_2O_3, passivation
PACC: 7340N, 7340Q

1. Introduction

The gate leakage current due to the surface defects and finite barrier height is one of the major factors that limit the performance and reliability of GaN high electron mobility transistor (HEMT). The high gate leakage directly impacts the drain breakdown voltage, radio frequency (RF) performance, and reliability of the device. There is great interest in the development of GaN-based metal–oxide–semiconductor (MOS) transistor structures to get around the high gate leakage.[1−16] Khan *et al*[1] have shown that the gate leakage current for the MOS-HEMT was more than six orders of magnitude smaller than that for the HEMT. And without proper passivation, GaN devices exhibit serious current collapse, which significantly reduces RF output power and degrades the device performance.[2,3] An additional advantage of GaN MOS-HEMT is that the material used as the gate dielectric can also be used as a surface passivation layer, reducing the current collapse.[4−6]

In this paper, we demonstrate good passivation effect of atomic layer deposition (ALD) $A1_2O_3$ which can be used simultaneously as gate dielectric and surface passivation layer in MOS-HEMT by applying pulsed stress to the devices. Similar to SiO_2,[7−9] Si_3N_4,[10,11] and Sc_2O_3,[12] Al_2O_3 can significantly reduce the gate leakage current of AlGaN/GaN HEMTs and thereby improve the performance and reliability of the devices. It also offers additional benefit of a wide band gap (9 eV), high dielectric constant (κ ∼10), high breakdown field (5–10 MV/cm), thermal stability (amorphous up to at least 1000°C), and chemical stability against AlGaN. The quality of the ALD Al_2O_3 is much higher than those deposited by other methods.The ALD equipment for Al_2O_3 has demonstrated low defect density, high uniformity, and nanometre scalability.

2. Device fabrication

Figure 1 shows the cross sections of (a) an ALD Al_2O_3/AlGaN/GaN MOS-HEMT and (b) a conventional AlGaN/GaN HEMT of similar design. The heterostructure was grown by metal-organic chemical vapour deposition and it consists of 40 nm undoped AlN buffer layer, 1 μm undoped GaN layer, and 25 nm n-$Al_{0.3}Ga_{0.7}N$ barrier layer ($2\times10^{18}cm^{-3}$) on a 2-inch sapphire substrate. Mesa isolation process with BCl_3 plasma reactive ion etching was used for device isolation. The source-drain ohmic contacts were formed by Ti/Al/Ni/Au structure. These contacts were an-

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nealed at 830°C for 60 s by using rapid thermal annealing in nitrogen atmosphere. And then 3.5-nm-thick Al_2O_3 was deposited by using trimethyl aluminium (TMA) and water as precursors in an F-120 ALD system. The deposition was performed at 300°C at a pressure of 266 Pa. Gate contacts were formed by Ni/Au. Conventional HEMTs of similar structures were processed together with the MOS-HEMTs. DC measurements were performed on the fabricated devices by using a HP4156B precision semiconductor parameter analyser.

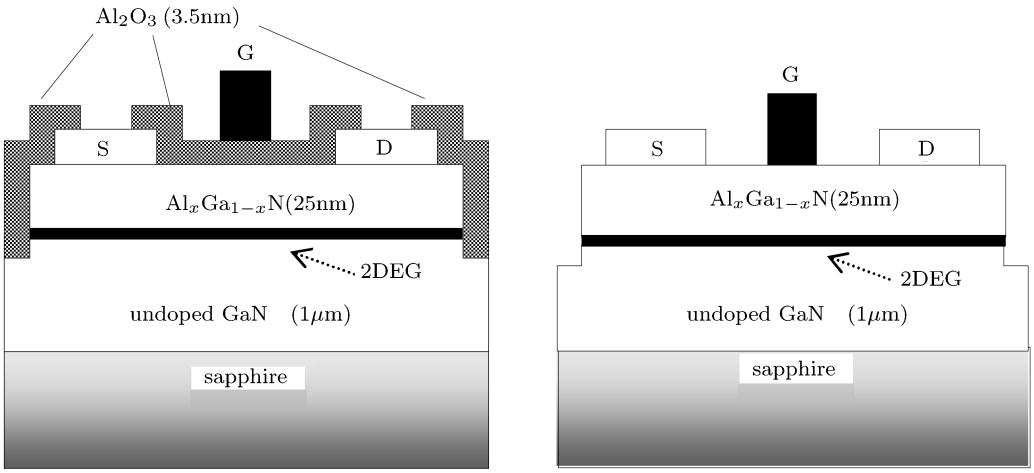


Fig.1. Schematic view of (a) a AlGaN/GaN MOS-HEMT with ALD Al_2O_3 as gate dielectric and (b) a conventional AlGaN/GaN HEMT of similar design.

3. Result and discussion

Figure 2 compares the gate–voltage dependence of the drain current for the identical geometry HEMT and MOS-HEMT. The drain current density was 30% higher for the MOS-HEMT, reaching a maximum value of over 860 mA/mm at a high positive gate voltage of V_{gs}=5V, however the drain current density of the HEMT was limited to 640 mA/mm at V_{gs}=1V, because the V_{gs} cannot be biased at high positive voltage due to the large gate leakage current. For the MOS-HEMT structure a threshold voltage shift ΔV_{th} ~0.5 V was measured because of the larger gate to channel separation.

To investigate the effectiveness of the Al_2O_3 for the surface passivation in these structures, we employed gate lag measurements. Figure 3 shows the drain current response of a Al_2O_3/AlGaN/GaN MOS-HEMT to a pulsed gate–source voltage, compared to the DC measurement. In Fig.3, V_{gs} was pulsed from –6V to 0V at 1 KHz with the pulse width which equals to 4 μs. There was less than a 10% decrease in drain–source current. This was the typical Al_2O_3 passivation result which is compared to a 50% decrease for unpassivated HEMTs shown in Fig.4. This was clear evidence that the Al_2O_3 retained its effectiveness in mitigating the surface state-induced current collapse.

The mechanism of Al_2O_3 passivation can be explained as follows. In the case of conventional AlGaN/GaN HEMT, electrons can be injected into the surface states assisted by large leakage currents under the deep pulsed stress. Electrons captured by the surface states at the area between the gate and drain electrodes cause reduction of two dimensional electron gas (2DEG) density due to the charge neutrality condition and behave as a virtual gate, causing a decrease in the drain current and the transconductance. The Al_2O_3-based passivation decreases the surface traps and induces increase of the sheet carrier density largely alleviating the current collapse effects and remarkably reducing the gate leakage current. Thus, Al_2O_3-based insulated gate and surface passivation structure is very effective in suppressing the current collapse effects, thereby leading to the reliability improvement of AlGaN/GaN HEMTs.

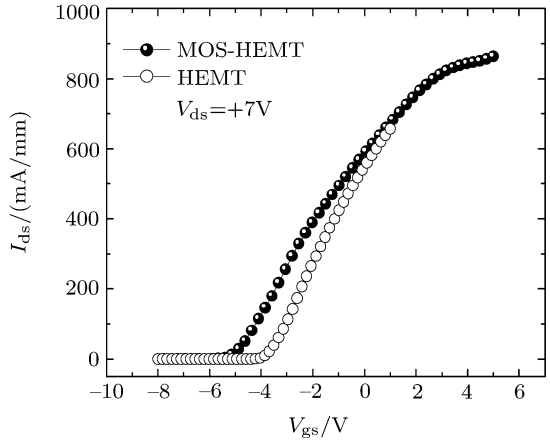


Fig.2. The gate–voltage dependence of the drain current for the identical geometry HEMT and MOS-HEMT.

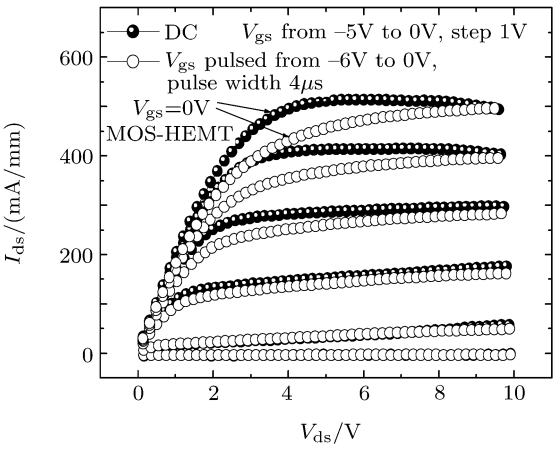


Fig.3. Drain current response of a Al_2O_3 /AlGaN/GaN MOS-HEMT to a pulsed gate–source voltage for both DC and pulsed measurements.

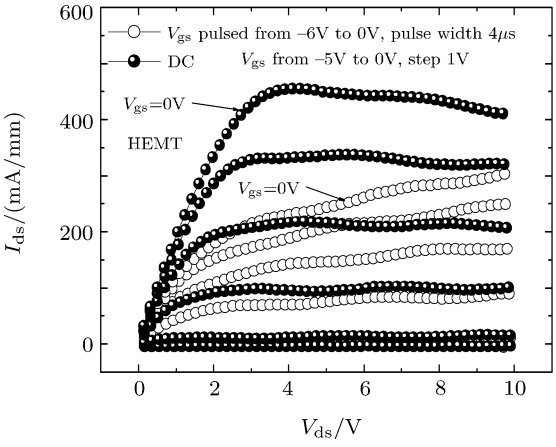


Fig.4. Drain current response of a GaN HEMT to a pulsed gate–source voltage for both DC and pulsed measurements.

Figures 5 and 6 show the experimental I_{ds}–V_{ds} characteristics at V_{gs}=0V in DC and in gate turn-on mode by pulsing V_{gs} from –6V to 0V for MOS-HEMT and HEMT. In DC, the decrease of saturation current density with the increase of V_{ds} was due to the self-heating effect. In gate turn-on mode, the pulse width varied from 4 μs to 16 μs with a 1ms period. Pulsed I_d values were obtained by averaging the I_d (t) samples over the final, stable portion of the pulse width. In Fig.6, very limited drain current response occurred for HEMT without passivation, but nearly ideal response occurs in Fig.5 for MOS-HEMT, exhibiting the superiority of the passivation effect with ALD Al_2O_3 gate dielectric. It should be noted that the pulse width used in this measurement is short relative to the time constant of the gate lag. If much longer pulses are used, both curves for HEMT and MOS-HEMT will approach the DC. Surface passivation with ALD Al_2O_3 can change the time constant of the gate lag, so the saturation current densities for the MOS-HEMT were higher than that for the HEMT in pulse mode shown in Figs.5 and 6.

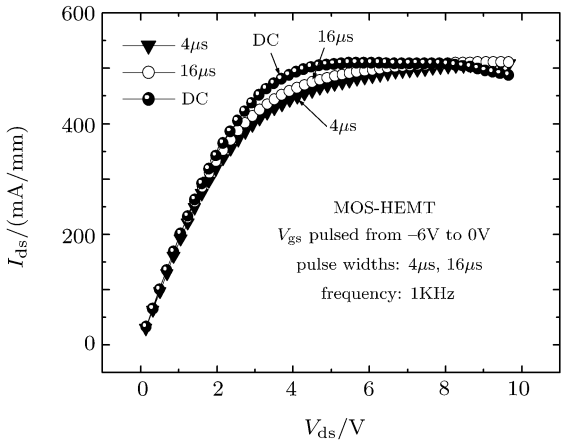


Fig.5. Experimental I_{ds}–V_{ds} characteristics at V_{gs}=0V obtained in DC and in gate turn-on mode by pulsing V_{gs} from –6V to 0V for MOS-HEMT.

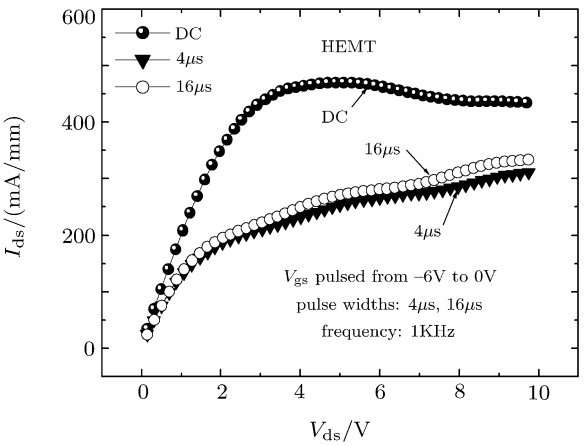


Fig.6. Experimental I_{ds}–V_{ds} characteristics at V_{gs}=0V obtained in DC and in gate turn-on mode by pulsing V_{gs} from –6 V to 0 V for HEMT.

Figure 7 compares the I_{ds}–V_{ds} characteristics at V_{gs}=0V measured in DC conditions with those obtained by pulsing the drain voltage for MOS-HEMT. A small increase in I_{ds} (with respect to DC conditions) was observed when V_{ds} was pulsed with different pulse width. This was due to the relieving of self-heating effect. Figure 8 compares the I_{ds}–V_{ds} characteristics at V_{gs}=0V obtained in DC and in two drain pulse modes with different bias point for MOS-HEMT. Under the first bias point (V_{gs}=0V and V_{ds}=0V), V_{ds} was pulsed from 0V to the x-axis value. The increase in I_{ds} was due to the relieving of self-heating effect which is also shown in Fig.7. Under the second bias point (V_{gs}=–6V and V_{ds}=10 V), V_{ds} was pulsed from the bias point to the x-axis value. The decrease in I_{ds} was due to both the effect of self-heating and a small current collapse. In Fig.9, the dynamic pulsed I_{ds}–V_{ds} characteristics for HEMT and MOS-HEMT were measured by pulsing both the drain–source voltage and gate–source voltage synchronously away from the bias point (V_{gs}=–6V and V_{ds}=10V) to the point where the current was measured. For these measurements, pulse width and pulse separation were 4 μs and 1ms, respectively. Improved pulsed characteristics were observed, which confirms the efficacy of the ultrathin ALD Al_2O_3 as a passivation layer.

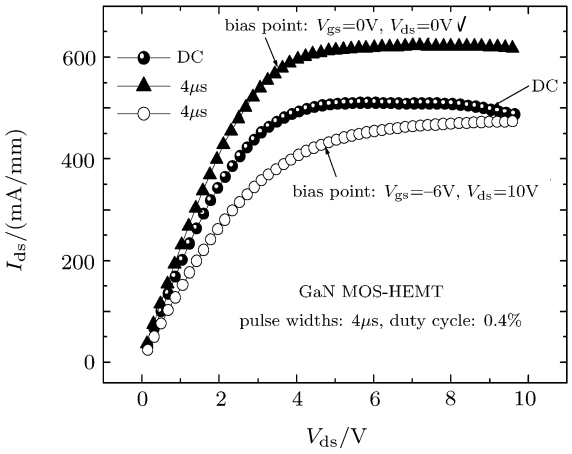


Fig.8. Experimental I_{ds}–V_{ds} characteristics at V_{gs}=0V obtained in DC and in two drain pulse modes with different bias point for MOS-HEMT.

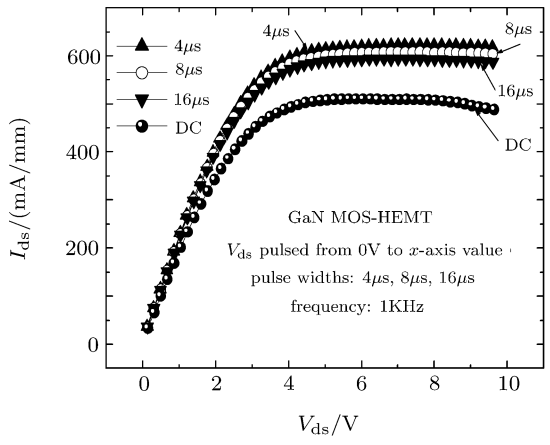


Fig.7. Experimental I_{ds}–V_{ds} characteristics at V_{gs}=0V obtained in DC and in drain pulse mode by pulsing V_{ds} from 0V to the x-axis value for MOS-HEMT.

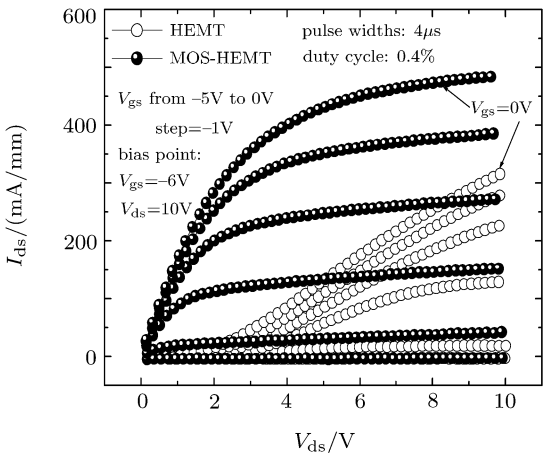


Fig.9. The dynamic pulsed $I-V$ characteristics measured by pulsing both the drain–source voltage and gate–source voltage synchronously away from the bias point (V_{gs}=–6V and V_{ds}=10V) to the point where the current was measured.

4. Conclusion

We have investigated the passivation effects of ultrathin ALD Al_2O_3 layer on GaN MOS-HEMTs on sapphire substrate by pulsed stress. The ALD Al_2O_3 can act as both the gate dielectric and a surface passivation layer. Compared to the conventional HEMTs fabricated on the same wafer, the MOS-HEMTs exhibit improved DC and pulsed $I-V$ characteristics, indicating excellent potential of Al_2O_3/AlGaN/GaN MOS-HEMTs for high-speed and high-power applications.

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