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GaN MOS-HEMT Using Ultrathin Al_2O_3 Dielectric with f_{max} of 30.8GHz*

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Abstract: We report on a GaN metal-oxide-semiconductor high electron mobility transistor (MOS-HEMT) using atomic-layer deposited (ALD) Al_2O_3 as the gate dielectric. Through decreasing the thickness of the gate oxide to 3.5nm, a device with maximum transconductance of 130mS/mm is produced. The drain current of this 1μm gate-length MOS-HEMT can reach 720mA/mm at +3.0V gate bias. The unity current gain cutoff frequency and maximum frequency of oscillation are obtained as 10.1 and 30.8GHz, respectively.

Key words: AlGaN/GaN; MOS-HEMT; ultrathin Al_2O_3
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1 Introduction

One of the major factors that limit the performance and reliability of AlGaN/GaN HEMT for high-power radio-frequency (RF) and high temperature applications is their high gate leakage due to the surface defects and finite barrier height[1]. The high gate leakage directly impacts the drain breakdown voltage, RF performance, and noise figure of the device. In the past, several groups attempted to suppress the gate leakage by using the metal-insulator-semiconductor field-effect-transistor (MISFET)[2,3] or metal-oxide-semiconductor field-effect-transistor (MOSFET)[4] approaches. However, these insulated gate devices were not superior in many respects to the state-of-the-art AlGaN/GaN HEMTs. More recently, significant progress has been made on metal-insulator-semiconductor high electron mobility transistors (MIS-HEMT) and metal-oxide-semiconductor high electron mobility transistors (MOS-HEMT) using SiO_2[5~9], Si_3N_4[10,11], Al_2O_3[12] (formed by electron cyclotron resonance plasma oxidation of Al), and other oxides[13,14].

In this work, we report on the fabrication and characterization of AlGaN/GaN MOS-HEMT with atomic-layer-deposited Al_2O_3 as the gate dielectric. Similar to SiO_2, Si_3N_4, and Sc_2O_3[14], Al_2O_3 as a gate dielectric can significantly reduce the gate leakage, which allows for application of high positive gate voltage to further increase the sheet electron density in the 2D channel. It also offers the additional benefits of a wide band gap (9eV), high dielectric constant ($\kappa \approx 10$), high breakdown field (5 ~ 10MV/cm), thermal stability (amorphous up to at least 1000℃), and chemical stability when compared to AlGaN. 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 quality of this 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 nanometer scalability.

2 Device structure and fabricating process

In Fig. 1, the device structure of the fabricated ALD Al_2O_3/AlGaN/GaN MOS-HEMT is presented. It was grown by metal-organic chemical vapor deposition and consisted of a 40nm un-

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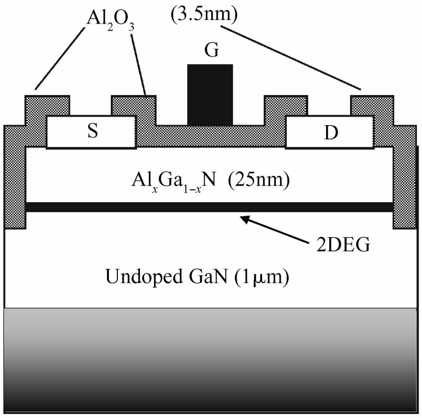

Fig. 1　Schematic view of an AlGaN/GaN MOS-HEMT with ALD-grown Al_2O_3 as gate dielectric

doped AlN buffer layer, a 1μm undoped GaN layer, and a 25nm n-$Al_{0.3}Ga_{0.7}N$ barrier layer ($2\times10^{18}cm^{-3}$) on a 50mm sapphire substrate. The room temperature Hall mobility $1150cm^2/(V\cdot s)$ and sheet carrier concentration $1.2\times10^{13}cm^{-2}$ were measured. A mesa isolation process with a BCl_3 plasma reactive ion etching was used for device isolation. The source-drain ohmic contacts were formed with a Ti(30nm)/Al(180nm)/Ni(55nm)/Au(45nm) structure. These contacts were annealed at 830℃ for 60s using rapid thermal anneal in nitrogen atmosphere. A 3.5nm Al_2O_3 layer was deposited on half of the wafer at 300℃. Using Ni/Au (20nm/200nm) for the gate electrode fabrication, two kinds of devices were then fabricated on the same wafer. The first were MOS-HEMTs with the gate metal on top of the Al_2O_3 layer and the second were HEMTs with the gate metal directly on the AlGaN barrier layer. The gate lengths (L_g) are 1μm with a gate width (W_g) of 120μm. The source-to-gate and gate-to-drain spaces are both 2μm.

3　DC and microwave performances

Figure 2 shows the *C-V* characteristics at 1MHz of gate capacitors with both the MOS-HEMT and HEMT structures. A round test pattern with the area of $A=\pi\times63\mu m\times63\mu m$ was used for the *C-V* measurements. Using the MOS-HEMT capacitance measurement, we estimate the upper limit on surface charge density in Al_2O_3 layer to be $n_s=5\times10^{11}cm^{-2}$[15]. This charge density is two orders of magnitude less than the sheet carrier density in the 2D channel of the MOS-HEMT, thereby indicating a high quality for the Al_2O_3/AlGaN interface. However, the interface state density is several orders of magnitude higher than that of the Si MOSFETs at the nearly perfect SiO_2/Si interface. For the GaN MOS-HEMT structure, a threshold voltage shift $\Delta V_{th}=0.5V$ is shown in Fig. 2. This threshold voltage shift can be attributed to the larger distance between the gate and the channel or the interface states, which partially screen the electric field from the gate electrode, preventing it from reaching the channel. The solution is to replace Al_2O_3 gate oxides with a material having higher permittivity. High-*k* insulators can be grown physically thicker for the same (or thinner) equivalent electrical oxide thickness (EOT), thus offering significant gate leakage reduction. On the other hand, the surface pretreatment is required to improve the interface properties before the deposition of Al_2O_3 on AlGaN. The Al_2O_3 thickness d_{OX} is estimated from the following equations:

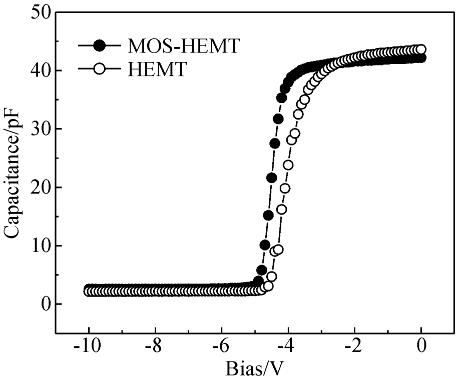

Fig. 2　Measured *C-V* characteristics of GaN MOS-HEMT and HEM

$$\frac{1}{C_{MOS\text{-}HEMT}}=\frac{1}{C_{OX}}+\frac{1}{C_{HEMT}} \tag{1}$$

$$C_{OX}=\varepsilon_0\varepsilon_{OX}A/d_{OX} \tag{2}$$

$$A=\pi\times63\times63(\mu m^2) \tag{3}$$

where $C_{MOS\text{-}HEMT}=39.9pF$ is the zero-bias capacitance of the MOS-HEMT, $C_{HEMT}=43.6pF$ is the zero-bias capacitance of the HEMT, ε_0 is the vacuum permittivity, ε_{OX} is the dielectric constant of ALD Al_2O_3, and A is the capacitor area. The calculated oxide thickness of 2.4nm is less than the design value of 3.5nm. That is probably due to the chemical cleaning of the Al_2O_3 surface before the gate metal deposition.

In Fig. 3, the gate leakage current of the MOS-HEMT is generally lower than that of the

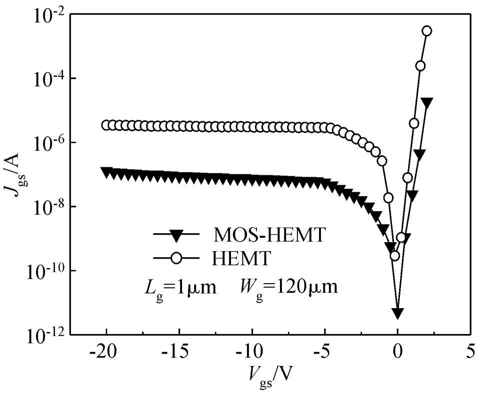

Fig. 3 Gate leakage current for the MOS-HEMT and the HEMT

HEMT. Specifically, under a negative gate bias $V_{gs} = -20$V, the gate leakage current of the MOS-HEMT is approximately two orders of magnitude lower than that of the HEMT with similar gate dimensions. Figure 4 shows that the *I-V* characteristics of the AlGaN/GaN MOS-HEMT with a gate length L_g of 1μm and a gate width W_g of 120μm are well behaved over a drain bias V_{ds} of 0～10V and a gate bias V_{gs} of $-5 \sim 3$V. The pinch-off voltage is consistently -5V. The drain current density of the HEMT with the same dimensions, which is not shown here, is limited to 640mA/mm at $V_{gs} = 1$V because the V_{gs} cannot be biased at a more positive voltage due to the large gate leakage current. By contrast, the drain current density of the MOS-HEMT is 720mA/mm at a high positive gate voltage of $V_{gs} = 3$V. The combination of higher breakdown voltage and higher drain current imply that the output power of the MOS-HEMT can be much higher than that of the HEMT. Using $I_{ds}/W_g = en_s v_{sat}$ and a saturated $v_{sat} = 5 \times 10^6$cm/s, we estimate the maximum sheet carrier density to be $n_s = 1.0 \times 10^{13}/\text{cm}^2$ as expected for a AlGaN/GaN two-dimensional channel density. No noticeable *I-V* hysteresis is observed in the drain current in both forward and reverse gate-voltage sweep directions. This indicates that no significant mobile bulk oxide charge is present and that density of the low interface traps is low.

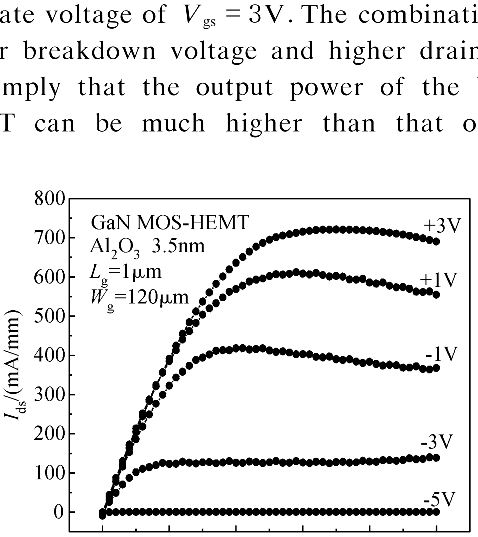

Fig. 4 Measured *I-V* characteristics of the MOS-HEMT

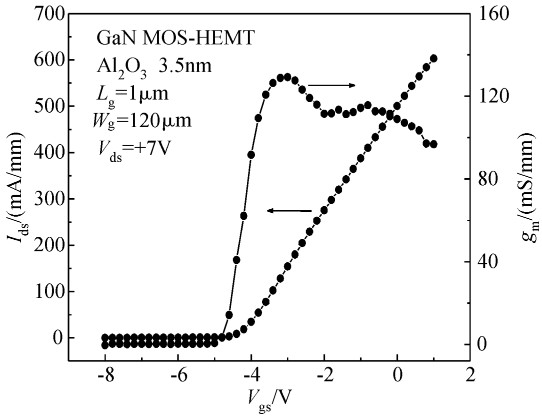

Fig. 5 DC transfer characteristics of 1.0μm × 120μm AlGaN/GaN MOS-HEMT on sapphire substrate at a drain bias of 7V

Figure 5 shows the drain current and transconductance of AlGaN/GaN MOS-HEMT with a gate length L_g of 1μm and a gate width W_g of 120μm. As can be seen from Fig. 5, the MOS-HEMT transconductance measured for the 1μm gate length device is 130mS/mm. This is smaller than 145mS/mm for the HEMT with the same device dimensions, which is not shown here. This decrease is consistent with a separation between the MOS-HEMT channel and the gate contact. The increased gate-to-channel separation is also responsible for a more negative MOS-HEMT threshold voltage.

The microwave characteristics were measured on a wafer using an Agilent E8363B network analyzer in the range from 10MHz to 40GHz. Both short-circuit current gain h_{21} and maximum available power gain U were calculated from the measured S-parameters, which is shown in Fig. 6, and extrapolated at -20dB/decade to find f_T and f_{max}, respectively, as shown in Fig. 7. Under these conditions, the 1μm gate length device shows $f_T = 10.1$GHz and $f_{max} = 30.8$GHz at a drain bias of 7V and a gate bias of -3.15V. Compared to the conventional AlGaN/GaN HEMTs of 0.8μm gate

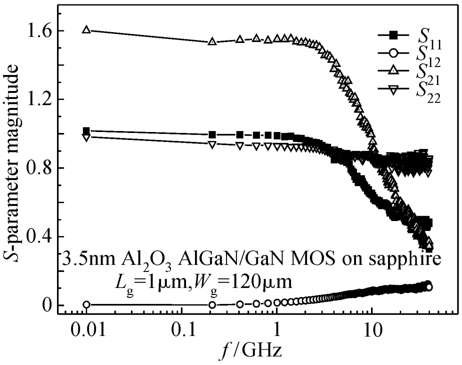

Fig. 6　Measured *S*-parameters versus frequency

length, which exhibit an f_T of 10. 7GHz[16] on sapphire substrate, and an f_T of 20GHz and an f_{max} of 28GHz[17] on 6H-SiC substrate, equivalent device performance is obtained, exhibiting the superiority of this MOS-HEMT device structure with an ALD Al_2O_3 gate dielectric.

4　Conclusions

In summary, ALD Al_2O_3 was proven to be an excellent gate dielectric for GaN MOS-HEMTs. We have fabricated a 1μm gate length GaN MOS-HEMTs with an Al_2O_3 gate oxide thickness of 3. 5nm which exhibits a maximum transconductance of 130mS/mm and a strong accumulation current of 720mA/mm at V_{gs} = 3V. The f_T and f_{max} were measured as 10. 1 and 30. 8GHz, respectively. These ideal characteristics imply the huge potential of the ALD Al_2O_3/AlGaN/GaN MOS-HEMT for high-power RF applications.

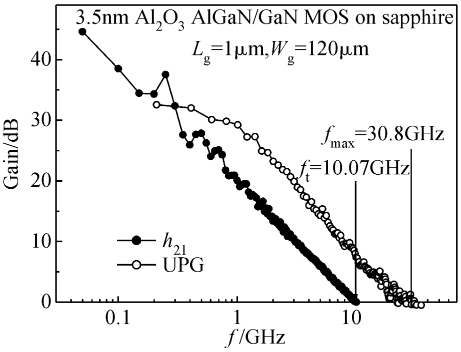

Fig. 7　Short-circuit current gain h_{21} and unilateral power gain *U* versus frequency of 1. 0μm × 120μm AlGaN/GaN MOS-HEMT on sapphire substrate　Device is biased at V_{ds} = + 7V and V_{gs} = − 3. 15V.

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$f_{\max}$为 30.8GHz 的超薄 Al_2O_3 绝缘栅 GaN MOS-HEMT 器件*

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摘要： 报道了一种利用原子层淀积（ALD）生长超薄（3.5nm）Al_2O_3 为栅介质的高性能 AlGaN/GaN 金属氧化物半导体高电子迁移率晶体管（MOS-HEMT）. 新型 AlGaN/GaN MOS-HEMT 器件栅长 1μm，栅宽 120μm，栅压为 +3.0V时最大饱和输出电流达到 720mA/mm，最大跨导达到 130mS/mm，开启电压保持在 −5.0V，特征频率和最高振荡频率分别为 10.1 和 30.8GHz.

关键词： AlGaN/GaN；MOS-HEMT；超薄 Al_2O_3

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