Influence of Substrate on the RF-related electric characteristics for W-Band AlGaN/GaN HEMTs

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Abstract

Using the same device processing GaN-based High Electron Mobility Transistors (HEMTs) with 90nm T-shaped gate are fabricated on the AlGaN/GaN heterostuctures epitaxially grown on sapphire and SiC substrate, respectively. The DC outputs/transfer and RF characteristics are measured and compared. It's found that the sheet carrier density and electron mobility of AlGaN/GaN heterostucture on SiC substrate are both much higher than the ones on sapphire substrate, indicating better crystal quality for the one on SiC substrate. Moreover, attributed to the better crystal quality and higher thermal conductivity of SiC, the maximum peak transconductance, current gain cut-off frequency (f_T) and maximum oscillation frequency (f_{max}) of AlGaN/GaN HEMT on SiC substrate are much larger than the ones of AlGaN/GaN HEMT on sapphire substrate, respectively.

1 Introduction

Next generation wireless communication systems will offer better telecommunication services with higher data rate and bandwidth. The microwave active device in the front-end high power amplifier (HPA) delivers large RF power levels at high frequency operating at elevated temperature [1]. Due to the characteristics of wide band-gap materials such as high breakdown field, high electron saturation velocity and high operating temperature, GaN-based High Electron Mobility Transistors (HEMTs) have shown enormous potential for realizing high-power and high-efficiency amplifiers for next generation wireless communication, satellite communication and radar systems [2]. Nowadays, improvements in GaN HEMTs technology have allowed the demonstration of high-power broadband solid state PA at W-band (75-110 GHz). These amplifiers will enable the next generation of high data rate W-band communication systems, phased array radars and active imagers [3]. HRL has reported a W-band GaN PA produces a peak output power of 2.1W with an associated PAE of 19% at 93.5 GHz [4]. QuinStar Technology has reported a high-power GaN PA covering 70 percent of W-band. Thus, investigation of the RF-related electric characteristics for the W-Band AlGaN/GaN HEMTs is of great importance for improving the performance of high-power broadband solid state PA [5].In this paper, AlGaN/GaN heterostuctures were epitaxially grown on sapphire and SiC substrate, respectively. Same device processing was employed on the two heterostuctures to achieve high-frequency HEMTs with 90nm T-shaped gate. And then the RF-related electric characteristics were measured and compared.

2 Device design

The AlGaN/GaN heterostuctures employed in this work were epitaxially grown by metal organic chemical vapor deposition (MOCVD) on sapphire and SiC substrate, respectively. The epitaxial structure on the sapphire substrate consisted of a 21 nm undoped AlGaN barrier layer, a 1 nm AlN layer and a 2 μm undoped GaN layer. Hall measurements indicate a sheet carrier density of around 9.5×10^{12} cm^{-2} and an electron mobility of 1980

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cm^2/V.s at room temperature. The epitaxial structure on the SiC substrate consisted of a 18 nm undoped AlGaN barrier layer, a 1 nm AlN layer, a 2 μm undoped GaN layer and a 200nm AlN nuclear layer. Hall measurements indicate a sheet carrier density of around 1.1×10^{12} cm^{-2} and an electron mobility of 2020 cm^2/V.s at room temperature. Although the barrier layer is thinner in the AlGaN/GaN heterostucture on SiC substrate, the sheet carrier density and electron mobility are much higher than the ones of AlGaN/GaN heterostucture on sapphire substrate, indicating better crystal quality for the AlGaN/GaN heterostucture on SiC substrate.

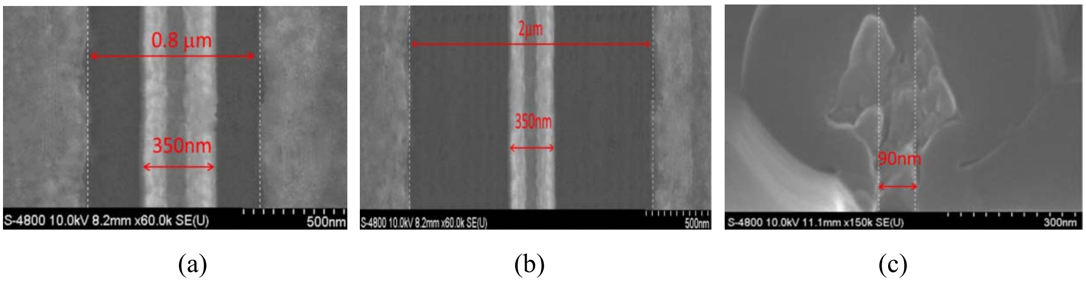


Figure 1: SEM image of AlGaN/GaN HEMTs on sapphire (a), SiC substrate (b) and the 90-nm T-shaped gate (c).

For device processing, device mesa isolation was performed using a Cl_2/BCl_3 plasma-based dry etch. The source and drain regions with a 0.8-μm and 2-μm separation [Fig. 2 (a) and (b)] were defined by Electron-beam photolithography for the AlGaN/GaN heterostuctures on sapphire and SiC substrate, respectively. Source and drain Ohmic contacted of Ti/Al/Ni/Au were formed by e-beam evaporation and lift-off. A rapid thermal annealing was taken to form good Ohmic contacts at 850 ℃ for 30s under nitrogen atmosphere. Using transmission line method (TLM) patterns, the Ohmic contact resistances were typically measured to be around 0.45 and 0.34 Ω·mm for the AlGaN/GaN heterostuctures on sapphire and SiC substrate, respectively. The smaller resistance for AlGaN/GaN heterostucture on SiC substrate might be due to the higher sheet carrier density and thinner AlGaN barrier layer. Electron-beam lithography was employed to define a 90nm T-shaped gate in the center of the source-to-drain space using a tri-layer photoresist. A Ni/Au metal stack was deposited for the Schottky contact. The 90-nm physical gate length was confirmed by scanning electron microscope (SEM), as shown in Fig. 2 (c). DC characteristics were measured using a Keithley 4200-SCS/F semiconductor characterization system. Small-signal RF performances were characterized with an Agilent vector network analyzer, which swept from 0.1 to 40 GHz in 0.05 GHz steps.

3 Results and Discussion

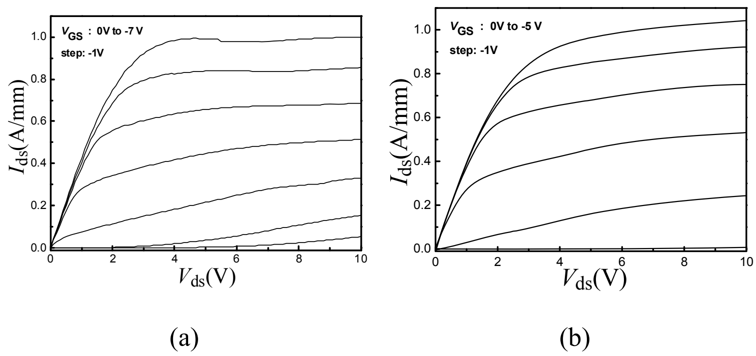
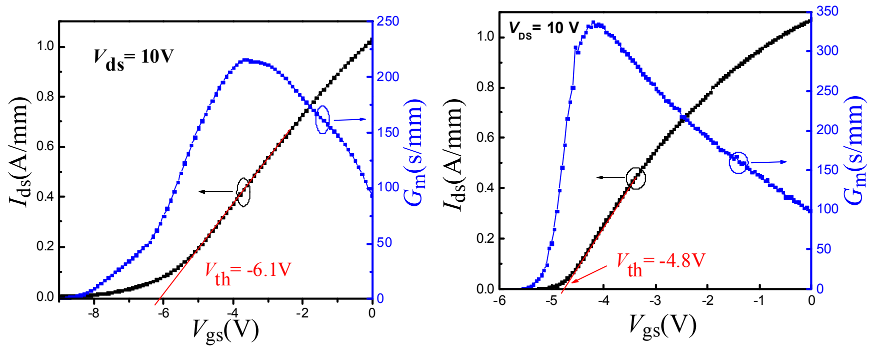


Figure 2: DC Output characteristics of the AlGaN/GaN HEMTs on sapphire (a) and SiC substrate (b).

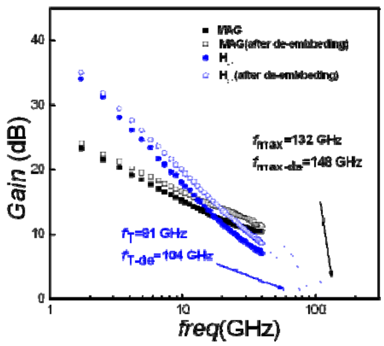
Figure 2 (a) and (b) show DC outputs of the fabricated AlGaN/GaN HEMTs on sapphire and SiC substrate, respectively. As seen from Fig. 2, although the drain-to-source distance (2μm) of AlGaN/GaN HEMT on SiC substrate is much larger than the one (0.8μm) of AlGaN/GaN HEMT on sapphire substrate, the maximum drain current densities at V_{gs} = 0 V of the two ones are almost the same (~1A/mm). Moreover, the suppression of short-channel effect for AlGaN/GaN HEMT on SiC substrate is much obvious than the one on sapphire substrate. Thin AlGaN barrier layer can weaken the short-channel effect [6]. Moreover, the crystal quality of AlGaN/GaN heterostucture on SiC substrate is better than the one on sapphire substrate, resulting in larger sheet carrier density and higher electron mobility and further inducing lower Ohmic contact resistance and larger maximum drain current density. In addition, the thermal conductivity of SiC is higher than the one of sapphire, which further improves the DC current characteristics [7]. Besides, better crystal quality can decrease the surface defects and improve gate control. As a result, the short-channel effect is suppressed much better for AlGaN/GaN HEMT on SiC substrate compared to the one on sapphire substrate.



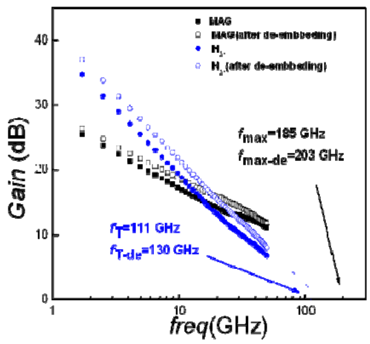
(a) (b)

Figure 3: Transfer characteristics of the AlGaN/GaN HEMTs on sapphire(a) and SiC substrate(b).

Figure 3 (a) and (b) show the transfer characteristics of the AlGaN/GaN HEMTs on sapphire and SiC substrate, respectively. As shown in Fig.3, the threshold voltage (V_{th}) can be extracted from the transfer characteristics. The obtained values of V_{th} are – 6.1V and -4.8V for AlGaN/GaN HEMTs on sapphire and SiC substrate, respectively. The maximum peak extrinsic transconductance G_m (225 mS/mm) for AlGaN/GaN HEMTs on sapphire substrate is much smaller than the one (335 mS/mm) of AlGaN/GaN HEMT on SiC substrate. This is mainly due to the larger absolute value of V_{th} and obvious short-channel effect for AlGaN/GaN HEMTs on sapphire substrate.



Model parameters	Shappire
g_m(ms/mm)	256
C_{gs}(fF/mm)	281
C_{gd}(fF/mm)	67
C_{ds}(fF/mm)	132.8
R_i(Ω)	9.5
g_d(ms/mm)	46
R_g(Ω)	3.6
R_d(Ω)	11.1
R_s(Ω)	5.1



Model parameters	SIC
g_m(ms/mm)	385
C_{gs}(fF/mm)	375
C_{gd}(fF/mm)	44.7
C_{ds}(fF/mm)	196
R_i(Ω)	6.3
g_d(ms/mm)	36.5
R_g(Ω)	9.8
R_d(Ω)	14.3
R_s(Ω)	11

(a) (b)

Figure 4: RF characteristic of the AlGaN/GaN HEMTs on sapphire (a) and SiC substrate (b).

Figure 4 (a) and (b) show the RF characteristic of the AlGaN/GaN HEMTs on sapphire and SiC substrate, respectively. The current gain ∣ h_{21} ∣ and the maximum available/stable gain (MAG/MSG) derived from measured S-parameters are plotted against frequency. As seen from Fig. 4, the current gain cut-off frequency (f_T) (130GHz) for AlGaN/GaN HEMTs on SiC substrate is much larger than the one (104GHz) of AlGaN/GaN HEMT on sapphire substrate. Meanwhile the maximum oscillation frequency (f_{max}) (203GHz) for AlGaN/GaN HEMTs on SiC substrate is much larger than the one (148GHz) of AlGaN/GaN HEMT on sapphire substrate. This is mainly due to the larger RF g_m for AlGaN/GaN HEMTs on SiC substrate due to the smaller Ohmic cantact resistance and suppressed short-channel effect.

4 Conclusion

In summary, AlGaN/GaN heterostuctures were epitaxially grown on sapphire and SiC substrate, respectively. And then same device processing was employed on the two heterostuctures to achieve high-frequency HEMTs with 90nm T-shaped gate. The DC outputs/transfer and RF characteristics are measured and compared. It's found that the crystal quality of AlGaN/GaN heterostucture on SiC substrate is much better than the one on sapphire substrate, inducing larger sheet carrier density and higher electron mobility. Moreover, It's found that the Ohmic contact resistance, the maximum peak extrinsic transconductance, current gain cut-off frequency (f_T) and maximum oscillation frequency (f_{max}) for for AlGaN/GaN HEMT on SiC substrate are much larger than the ones of AlGaN/GaN HEMT on sapphire substrate, respectively. This is mainly due to the better crystal quality and higher thermal conductivity of SiC.

5 References

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