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AlGaN/GaN HEMT with 200 GHz fmax on sapphire substrate with InGaN back-barrier

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Abstract: A gate-recessed AlGaN/GaN high electron mobility transistor (HEMT) on sapphire substrate having f_{max} of 200 GHz is reported. The gate-recessed device with a T-shaped gate exhibits a maximum drain current density of 1.1 A/mm, and a peak value of 421 mS/mm for extrinsic transconductance with minimum short-channel effects because of an InGaN back-barrier layer. A unity current gain cut off frequency (f_T) of 30 GHz and a maximum oscillation frequency (f_{max}) of 105 GHz were obtained. After removing SiN by wet etching, the f_T of the device increase from 30 GHZ to 50 GHz and the fmax increases from 105 GHz to 200 GHz, which are the results of lower C_{gs} and C_{gd} after removing of Si_3N_4.

Key words: AlGaN/GaN; HEMT; sapphire substrate; f_{max}; InGaN back-barrier; wet etching
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最大振荡频率为200 GHz的蓝宝石衬底AlGaN/GaN HEMT

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摘要:报道了最大振荡频率为200 GHz的基于蓝宝石衬底的AlGaN/GaN高电子迁移率晶体管(HEMT).外延材料结构采用InGaN背势垒层来减小短沟道效应,器件采用凹栅槽和T型栅结合的工艺,实现了Ka波段AlGaN/GaN HEMT.器件饱和电流达到1.1 A/mm,跨导为421 mS/mm,截止频率(f_T)为30 GHz,最大振荡频率(f_{max})为105 GHz.采用湿法腐蚀工艺将器件的Si_3N_4钝化层去除后,器件的C_{gs}和C_{gd}减小,器件截止频率提高到50 GHz,最大振荡频率提高到200 GHz.

关 键 词:AlGaN/GaN;HEMT;蓝宝石衬底;f_{max};InGaN背势垒;湿法腐蚀
中图分类号:TN325+.3 **文献标识码**:A

Introduction

Great development of AlGaN/GaN high-electron mobility transistors (HEMTs) has been achieved in recent years. AlGaN/GaN HEMTs have demonstrated high current levels, high breakdown voltages, and high frequency power performance due to the unique properties of the material. At Ka-band and higher frequency, excellent performances were reported, such as output power densities in excess of 10 W/mm at 40 GHz and more than 2 W/mm at 80.5 GHz on SiC substrates[1-3].

However, for a Ka-band power device there are still some problems to be solved such as short-channel effects [4-6], higher fmax and so on. The short-channel effects deteriorate the pinch-off characteristic; the threshold voltage will reduce with the increase of the drain voltage. The short-channel effects also limit the high-frequency characteristics, which increasing moni-dealities in cut off frequency and maximum oscillation

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frequency of the devices. Some effective methods were reported to restrain short-channel effects, for example, introducing an extrinsic impurity such as Fe and inserting an InGaN back-barrier on the GaN buffer layer[7-8].

Another problem is how to increase the maximum oscillation frequency (f_{max}) which describing the devices' power ability. Some effective methods were reported: using gate-recess technology, optimizing the structure of the device and so on [9].

In this article, we report a gate-recessed AlGaN/GaN HEMT on sapphire substrate having f_{max} of 200 GHz.

1 Experimental

The AlGaN/GaN transistor structure was grown on a sapphire substrate by MOCVD. The heterostructure is consisted of a 1.5 μm-thick GaN buffer layer, a 80Å $In_{0.05}Ga_{0.95}N$ back-barrier layer, a 80Å GaN layer, a 1nm AlN layer, a 14 nm undoped AlGaN layer in which the Al composition is 30%, and an undoped 15Å-thick GaN cap layer, as shown in Fig. 1. The 2DEG mobility and sheet carrier concentration were 1296 $cm^2/V \cdot s$ and 1.37×10^{13} cm^{-2}, respectively.

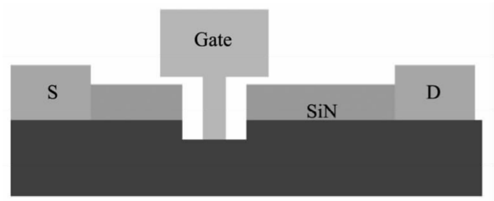

Fig. 2 Schematic of AlGaN/GaN HEMTs devices
图 2 AlGaN/GaN HEMT 器件示意图

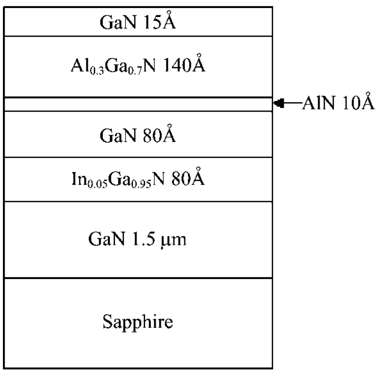

Fig. 1 Structure of epi-layers
图 1 外延层结构

Source and drain ohmic electrodes were formed by evaporating Ti/Al/Ni/Au, which was then alloyed using rapid thermal annealing at 850℃ for 30 seconds. The contact resistivity evaluated by transmission-line matrix measurements was 10^{-6} $\Omega \cdot cm^2$. Device isolation was accomplished by ion implantation. A 120 nm-thick Si_3N_4 was then deposited using plasma-enhanced CVD. After a gate footprint was opened through the SiN film using SF_6 plasma dry etching, gate recess etching was performed using Cl_2 and BCl_3 plasma dry etching by ICP. Electron-beam lithography was applied to define a T-shaped gate using PMMA/Al/UVIII. Ni/Au was used as a gate metal, and then the device was provided with a Ti/Au metallization, as shown in Fig. 2.

Finally, the Si_3N_4 film was wet etched by HF (49%): NH_4F(40%): H_2O = 1: 1: 1, then the 215 nm physical gate length was confirmed by scanning electron microscope (SEM), as shown in Fig. 3.

2 Results and discussion

A 75 μm AlGaN/GaN HEMT device was selected, with 2.4 μm source and drain separation. The dc characteristics, the small signal RF characteristics were tested.

Fig. 4 shows the DC characteristics of the fabricated 215 nm gate-recessed AlGaN/GaN HEMT. The maximum drain current at U_{gs} = 3 V was 1.1 A/mm, and the peak transconductance at U_{ds} = 6 V was 421 mS/mm. The breakdown voltage was over 100 V at U_g = −2 V.

To study the short-channel effects of the AlGaN/GaN HEMT device, the transconductances of the tran-

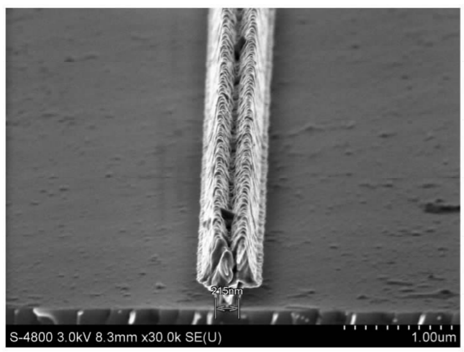

Fig. 3 SEM image of the 215 nm T-shaped gate
图 3 215 nm T 型栅的 SEM 照片

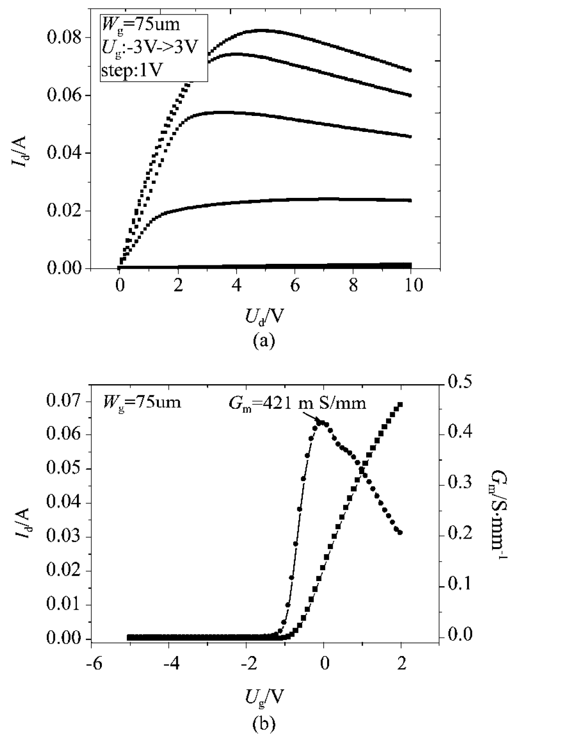

Fig. 4　Characteristics of AlGaN/GaN HEMT (a) DC characteristics (b) transfer characteristics at U_{ds} = 6 V
图 4　AlGaN/GaN HEMT 的特性 (a) 直流特性 (b) U_{ds} = 6 V 时的转移特性

sistor at different drain voltages were measured. It can be seen in Fig. 5, the pinch-off characteristic of the device was excellent. The threshold voltage changed from −1.5 V to −2.4 V when drain voltages changing from 10 V to 50 V. And the drain-induced barrier lowering (DIBL) is 30 mV/V.

It is because of a better confinement of the electrons in the 2DEG channel with an InGaN back-barrier layer. Although the InGaN layer has a narrower bandgap compared with the GaN layer, the strain-induced piezoelectric polarization in the InGaN layer raises the potential in the InGaN layer, effectively creating a high potential barrier. This additional barrier at the backside of the channel leads to better carrier confinement and better buffer isolation, which in turn, enables improved device performance, such as better pinch-off characteristic and higher fmax.

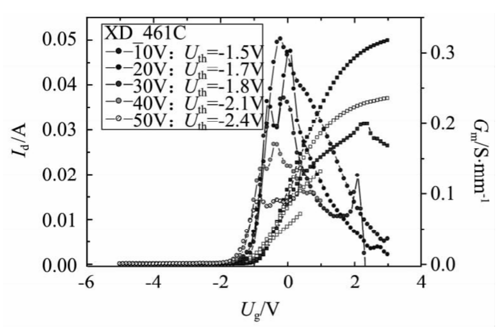

Fig. 5　Change in transfer characteristics with U_{ds}
图 5　转移特性随 U_{ds} 的变化

The small signal RF measurements of AlGaN/GaN HEMT were applied. Fig. 6 shows the plots of the current gain $|H_{21}|$, the maximum stable power gain (MSG) and maximum available gain (MAG) versus frequency for the device. It can be seen that the f_T is 30 GHz, the f_{max} is 105 GHz.

The Si_3N_4 film of the device was wet etched by HF (49%) : NH_4F (40%) : H_2O = 1 : 1 : 1. Fig. 7 shows the DC characteristics of AlGaN/GaN HEMTs devices before and after wet etching of Si_3N_4 film.

It can be seen that after wet etching of Si_3N_4 film, drain saturation currents at U_{gs} = 3 V was reduced by 20%. The peak transconductance at U_{ds} = 6 V was reduced by 5%.

Fig. 8 shows the plots of the small signal characteristics of AlGaN/GaN HEMT before and after wet etching of Si_3N_4 film. It can be seen that after wet etching of SiN film, the f_T increases to 50 GHz and the f_{max} increases to 200 GHz.

The small-signal equivalent circuit parameters of the device before and after wet etching of Si_3N_4 film were extracted. Table 1 shows the small-signal equivalent circuit parameters, C_{gs} and C_{gd}.

表 1　SiN 腐蚀前后器件的 C_{gs} 和 C_{gd}
Table 1　C_{gs} and C_{gd} of the device before and after wet etching of SiN

	C_{gs} (pF)	C_{gd} (pF)
Before wet etching	0.111	0.02
After wet etching	0.083	0.013

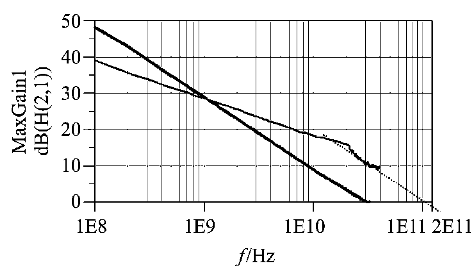

Fig. 6　Small signal characteristics of AlGaN/GaN HEMT
图 6　AlGaN/GaN HEMT 的小信号特性

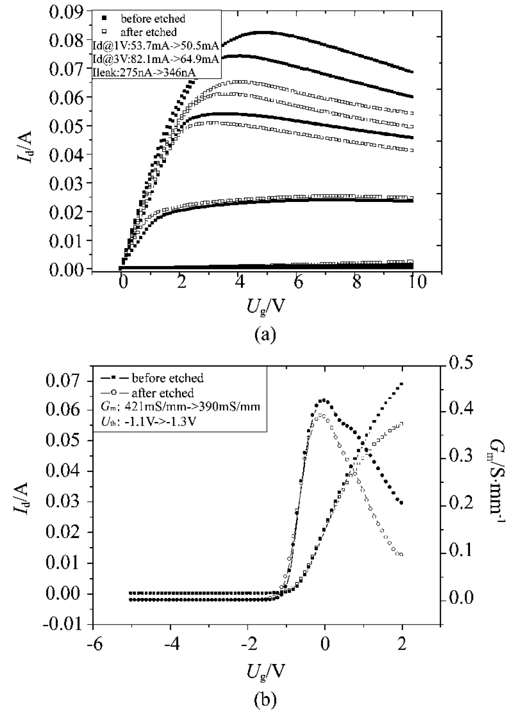

Fig. 7 Characterigtics of AlGaN/GaN HEMT before and after wet etching of SiN (a) DC characteristics (b) transfer characteristics at $U_{ds}=6$ V

图7 SiN腐蚀前后, AlGaN/GaN HEMT的特性 (a)直流特性 (b) $U_{ds}=6$ V时的转移特性

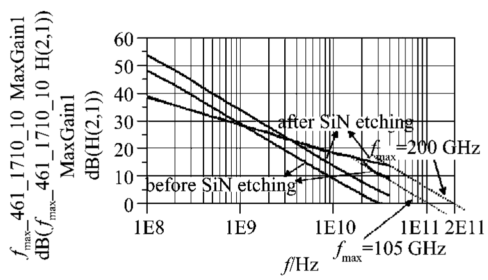

Fig. 8 Small signal characteristics of AlGaN/GaN HEMT before and after wet etching of SiN

图8 SiN腐蚀前后, AlGaN/GaN HEMT的小信号特性

With the removing of Si_3N_4 film, the capacitances between passivation layer and gate metal are decreased. Thus, C_{gs} and C_{gd} are decreased. Then the f_T and f_{max} will increase based on Eq. 1 and 2.

$$f_T=\frac{g_m}{2\pi\left[(C_{gs}+C_{gd})\left(1+\frac{R_s+R_d}{R_{ds}}\right)+g_mC_{gd}(R_s+R_d)\right]}, \quad (1)$$

$$f_{max}=\frac{f_t}{\sqrt{2\varpi tC_{gd}(R_s+2R_g+R_i+\omega_tL_S)+\frac{4}{R_{ds}}(R_s+R_g+R_i+\frac{\omega_tL_S}{2})}}, \quad (2)$$

It can be seen that except C_{gs} and C_{gd}, the other parameters such as R_s, R_d, R_i, R_g, R_{ds}, L_s, etc. also effect f_T and f_{max}. More works should be done to optimize the structure of AlGaN/GaN HEMTs devices.

3 Conclusion

In this article, we report a gate-recessed AlGaN/GaN HEMT on sapphire substrate having a f_{max} of 200 GHz. The gate-recessed device with a T-shaped gate exhibits a maximum drain current density as high as 1.1 A/mm, and a peak extrinsic transconductance of 421 mS/mm with minimum short-effects. A unity current gain cutoff frequency (f_T) of 30 GHz and a maximum oscillation frequency (f_{max}) of 105 GHz were obtained. After the Si_3N_4 film wet etched, the f_T of the device increases to 50 GHz and the f_{max} increases to 200 GHz. The reason is that with the removing of Si_3N_4 film, C_{gs} and C_{gd} are decreased.

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