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Ultrahigh-Speed Lattice-Matched $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ HEMTs with 218GHz Cutoff Frequency*

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Abstract: Lattice-matched $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ high electron mobility transistors (HEMTs) with a cutoff frequency (f_T) as high as 218GHz are reported. This f_T is the highest value ever reported for HEMTs in China. These devices also demonstrate excellent DC characteristics: the extrinsic transconductance is 980mS/mm and the maximum current density is 870mA/mm. The material structure and all the device fabrication technology in this work were developed by our group.

Key words: cutoff frequency; high electron mobility transistor; InGaAs/InAlAs; InP
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1 Introduction

High performance devices that operate in the millimeter-wave (30～300GHz) and sub-millimeter-wave (300GHz～3THz) frequency ranges will be major elements in future communication systems. InP-based InGaAs/InAlAs high electron mobility transistors (HEMTs) are one of the most promising candidates because of their superior high frequency and low noise performances[1,2]. These high performances are attributed to high electron mobility, high saturation velocity, and high sheet carrier density obtained in this material system[3,4].

In our previous work, we fabricated lattice-matched $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ HEMTs with a 120GHz cutoff frequency (f_T)[5]. In this work, after simulation and optimization on material structure and device fabrication technology, we develop lattice-matched $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ HEMTs with an f_T of 218GHz. This f_T is the highest value ever reported for HEMTs in China.

2 Material structure

The lattice-matched HEMT epitaxial layers used in this work were grown on a semi-insulating (100) InP substrate by molecular beam epitaxy (MBE). Before the growth of epitaxial layers, behaviors of the device with different material structures were simulated using the hydrodynamic model (HD) and the density gradient model (DG)[6,7].

The layer's structure, shown in Table 1 from the bottom up, consist of a 300nm-thick $In_{0.52}Al_{0.48}As$ buffer, a 15nm-thick $In_{0.53}Ga_{0.47}As$ channel, a 3nm-thick $In_{0.52}Al_{0.48}As$ spacer, a Si-δ-doped sheet ($5\times10^{12}cm^{-2}$), a 8nm-thick $In_{0.52}Al_{0.48}As$ barrier, a 4nm-thick InP etch-stopper layer, and a 30nm-thick Si-doped $In_{0.53}Ga_{0.47}As$ cap ($1\times10^{19}cm^{-3}$) layer. All the layers are lattice-matched to the InP substrate. Hall measurements on this structure show a two-dimensional electron gas

Table 1 Lattice-matched HEMT epitaxial layer structure

Layer		Thickness /nm	Dopant	Concentration
$In_{0.53}Ga_{0.47}As$	Cap	30	Si	$1\times10^{19}cm^{-3}$
InP	Etch-stopper	4		
$In_{0.52}Al_{0.48}As$	Barrier	8		
Si-δ-doped layer			Si	$5\times10^{12}cm^{-2}$
$In_{0.52}Al_{0.48}As$	Spacer	3		
$In_{0.53}Ga_{0.47}As$	Channel	15		
$In_{0.52}Al_{0.48}As$	Buffer	300		
SI InP substrate (100)				

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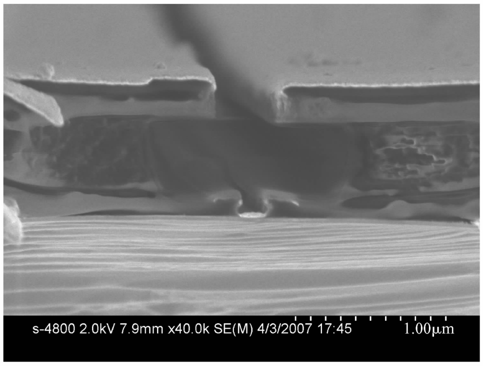

Fig. 1 SEM photo of T-shaped pattern after development

(2DEG) sheet density of $3.32\times10^{12}\,cm^{-2}$ and a mobility of $9300cm^2/(V\cdot s)$ at room temperature. The epitaxial layers were designed by us and grown by MBE technology in Singapore.

3 Fabrication process

First, source and drain ohmic contacts were formed using alloyed Ni/Ge/Au/Ge/Ni/Au. A long timeframe, low temperature alloy method, which was studied in our previous work, was used to prevent degradation of the eptaxial structure and achieve low contact resistance[8]. The spacing between source and drain electrode pads was 2μm. The contact resistance, measured by the transmission line model (TLM) method, was typically 0.1Ω · mm. Then the mesa isolation was formed by wet chemical etching using $H_3PO_4/H_2O_2/H_2O$ solution and Ti/Au connecting wire metal was evaporated by an electronic beam evaporation system.

The gate formation process was similar to that used in our previous works[5]. A trilayer EB resist (PMMA/PMGI/PMMA) was first spun onto the substrate. A single alignment, EB exposure and a series of development steps was then carried out to form a recess above the InGaAs cap layer. The SEM photo of T-shaped pattern after development is shown in Fig. 1. The gate-recess etching was performed by wet chemical etching using an aqueous mixture of citric acid ($C_6H_8O_7$) and hydrogen peroxide (H_2O_2), whose etching selectivity of InGaAs over InP is about 160[9]. Finally, a Ti/Pt/Au gate metal was evaporated and lifted off. Figure 2 is the photograph of the device we obtained, with a gate length of 0.15μm and a gate width of 2×50μm.

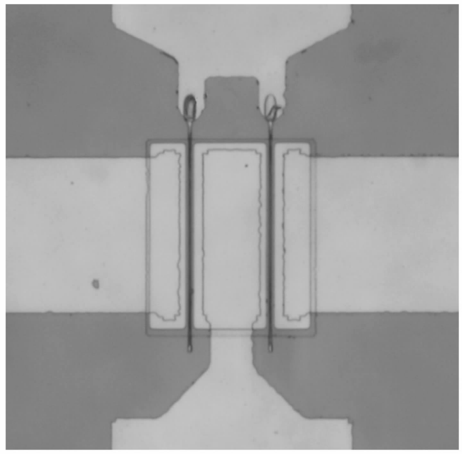

Fig. 2 Partial photograph of an InP HEMT

4 Device performance

Figure 3 shows the typical current-voltage (*I*-*V*) characteristics of the HEMTs. The gate-source voltage (V_{gs}) is increased from −2.0 to 0V in 0.4V steps, and the device is well pinched off. The maximum current density at $V_{gs}=0V$ is 870mA/mm. Figure 4 shows the transfer characteristics and transconductance characteristics of the HEMTs. The threshold voltage is −1.65V, and a maximum transconductance (g_m) of 980mS/mm is achieved. Off-state gate-drain breakdown voltage defined at a gate-drain current of 1.0mA/mm is −1.7V. The on-state drain to source breakdown voltage, i.e. $V_{gs}=0V$, is 1.8 V.

S-parameter measurements were carried out in the frequency range from 0.1 to 20.1GHz using a vector network analyzer (HP8510C) in on-wafer configuration and the measurement results are shown in Fig. 5. *S*-parameters for open

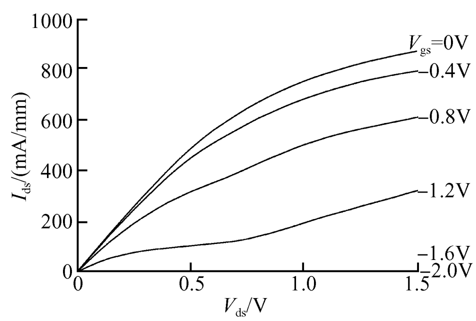

Fig. 3 Current-voltage (*I*-*V*) characteristics of the InP HEMT

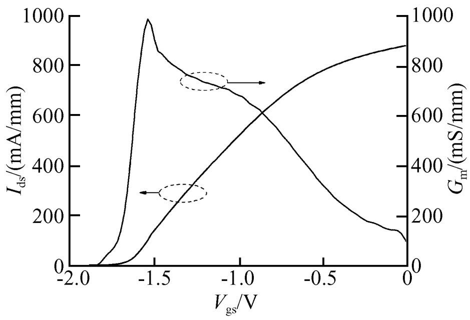

Fig.4 Transfer and transconductance characteristics of the InP HEMT when $V_{ds}=1.5V$

pad on the same wafer were also measured to calibrate the parasitic capacitance components related to the pad metals. Figure 6 shows the frequency dependence of current gain ($|h_{21}|^2$) and maximum available power gain/stable power gain (MAG/MSG) of the HEMTs with a drain-source voltage (V_{ds}) of 1.5V and a gate-source voltage (V_{gs}) of $-1.2V$. We obtained an f_T of 218GHz and an f_{max} of 171GHz by extrapolating $|h_{21}|^2$ and MAG/MSG with a -20dB/decade slope.

5 Summary

We have successfully developed lattice-matched $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ HEMTs with 218GHz f_T, which is the highest value for HEMTs in China. The device also exhibited excellent DC characteristics: the extrinsic transconductance is

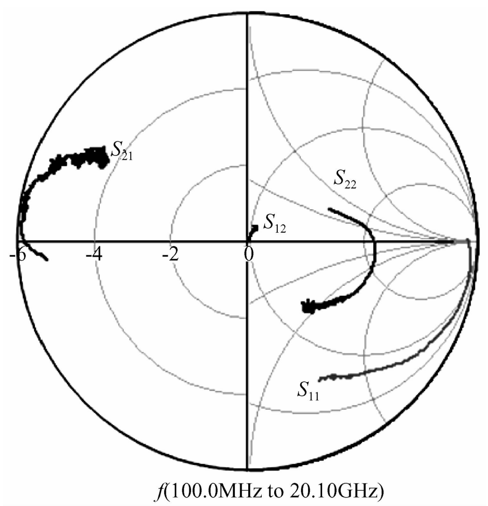

Fig.5 S-parameter of the InP HEMT bias at $V_{ds}=1.5V$, $V_{gs}=-1.2V$ in a frequency range from 0.1 to 20.1GHz

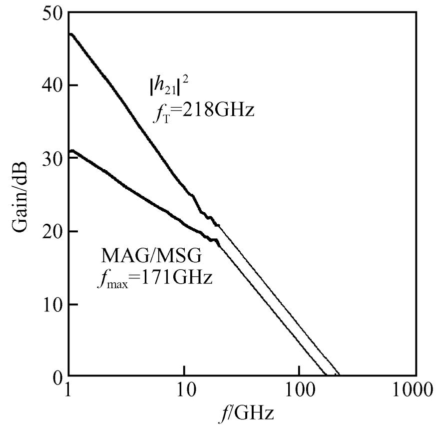

Fig. 6 Frequency dependency of current gain ($|h_{21}|^2$) and maximum available power gain/stable power gain (MAG/MSG) of the InP HEMT biased at $V_{ds}=1.5V$ and $V_{gs}=-1.2V$

980mS/mm and the maximum current density is 870mA/mm. The material structure and all the device fabrication technology in this work were developed by our group.

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截止频率为 218GHz 的超高速晶格匹配 $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ 高电子迁移率晶体管*

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摘要：报道了截止频率为 218GHz 的晶格匹配的 $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ 高电子迁移率晶体管.这是迄今为止国内报道的截止频率最高的高电子迁移率晶体管.器件直流特性也很优异：跨导为 980mS/mm，最大电流密度为 870mA/mm.文中的材料结构和所有器件制备工艺均为本研究小组自主研制开发.

关键词：截止频率；高电子迁移率晶体管；InGaAs/InAlAs；InP

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