III-V Semiconductor Devices on 6-inch wafer for sub-Terahertz Communications

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Keywords: pHEMT, mHEMT, InP HBT, Sub-Terahertz, 6-inch, Foundry service

Abstract

Lg=0.1um pHEMT, Lg=0.1um mHEMT and InP HBT technologies have been developed on 6-inch wafer with proven reliability for mass production. Among those technologies, Lg=0.1um pHEMT provides the highest power density of 724.4mW/mm with fmax of 247.2GHz; Lg=0.1um mHEMT demonstrates superior fmax of 321.0GHz with power density of 247.8mW/mm; InP HBT shows the highest fmax of 352.5GHz with power density of 2.59mW/um^2. Foundry service of those cost-effective technologies is ready for sub-terahertz communication applications and designers can choose the appropriate one according to the requested operation frequency and power to realize their MMICs.

INTRODUCTION

With the soaring demand of mobile data, carrier frequencies used for wireless communications keep increasing. Recently, sub-terahertz (90~300GHz) attract more attention for 5G and beyond 5G applications due to its wider bandwidth, especially for D-band (110~170GHz). To fulfill the requirement of monolithic microwave integrated circuits (MMICs) under such high frequency, cost-effective and reliable device technology with sufficient device performance is the key element to make it commercialization.

III-V semiconductor devices such as GaAs pseudomorphic high electron mobility transistors (pHEMTs), InGaP hetero-junction bipolar transistors (HBTs), have been widely used in MMICs for power amplifiers, low noise amplifiers, and switches in the past decades. However, the existing technologies can't fulfill the requirement of power gain for the amplifier under sub-terahertz frequency. To achieve higher maximum oscillation frequency (fmax), changing the material system for higher electron mobility is the way to go and GaAs metamorphic high electron mobility transistor (mHEMT), InP HEMT and InP HBT are the possible candidates. The technologies have been reported for D-band MMICs include gate length (Lg)=0.1um pHEMT, Lg=70nm GaAs mHEMT [1] and InP HBT [2]. Unfortunately, most of them are designed on the technologies with smaller wafer size and the lack of cost-effective open foundry service for the above technologies could be the barrier limiting the product development.

In this work, Lg=0.1um pHEMT, Lg=0.1um mHEMT and InP HBT technologies developed on 6-inch wafer production line with performance benchmark are reported. Reliability is also proven based on high temperature operating life (HTOL) verification.

EPI DESIGN AND DEVICE FABRICATION

The pHEMT epi wafers are grown on GaAs substrate by metal-organic chemical vapor deposition (MOCVD). It features a high Indium percentage InGaAs channel to increase channel mobility for better carrier transport. Above the channel, the epi layer consists of, from bottom to top, AlGaAs spacer, n-type doped AlGaAs carrier supply layer, AlGaAs Schottky barrier and heavily doped GaAs cap layer. Layer thickness and doping concentration are optimized for target device pinch-off voltage and minimum metal–semiconductor contact resistance.

pHEMT device fabrication began with Ohmic contact for source and drain formation. Ion implant is applied for device isolation. To pursue higher fmax, electron-beam lithography was applied to define a Lg=0.1um T-shaped gate with sufficient stem and gate overhang height. The SEM cross section image is shown in Figure 1. SiNx passivation and 2um air-bridge interconnect metal were also formed afterwards.

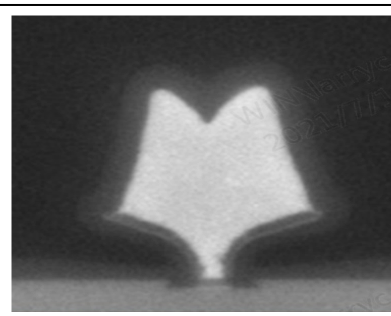

Fig. 1. SEM image of the fabricated Lg=0.1um T-gate

To optimize the device for high frequency gain, InGaAs channel with even higher indium content need to be introduced. In comparison with InP HEMT, mHEMT has much lower substrate cost and comparable device performance. The epi wafers of mHEMT are grown on GaAs substrate by Molecular Beam Epitaxy (MBE) with the metamorphic buffer layer. This layer is used to tailor the lattice constant from GaAs to InP and trap the dislocations. Above the buffer layer, the epi layer consists of, from bottom to top, the InAlAs barrier layer, InGaAs channel layer, InAlAs Schottky barrier and heavily doped InGaAs cap layer. mHEMT device fabrication took place broadly along the line of pHEMT, except for isolation process done by wet etching.

The breakdown voltage of mHEMT is limited by the small band gap of high indium content channel, but one for InP HBT can be optimized by design of epi structure. Therefore, InP HBT can be taken usage under higher operation voltage and similar fmax. The tradeoff between fmax and the collector-emitter breakdown (BVceo) can be tuned by collector thickness. The epitaxial layer structure and process flow used in this letter is the same as in [3].

DEVICE PERFORMANCE

Typical output characteristics of Lg=0.1um pHEMT and mHEMT with Wg= 2 × 50 µm are shown in Fig. 2. pHEMT shows ability to withstand high drain voltage of 6V while keeping gate leakage <0.1mA/mm under Vg= -1V. Although mHEMT has narrower bias range of drain voltage, it demonstrates superior on-state resistance of 0.65ohm-mm and higher maximum drain current of 831.5mA/mm. Fig. 3 shows a sub-threshold characteristics of Lg=0.1um pHEMT and Lg=0.1um mHEMT, together with gate leakage and transconductance (gm), at VDS =1.5 V. Threshold voltage (Vt) of mHEMT, defined as gate voltage yielding drain current is 1mA/mm, is -1V which is more negative than the pHEMT Vt of -0.75V. However, mHEMT still shows superior maximum transconductance of 876mS/mm than pHEMT. For both devices, the minimum subthreshold current is dominated by Schottky gate leakage current, and the epi structure is optimized to balance the gate leakage and transconductance.

Gummel plot characteristics of 0.8x3µm^2 InP HBTs is shown in Fig. 4. The value of DC current gain, β, is 33.2 at J_C= 300kA/cm^2, VCE=2V based on the optimized base layer epi structure. The beta value is lower than the commercial InGaP HBT, and the motivation is to achieve better RF performance.

Within wafer uniformity is always the concern of the designers for mass production. Fig. 5 exhibits the 6-inch wafer map of threshold voltage value for pHEMT/mHEMT. This results achieve an industry-milestone with highly uniform threshold voltage variation of 17mV (1σ) and 16mV (1σ) on 6-inch GaAs wafer for pHEMT and mHEMT, respectively. The decent uniformity of InP is also

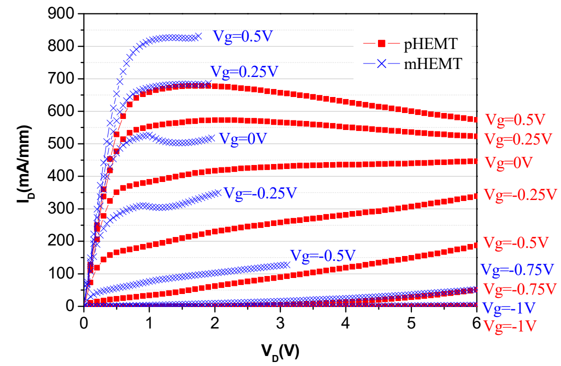

Fig. 2. Output characteristics of Lg=0.1um pHEMT and Lg=0.1um mHEMT with Wg= 2 × 50 µm

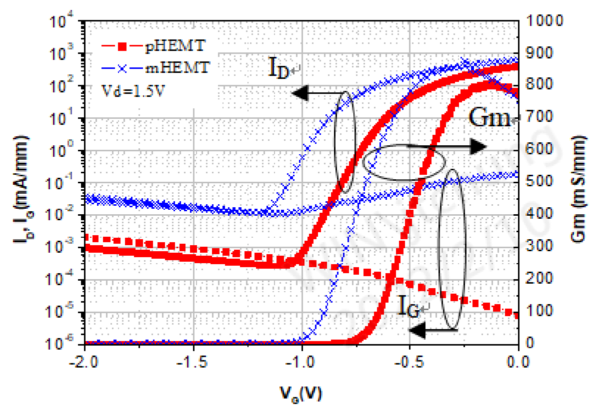

Fig. 3. Sub-threshold characteristics, gate leakage and trans-conductance of Lg=0.1um pHEMT and Lg=0.1um mHEMT

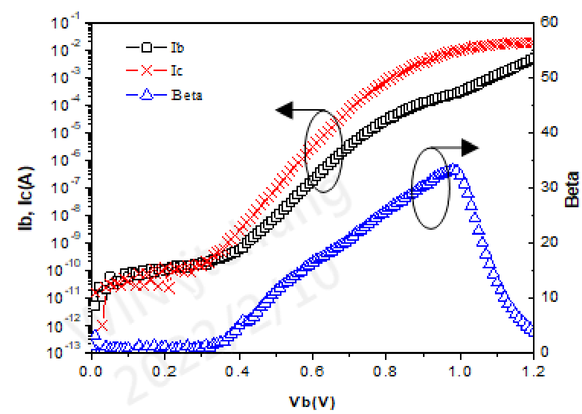

Fig. 4. Gummel plot characteristics of 0.8x3µm^2 InP HBT

(a)		-0.77	-0.77		
	-0.79	-0.80	-0.81	-0.80	
-0.78	-0.79	-0.82	-0.80	-0.79	-0.77
-0.79	-0.79	-0.81	-0.81	-0.80	-0.77
	-0.76	-0.77	-0.78	-0.78	
		-0.75	-0.76	-0.76	

(b)		-0.94	-0.95		
	-0.94	-0.94	-0.95	-0.95	
-0.94	-0.99	-0.95	-0.97	-0.96	-0.95
-0.96	-0.96	-0.95	-0.95	-0.95	-0.95
	-0.95	-0.95	-0.93	-0.95	
		-0.91	-0.92	-0.92	

(c)		0.96	1.04		
	1.00	0.97	1.04	1.04	
1.05	0.91	0.84	1.08	1.08	1.07
1.08	0.98	1.00	0.90	0.90	0.90
	1.12	1.09	1.04	1.02	
		1.09	1.09	1.10	

Fig. 5. Within wafer Uniformity of (a)Lg=0.1um pHEMT Vt, (b)Lg=0.1um mHEMT Vt and (c) normalized beta of InP HBT

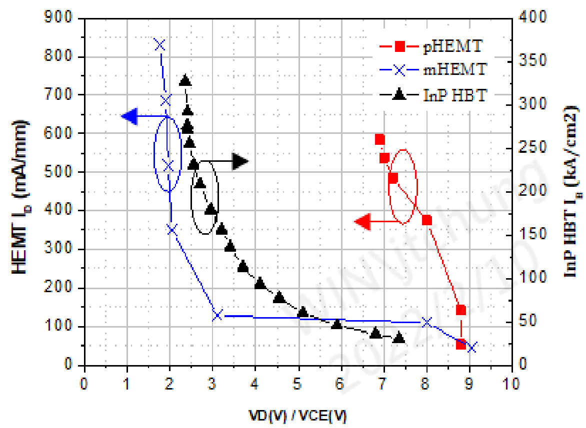

Fig. 6. ID-VDS/IC-VCE Maximum rating of Lg=0.1um pHEMT, Lg=0.1um mHEMT and InP HBT

demonstrated with current gain variation of 8% (1 σ) over 6-inch wafer.

The appropriate bias condition and the load-line swing region are critical for device power delivery. The output characteristics maximum rating of Lg=0.1um pHEMT, Lg=0.1um mHEMT and InP HBT are depicted in Fig. 6. Each point is measured by different device by sweeping VDS/VCE to burn-out under the same Vg/IB. pHEMT shows the widest load-line swing region and InP HBT has potential to be biased under higher voltage than mHEMT.

Fig. 7 shows the saturation power (Psat) of Lg=0.1um pHEMT, Lg=0.1um mHEMT and InP HBT unit cell under different operation voltage measured by load-pull system. Considering the transmission line loss of power cell, shrinking the device layout footprint is helpful to introduce more unit cells. It indicates that InP HBT power cell has potential to achieve superior power handling capability in

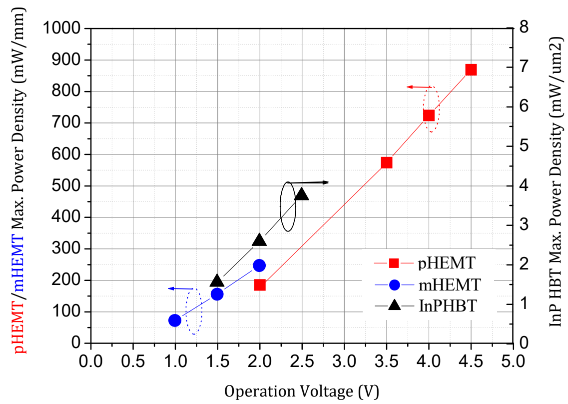

Fig. 7. Power handling capability of Lg=0.1um pHEMT, Lg=0.1um mHEMT and InP HBT unit cell under different operation voltage measured by load-pull system

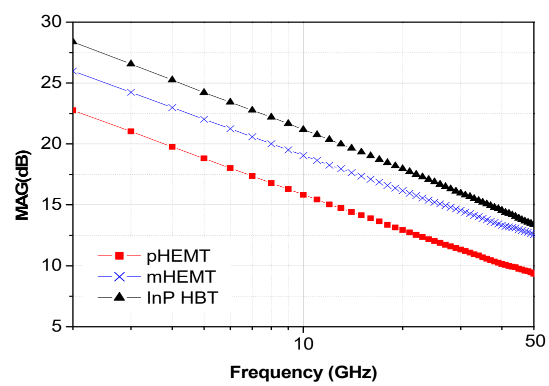

Fig. 8. MAG comparison of Lg=0.1um pHEMT, Lg=0.1um mHEMT and InP HBT

comparison with mHEMT. For sub-terahertz application, maximum available gain (MAG) is one important parameter to evaluate high frequency performance and compared in Fig. 8. Fmax of Lg=0.1um pHEMT, mHEMT and InP HBT is 247.2GHz, 321.0GHz and 352.5GHz, respectively.

Reliability

Reliability concern among above sub-terahertz candidates, especially for mHEMT and InP HBT, are also qualified by High Temperature Operation Life (HTOL). Taking Lg=0.1um mHEMT as an example, the test vehicles are biased under drain voltage of 2V for 500hours under ambient temperature of 165℃. Device DC characteristics is measured and compared to make sure threshold voltage, transconductance, maximum drain current and gate leakage shift less than 20% after HTOL. The related diagrams are

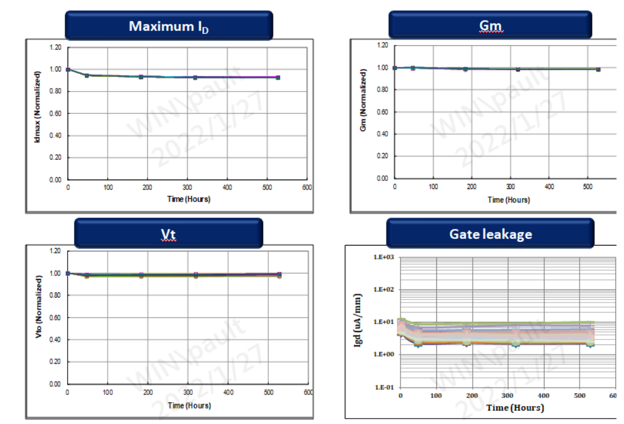

Fig. 9.Performance degradation percentage of Lg=0.1um mHEMT 2V 500hrs HTOL under Ta=165C.

disclosed in Fig. 9. Traditionally, mHEMT targets LNA application and reliability is generally tested under drain voltage of around 1V. By optimizing epi structure and process condition, it can pass VDS=2V HTOL. InP HBT is also expected to pass VCE=2V HTOL. The relative reliability test is ongoing and could be updated in the near future.

TABLE. I III-V SEMICONDUCTOR DEVICES BENCHMARK FOR SUB-TERAHERTZ AMPLIFIER

Technology	pHEMT	mHEMT	InP HBT
Critical Dimension (um)	Lg=0.1	Lg=0.1	Ew =0.8
DUT (um)	2*50	2*50	0.8*3
Fmax (GHz)	247.2	321.0	352.5
Operation Voltage (V)	4	2	2
Power Density (mW/mm ; mW/um2)	724.4	247.8	2.59
HTOL	4V Pass	2V Pass	2V Ongoing

CONCLUSIONS

In summary, we have successfully developed the 0.1um pHEMT/ mHEMTs and InP HBTs by 6-inch mass production tools. RF power performance and reliability have been verified for pHEMT, mHEMT and InP HBT for sub-terahertz amplifier application. Those technologies are promising solutions with mass production capability, leveraging to WIN's existing 6-inch production line. Circuit designers could choose the appropriate technology depends on their requirement to realize their sub-Terahertz MMICs.

ACKNOWLEDGEMENTS

The authors would like to appreciate the efforts made by WIN's engineers that realize the pHEMT, mHEMT and InP HBT technologies. They support technology development, device characterization, layout preparation, modeling, device fabrication and integration.

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ACRONYMS

HBT: Heterojunction Bipolar Transistor
HEMT: High Electron Mobility Transistors
Fmax: maximum oscillation frequency
MMIC: Monolithic Microwave Integrated Circuits
MOCVD: Metal-Organic Chemical Vapor Deposition
MBE: Molecular Beam Epitaxy
HTOL: High Temperature Operation Life