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Design and realization of D-band InP MMIC amplifier with high-gain and low-noise

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Abstract: In this paper, two D-band (110 ~ 170 GHz) monolithic millimeter-wave integrated circuit (MMIC) amplifiers have been designed and realized using 90-nm InAlAs/InGaAs/InP high gain electron mobility transistors (HEMT) technology. The amplifiers are developed in common source and microstrip technology. The three-stage MMIC amplifier A is designed based on device A and measured on wafer with a small-signal peak gain of 11.2 dB at 140 GHz and 3-dB-bandwidth is 16 GHz with a chip size of 2.6 mm × 1.2 mm. The two-stage MMIC amplifier B is designed based on device B and measured on wafer with a small-signal peak gain of 15.8 dB at 139 GHz and 3-dB-bandwidth is 12 GHz and the gain is higher than 10 dB from 130 GHz to 150 GHz with a chip size of 1.7 mm × 0.8 mm. The amplifier B also shows an excellent noise character with noise figure of 4.4 dB when the associated gain of 15 dB is acquired at 141 GHz and the average noise figure is about 5.2 dB over the bandwidth. The amplifier B exhibits a higher gain-per-stage, competitive gain-area ratio and lower noise figure. The successful realization of MMIC amplifiers is of great potential for receiver-front-end applications at D-band.

Key words: InAlAs/InGaAs/InP, PHEMTs, 90-nm, MMIC, amplifiers, D-band

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D 波段 InP 基高增益低噪声放大芯片的设计与实现

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摘要: 利用 90 nm InAlAs/InGaAs/InP HEMT 工艺设计实现了两款 D 波段(110 ~ 170 GHz)单片微波集成电路放大器. 两款放大器均采用共源结构, 布线选取微带线. 基于器件 A 设计的三级放大器 A 在片测试结果表明: 最大小信号增益为 11.2 dB@140 GHz, 3 dB 带宽为 16 GHz, 芯片面积 2.6 mm × 1.2 mm. 基于器件 B 设计的两级放大器 B 在片测试结果表明: 最大小信号增益为 15.8 dB@139 GHz, 3 dB 带宽 12 GHz, 在 130 ~ 150 GHz 频带范围内增益大于 10 dB, 芯片面积 1.7 mm × 0.8 mm, 带内最小噪声为 4.4 dB、相关增益 15 dB@141 GHz, 平均噪声系数约为 5.2 dB. 放大器 B 具有高的单级增益、相对高的增益面积比以及较好的噪声系数. 该放大器芯片的设计实现对于构建 D 波段接收前端具有借鉴意义.

关 键 词: InAlAs/InGaAs/InP; 赝高电子迁移率晶体管(PHEMTs); 90 nm; 单片微波集成电路(MMIC); 放大器; D 波段

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Introduction

With the progress of recent advance in the semiconductor device technologies, the millimeter wave even up to terahertz circuits attracts more attention for various applications[1-4]. Some applications are mm-wave imaging systems, space-to-space communication systems, radar system, high-speed wireless communication, atmospheric sensing and high-resolution imaging[2-7]. Frequencies in the range of D-band (110 ~ 170 GHz) are attractive for these applications due to an atmospheric propagation win-

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dow around 140 GHz[5,8-9]. The monolithic millimeter-wave integrated circuit (MMIC) amplifier with high gain, wideband, low noise and low power consumption plays a vital role in those applications. Aiming at these characteristics, indium phosphide-based high electron mobility transistor is a preferred section due to its high electron mobility[10]. In the last decade, many MMIC amplifiers operate at millimeter even up to terahertz have been reported over the world with different technologies[2-4,11-15].

Two D-band MMIC amplifiers were described in this paper. The MMIC amplifiers were measured on-wafer at room temperature. For amplifier A, the small-signal peak gain of 11.2 dB was obtained at 140 GHz and 3 dB bandwidth was 16 GHz. The amplifier B shows a small-signal peak gain of 15.8 dB at 139 GHz and higher than 10 dB from 130 GHz to 150 GHz. The amplifier B also shows an excellent noise character with noise figure of 4.4 dB at 141 GHz and the average noise figure is about 5.2 dB over the bandwidth.

1 InP HEMT technology

The MMIC amplifiers ware fabricated in 90 nm InGaAs/InAlAs/InP-based HEMT technology with the material epitaxial structure shown in Table 1. Figure 1 shows the photo of the device A and device B. The PHEMTs were grown by molecular beam epitaxy (MBE) on a 3-inch semi-insulating (100) InP wafers. Compared with device A, device B has increased In-content to 65%, with the composite cap layer and shorten distance between the source and drain[16]. Table 2 summarizes the key performance parameters of the two pHMETs.

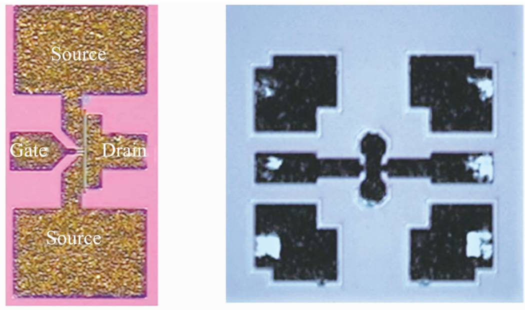
Table 1 InP-based pHEMT epitaxial structure
表 1 InP 基 pHEMT 外延材料结构

Layer	Material	
	A	B
Cap	$In_{0.53}Ga_{0.47}As$	$In_{0.6}Ga_{0.4}As$ / $In_{0.53}Ga_{0.47}As$
Barrier	$In_{0.52}Al_{0.48}As$	$In_{0.52}Al_{0.48}As$
Si-δ-doping	-	-
Spacer	$In_{0.52}Al_{0.48}As$	$In_{0.52}Al_{0.48}As$
Channel	$In_{0.6}Ga_{0.4}As$	$In_{0.65}Ga_{0.35}As$
Buffer	$In_{0.52}Al_{0.48}As$	$In_{0.52}Al_{0.48}As$
	S. I. InP Substrate	

Table 2 Key parameters of the device A and device B
表 2 器件 A 与器件 B 相关参数

	Device A	Device B
Idss/(mA/mm)	755	894
$g_{m,max}$/(mS/mm)	1 006	1 640
f_T/GHz	180	252
f_{max}/GHz	264	394

The backside of InP HEMT MMIC process provides a 50-um-thick wafer for reduce the high frequency loss with through substrate vias, which connect the backside metal ground plane to the front side device and circuit



(a) Device A (b) Device B

Fig. 1 The photo of the devices
图 1 两个器件实物照片

elements. Additionally, 30 μm diameter through-substrate vias are used for minimizing source inductance and maintaining high device gain. The process further includes 50Ω/sq NiCr thin film resistors (TFRs), 0.3 fF/μm^2 metal-insulator-metal (MIM) capacitors, and thru-substrate vias.

2 Circuit design

For maximum comparability of the two amplifiers after improving material structure and technology, the topologies are identical and the entire MMIC designs are kept as similar as possible. A simplified schematic of the MMIC amplifier is depicted in Fig. 2.

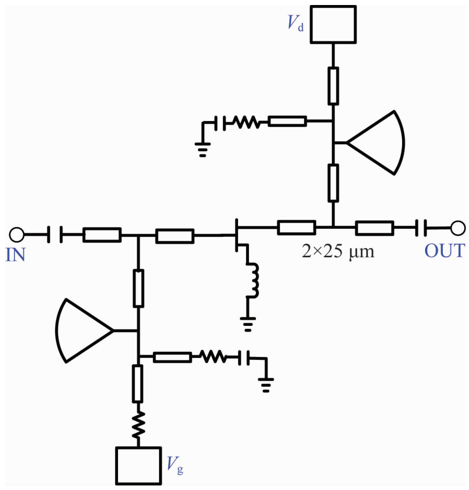


Fig. 2 Simplified schematic of an amplifier stage
图 2 放大器单级电路结构

Due to the gain of device A is lower, a three-stage topology was adopted for amplifier A. All transistors are in common source configuration, each device with dual source vias and the total gate width of the InP PHEMT device is 2 × 25 μm. The wafer was thinned down to 50 μm for preventing the excitation of parasitic modes in the substrate. The input and output matching network topologies are both proposed to be open stub network topology in Smith chart and edge-coupled lines are used for DC blocking between the first and second stage. Quarter-wave shunt stubs were employed as RF shorts to provide bias to the transistors and radial stubs are employed for RF bypass. In order to stabilize the MMIC, resistor-capacitor networks and inductive source feedback for the HEMTs were employed. The chip photograph of the manufactured D-band MMIC amplifier is shown in Fig. 3 and Fig. 4 and the size of the chip is about 2.6 mm × 1.2 mm and 1.7 mm × 0.8 mm for amplifier A and B respectively.

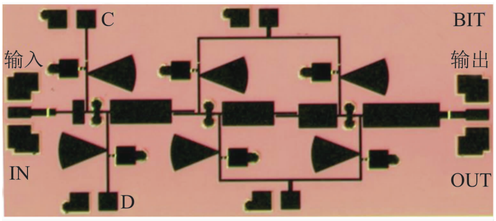


Fig. 3 Chip photograph of the presented amplifier A: three-stage amplifier
图 3 放大器 A:三级放大器

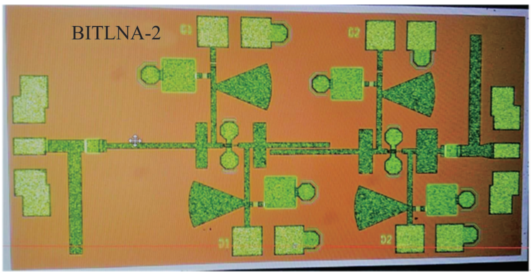


Fig. 4 Chip photograph of the presented amplifier B: two-stage amplifier
图 4 放大器 B:两级放大器

3 On-wafer measurement

Characterization of the MMIC amplifiers was done by on-wafer measurements. The measurement setup is shown in Fig. 5. The S-parameter measurements were performed using an Agilent N5245A PNA-X network analyzer with Farran Technology of series FEV-06 (110 ~ 170 GHz) frequency extenders. To measure the noise figure, the D-band output signal was down-converted and measured by Agilent N8975A. Off-chip bypass capacitors were wire-bonded to every gate and drain bias pad for suppress the potential self-oscillations. The on-wafer measured S-parameters of the two MMIC amplifiers are depicted in Figs. 6 and 7, respectively.

The on-wafer S-parameters of amplifier A measured at room temperature are shown in Fig. 6. The MMIC was biased at V_d = 1.5 V, while the entire drain current was 43 mA. The maximum linear gain of approximately 11.2 dB was achieved at 140 GHz and 3 dB bandwidth is about 16 GHz from 131 GHz to 147 GHz with input return loss (S11) of 1 ~ 7 dB and output return loss (S22) of 6 ~ 15 dB, which ensuring a better standing wave ratio.

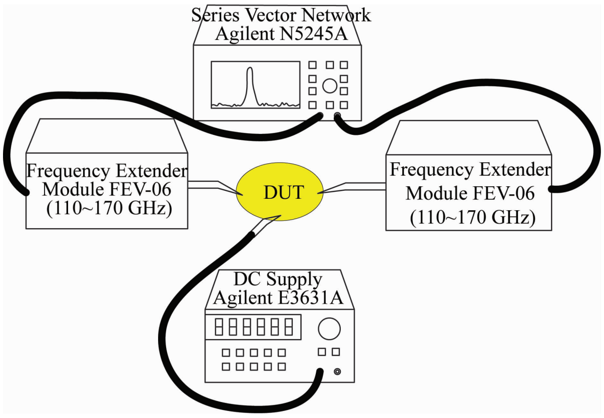


Fig. 5 Measurement setup (S-parameters)
图 5 S 参数测试平台示意图

The on-wafer S-parameters of MMIC amplifier B measured at room temperature are depicted in Fig. 7. The maximum linear gain of approximately 15.8 dB was obtained at 139 GHz and greater than 10 dB from 130 to 150 GHz. The measured input return loss and output return loss are better than 3.6 dB and 7 dB in operating frequencies, respectively. The total power consumption of the MMIC is 26.4 mW with a drain voltage of V_{ds} = 1.2 V. Figure 8 shows the noise figure of the MMIC, the optimal noise figure of 4.4 dB with the relatively high associated gain of 15 dB is acquired at 141 GHz and the average noise figure is about 5.2 dB over the bandwidth.

Table 3 Performance summary of amplifiers at D-band with different technologies
表 3 D 波段不同工艺放大器性能对比

Ref.	Freq /GHz	Technology	Gain/stage (dB)	Topology	NF/dB	Chip-size /mm^2	Pdc/mW
[5]	115 ~ 160	40 nm GaAs mHEMT	>5	4-CC	4	2.0 × 1.0	60
[10]	110 ~ 140	70 nm InP HEMT	4.6	4-CC	6	2.6 × 1.3	402
[15]	122 ~ 150	90 nm SiGe BiCMOS	7.5	3-CS	6.2	0.7 × 0.75	45
[17]	121 ~ 139	65 nm CMOS	3.3	8-CC	12	1.9 × 1.0	115.2
[18]	97 ~ 155	100 nm GaAs mHEMT	7.6	3-CS	4.2	2.0 × 0.75	31.5
A	130 ~ 150	90 nm InP HEMT	3.8	3-CC	–	2.6 × 1.2	64.5
B	130 ~ 150	90 nm InP HEMT	7.9	2-CC	4.4	1.7 × 0.8	26.4

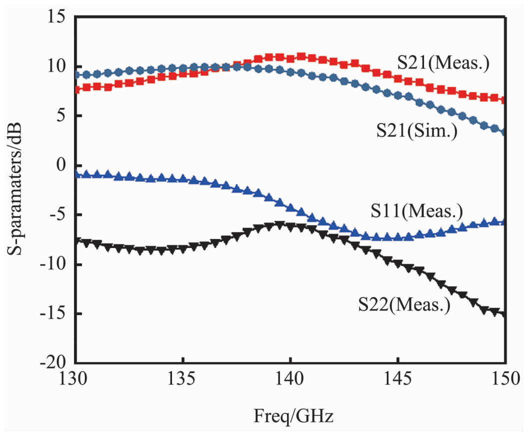


Fig. 6 On-wafer measured S-parameters of MMIC amplifier A
图 6 MMIC 放大器 A 在片测试所得 S 参数

The equivalent circuits model of the devices is based on the measured S-parameters from 0.5 GHz to 110 GHz, however the model performance beyond 110 GHz is extrapolated. So the discrepancy between the simulation and measured can be attributed to model errors. The MMIC amplifiers are measured on-wafer that may lead to self-excitation and mismatch, so the input and output return loss is not ideal.

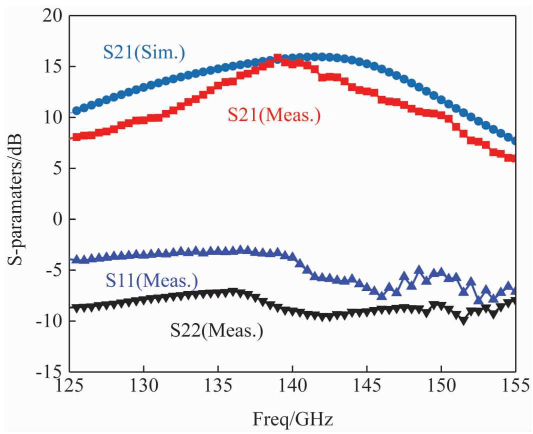


Fig. 7 On-wafer measured S-parameters of MMIC amplifier B
图 7 MMIC 放大器 B 在片测试所得 S 参数

The comparison of this work with previously published amplifiers at D-band are shown in Table 3. Our D-band MMIC amplifier B exhibits higher gain per stage and a better noise figure. Compared with our previous work, the excellent performance of the amplifier B benefits from the improved device performance, which has higher maximum oscillation frequency by optimal material structure and technology.

As above-mentioned, the topologies of amplifier A and B are identical and the entire MMIC designs are kept as similar as possible. Therefore, the difference in performance between amplifier A and B is derived from the technology and material structure. For device A, the semiconductor manufacturing process is immaturity and

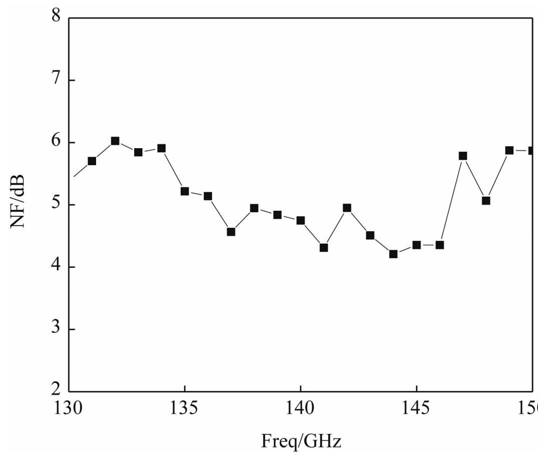


Fig. 8 On-wafer measured noise figure of MMIC amplifier B
图 8 MMIC 放大器 B 在片噪声系数

the gate length is greater than 90 nm. In addition, the optimized material structure with In-content increased, a-doping composite cap layer and introducing energy quantization by reducing the channel thickness also improved the performance of the device B. After improving the manufacturing technology and optimizing material structure, the device B shows higher f_T and f_{max}. Therefore, amplifier B exhibits better performance than amplifier A in the aspect of gain-per-stage and power consumption.

4 Conclusion

Two D-band common source MMIC amplifiers have been designed and developed using 90 nm InP-based HEMT technology. For amplifier A, the small-signal peak gain of 11.2 dB was obtained at 140 GHz and 3 dB bandwidth was 16 GHz. After improving material structure and technology, amplifier B has been designed and fabricated. The amplifier B shows a small-signal peak gain of 15.8 dB at 139 GHz and higher than 10 dB from 130 GHz to 150 GHz. Amplifier B shows a better return loss and higher gain-per-stage. The optimum noise figure of 4.4 dB with a relatively high associated gain of 15 dB at 141 GHz. Amplifier B has characters of higher gain per stage and low noise. Increased the In-content, shorter the gate length and optimum Ohmic contact can further improve the MMIC amplifier characteristics.

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