18 GHz High Gain, High Efficiency Power Operation of AlGaAs/GaAs HBT

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ABSTRACT

Outstanding power performance has been achieved from an AlGaAs/GaAs HBT at 18GHz. A common emitter HBT has achieved 48.5% added efficiency, 6.2dB associated gain and 0.17W output power. Common base operation of HBT exhibits higher gain at 18GHz: 0.358W (3.58W/mm) was achieved with 11.4dB gain and 43% added efficiency; at a reduced power level of 0.174W (1.74W/mm), 15.3dB associated power gain is achieved with 40% efficiency. This performance compares favorably with the results reported for MESFETs, HEMTs, and PBTs.

I. INTRODUCTION

Recently, AlGaAs/GaAs HBTs have emerged as high performance power transistors at the lower end of microwave spectrum. At L band (1.5GHz) 70% power added efficiency, 15dB associated gain and 0.8W were achieved. Excellent power performance has been reported from AlGaAs/GaAs HBTs at 10GHz. 5W total power was achieved with about 40% efficiency (1). The record high power added efficiency of 68% and 11.6dB gain was also achieved (2). The highest power density is 2.8mW/μm^2 of emitter area (or 5.6W/mm of emitter finger length in this case). High linearity HBT amplifiers operating to 11 GHz has been reported by TRW (3). The features of high gain, high power added efficiency and high power density are very attractive in microwave power application: The minimum feature size required in these HBTs is 2µm. This allows easy processing with optical lithography, which translates to high throughput and high yield for the large transistor areas such as used in power amplifier.

However, many systems require a frequency range beyond 10GHz. In this paper, the power performance of HBT is reported at 18GHz. The HBT used in this experiment is of the same type tested at 10GHz. It achieves 47% added efficiency and 11.3dB associated power gain at 18GHz in common base configuration. Such high level performance substantiates the advantages of HBT in power applications throughout the most commonly used microwave band.

II. HBT STRUCTURE

To achieve high speed, high frequency performance from HBT, two issues must be addressed:

1. low ohmic contact resistance to both emitter and base.
2. low collector capacitance.

To achieve these goals, the AlGaAs/GaAs HBT material was grown by MBE. The layer specifications are shown in Table 1. The collector thickness was 0.7µm. The base was highly doped with Be; the concentration was varied in different wafers from 5×10^{19} to $1\times10^{20}/cm^3$. The base thickness was usually 700Å. The AlAs concentration in the emitter was about 25%.

Table 1
HBT Layer Structure

LAYER	THICKNESS (µm)	TYPE	DOPING cm^{-3}	AlAs FRACTION
CAP	0.16	n^+	5×10^{18}	0
EMITTER	0.1	n	$0.5\text{-}1.5 \times 10^{18}$	0-0.25-0
BASE	0.07	p^+	$0.5\text{-}1 \times 10^{20}$	0
COLLECTOR	0.7	n	$3\text{-}6 \times 10^{16}$	0
SUBCOLLECTOR	0.6	n^+	6×10^{18}	0

The HBTs were fabricated with the self-aligned dual-liftoff process [4]. Selective etching exposes the thin base layer. The base metal contact is self-aligned to emitter; thus the lowest base resistance can be achieved. Proton implantation into the area under base metal contact was used to reduce the collector capacitance. The cross section view is shown in Figure 1.

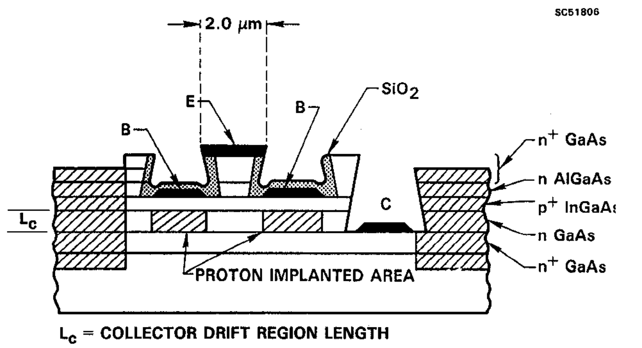

Fig. 1 Cross section of HBT.

The layout used in the present study is shown in Figure 2. Emitter finger size is 2µm×10µm, with two emitter fingers grouped into a cell. Collector contacts are placed at both sides of the cell; several cells are combined into a

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single transistor. Grounding is achieved with a common bus and through-substrate via holes. The interconnection line to collector contact has a crossover with the grounding bus. Substrate thickness is 3 mils.

III. DC PARAMETERS AND SMALL SIGNAL GAIN OF HBT

Table 2 lists the key dc parameters of HBT. The current gain is about 10. Base-collector breakdown voltage is over 20V which can be accurately controlled by the material growth. Common emitter breakdown voltage is around 14V. The saturation voltage is about 0.3V at low current, and is less than 1V at peak current. The I-V curve is extremely flat (very large output resistance). Contrary to Si bipolar transistor, the current gain de-

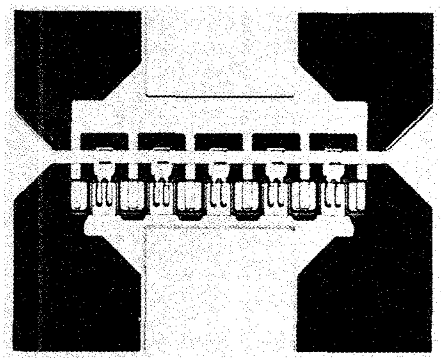


Fig. 2 Picture of HBT showing the layout.

Table 2
DC Parameters of HBT

β	9 TO 15
BV_{cbo}	>20 V
BV_{ceo}	~14 V
KNEE VOLTAGE	<1 V
EARLY VOLTAGE	>>100 V

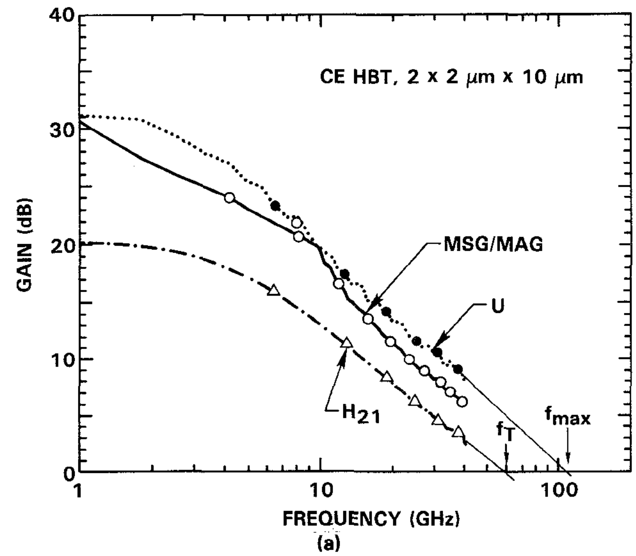
creases with rising temperature in AlGaAs/GaAs HBTs. Therefore, the Early voltage can be measured only at low current level, and the value is very high (>100V).

S parameters of both common emitter and common base HBTs are measured with calibrated systems of HP8510B and Cascade RF probes to 40GHz. The measured result is used to calculate the gain. No further de-embedding (such as pad capacitance removal) is used. The gain versus frequency of both 1 cell HBT (40μm^2 emitter area) is shown in Figure 3. f_{max} is over 100GHz and f_T is near 60GHz. Common base (CB) configuration offers more MSG/MAG at higher frequency than the common emitter (CE) configuration. At 18GHz, CE HBT has a MAG of 12.5dB and CB HBT has a MSG of 19dB. These wafer probe results agree well with measurements on bonded devices measured in a fixture.

IV. POWER PERFORMANCE AT 18GHz

Power measurement was carried out at 18GHz. The HBTs were diced and soldered onto carriers. They were subsequently tested in a fixture which uses OS-50 connectors and 50 ohms microstrip line on 10 mil thick Alumina substrates. The 2.4mm connector allows the mounted HBT be tested to 50GHz. The HBT chip is ribbon bonded to the fixture. Matching is done with bonding wires and pads on the Alumina substrate, as well as with external tuners.

A three cell CE HBT achieved 170mW output power. The associated gain was 6.2B and 48.5% power added efficiency. Although the efficiency is high, a higher power gain is desired. Figure 4 is the power saturation curve of this CE HBT. The power density is about 1.4mW/μm^2, which is lower than the density of 2mW/μm^2 achieved with similar devices at 10GHz.



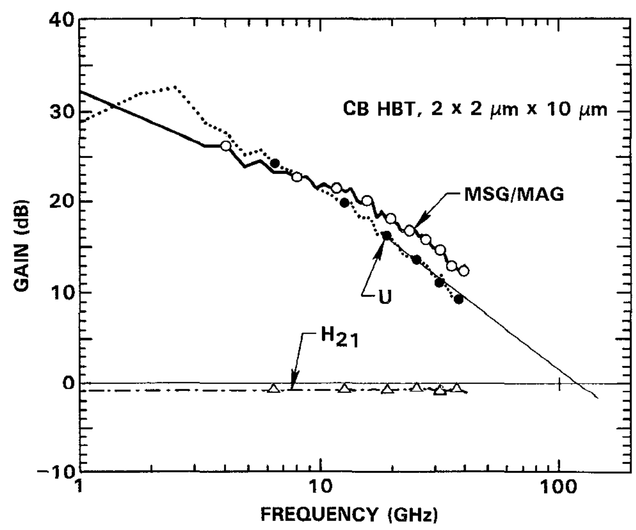


Fig. 3 Gain vs frequency for (a) CE HBT, (b) CB HBT. U is the unilateral gain. H_{21} is the short circuit current gain.

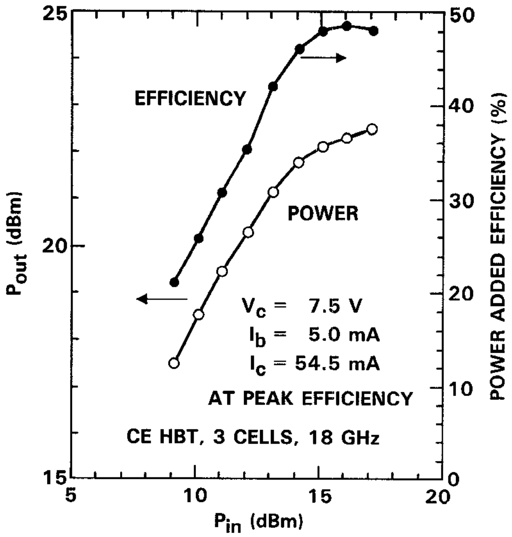


Fig. 4 Output power and power added efficiency vs input power for CE HBT at 18GHz.

As mentioned in the previous section, CB HBT has higher gain at high frequency. A three cell CB HBT was tested in the fixture first to determine the small signal gain. The 19.6dB achieved is in good agreement with the gain calculated from measured S parameters.

47% power added efficiency was achieved with 3-cell CB HBT. The associated power gain was 11.3dB and output power was 218mW. The power density is 1.82mW/μm², very close to the power density achieved at 10GHz. Figure 5 shows the result.

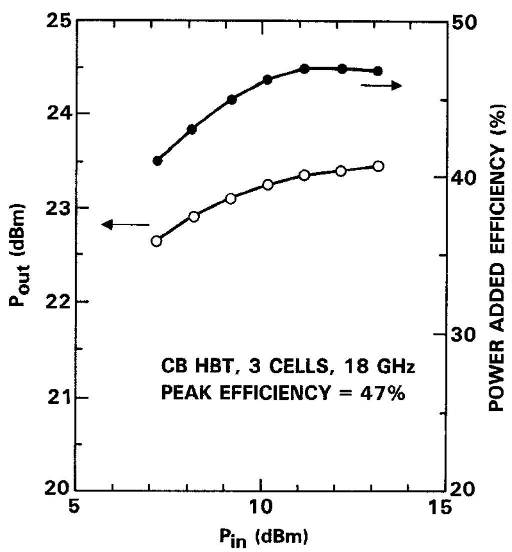


Fig. 5 Output power and power added efficiency vs input power for CB HBT at 18GHz.

The highest output power measured was 0.385W from a 5-cell HBT. The efficiency is 41.3% and the gain is 9.7dB. Table 3 lists the results from this study, as well as published power result from various transistors around 18GHz (4-7). Evidently, the HBT in this study is capable of much higher output power and power gain.

Table 3
Comparison of Transistor Power Performance Around 18GHz

DEVICE	TYPE	FREQ	GAIN	P_{OUT}	ADDED EFFICIENCY	MINIMUM FEATURE SIZE	REF
AlGaAs/GaAs	HEMT	20 5 GHz	6 dB	28 mW	40%	0 50 μm	4
GaAs	PBT	20 GHz	7 3 dB	54 mW	41%	0.16 μm	5
AlGaAs/GaAs	MISFET	18.5 GHz	5 5 dB	320 mW	33%	0.50 μm	6
AlGaAs/InGaAs	MISFET	18 GHz	6 8 dB	75 mW	50%	0 25 μm	7
CE AlGaAs/GaAs	HBT	18 GHz	6 2 dB	170 mW	48 5%	2 00 μm	
CB AlGaAs/GaAs	HBT	18 GHz	11.3 dB	218 mW	47%	2 00 μm	

Although HBT uses 2μm minimum feature size, the efficiency is comparable to or better than other transistors with sub-half micron feature size.

A salient feature of HBT power performance is the fact that high efficiency can be obtained over a wide range of biases. This feature is shown in Figure 6, where three sets of curves are overlapped. These results were obtained from a single 5-cell HBT with different bias currents. The peak efficiency values for each current are also listed in Table 4. The added efficiency in all cases is greater than 40%. However, the gain, output power and bias current can be quite different. With smaller bias current, the output power is also lower, but the associated power gain is very high. At 48mA bias current, 15.3dB gain was achieved with 174mW. As bias current increases, the power increases but the gain degrades. At 88mA, only 11.4dB gain is available, but output power reaches 358mW. This feature allows HBT be used in efficient power amplification with a wide bias range.

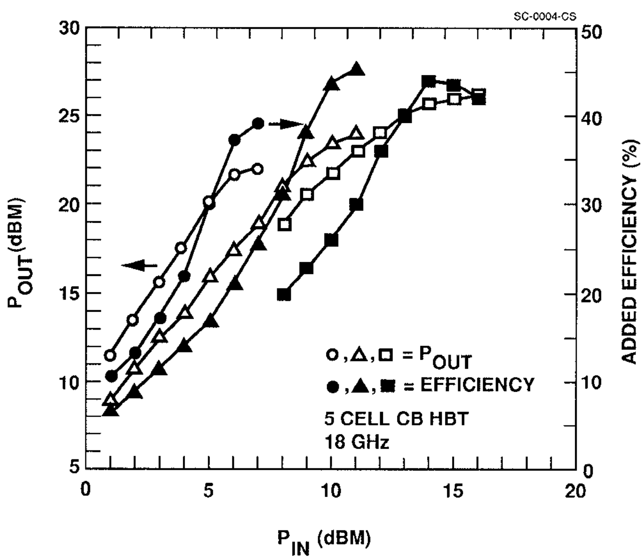


Fig. 6 Power saturation curves of a single CB HBT at three bias conditions. The peak efficiency in any case is greater than 40%.

Table 4
Operating Conditions at Peak Efficiency for the HBT in Figure 6

GAIN	P_{out}	η_a	I_c
15.3 dB	0.174 W	40%	47 7 mA
13.5 dB	0.232 W	43.8%	59.6 mA
11.4 dB	0.358 W	43%	82 mA
9.7 dB	0.384 W	41.2%	88 mA

Table 5
Comparison of HBT power performance at 18GHz Against Device Size

SIZE	GAIN	η_a	P_{out}	POWER DENSITY	I_c
3 CELLS	10.9 dB	42%	0.20 W	1 67 mW/μm^2	45.5 mA
5 CELLS	11.4 dB	43%	0.36 W	1 80 mW/μm^2	88 mA

Table 5 is a comparison of performance against device size. The result is essentially the same except the scaling of HBT size. 1.92W/μm^2 power density is achieved, which translates to 3.85W/mm of emitter finger length. This is only slightly less than the result of 4 to 5W/mm which is characteristic of HBT operation at 10GHz.

Since $S_{21} \cdot S_{12}$ is very small in magnitude for CB HBT, the input impedance is essentially the same as S_{11} of the transistor. It is between 1 and 2 Ω for the 5 cell CB HBT. The CE HBT has a capacitive input impedance; the real part is similar to the input resistance of the CB HBT, around 1 to 2 Ω. Input impedance of both configurations can be easily matched at 18GHz.

The output matching is different from the conjugate of S_{22} of the HBT in a power operation. The load resistance for power operation is estimated to be around 100 Ω for the 5 cell HBT.

The temperature rise is estimated to be around 100 ^{o}C. It depends on the bias condition and operation efficiency. Result of reliability test will determine the operation condition.

V. CONCLUSION

The performance of HBTs was found to be superior to other transistors with much smaller feature size around 18GHz. 48.5% added efficiency and 6.2dB gain are achieved with CE HBT at 18GHz. The highest associated power gain of CB HBT is 15.3dB; the highest efficiency is 47% and the highest output power is 0.385W. The performance at 18GHz is expected to be improved further with the optimization of HBT structure.

Over 40% efficiency can be maintained with a wide bias current range. The associated power gain can be used to trade for output power. This feature allows HBT be used in a wide range of condition. Maximum power density is 3.8W/mm, or 1.9mW/um^2.

The 2μm feature size of HBT guarantees good yield and high throughput, which are crucial to the fabrication of power amplifier. These results confirm the advantages of HBTs as power transistors over the microwave band.

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