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Self-Aligned AlGaAs/GaAs Heterojunction Bipolar Transistors for Microwave Power Amplification

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This paper describes the recent development of AlGaAs/GaAs Heterojunction Bipolar Transistors (HBTs) for microwave power applications. We report operation of self-aligned HBTs at both 10 and 18 GHz with record power-added efficiency as well as high gain and high power density. At 10 GHz, a 68% power added efficiency was obtained by using common-emitter (CE) HBTs with 11.6 dB gain and 5.7 W/mm power density. At 18 GHz, 47% power added efficiency was achieved by using common-base (CB) HBTs with 11.4 dB associated gain and 3.58 W/mm power density . The tested HBTs have a minimum feature size of 2 μm. Projection optical alignment was used for enhancing device yield and reproducibility.

I. Introduction

The HBTs offer many intrinsic advantages over GaAs FETs for high frequency power applications.[1] The electron transit time of HBTs is mainly governed by the thin active layers grown by MBE. This allows high gain and high current cutoff frequency without submicrometer lithography. The HBT also has high current handling capability per unit chip area because the entire emitter area conducts current vertically. As is typical of bipolar transistors, high transconductance of HBTs results from the direct control over the current flow by the input voltage. The breakdown voltage of HBTs can be easily controlled by tailoring the collector epitaxial structure of the device. High microwave gain of HBTs can be obtained by combining an appropriate epitaxial layer design with a self-aligned process approach that minimizes device parasitics.

The recent demonstration of HBTs based on the AlGaAs/GaAs heterojunction has offered improved high frequency performance over that of the GaAs FETs. Power density over 4 W per millimeter of emitter length at 10 GHz has been reported by both Texas Instrument and Rockwell.[2,3] TI has also reported 5 W CW power operation from a single HBT chip at 10 GHz.[4]

In this paper, the performance of AlGaAs/GaAs power HBTs will be presented, with a discussion of the merit of HBTs in power amplification applications.

II. Device Fabrication

MBE was used to form the layer structure shown in Table I on a semi-insulating undoped LEC GaAs substrate. Subsequent processing steps that generate fully self-aligned HBTs are shown in Fig. 1.[5]

Table I

HBT Epitaxial Structure

Layer	Thickness (μm)	Type	Doping (cm^{-3})	AlAs Fraction
Cap	0.16	n+	5E18	0
Emitter	0.095	n	0.5-1.5E18	0-0.25-0
Base	0.07	p+	0.5-1E20	0
Collector	0.7	n	3-6E16	0
Subcollector	0.6	n+	6E18	0

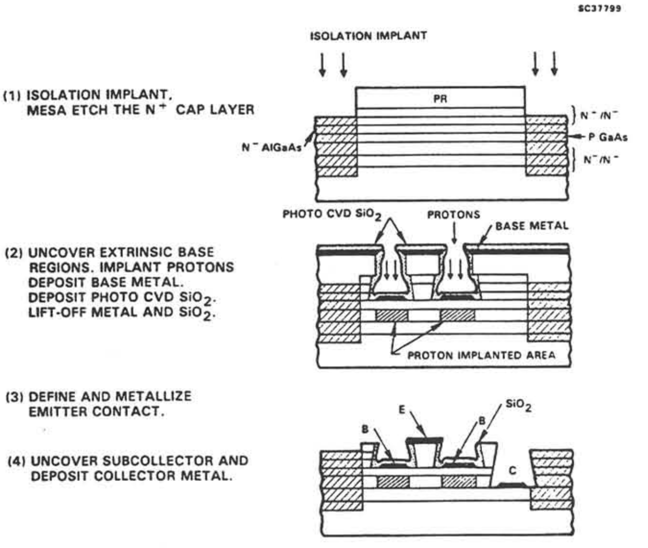

Fig. 1 Schematic processing steps and descriptions for dual-lift-off HBTs.

A photoresist pattern was used to define an etch-down to the base layer of an HBT structure, thereby establishing the emitter area at the same time. The same photoresist was used in masking the proton implantation for base-collector capacitance reduction and the base metal evaporation. Finally, the photoresist was used again to mask the deposition of a low-temperature-deposited photo-CVD Si_3N_4. The resultant structure has base metal in the base contact areas overlaid with a dielectric which protects both the metal and the emitter side-walls. The process was termed "dual lift-off" because the unwanted base metal and dielectric were lifted off simultaneously. The distance between the base ohmic metal and the emitter side-wall was approximately 0.2 μm. HBTs examined in this work had emitter finger width of 2 μm. However, the minimum emitter width ever achieved by the dual lift-off process was 1.2 μm.

The f_t and f_{max} were usually about 45 GHz and 110 GHz, respectively, for HBTs fabricated with 2 μm emitter fingers. The collector length was 0.7 μm to provide a collector breakdown voltage of 20 V. Projection optical alignment was used for enhancing device yield and reproducibility. The substrate was thinned to 3 mils. Through substrate via holes were made to ground the transistors. Both common-emitter (CE) and common-base (CB) HBT configurations were made for testing.

III. RF Performance of HBTs

Self-aligned HBTs fabricated with the dual lift-off process have shown excellent microwave power performance.

At 10 GHz, the CE power HBTs have demonstrated a 67.8% power-added efficiency with 11.6 dB gain and 0.266 W output power. The corresponding power saturation curve is shown in Fig. 2. The power density reaches 5.66W/mm, or 2.83 mW/μm^2. This is the highest CW power density and efficiency reported for any transistor at this frequency. The highest small signal gain is 16 dB, which agrees very well with the gain calculated from measured S parameters.

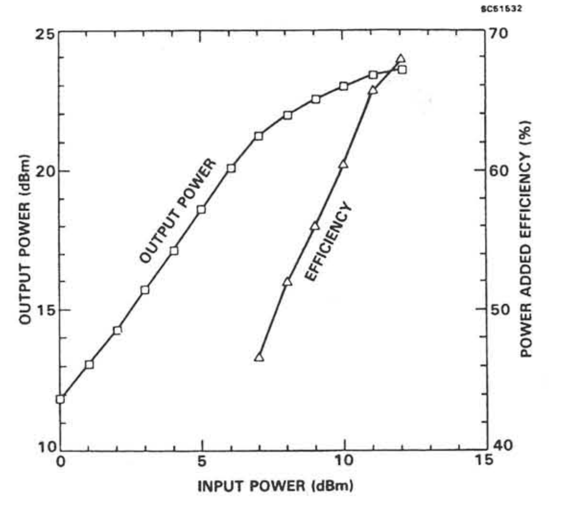

Fig. 2 Power saturation curves of CE HBT at 10 GHz.

In CB operation, HBTs are also capable of high efficiency at 10 GHz. A 62.3% added efficiency with 11.85 dB gain and 0.385 output power were achieved. Figure 3 illustrates the performance. Since the CB configuration leads to a higher breakdown voltage, a higher power density is achievable. A power density of 3.2 mW/μm^2 was obtained with 8.65 dB gain.

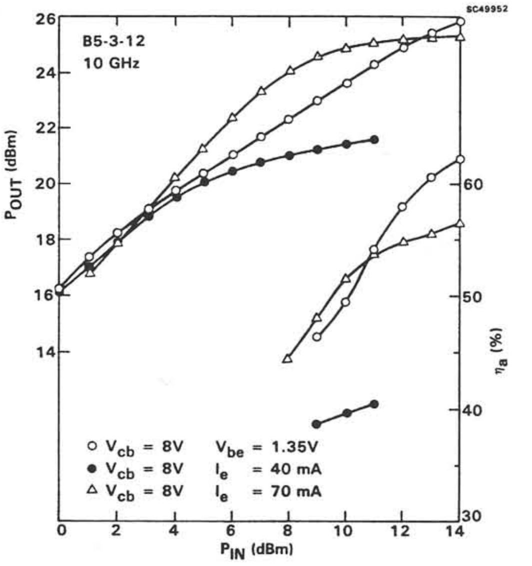

Fig. 3 Power saturation curves of CB HBT at 10 Hz.

The small signal gain of CB HBT at 10 GHz has reached 19 dB. It again agrees well with the calculated gain from measured S parameters. Both configurations have similar associated power gain, power added efficiency, and power density at 10 GHz. The peak current density in the RF operation is over 100 KA/cm^2. In general, CE HBTs are easier to match impedance than CB HBTs. The CE HBTs is also more stable as indicated by the K factor calculated from measured S parameters. In agreement with this, the CB HBT can be induced to oscillate during the testing.

At 18 GHz, the CE HBTs achieves 48.5% added efficiency with 6.2 dB associated gain, and 0.17 W output power. In the power matching condition, the small signal gain was 8.3 dB as shown in Fig.4. The power density was 1.6 mW/μm^2, which is lower than the power densities of achieved at 10GHz.

The CB HBTs, at the same frequency, have reached an even higher power gain of 11.4 dB with added efficiency of 47% and 0.218 W output power, corresponding to a power density of 3.58W/mm, or 1.82 mW/μm^2. This result is favorable in comparison with the CE HBT results. An interesting feature is the high associated power gain which is about the same as at 10 GHz.

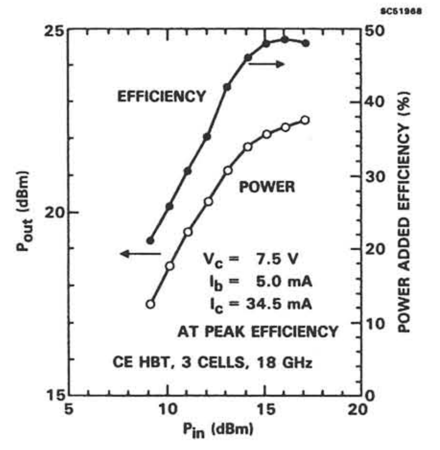

Fig. 4 Power saturation curves of CE HBT at 18 GHz.

Figure 5 shows the result of a single CB HBT of 200 μm^2 emitter area. The HBT was measured at different power levels. The peak efficiency in any case is over 40%, but the associated power gain is traded for output power. This is part of the benefit obtainable from the high power gain of CB HBTs. The HBT is comparable in performance to or better than other transistors with much smaller feature size.

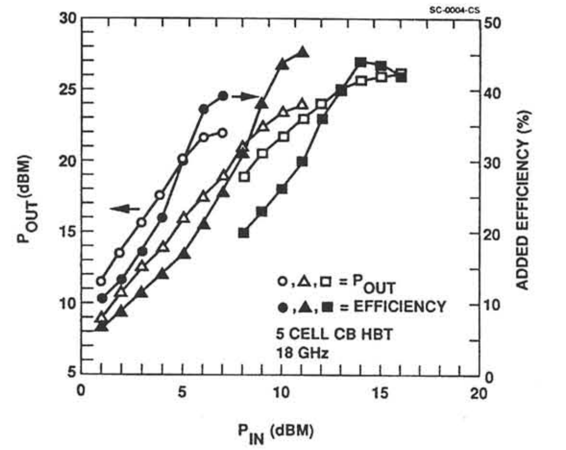

Fig. 5 Power saturation curves of CB HBT at 18 GHz.

IV. Discussion

Unlike CE HBTs, CB HBTs have demonstrated similar power gain at both 10 and 18 GHz. Comparing with CE HBTs, CB HBTs have a relatively low feedback from output to input.

Consequently, CB HBTs are very much like a unilateral transistor over the microwave frequency band. The input impedance of CB HBTs is also very constant over the band. As a result, the transistor gain under power matching conditions does not vary significantly with frequencies. Furthermore, as demonstrated earlier, HBTs can maintain a high efficiency over a wide matching range. The power gain can be traded with the output power. Therefore, the gain at 18 GHz can be maintained by a slight reduction of output power. The maximum power density is 2 to 3 mW/ μm^2 at 10 GHz. It drops slightly to 1.5 to 2 mW/ μm^2 at 18 GHz. The power added efficiency also drops from X to Ku band. It is likely that the HBT structure can be refined to achieve higher performance at 18 GHz.

HBTs have several advantages over GaAs FETs or HEMTs in contributing high efficiency amplification at microwave frequencies: (1) No leakage current when the HBT is turned off. (2) No breakdown voltage degradation in class B operation for HBTs. (3) The transconductance of HBTs is exponentially dependent on input voltage, resulting in a higher theoretical efficiency of 91% in class B.

To obtain high efficiency operation, the transistor must be operated in class AB, class B or even in class C. In class B operation, the transistor is turned off for every half cycle. Since FETs can not have a clean pinch-off, there still exists some leakage current in the "off" cycle, which degrades the output power at the fundamental frequency, and therefore decreases efficiency. Moreover, when the gate voltage is negatively biased, the drain breakdown voltageof a FET is lowered. Class B operation also requires the gate voltage to swing from V_{on} to $(-2V_p-V_{on})$. The breakdown voltage at the lowest gate voltage is lower than what is usually quoted for class A operation. For HBTs the V_{be} is always positive, and the breakdown voltage does not change. The transconductance of HBTs also behaves quite differently from FETs. For FETs, the transconductance is usually a linear function of gate voltage. But the transconductance of HBTs is exponentially dependent on V_{be}. The exponential transconductance can have a higher efficiency than the linear one.

V. Conclusion

The power performance of AlGaAs/GaAs HBTs at both 10 and 18 GHz is reported. The minimum feature size was 2 µm. Excellent performance has been achieved, which compares favorably with that of other transistors of much smaller feature size. The major differences between HBTs and FETs in microwave power operation are discussed. Since FETs do not have as clean a pinch-off during the turn-off cycle as HBTs, HBTs are uniquely suitable for high efficiency power amplification in class AB, class B or even class C operations.

VI. References

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