2.5 W CW X-BAND HETEROJUNCTION BIPOLAR TRANSISTOR

by
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ABSTRACT

2.43 W CW output power was obtained with AlGaAs/ GaAs heterojunction bipolar transistors at 10 GHz with 5.8 dB gain and 30% power-added-efficiency using 2 μm minimum geometry devices. The device design and fabrication techniques were improved to maintain the high power density (> 3 W/mm of emitter length) operation as the device size is increased. Accurate device models were developed both for common-emitter and common-base devices to aid in this size scaling.

INTRODUCTION

Heterojunction bipolar transistors are more suited to the high power generation at microwave frequencies than both the Si bipolar transistors and the GaAs FETs. The use of a heterojunction to suppress the hole injection into the emitter together with the superior electronic properties of GaAs, result in greatly improved microwave power gains for HBTs compared to Si bipolar transistors. Compared to GaAs FETs, HBTs offer much higher power density operation. The breakdown voltage in an HBT is basically the reverse bias breakdown voltage of the base-collector junction which can be made several times higher than the breakdown voltage of FETs operating at the same frequency. Since the maximum current in a properly designed HBT is also higher than in FETs, the output power (normalized to device size or impedance) is expected to be higher. It was shown experimentally that the HBT power densities can be as high as 4 W/mm of emitter length under CW conditions at X-band[1,2]. Under pulsed conditions power densities as high as 10 W/mm were obtained[3]. All high power density HBTs so far have been limited in their CW output power to below 0.5 W. Larger output power devices require the operation of large emitter length devices which, in turn, require careful thermal designs and an accurate knowledge of the device input/output impedances. We have developed, in this work, thermal and electrical designs to enable continuous operation of high power HBTs under both common-emitter and common-base modes.

DESIGN AND FABRICATION

All epitaxial layers used in this study were grown by MOCVD on a semi-insulating (SI) GaAs substrate. Si and Zn were used as the n- and p-type dopants. A typical device vertical structure is shown in Table 1. A thin layer of $In_{0.1}Ga_{0.9}As$ layer was incorporated in the base layer to act as an etch-stop layer and to facilitate a uniform removal of the emitter layer during fabrication. This layer also reduced the contact resistance of non-alloyed base metallization.

Table 1: *The HBT Vertical Structure*

LAYER	Doping (cm^{-3})	Thickness (μm)
n^+–InGaAs	5 x 10^{18}	0.02
n^+–GaAs	5 x 10^{18}	0.05
n–grading	1 x 10^{18}	0.03
n–$Al_{.3}Ga_{.7}As$	3 x 10^{17}	0.1
p^+–$In_{.1}Ga_{.9}As$	1 x 10^{19}	0.02
p^+–GaAs	1 x 10^{19}	0.08
n–GaAs	3 x 10^{16}	1.5
n^+–GaAs	5 x 10^{18}	1.5
SI SUBSTRATE	Undoped	500

A self-aligned fabrication technique similar to that described in [4] was used to place the base contact as close to the emitter as possible. AuGe/Ni and TiPtAu alloys were used as the contacts for n- and p- type layers, respectively. The device is made up of 2 X 20 μm emitter fingers placed 25 μm apart. Two 2 X 20 μm base fingers were used with each emitter. Figure 1 shows a 10 emitter finger sub-cell made up of 2 rows of 5 fingers. Such 10 finger cells were combined to form larger devices geometries. Via holes were used to ground the emitter (or the base terminal) at each sub-cell level.

In any power device layout the dissipation of heat is a critical factor in achieving high absolute power. The 25 μm spacing between emitter fingers was chosen by a computer optimization of the device microwave performance and thermal isolation. Figure 2 shows the calculated temperature rise as a function of distance across one row of a 10 finger sub-cell. The center finger reaches a maximum temperature of 160° C at a dissipated power density of 2000 W/mm^2 of emitter area (i.e. output power of 0.7 W and 1.06 W at 30% and 40% power-added-efficiencies, respectively, for this sub-cell). Also shown are the temperatures at various depths in the substrate.

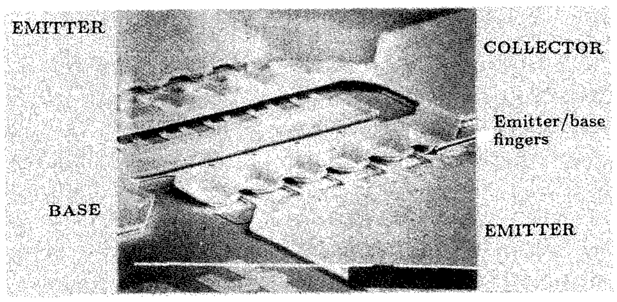

Figure 1: *SEM Picture of a 10-finger Sub-cell*

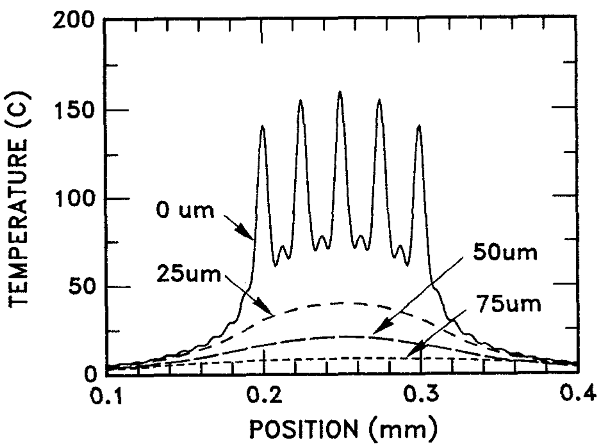

Figure 2: *Temperature profile across one row of a 10-finger sub-cell as function of depth into the wafer at a power dissipation of 2000 W/mm² of emitter area.*

RESULTS AND DISCUSSION

a. Small-Signal

In order to determine the frequency response and impedance levels of HBTs, the S-parameters of several devices with various sizes were measured on-wafer using CASCADE RF probes. Both common-emitter and common-base devices with 2 , 4 , 6 , 8 and 10 emitter fingers were characterized and small-signal equivalent circuit models were developed for each. S-parameters of 20-finger CE devices were also measured in appropriate test fixtures that were de-embedded using the TRL (thru-reflection-line) technique. Figure 3 shows the measured maximum stable/available gain (MSG/MAG) and current gain ($|h_{21}|^2$) versus frequency for common-emitter devices with 2, 10 and 20 emitter fingers, respectively. As seen from Figure 3, no significant degradation in the performance is observed by increasing the number of emitter fingers from 2 to 20. Equivalent circuit models developed for these devices show that the HBT impedance levels scale with the device size while the gain is unaffected. This is attributed to the compactness of the physical layout of the HBTs versus that of MESFETs. It is worth noting that, in terms of the rated output power at 10 GHz, the 20-finger HBT (1.4 W) is equivalent to a MESFET with about 2.0 mm of gate width.

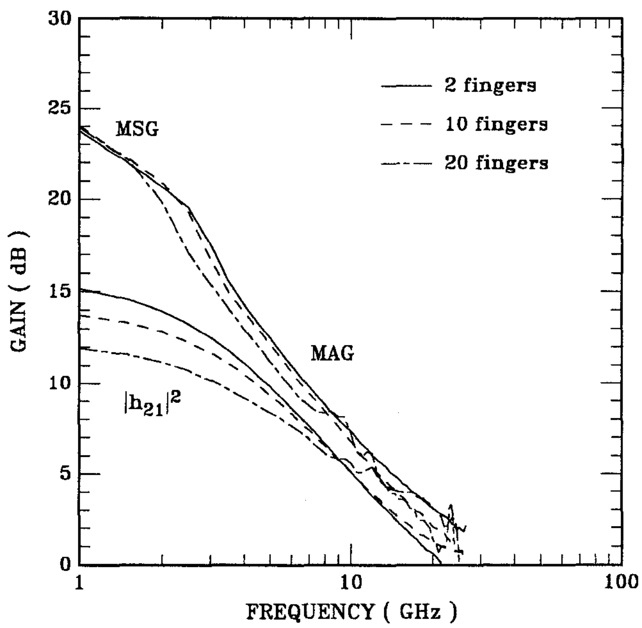

Figure 3: *Measured current gain ($|h_{21}|^2$) and maximum stable/available gain (MSG/MAG) of three common-emitter device with 2 , 10 , and 20 emitter fingers.*

Excellent yield and uniformity of the RF performance were achieved across the wafer with typical current gain cut-off frequency (f_t) of 20-30 GHz and maximum frequency of oscillation (f_{max}) of 30-40 GHz. The RF performance uniformity of the HBTs is mainly due to two factors: (1) the self-aligned fabrication process with minimum feature sizes defined by optical lithography and, (2) the uniformity of the epitaxial layers with $In_xGa_{1-x}As$ etch-stop layers. Note that the HBTs discussed in this paper were optimized for X-band power application which require not only high values of f_t and f_{max} but also high breakdown voltage. The collector design (thickness and doping) involves a trade-off between f_t and breakdown voltage[3]. From the measured value of f_t, the total emitter-collector transit time is calculated to be 6.4 pS , 40% of which (2.5 pS) is due to the transit time in the collector depletion layer.

Figure 4 shows the small-signal equivalent circuit model of a 10-finger CE device with the element values listed in Table 2 . The two short sections of 50 Ω transmission lines in the base and collector account for the coplanar waveguide lines used to access the 10-finger cell. Figure 5(a) shows the measured and modeled S-parameters of the 10-finger CE device in the 1-26 GHz range. The input reactance does not change significantly over the 1-26 GHz band. This implies that the input impedance of HBTs can be matched to 50 Ω over a broader bandwidth compared to MESFETs of equivalent size. Figure 5(b) shows the measured and modeled S-parameters of a 10-finger common-base HBT. The CB configurations has higher small-signal gain (12 dB) at 10 GHz due to lower series-equivalent output impedance level compared to the CE device. The output impedance can be simply modeled by the reverse-biased base-collector junction capacitance in parallel with a very large shunt resistance due to the low B-C leakage current. The low (series equivalent) output impedance, while increasing the gain, poses stability and impedance matching problems. Nevertheless, at 10 GHz, high gain and high breakdown voltage make CB HBT suitable for power amplification.

b. Power

The CW power performance of HBTs were measured at 10 GHz. Devices with up 10 emitter fingers were tuned using external tuners with 15:1 VSWR tuning range while the 20- and 40-finger devices were matched to 50 Ω using on-carrier lumped-element capacitors and bond-wire inductors. Table 3 summarizes the large-signal performance of CB HBTs. Typical operating collector voltages were 10-12 V and collector currents of 11-12 mA/finger. The DC common-emitter current gains of these devices at the operating points were about 5 . As shown in Table 3, the output power of the HBTs scale well with the number of emitter fingers. Output power level of 2.43 W with 5.8 dB gain and 30% power-added efficiency was achieved at 10 GHz with a 40-finger HBT. This is the highest absolute

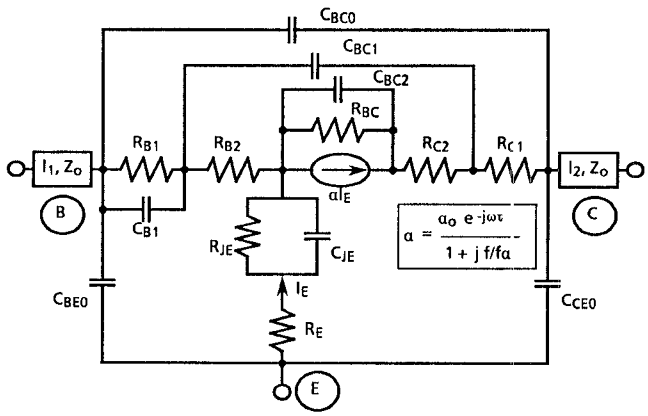

Figure 4: *Small-signal equivalent circuit model of CE HBTs.*

Table 2: *Element values of the equivalent circuit model for the 10-finger CE device at V_c= 4.0 V and I_c= 150 mA*

Element	Value	Element	Value
R_{B1}	5.47 Ω	C_{BC1}	0.22 pF
R_{B2}	1.90 Ω	C_{BC2}	0.02 pF
R_{C1}	0.19 Ω	C_{CEO}	0.08 pF
R_{C2}	0.78 Ω	C_{BEO}	0.04 pF
R_E	1.26 Ω	α_o	0.84
R_{JE}	0.65 Ω	f_α	31 GHz
R_{BC}	1 MΩ	τ	2.56 pS
C_{B1}	1.68 pF	l_1	0.01 λ
C_{JE}	2.37 pF	l_2	0.01 λ
C_{BCO}	0.07 pF	Z_o	50 Ω

CW output power level reported for an HBT at 10 GHz and corresponds to an output power density of 3.04 W/mm of emitter length. Power densities of up to 3.8 W/mm was achieved at 750 mW output power for the 10-finger devices. The collector efficiency of the 2.43 W device was measured to be 51% indicating class-A operation. The difference between the collector efficiency and the power-added efficiency of the device is not only due to its finite gain, but also due to the common-base configuration which requires more dc power. The bias levels of the 2.43 W device were: V_c= 11 V, I_c= 431 mA, V_e= -1.8 V, and I_e= 561 mA . This indicates that 18% of the total DC power was supplied to the emitter thus reducing the overall PAE. Efficiencies (PAE) of up to 38% were measured for 5 finger devices with 300 mW output power and 6.1 dB gain.

CONCLUSIONS

The high power operation of MOCVD grown AlGaAs/GaAs HBTs was demonstrated at 10 GHz by fabricating devices designed for CW operation. It was shown that both the small-signal and the high power density characteristics of HBTs can be maintained as the device size is increased.

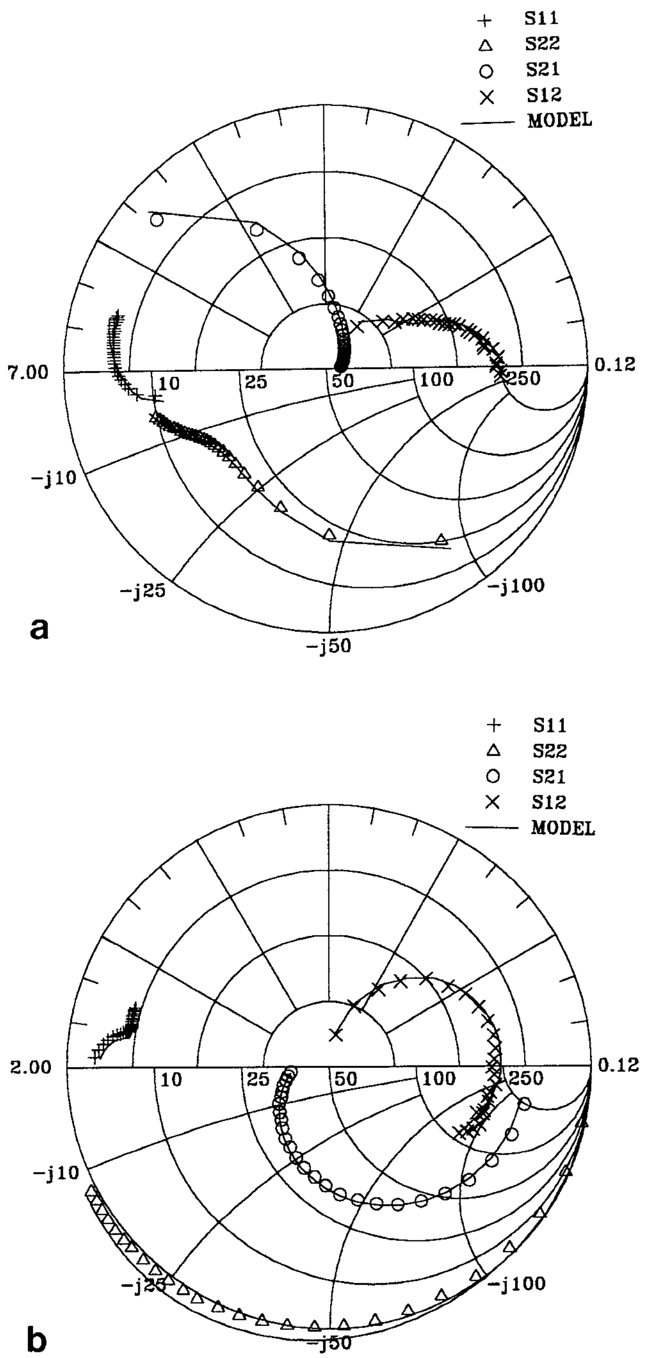

Figure 5: *Measured and modeled S-parameters of; (a) 10 finger CE device and, (b) 10 finger CB device. The frequency range is 1-26 GHz with 1 GHz increment. The bias voltages are:* $V_c = 4.0$ *V,* $I_c = 150$ *mA for the CE device and* $V_c = 4.0$ *V,* $I_c = 123$ *mA for the CB device.*

Table 3: *Large-signal CW performance of HBTs at 10 GHz.*

No. Emitter Fingers	Output Power (mW)	Power Density (W/mm)	Gain (dB)	Power Added Efficiency (%)
5	300	3.0	6.1	38
10	750	3.8	5.2	31
20	1435	3.6	6.0	31
40	2432	3.1	5.8	30

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REFERENCES

[1] B. Bayraktaroglu, N. Camilleri, H.D. Shih, and H.Q. Tserng, "*AlGaAs/GaAs Heterojunction Bipolar Transistor With 4 W/mm Power Density at X-band,*" IEEE MTT-S International Microwave Symp. Dig., p.969, 1987.

[2] N.H. Sheng, M.F. Chang, P.M. Asbeck, K.C. Wang, G.J. Sullivan, D.L. Miller, J.A. Higgins, E. Sovero, and H. Basit, "*High Power GaAlAs/GaAs HBTs for Microwave Applications,*" IEDM Tech. Dig., p.95, 1987.

[3] B. Bayraktaroglu, N. Camilleri, and H.Q. Tserng, "*AlGaAs/GaAs Heterojunction Bipolar Transistors for Power Application,*" IEEE/Cornell Conf. on Adv. Concepts in High Speed Semiconducd. Dev and Circuits, Ithaca, NY, 1987.

[4] B. Bayraktaroglu, N. Camilleri, "*Microwave Performances of npn and pnp AlGaAs/GaAs Heterojunction Bipolar Transistors,*" IEEE MTT-S Inter. Microwave Symp. Dig., p.529, 1988