ROBUST CASCODE HBTs for EFFICIENT HIGH POWER MICROWAVE APPLICATIONS

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ABSTRACT

A new Cascode HBT design was developed to overcome the thermal instability of high power HBTs without using ballast resistors. Thermally-Stabilized Cascode HBTs (TSC-HBTs) achieved unconditional thermal stability under dc bias as well as under high RF drive with large output mismatch conditions. Various cell sizes were developed for X/Ku-band applications to produce 0.25 W to 1.0 W output power with high power-added efficiency (70% at 8 GHz) and high power gain (>20 dB at 14 GHz).

INTRODUCTION

High power microwave HBTs, like their Si BJT counterparts, exhibit thermal instability related failures when operated under large dc or RF drive conditions. The basic cause of this instability is the negative temperature coefficient of the emitter-base turn-on voltage and the strong electrothermal feedback in devices with moderate to high thermal resistances. When a multi-finger HBT is biased from a single base voltage, the electrothermal feedback can cause one of the emitter fingers to conduct most of the available current to the whole device and therefore create a "hot spot". This condition is readily identified as a sharp drop in collector current ("*current crunch*" [1] *or* "*current collapse*" [2]) when devices are under strong dc bias.

The thermal instability in HBTs can be reduced by the use of ballast resistors in series with each emitter[3] or base finger[4], or by thermal-shunt techniques[5]. The stability achieved with ballast resistors usually come at the expense of reduced microwave performance, such as microwave gain and power-added efficiency (PAE). The reduction in power gain due to ballast resistors is especially undesirable at X-band and higher frequencies, where the power gain is already limited. Similarly, PAE above 50% is more difficult to achieve at these frequencies, since the higher efficiency amplifier modes require high external device transconductance, g_m, and g_m is inversely proportional to total emitter resistance. Further, emitter ballast resistors can cause an increase in the "knee voltage", which limits RF voltage swing amplitude and therefore PAE. Thermal shunt technique does not have the disadvantages associated with ballast resistors, and have demonstrated very high power density operation at 10 GHz with good PAE[5]. However, the robustness of thermal shunt HBTs under strong RF drive conditions has not yet been demonstrated.

In a TSC-HBT, thermal stability is achieved by regulating the current in each emitter finger independently[6]. It was shown that the DC power handling capability of an HBT can be increased by 300% in such designs by eliminating the negative electrothermal feedback effects. In this paper, we demonstrate that TSC-HBTs can produce high gain and efficiency at X/Ku-band frequencies while maintaining unconditional thermal stability. We have examined unit-cell sizes from 120 μm^2 to 720 μm^2 of emitter area to obtain output power values of 0.25 W to 1.0 W. All devices were tested for robustness by overstressing with dc bias and/or under high output VSWR conditions.

RESULTS AND DISCUSSION

A photograph of a 6-subcell TSC-HBT cell is shown in Figure 1. Each subcell contains two 1.5 x 20 μm^2 emitter fingers and 3 base fingers. A self-aligned emitter-base fabrication technique was used to fabricate HBTs on MOCVD-grown wafers. The spacing between the emitter fingers in the same subcell was 1.5 µm, which ensured an almost constant temperature within the subcell. No thermal runaway was observed with single subcell devices. Thermal shunt structures were used to thermally and electrically connect all emitters of the CE device. This further ensured the uniformity of collector current of each subcell. Cell designs with 2 to 6 subcells were included on the same mask so that the thermal and electrical properties of HBTs with 4 to 12 emitter fingers can be measured. No intentional ballast resistors were used in the cell designs. However, each emitter finger had 1.8Ω series resistance, mostly due to contact resistance.

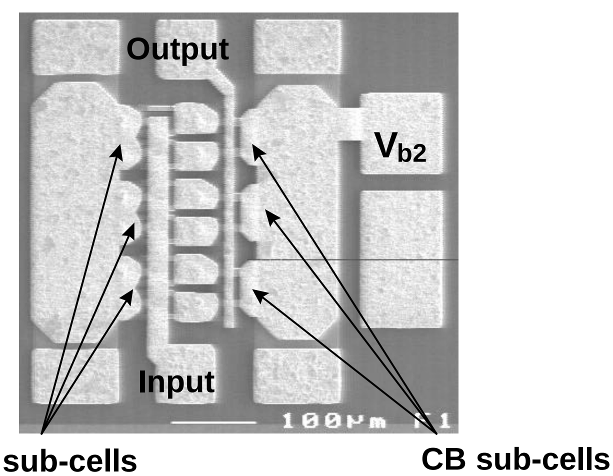

Figure 1: *Photograph of a 12-finger Cascode HBT with 6 sub-cells in common-emitter and common-base stages. The base voltage of the CB device is adjusted with V_{b2}.*

The small-signal microwave characteristics were measured on-wafer using coplanar probes in the frequency range of 0.5 - 26.5 GHz. The results are shown in Figure 2 for a 8-finger cell biased at V_c=10 V and various collector current values. The current gain cutoff frequency, f_T, extrapolated from $|h_{21}|^2$ vs. frequency curves is about 50 GHz, whereas the maximum frequency of oscillation, f_{max}, is much higher than 100 GHz by extrapolating along a -6 dB/octave line. The available power gain values at X-band frequencies are 30 dB or higher. This is the highest gain value reported to date with Cascode GaAs HBTs at these frequencies.

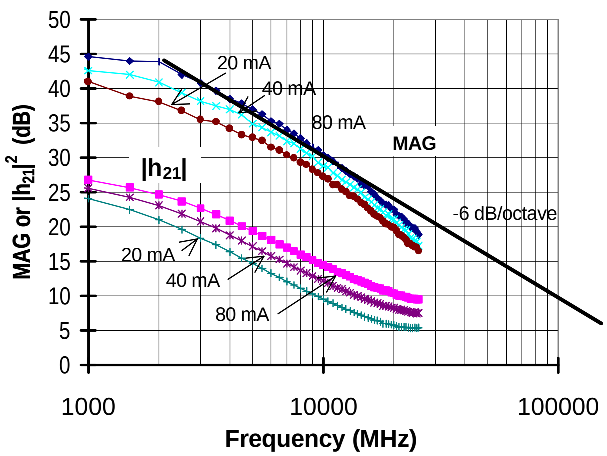

Figure 2: *Small-signal microwave characteristics of 8-finger TSC-HBT cell*

The large-signal microwave characteristics of various size cells were determined in a RCA automatic load-pull system in the range of 8 to 14 GHz. Figures 3 and 4 shows the performance of a 4-finger cell at 8 and 14 GHz. Minimum output power levels of 0.25 W were obtained with PAE values of 68% at 8 GHz and 58% at 14 GHz. It is interesting to note that the power gain is maintained above 20 dB across this frequency range. Up to 70% PAE was achieved with 8-finger cells with a minimum of 0.5 W output power. A 12-finger cell produced up to 1 W output power at 8 GHz with 61.5% PAE and 19.5 power gain. The results summarized in Table 1 demonstrate clearly the high gain and high efficiency potential of TSC-HBTs at X/Ku-band frequencies.

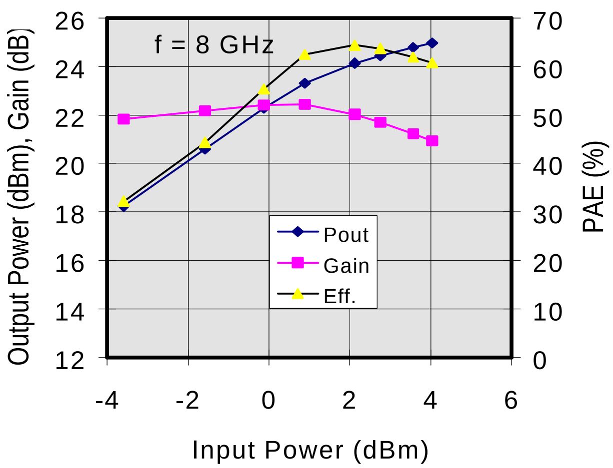

Figure 3: *Microwave performance of 160 m^2 TSC-HBT at 8 GHz.$_{Vc}$ = 10 V*

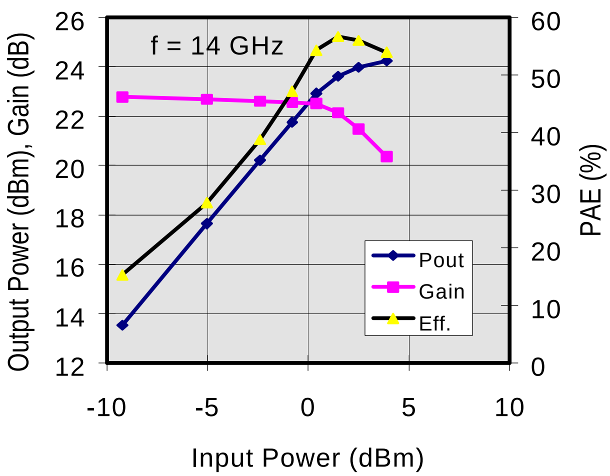

Figure 4: *Microwave performance of 160 m^2 TSC-HBT at 14 GHz. V_c = 10 V*

To demonstrate further that the high efficiency operation of TSC-HBT cells is not at the expense of robustness, we have tested 8-finger cells under high output VSWR conditions. The transistor was subjected to load impedances of 4:1 VSWR circle relative to the optimum load. The RF input drive was kept at the level where the transistor puts out the optimum power with a matched load. Such tests are instructive in determining the device robustness because when the load impedance is high and the output capacitance is not resonated out, the dynamic load line can swing into the thermal instability region of the I-V characteristics. The problem is illustrated for a transistor with conditional stability in Figure 5. A device failure can occur if the dynamic load line extends beyond the current collapse region, as shown. Since TSC-HBT does not exhibit thermal instability, no such failures were observed with 4:1 VSWR. We have also increased the dc voltage and current so that the transistor was biased with up to 300% the nominal bias conditions. No failures were observed with normal and 4:1 VSWR load lines with these bias conditions. Figure 6 illustrates schematically the tests conditions applied with no failures. Additional RF tests under open and short circuit conditions with 10V collector bias produced no failures either.

In conclusion, we have demonstrated that TSC-HBTs can produce efficient microwave power up to 14 GHz while demonstrating excellent ruggedness to overdrive and output mismatch conditions.

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Table I: Summary of TSC-HBT microwave results for various size cells.

DEVICE SIZE	Collector Voltage (V)	Pout (W)	Frequency (GHz)	Gain (dB)	PAE (%)
160 μm²	10	0.3	8	22.1	65.2
	10	0.25	14	22.0	56.1
320 μm²	10	0.5	8	19.5	70.0
	10	0.5	10	18.7	57.7
	10	0.5	12	17.2	55.5
	10	0.5	14	17.0	54.5
480 μm²	11	1.0	8	19.5	61.5

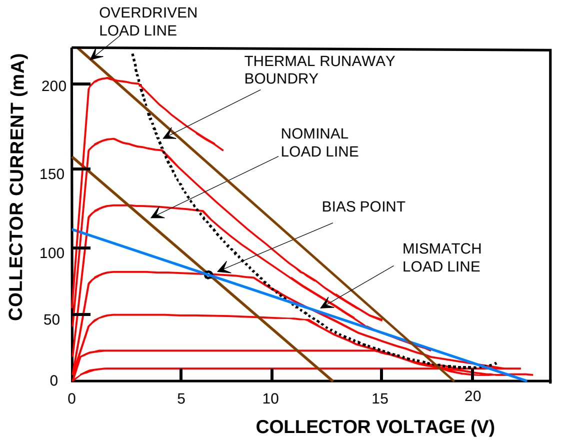

Figure 5: *Schematic drawing showing that the dynamic load line can extend beyond the stable I-V region when output is mismatched.*

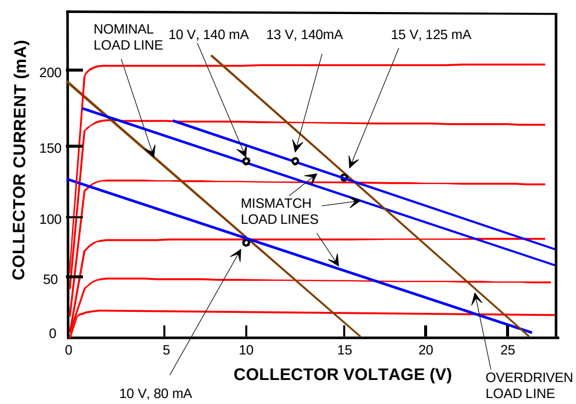

Figure 6: *The test conditions applied to TSC-HBT to demonstrate ruggedness under mismatch load conditions.*

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