Unconditionally Thermally Stable Cascode GaAs HBT's for Microwave Applications

Burhan Bayraktaroglu and Mike Salib

Abstract—**This letter describes the performance of a thermally stabilized cascode-heterojuction bipolar transistor (TSC-HBT) that exhibits unconditional thermal stability without the use of ballast resistors. A thermal isolation inserted between the current source (CE stage) and the power stage (CB stage) eliminates the positive electrothermal feedback that causes thermal runaway in bipolar transistors. The TSC-HBT cell designs with $f_{\max}$ values in excess of 100 GHz demonstrated about 300% improvement in dc power dissipation capability compared to conventional cascode HBT's in a direct comparison.**

I. Introduction

Heterojunction bipolar transistors (HBT's) used in high-power microwave amplifiers necessarily operate under large current and voltage bias conditions, which together cause an increase in the device temperature over the baseplate. The temperature rise due to self-heating is very significant in devices fabricated on GaAs substrates since the thermal conductivity of this material is particularly poor. The increase in the junction temperature has the net effect of lowering the emitter-base junction turn-on voltage. Because large devices have multiple emitter fingers and all fingers are electrically biased from the same voltage or current source, local variations in junction temperature can give rise to thermal runaway. This type of thermal instability has been observed and studied extensively in GaAs HBT's [1]–[3].

The common solution to the thermal runaway problem is the use of ballast resistors in series with each emitter finger [4] or base finger [5]. Such resistors consume real estate on the wafer surface, however, and can limit the microwave performance. An alternative to ballast resistors is the use of thermal-shunt structures between each emitter finger to maintain a uniform temperature across the unit-cell. It was shown that by connecting all emitter fingers by a single thermal shunt structure, 10 mW/μm^2 power density can be achieved at 10 GHz with 60% power-added efficiency [6].

Cascode HBT's are useful in wideband monolithic microwave integrated circuit (MMIC) applications [7] and are compatible with thermal shunt fabrication techniques [8]. In the thermally stabilized cascode HBT (TSC-HBT) described here, the thermal runaway conditions are prevented by placing the current and power generation regions into separate temperature zones. Unlike the conventional Cascode designs where the collector current of the *entire* common-emitter (CE) cell is connected to the emitter of the *entire* common-base (CB) cell, the connection is made at the subcell level in a TSC-HBT. This is illustrated in Fig. 1 by identifying each subcell as a transistor (three subcells are used for this example). In a conventional CE device [Fig. 1(a)], the base current component of each subcell is a function of the local temperature. The local temperature, which is influenced by the power consumed in each subcell, is proportional to the collector current component. Because the temperature dependent current regulator (e-b junction) and the temperature generator (b-c junction) are in the same physical location, a strong positive electrothermal feedback exists. For the TSC-HBT cell shown in Fig. 1(b), the CE stage is the current regulator, which is kept at a low temperature zone since it is biased at a low collector voltage. In effect, $i_{c1} = i_{c2} = i_{c3}$ condition is maintained. The CB stage, which is responsible for power generation, maintains a uniform temperature profile since $i_{c1} = i_{c2} = i_{c3}$ and $I_c = \alpha i_c$. The thermal runaway condition is avoided because the positive thermal feedback is eliminated between the current regulator (CE stage) and the power generator (CB stage). The two parts of the device are kept at two separate temperature zones. Any residual heat transfer from one part to the other is controlled by the cell design.

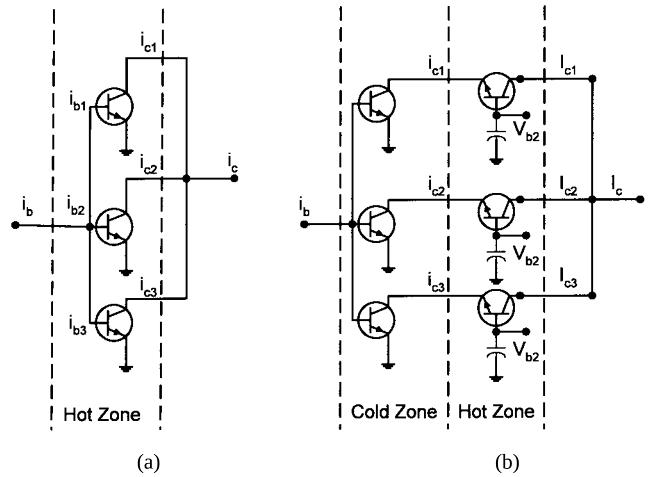

Fig. 1. Schematic drawing of a multifinger HBT showing current components. (a) Conventional common-emitter (CE) cell. (b) The new individually connected Cascode cell.

II. Results and Discussion

Fig. 2 shows a picture of a Cascode cell with six subcells. Each subcell contains two 1.5 × 20-μm^2 emitter fingers and

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The authors are with Northrop Grumman Corporation, Baltimore, MD 21203 USA.

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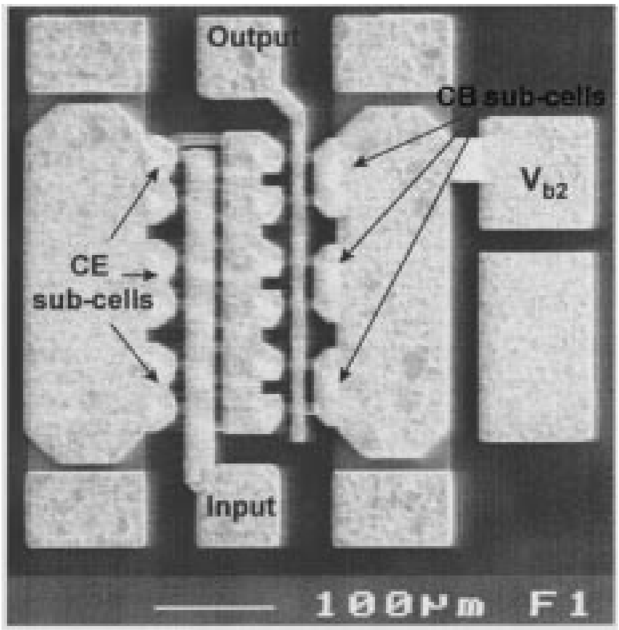

Fig. 2. Photograph of a 12-finger Cascode HBT with six subcells in common-emitter and common-base stages. The base voltage of the CB device is adjusted with V_{b2}.

three base fingers. A self-aligned emitter-base fabrication technique was used to fabricate HBT's 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 as shown in Fig. 2. This further ensured the uniformity of collector current of each subcell. Cell designs with two–six subcells were included on the same mask so that the thermal properties of HBT's with four–twelve emitter fingers can be compared. Further, identical-size Cascode designs with conventional connections were included for comparison. In a conventional Cascode cell, the all-collector contacts of the CE device were tied together. No intentional ballast resistors were used in the new or the conventional cell designs. Each emitter finger, however, had 1.8-Ω series resistance mostly due to contact resistance.

A direct comparison of the conventional and the TSC-HBT cells was made by measuring the maximum collector voltage that can be applied at 41-kA/cm^2 current density. It was observed that the conventional devices all had "current crunch" characteristics [2] due to thermal runaway, whereas all new designs were free from these effects up to the avalanche breakdown voltage at 14.5 V. The measured results are summarized in Fig. 3. The maximum voltage, $V_{\max}$ (i.e., the voltage at the onset of thermal runaway at 41 kA/cm^2 current density) shows an inverse relationship with the number of fingers contained in the cell for the conventional device. The TSC-HBT's had voltage values independent of the number of fingers. $P_{\max}$ was calculated by multiplying the maximum voltage across the CB device and the collector current, i.e., $P_{\max} = (V_{\max} - V_{b2}) * I_c$. It is seen that $P_{\max}$ value for the conventional device designs saturates at about 0.65 W as the number of fingers are increased from four to 12, whereas a monotonic increase is seen for the TSC-HBT. The power-handling capability of the 12-finger TSC-HBT is 300% higher than the conventional Cascode HBT fabricated on the same wafer.

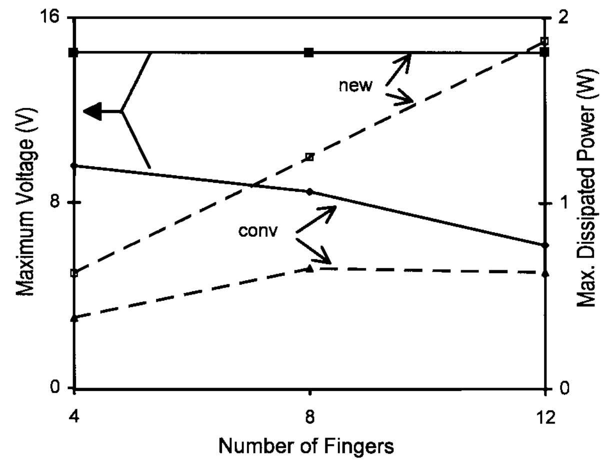

Fig. 3. The maximum voltage and power dissipation as a function of Cascode cell size. Both device types were fabricated on the same wafer. The measurements were taken at 41 kA/cm^2 current density.

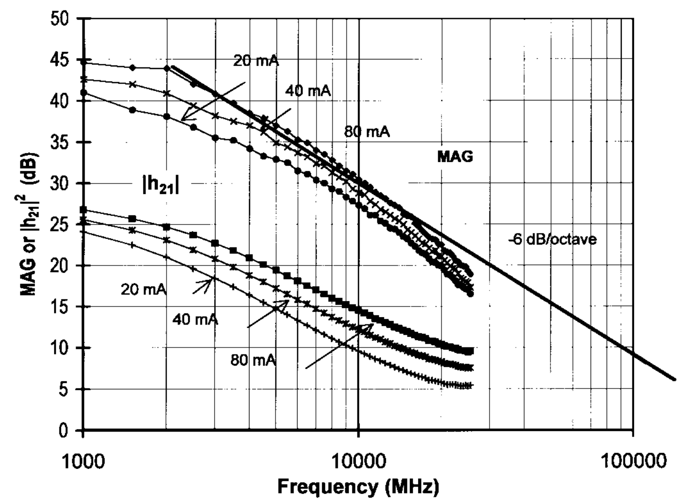

Fig. 4. Small-signal microwave characteristics of a eight-finger Cascode HBT as a function of collector current at $V_{\rm ce} = 9$ V and $V_{b2} = 2$ V.

The microwave performance of both Cascode types was compared by making on-wafer S-parameter measurements. The maximum available gain (MAG) values obtained with both device types were identical over a collector current range of 10–50 kA/cm^2 at 9-V collector bias. The measured values for a eight-finger TSC-HBT is shown in Fig. 4 as a function of the collector current. We estimate the maximum frequency of oscillation $f_{\max}$ to be higher than 100 GHz by extrapolating along a −6-dB/octave line.

In conclusion, we have demonstrated that TSC-HBT's can prevent thermal runaway conditions by individually regulating the emitter current of subcells in a power unit-cell. A direct comparison of devices fabricated on the same wafer indicated that TSC-HBT's can dissipate up to 300% more power than the conventional devices. It was also shown that the cells developed are suitable for microwave frequency applications.

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REFERENCES

[1] J. Higgins, "Thermal properties of power HBT's," *IEEE Trans. Electron Devices*, vol. 40, p. 2171, 1993.

[2] L. L. Liou and B. Bayraktaroglu, "Thermal stability analysis of AlGaAs/GaAs heterojunction bipolar transistors with multiple emitter fingers," *IEEE Trans. Electron Devices*, vol. 41, pp. 629–636, 1994.

[3] W. Liu and A. Khatibzadeh, "The collapse of gain in multi-finger heterojunction bipolar transistors: Its substrate temperature dependence, instability criteria, and modeling," *IEEE Trans. Electron Devices*, vol. 41, pp. 1698–1707, 1994.

[4] G. B. Gao *et al.*, "Emitter ballasting resistor design for, and current handling capability of AlGaAs/GaAs power heterojunction bipolar transistors," *IEEE Trans. Electron Devices*, vol. 38, pp. 185–196, 1991.

[5] W. Liu, A. Khatibzadeh, J. Sweder, and H. F. Chau, "The use of base ballasting to prevent the collapse of current gain in AlGaAs/GaAs heterojunction bipolar transistors," *IEEE Trans. Electron Devices*, vol. 43, pp. 245–251, 1996.

[6] B. Bayraktaroglu *et al.*, "Very high power density CW operation of AlGaAs/GaAs microwave heterojunction bipolar transistors," *IEEE Electron Device Lett.*, vol. 14, pp. 493–495, 1993.

[7] R. J. J. Komiak and L. W. Yang, "5 watt high efficiency wideband 7 to 11 GHz HBT MMIC power amplifier," in *IEEE Microwave and Millimeter Wave Monolithic Circuits Symp. Tech. Dig.*, 1995, pp. 17–20.

[8] C. A. Bozada *et al*., "Microwave power heterojunction bipolar transistors fabricated with thermal shunt and bathtub," in *IEEE GaAs IC Symp. Dig.*, 1995, pp. 155–158.