1 Watt, 65% PAE K-Band AlGaAs/GaAs Heterojunction Bipolar Transistors Using Emitter Air-Bridge Technology

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ABSTRACT

We report on the state-of-the-art power performance of K-band AlGaAs/GaAs heterojunction bipolar transistors (HBTs) which had emitter air-bridges to connect individual emitter fingers within the unit cells to reduce the emitter inductance and device thermal impedance. A $8 \times (1.6 \times 30)\ \mu m^2$ HBT achieved 1.04 W CW output power and 65.7 % power-added efficiency with 6.3 dB associated gain at 20 GHz. The maximum power-added efficiency measured was 67.5 % at an output power level of 0.93 W.

I. INTRODUCTION

Continual improvement in solid-state power transistor design and process technology has recently resulted in several K-band transistors with record performances. At 20 GHz, for example, a GaAs pHEMT operated at 8 V achieved 0.5 W output power and 60 % power-added efficiency (PAE) [1], an AlGaAs/GaAs HBT operated at 10.5 V delivered 1.18 W output power and 57.1 % PAE [2], and a flip-chip, low-thermal impedance AlGaAs/GaAs HBT operated at 12.7 V exhibited 1.21 W output power and 53 % PAE [3]. Compared to MESFETs and pHEMTs, HBTs offer significantly higher output power, power density and operating voltage [2].

This paper describes further advances in our K-band HBTs with 65.7 % PAE at an output power level of 1.04 W at 20 GHz at a collector bias voltage of 10.5 V. The PAE was significantly improved by replacing the collector air-bridge used in Ref. [2] with an emitter air-bridge without the need for any modification of our baseline HBT process.

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II. DEVICE DESIGN AND FABRICATION

The K-band HBT epitaxial layer structure is the same as that reported in [2] and is shown in Table 1. A key feature in the HBT structure was a 800 Å GaAs base doped at 1×10^{20} cm^{-3} with carbon, which resulted in a low base sheet resistance of 130 ohms/square. The base-emitter heterojunction was compositionally graded. The collector had a thickness of 7000 Å and was doped at 3×10^{16} cm^{-3}. The structure was grown by metal-organic chemical vapor deposition (MOCVD) using trimethylgallium, trimethylaluminum and tertiarybutylarsine for Ga, Al and As sources, and disilane and carbontetrachloride for n- and p-type sources, respectively.

Table 1. Epitaxial structure of K-band HBT.

Layer	Material	Thickness (nm)	Doping (cm^{-3})
Contact cap	$In_{0.5}Ga_{0.5}As$	40	Si: 1×10^{19}
Grading	InGaAs→GaAs	30	Si: 1×10^{19}
Emitter cap	GaAs	190	Si: 1×10^{18}
Grading	GaAs→AlGaAs	20	Si: 1×10^{18}
Emitter	$Al_{0.35}Ga_{0.65}As$	30	Si: 1×10^{18}
Grading	AlGaAs→GaAs	20	Si: 1×10^{18}
Base	GaAs	80	C: 1×10^{20}
Collector	GaAs	700	Si: 3×10^{16}
Subcollector	GaAs	1000	Si: 5×10^{18}
Buffer	$Al_{0.4}Ga_{0.6}As$	300	Undoped

The K-band HBT had a total emitter length of 240 μm, consisting of 8 emitter fingers with each finger having an area of $1.6 \times 30\ \mu m^2$. They were fabricated using TI's standard 4-mil substrate AlGaAs/GaAs HBT technology [4] with the exception of the addition

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of a self-aligned base, self-aligned ledge passivation process for improved device reliability. The base finger width was 0.8 μm and the passivation ledge width was about 0.35 μm. Center-to-center emitter finger spacing was 25 μm. Unlike our baseline collector air-bridge layout configuration, however, the power gain and therefore the power-added efficiency were significantly improved by using an emitter air-bridge to connect individual emitter fingers within the unit cell to nearby ground vias to reduce the emitter inductance. The 5-μm-thick electroplated air-bridge also provides a second heat conduction path from the collector through the base, emitter, emitter air-bridge and ground vias to the backside heatsink. Fig. 1 compares the heat conduction paths in both types of transistors. Despite the significant difference in layout topology between the two types of transistors, no process modification was needed to realize the emitter air-bridged transistors. In fact, the HBTs with collector air-bridges reported in [2] and emitter air-bridges reported in this work were fabricated on the same wafers in the same process lot. The power unit cells were fully base-ballasted to ensure absolute thermal stability [5]. All power unit cells incorporate partial input matching circuitry to increase the low device input impedance to a reflection tolerated by the source tuner for input matching to facilitate accurate

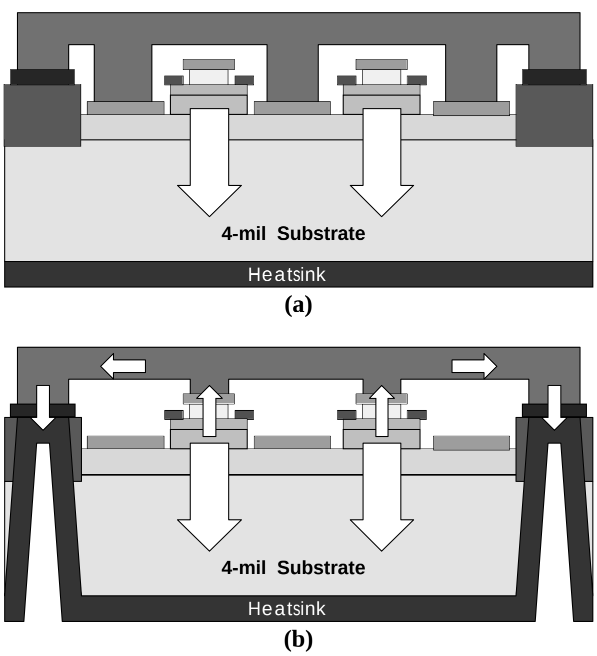

Fig. 1. Heat conduction paths in HBTs with (a) collector air-bridge and (b) emitter air-bridge.

load-pull measurements. Fig. 2 shows the scanning electron micrograph of the completed HBT unit cell. Unit cells without the prematching circuitry were also fabricated for on-wafer small-signal characterization.

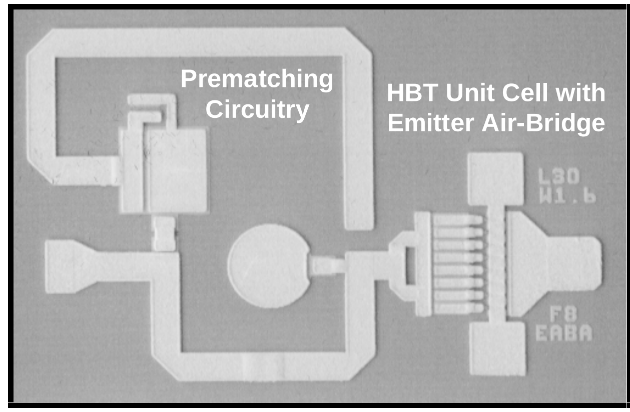

Fig. 2. Fabricated 8 × (1.6 × 30) μm^2 HBT unit cell with partial input matching circuitry.

III. TRANSISTOR CHARACTERISTICS

The common-emitter I_C-V_{CE} characteristics of a 8 × (1.6 × 30) μm^2 HBT unit cell is shown in Fig. 3. The transistor exhibited a dc current gain of 10 and a base-collector breakdown voltage of 24 V.

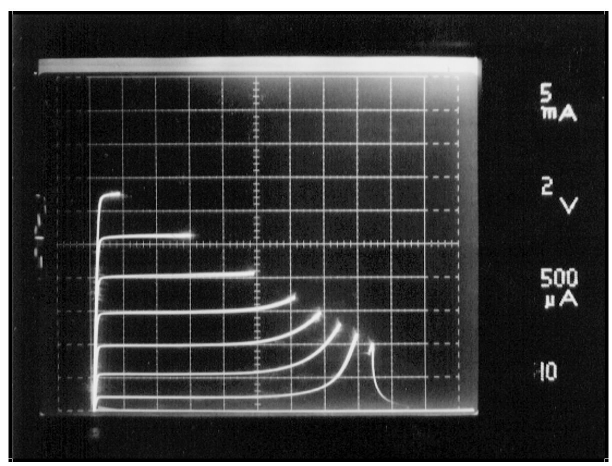

Fig. 3. Common-emitter I_C-V_{CE} characteristics of a 8 × (1.6 × 30) μm^2 HBT unit cell.

On-wafer small-signal S-parameter measurements indicated that the HBT exhibited a maximum available gain (MAG) of 10.1 dB at 20 GHz at a bias of V_{CE} = 5 V and I_C = 90 mA (which corresponds to a current density J_C = 23 kA/cm^2) (Fig. 4). At the same V_{CE}

bias voltage of 4 V and current density J_C of 23 kA/cm^2, HBT with an emitter air-bridge had about 0.65 dB higher gain than one with a collector air-bridge.

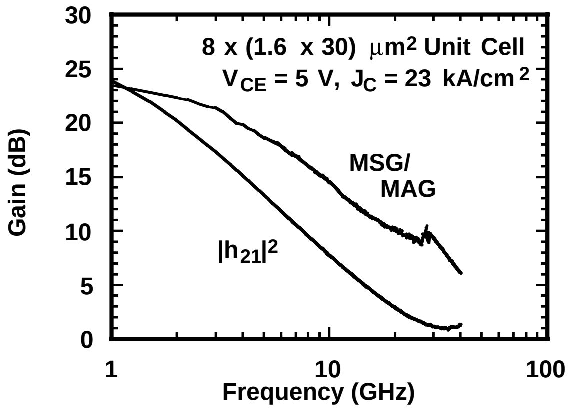

Fig. 4. Microwave characteristics of a 8 × (1.6 × 30) μm^2 HBT unit cell.

Bias-dependent measurements were also performed on the unit cell with a collector voltage ranging from 4 to 5 V and current density varying from 8 to 23 kA/cm^2. As shown in Fig. 5, the measured MAG at 20 GHz increased monotonically with current density and collector bias voltage. Since the device had no proper heat sinking, we did not attempt to go to higher collector voltage and current with on-wafer measurements.

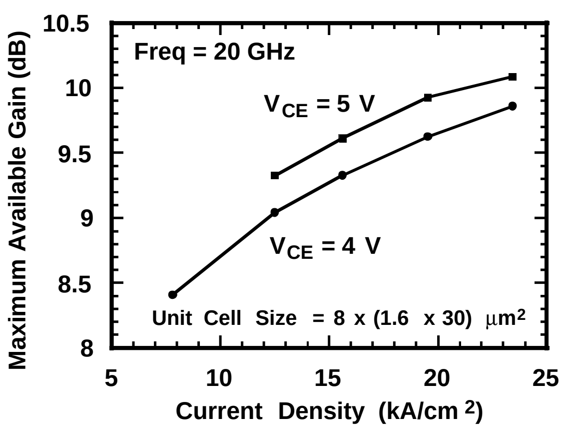

Fig. 5. Measured small-signal maximum available gain as a function of J_C and V_{CE} for a 8 × (1.6 × 30) μm^2 HBT unit cell.

Power characterization of 8 × (1.6 × 30) μm^2 HBT devices at 20 GHz was made with an automated K-band load-pull system in a test fixture environment. HBT unit cells were mounted on Au carriers with AuSn solder, and bonded to 50 Ω microstrip lines on 10 mil thick alumina substrates mounted on a brass test fixture with 3.5 mm K-connectors. Partial input matching circuitry and test fixture losses have been characterized and removed from the measurements to obtain de-embedded results.

Fig. 6 shows the measured output power (P_{out}), power-added efficiency (PAE) and collector efficiency of a 8 × (1.6 × 30) μm^2 cell at a collector voltage of 10.5 V and quiescent current of 30 mA. A CW output power

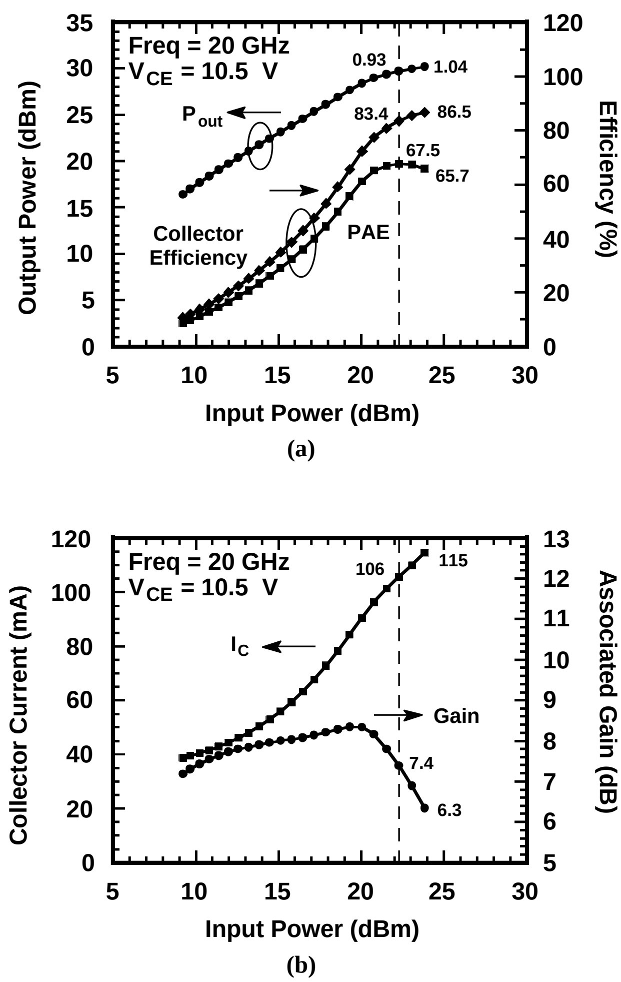

Fig. 6. Measured (a) CW output power, PAE and collector efficiency, and (b) collector current and associated gain of a 8 × (1.6 × 30) μm^2 HBT unit cell.

of 1.04 W (4.3 W/mm), 65.7 % power-added efficiency, 86.5 % collector efficiency, and 6.3 dB associated gain were achieved at 20 GHz from the 240 μm transistor. This combination of power, power density, efficiency and operating voltage is state of the art for any solid-state technology at this frequency. The transistor exhibited 67.5 % maximum power-added efficiency at 0.93 W (3.9 W/mm) output power level. No intentional harmonic tuning was applied in the measurements.

We also measured the frequency-dependent CW power performance of a 8 × (1.6 × 30) μm^2 HBT. The results are plotted in Fig. 7. We observed that even though a K-band transistor held well at 10.5 V at 20 GHz, it might degrade or fail at slightly different frequencies probably due to different mismatch conditions. For this reason, the collector bias voltage was lowered to 10 V and the RF input power was fixed at 21.2 dBm. As shown, the output power and associated gain were highest at 22 GHz. At this frequency, the transistor delivered 0.75 W output power and 7.6 dB associated gain while maintaining a respectable PAE of 62.2 %.

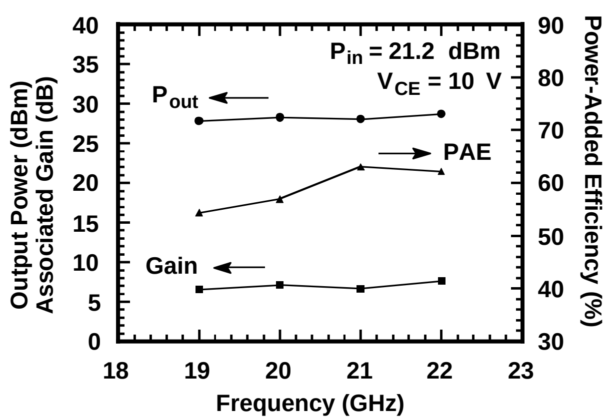

Fig. 7. Measured frequency-dependent CW power performance of a 8 × (1.6 × 30) μm^2 HBT unit cell biased at V_{CE} = 10 V. The input power was fixed at 21.2 dBm.

IV. CONCLUSION

We have demonstrated state-of-the-art performance of AlGaAs/GaAs HBTs at K-band. 240 μm unit cells achieved 1.04 W CW output power (4.3 W/mm output power density) with 65.7 % power-added efficiency, 86.5 % collector efficiency and 6.3 dB associated gain at 20 GHz at a collector bias of 10.5 V. The maximum PAE achieved was 67.5 % at 0.93 W output power level at the same frequency. Considering the combination of high power density, power-added efficiency, collector efficiency and operating voltage, we believe that the AlGaAs/GaAs HBT with an emitter air-bridge is a promising technology for microwave power applications at K-band, and no modification in HBT baseline process is needed.

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