High-Power High-Efficiency X-Band AlGaAs/GaAs Heterojunction Bipolar Transistors with Undercut Collectors

Hin-Fai Chau, *Senior Member, IEEE*, Grant Wilcox, Wenliang Chen, *Member, IEEE*, Marcel Tutt, and Timothy Henderson, *Member, IEEE*

***Abstract*— We report on the power performance of X-band AlGaAs/GaAs heterojunction bipolar transistors with undercut collectors for reduced base-collector capacitance. A 10 × (2.8 × 50) μm^2 HBT unit cell exhibited 2.09-W continuous wave (CW) output power (4.18-W/mm power density), 62.2% power-added efficiency, and 7.13-dB associated gain at 10 GHz at a collector bias voltage of 10 V. When tuned for maximum efficiency, the same transistor delivered a CW output power of 1.36 W, a power-added efficiency of 74.2%, and an associated gain of 7.32 dB at the same frequency and collector bias voltage. To our knowledge, this is the first demonstration of high-power (>1.3 W), high-efficiency (>74%) AlGaAs/GaAs HBT's using a simple collector undercut technique without the need for significant modifications of baseline HBT process.**

I. Introduction

Although previous reports have shown impressive power-efficiency performance of AlGaAs/GaAs heterojunction bipolar transistors (HBT's) [1]–[4], continual improvement in device and process design is needed for next-generation HBT power amplifiers. Several techniques were reported to enhance the HBT microwave and power performance. They can generally be classified into two categories: 1) improvement in HBT epitaxial layer structure and 2) improvement in layout and process design. In the former case, for example, the use of 1×10^{20} cm^{-3} base doping led to the demonstration of 1.2 W, 57% power-added efficiency (PAE) AlGaAs/GaAs HBT's at 20 GHz [2]; the use of extrinsic base regrowth and InGaAs graded base resulted in a maximum oscillation frequency ($f_{\max}$) in excess of 238 GHz [3]. In addition to better material design, HBT microwave performance can be improved by more aggressive layout and process design. For example, since the power performance of HBT's is thermally limited, great attention has been paid in recent years in reducing the device thermal impedance. Techniques in this category include thinner substrate (~30 to 50 μm) [4], bathtub via [5], thermal shunt [6], and flip-chip design [7]. The use of thinner substrate and bathtub via or having the transistor flipped brings the heatsink closer to the device. The thermal shunt provides a second heat conduction path from the heat-dissipated collector region through the base, emitter, and cap layers to the thick and wide emitter air-bridge (the shunt), substrate, and backside heatsink. These technologies, however, have several potential drawbacks. Thinner substrate leads to more difficult wafer handling. Bathtub via poses structural rigidity concern especially during assembly. Increased strain on HBT reliability in the thermal shunt and flipped transistors is not clear.

We recently demonstrated a simple collector undercut technique to reduce the base-collector capacitance by over 50% and increase the small-signal gain by 3 dB at 10 GHz [8]. In this letter, high-power (>1.3 W), high-efficiency (>74%) AlGaAs/GaAs HBT's were demonstrated for the first time using the same technique without the need for significant modifications of our baseline HBT process.

The standard X-band AlGaAs/GaAs HBT epitaxial layer structure has been published elsewhere [9]. To facilitate the collector undercut process, two AlGaAs etch stop layers were inserted in the collector and subcollector layers. Selective BCl_3/SF_6 reactive ion etching (RIE) was used to physically remove the extrinsic GaAs collector material over the two AlGaAs etch stop layers. When the vertical etching of GaAs collector was completed, the etch then proceeded laterally until an undercut of a desirable amount was accomplished. The etch stop layer in the collector prevented the base layer from being etched from the bottom. The etch stop layer in the subcollector prohibited vertical etching from the top. Since the undercut regions were filled up with air which has the smallest dielectric constant possible, the base-collector capacitance was minimized. Details of the collector undercut fabrication process were described in [8]. HBT unit cells with different emitter finger widths and lengths were fabricated using TI's standard collector air-bridge HBT process [9] except for the addition of a self-aligned base, self-aligned ledge passivation process for improved reliability. Fig. 1 shows the scanning electron micrograph of the cross-section of a completed X-band AlGaAs/GaAs HBT with undercut collector. The active emitter finger width was 2.8 μm and the passivation ledge width was 0.6 μm. The undercut was made to stop right at the edge of the emitter contact. Even though the base metal contacts and base layer were hanging as shown, the entire structure was mechanically stable. We have fabricated over 23

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H.-F. Chau was with Corporate Research & Development, Texas Instruments, Inc., Dallas, TX 75243 USA. He is now with EiC Corporation, Santa Clara, CA 95054 USA.

G. Wilcox is with Systems Group, Texas Instruments, Inc., Dallas, TX 75265 USA.

W. Chen, M. Tutt, and T. Henderson are with Corporate Research & Development, Texas Instruments, Inc., Dallas, TX 75243 USA.

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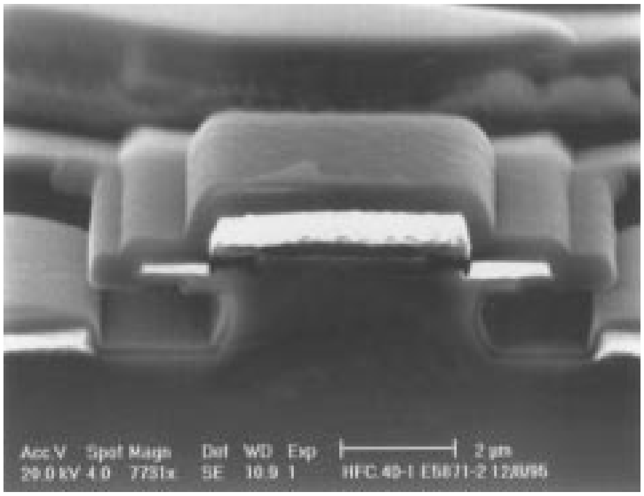

Fig. 1. Scanning electron micrograph of an AlGaAs/GaAs HBT with undercut collector.

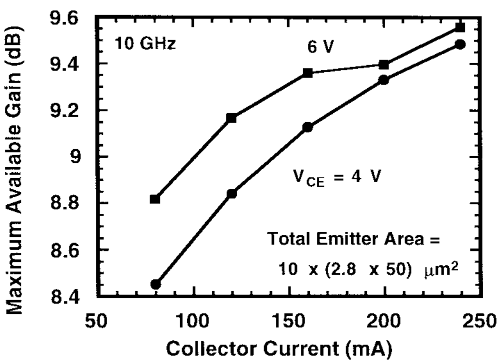

Fig. 2. Measured small-gain maximum available gain of a 10 × (2.8 × 50) μm^2 AlGaAs/GaAs HBT unit cell.

wafers thus far with the collector undercut process and have not observed any loss of transistors due to the crushing of the hanging base onto the subcollector layer.

To facilitate accurate on-wafer load-pull power measurements, all power unit cells incorporated partial input matching circuits to bring the input impedance reasonably close to 50 Ω. The loss due to this prematching circuit was 0.39 dB at 10 GHz. We also fabricated power unit cells of the same geometry without the prematching networks for on-wafer small-signal measurements. Fig. 2 shows the measured small-signal maximum available gain (MAG) of a ten-finger HBT unit cell, with each finger having an emitter area of 2.8 × 50 μm^2. At a collector bias of 4 V, the MAG increased from 8.4 to 9.5 dB when the collector current was raised from 80 to 240 mA. The gain was generally higher as the collector voltage was increased from 4 to 6 V. Since the transistor had no proper heat sinking, we did not attempt to go to higher collector voltage and current with on-wafer measurements.

The measured output power ($P_{\rm out}$), power-added efficiency (PAE), and associated gain of a 10 × (2.8 × 50) μm^2 HBT unit cell is shown in Fig. 3 when the transistor was tuned for maximum output power. The collector bias voltage was 10 V and the quiescent collector current was 125 mA. At 10-GHz frequency, the transistor exhibited 2.09-W CW output

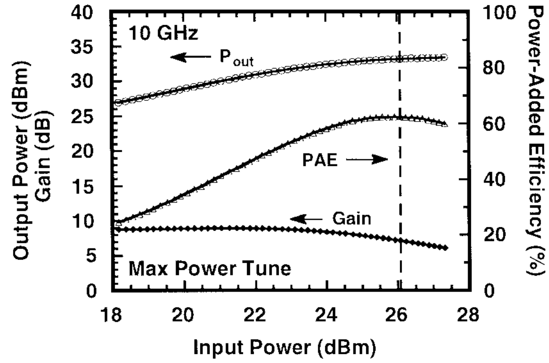

Fig. 3. Measured power performance of a 10 × (2.8 × 50) μm^2 AlGaAs/GaAs HBT unit cell when tuned for maximum power.

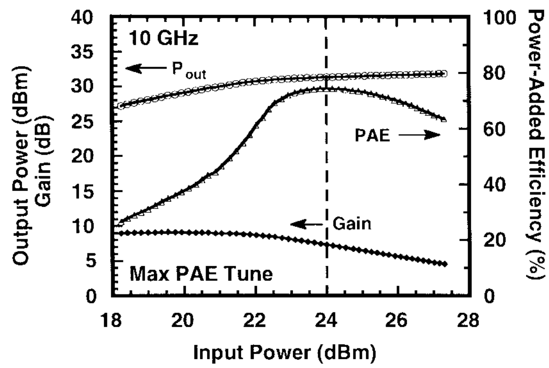

Fig. 4. Measured power performance of a 10 × (2.8 × 50) μm^2 AlGaAs/GaAs HBT unit cell when tuned for maximum efficiency.

power (4.18-W/mm power density), 62.2% PAE, and 7.13-dB associated gain. Under such conditions, the average collector current increased to 268 mA. No intentional harmonic tuning was applied in the measurements. When the same transistor was tuned for maximum efficiency under the same collector bias voltage, we achieved a record PAE of 74.2% at an output power level of 1.36 W (2.72-W/mm power density) at 10 GHz (Fig. 4). The corresponding associated gain was 7.32 dB and average collector current was 146 mA. Under the maximum efficiency bias conditions, the transistor was operated closer to class B operation. It has been shown that because the transconductance (g_m) of the HBT has an exponential dependence on input voltage ($V_{\rm in}$), class B operation was shown to achieve an output efficiency of 90.2% from an exponential $g_m(V_{\rm in})$ [10] as compared to 85% from a linear $g_m(V_{\rm in})$ and 78% from a constant $g_m(V_{\rm in})$ [11]. The 74% PAE achieved in our HBT's indicated that the HBT's have very small parasitic resistances.

To study the variations of power performance of these transistors across the 3-in wafer, we did load-pull power testing on a number of unit cells of the same geometry. When the 10 × (2.8 × 50) μm^2 HBT's were tuned for maximum output power, the maximum PAE varied from 61.4% to 62.2%, and the CW output power level varied from 2.09 to 2.19 W. When tuned for maximum efficiency, the transistors exhibited a maximum PAE in the range of 69.5% to 74.2% at an output power level of 1.37 to 1.52 W. This efficiency level was about 10% better than our standard X-band HBT's of the same geometry and similar output power level. The improvement in PAE was due to the more-than 50% reduction in the base-collector capacitance in the undercut collector HBT's as detailed in [8].

In summary, we have demonstrated high-power (>1.3 W), high-efficiency (>74%) X-band AlGaAs/GaAs HBT's using a simple collector undercut technique without the need for significant modifications of our baseline HBT process. This level of performance indicated that AlGaAs/GaAs HBT's with undercut collectors is a promising technology for next generation HBT power amplifiers.

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