A High-Performance AlInAs/InGaAs/InP DHBT *K*-Band Power Cell

Robinder S. Virk, Mary Y. Chen, Chanh Nguyen, Takyiu Liu, Mehran Matloubian, and David B. Rensch

***Abstract*— In this letter the device design and power performance of several AlInAs/InGaAs/InP double heterojunction bipolar transistors (DHBT's) are reported for 18 GHz. The power cells utilize a wet chemical etching technique to create a micro-airbridge base connection and to remove extrinsic collector material from beneath the base which both contribute to a reduced base–collector capacitance and improved $f_{\max}$ and power gain. For Class B operation, the eight-finger 2 μm × 30 μm power cells achieved 1.17-W output power, which indicates 4.88-W/mm emitter length, with 54% power-added efficiency (PAE) and 7.3-dB gain. This is believed to be the best combination of PAE and output power reported for this power density at *K*-Band frequencies.**

I. Introduction

SOLID-STATE power amplifiers are rapidly replacing traveling-wave tubes for satellite communication systems at *C*-, *Ku*-, and *K*-band frequencies because they are highly reliable and offer the advantages of lower cost, smaller size, and lighter weight. Heterojunction bipolar transistors (HBT's) are ideal devices to use in these amplifiers because of their power density, operating voltage, linearity, and efficiency.

The development of InP-based double heterojunction HBT's (or DHBT's) for microwave power applications has generated great interest due to the higher power density and larger power-added efficiency (PAE) which DHBT's offer in comparison to single HBT devices (SHBT's). Recently, excellent *X*-band power performance of AlInAs/InGaAs/InP DHBT's has been demonstrated where a linear-delta arsenide-chirped superlattice base–collector grade was utilized to aid the injection of electrons into the InP collector [1]. This unique bandgap engineering eliminated the conduction band discontinuity between the GaInAs base and the InP collector to achieve both speed and breakdown voltage advantages for the power cells [2]. In this letter, we report the high performance of various power cells at 18 GHz achieved through device design modifications of the successful *X*-band devices, employed to reduce the base–collector capacitance, minimize interfinger phase shift, and increase f_t and $f_{\max}$.

II. Device Design and Fabrication

The epitaxial device structure was grown on 3-in-diameter semi-insulating InP substrates using a gas-source Varian Mod Gen II MBE machine. The material layer structure for the 18-GHz power cells is shown in Table I. This structure is

TABLE I
K-Band DHBT Epitaxial Layer Structure. Note that CSL Represents Chirped Superlattice

Layer	Material	Thickness (nm)	Doping (cm^{-3})
Contact Layer	GaInAs	200	$n+ = 10^{19}$
Emitter	AlInAs	40	$n+ = 10^{19}$
Emitter	AlInAs	60	$n = 8\cdot10^{17}$
E-B SL Grade	10 x 3.3 nm CSL AlInAs/GaInAs	22 99	$n = 4\cdot10^{17}$ $p = 2\cdot10^{18}$
E-B Spacer Layer	GaInAs	5	$p = 2\cdot10^{18}$
Base	GaInAs	60	$p = 3\cdot10^{19}$
B-C Spacer Layer	GaInAs	5	$p = 2\cdot10^{18}$
C-B Grade	33 x 1.5 nm CSL GaInAs/AlInAs	25.5 25.5	$p = 10^{17}$ $n = 3\cdot10^{16}$
Delta Doping Sheet	InP	2.0	$n = 2\cdot10^{18}$
Collector	InP	500	$n = 3\cdot10^{16}$
Sub-Collector	InP	100	$n+ = 10^{19}$
Sub-Collector	InGaAs	700	$n+ = 10^{19}$

similar to that used in [1] except this device incorporates a thinner collector of 5000 Å, which is doped at 3 × 10^{16} cm^{-3}, resulting in a base–collector breakdown voltage of approximately 15 V.

In order to achieve high performance at *K*-band frequencies, the *X*-band power cells also required several device modifications. The utilization of a selective wet chemical etching technique [3] reduces the parasitic base–collector capacitance, which is significant for higher $f_{\max}$ and power gain, by allowing the use of a micro-airbridge to connect the base material to the feeding structure, shown in Fig. 1. Although this concept is not new in HBT's, previously reported results are only for GaAs/AlGaAs HBT's [4] and InP/InGaAs single-heterojunction HBT's [5]. During this etching process, the extrinsic collector material can also be removed from under the base material, reducing the capacitance further. The result is a total reduction of the parasitic base–collector capacitance by approximately 80%. By reducing the pitch of the emitter finger spacing to 10 μm, the inter-emitter phase shift of the multifinger power cells can be reduced to improve performance, since distributed effects can limit the gain at higher frequencies. To improve uniformity of the emitter–base junction temperature and the current flow among the emitter fingers of the power cells, a gold-plated airbridge is used to thermally connect all of the emitter fingers and shunt the heat to the 600-μm (unthinned) substrate.

III. Results

The common-emitter I_c–V_{ce} characteristics of a 2 μm × 20 μm HBT cell exhibited a dc current gain of 75 when

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The authors are with Hughes Research Laboratories, Inc., Malibu, CA 90265-4799 USA.

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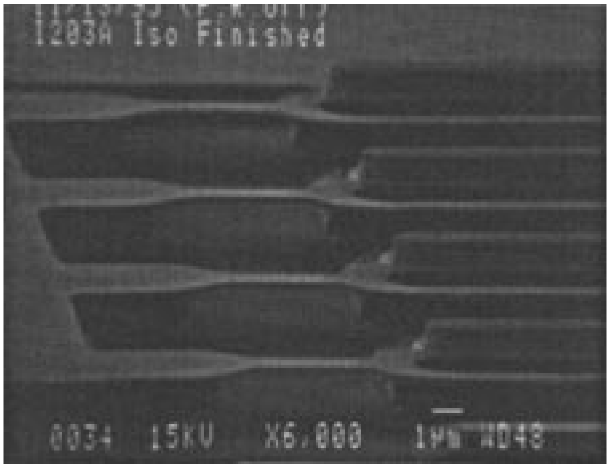

Fig. 1. SEM photograph of DHBT micro-airbridge base connection. The extrinsic collector material has been selectively etched to reduce the base–collector capacitance.

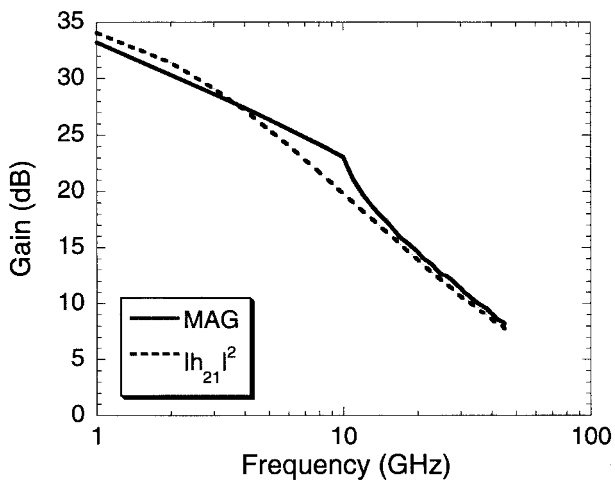

Fig. 2. Measured small-signal performance of a 2 μm $\times$ 30 μm DHBT power cell with micro-airbridge. The measured f_t and $f_{\max}$ are 99 and 102 GHz, respectively.

$J_c = 6.5 \times 10^4$ A/cm^2 and $V_{\rm ce} = 2$ V. The resulting small-signal performance has also been measured for a 2 μm $\times$ 30 μm emitter DHBT, as shown in Fig. 2, and the typical f_t and $f_{\max}$ was measured to be 99 and 102 GHz, respectively, where $J_c = 6.7 \times 10^4$ A/cm^2 and $V_{\rm ce} = 2.5$ V. The f_t and $f_{\max}$ of the typical eight-finger 2 μm $\times$ 30 μm DHBT power cell were also measured and found to be around 60 GHz for $J_c = 3.5 \times 10^4$ A/cm^2 and $V_{\rm ce} = 2$ V.

The power performance was measured at 18 GHz using an on-wafer active load-pull system provided by Hewlett-Packard [6]. Various devices were measured for CW output power and efficiency in Class B mode operation with both fundamental and second harmonic load tuning. Fig. 3 shows the PAE of the various devices tested where $V_{\rm ce} = 4.5$ V. All of the power cells exhibit a very repeatable PAE of 50% or above while providing 500–600-mW output power at around 10-dB gain. The figure also illustrates the improvement in performance attained using the micro-airbridge technique where the PAE is increased from 51% to 56% for the eight-finger 2 $\times$ 30 μm^2 device for comparable gain ($\sim$9.5 dB) and output power

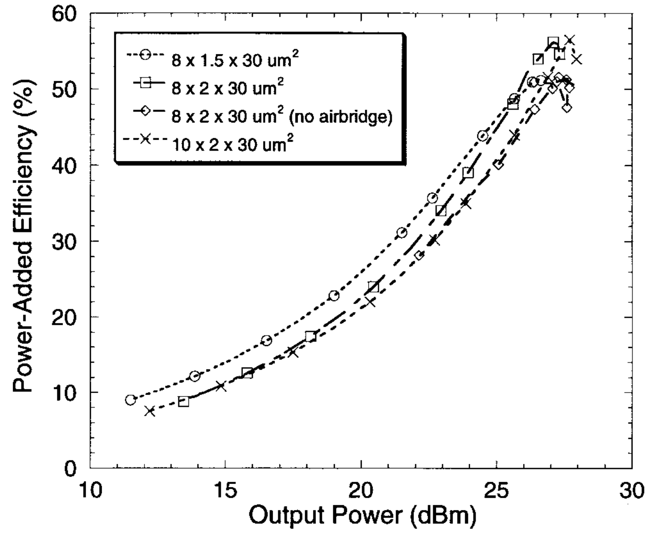

Fig. 3. Measured PAE of four different power cell designs at 18 GHz. The collector–emitter voltage is 4.5 V.

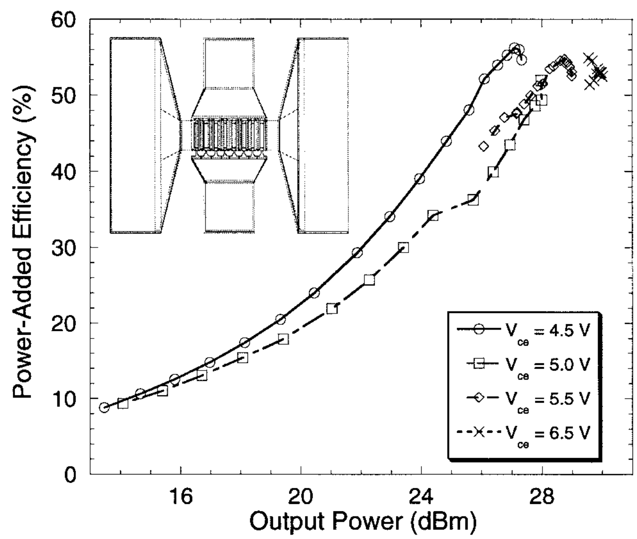

Fig. 4. Measured PAE at 18 GHz for the eight-finger 2 $\times$ 30 μm power cell with micro-airbridge for collector–emitter bias voltages ranging from 4.5 to 6.5 V. A sketch of the device layout is also shown.

($\sim$27 dBm). The PAE for the 8 $\times$ 2 $\times$ 30 μm^2 device with airbridge is shown, as a function of output power, for a variety of collector–emitter bias voltages in Fig. 4 with a sketch of the device layout. The power sweep at $V_{\rm ce} = 6.5$ V passes through the condition where the output power is 1.0 W with 53% PAE and 6.9-dB gain. With additional tuning of the load, the power cell achieved a maximum output power of 1.17 W, which indicates 4.88-W/mm emitter length, with 54% PAE and 7.3-dB gain. Note that the power sweeps have been limited at the larger bias voltages due to thermal stability issues. Previous experience with emitter–ballast resistors suggests that the thermal stability of these power cells could be substantially improved resulting in higher collector biases and higher output power levels as demonstrated in [7]. The results compare favorably to previously published reports; although comparable output power has been reported by Texas Instruments [8] at 20 GHz with a 57% PAE, the power cell's power density is only 3.93 W/mm with 6.6-dB gain.

IV. Conclusion

State-of-the-art device design and power performance of several AlInAs/InGaAs/InP DHBT's have been reported for 18 GHz. Through the incorporation of a wet chemical etching and a micro-airbridging technique, both the parasitic base–collector capacitance and emitter finger spacing have been reduced to improve f_t, $f_{\max}$, and power gain. For Class B operation, the eight-finger 2 μm $\times$ 30 μm power cells achieved 1.17-W output power, indicating 4.88-W/mm emitter length, with 54% PAE and 7.3-dB gain, which is believed to be the best combination of PAE and output power reported for this power density at *K*-band frequencies.

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