High-Power, High-Efficiency Cell Design for 26 GHz HBT Power Amplifier

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ABSTRACT

We describe a 6-chip combination HBT power amplifier and a single-cell chip with excellent power-added efficiency (PAE) and power density at 24-26 GHz. The power amplifier, based on our conventional chip design, exhibited 2.2 W outout power with 19 % PAE and 5 dB linear gain. To further improve the efficiency and power-density, various types of HBT cells were characterized. The optimum cell (184 μm^2) exhibited 740 mW output power equivalent to power density of 4.0 $mW/\mu m^2$, while a record high PAE of 42% was obtained. These results compare well with the best data reported at lower frequency bands (<18 GHz), thereby showing great potential for high-power, high-efficiency HBTs in near mmWave bands.

INTRODUCTION

Hetrojunction bipolar transistors (HBTs) have demonstrated excellent potential for microwave power amplifiers because of their exceptionally high power density [1], high-efficiency [2] and good linearity [3]. Most applications, however, have been limited to 1-18 GHz bands mainly due to limited f_{max} as compared to (P)HEMTs. We have shown that improving base contact using epitaxial regrowth makes it possible to routinely obtain an f_{max} of above 200 GHz [4]. The technology was then applied to a power HBT, resulting in 650mW output power per cell with 17% power-added efficiency (PAE) at 26 GHz [5].

In this paper we first describe the performance of a power amplifier consisting of 6 unit-cell chips based on conventional device design. For high-power applications such as SSPA for intersatellite communication, both PAE and power-density are crucial factors because the efficiency of power combination of the powers from many cells suffers as the frequency increases to higher bands. We demonstrate that the cell design is particularly important in such high-frequency bands as 26 GHz in achieving high PAE and power-density.

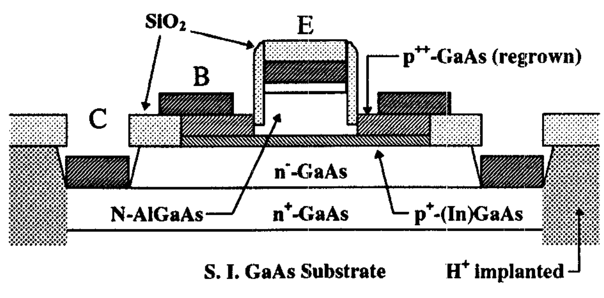

Fig. 1 Schematic cross section of AlGaAs/(In)GaAs HBT with regrown base contact layers

DEVICE DESCRIPTION

The details of the processing steps used to fabricate the HBTs are described elsewhere [4]. After SiO_2 emitter-sidewall formation, the extrinsic part of the base was selectively regrown by MOMBE in a self-aligned manner (Fig. 1). Due to extremely high carbon doping (2×10^{20} cm^{-3}) of the regrown epi-layer, the base contact resistivity was less than 10^{-7} Ωcm^2,

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thereby reducing the base resistance by a factor of 1/4 as compared to conventional technology. Note that the parasitic base-collector capacitance lying beneath the base contact can also be minimized becasue the base contact region width can be made as small as 0.75 μm without sacrificing the base resistance. With regard to the intrinsic base layer, both a uniform GaAs base (C-doped, 40nm, 4×10^{19} cm^{-3}) and a graded $In_xGa_{1-x}As$ base [4] (Be-doped, 40nm, 6×10^{19} cm^{-3}) were used. The f_{max} for 1.6μm x 6.5μm size emitter was 142 GHz and 238 GHz for a uniform base and graded base HBT, respectively.

POWER AMPLIFIER PERFORMANCE

Fig. 2 shows the HBT power amplifier consisting of 6 unit-cell chips. (We define a cell as a transistor with a *single feed* for both input and output.) Each chip with a total emitter junction area of 470 μm^2 is capable of producing 650 mW output power [5]. The chips were die-mounted on carrier which was then assembled into a 50-Ω microstrip line test fixture. Impedance matching was done by tuning within the fixture (Fig. 3). No active-load external tuning was attempted. The 6-chip combination produced 2.2 W with 5 dB associated gain and 19% PAE (corrected for fixture loss) at 24 GHz (Fig. 4). Considering the potential output power for each cell, greater power (>3W) should be obtained by optimizing the power combining circuit (note that the output power is not saturated).

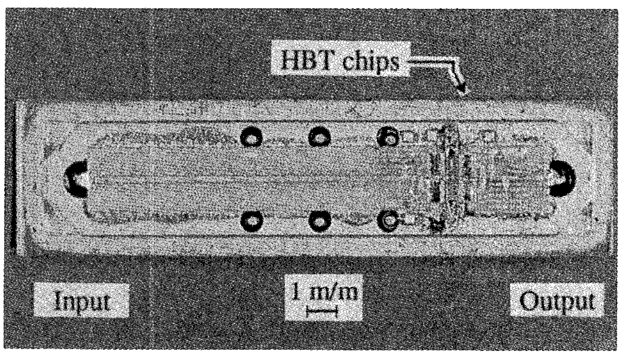

Fig. 2 Front view of HBT power amplifier module.

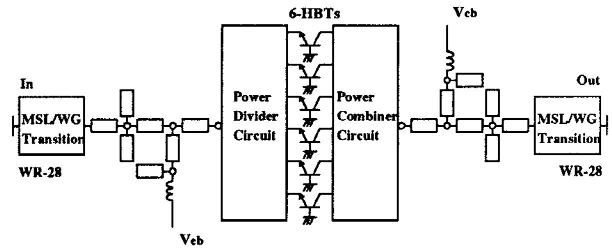

Fig. 3 Equivalent circuit of HBT power amplifier using 6 unit-cell chips.

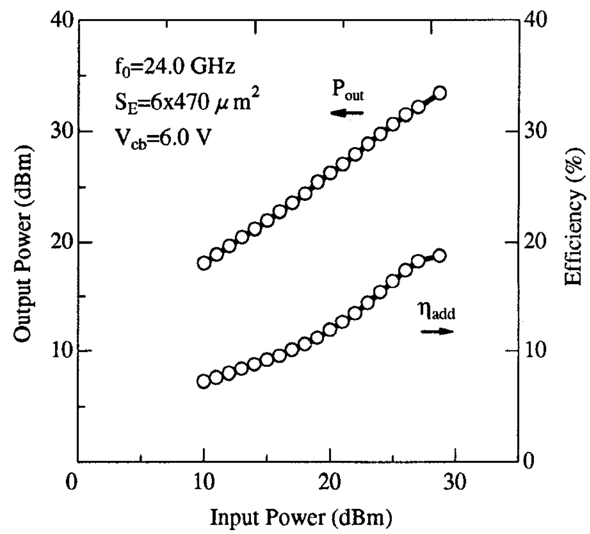

Fig. 4 Output power and power-added efficiency vs. input power for 6-chip combination HBT (CB).

OPTIMIZING CELL DESIGN

To further improve the amplifier performance, both PAE and output power, the device layout of each power-cell must be optimized. So far little is known about how cell design affects HBT power performance in (near) mmWave bands where only a few reports on power HBT are available [6, 7, 8]. A relatively long emitter (>20 μm) has been used in X-bands [1, 2] to obtain high output power, while typical power density ranges from 2 to 4 mW/μm^2. At 35 GHz, an HBT with a shorter, 10-μm length, double-finger emitter was reported to operate with 30% PAE and power density of 1.25 mW/μm^2 [6]. We compared three types of cells with different sub-cell structures

(Table 1), while a common fish-bone type layout was used for all of them (Fig. 5).

Cell Type	Sub-cell Structure
A	1.6x9.6-μm^2 *single* emitter
B	1.6x9.6-μm^2 *double* emitter
C	1.6x19.6-μm^2 *single* emitter

Table 1 Various cell types with different sub-cell structures used in this work. The fingers in double emitter sub-cell is spaced 2.5 μm apart.

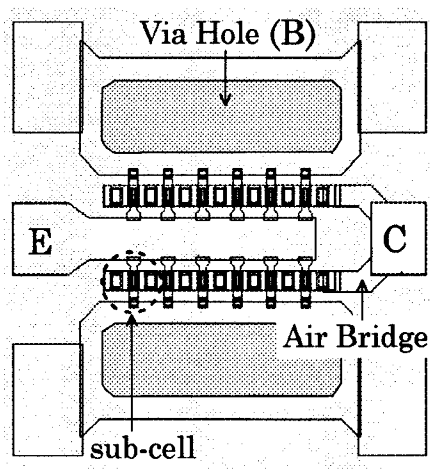

Fig. 5 Layout for CB HBT cell (type-A). The center-to-center spacing between sub-cells is 25 μm for the type-A and type-C cells, 35 μm for the type-B cell.

Power Density: Despite the superior power density of HBTs, the data shown in Fig. 6 vary among publications. Fig. 7 shows the power scaling for various HBTs. It can be clearly seen that the power density depends on the sub-cell structure. A long emitter (>20 μm) is preferred at X-bands, but is not suited to higher bands where the emitter behaves more like a lossy transmission line due to internal capacitances and resistances. This can be seen by the type-C cell (with a 19.6-μm length emitter) which suffers in both power density and PAE (<15 %). The device with short length, double emitter (type-B cell) showed reasonable power density (>1mW/μm^2) and PAE (>20 %). However, this particular type of cell showed a nonlinear relation between input and output power, probably due to thermally unstable operation.

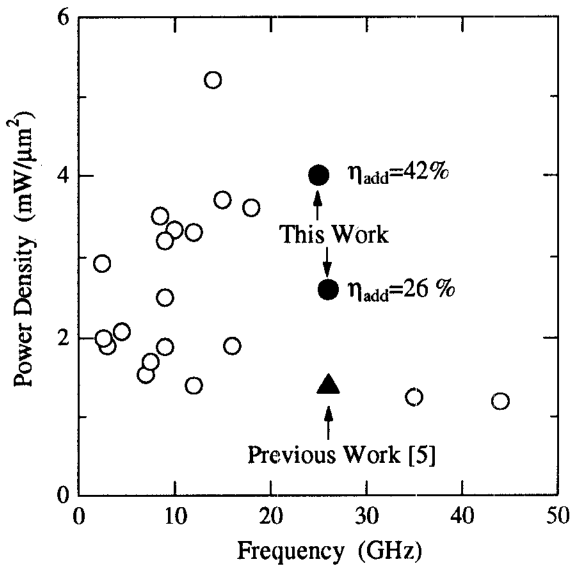

Fig. 6 Power density vs. frequency for GaAs-based HBTs. The open circles are taken from various publications. The 2.2 W amplifier is based on HBT technology reported in our previous work (triangle) [5].

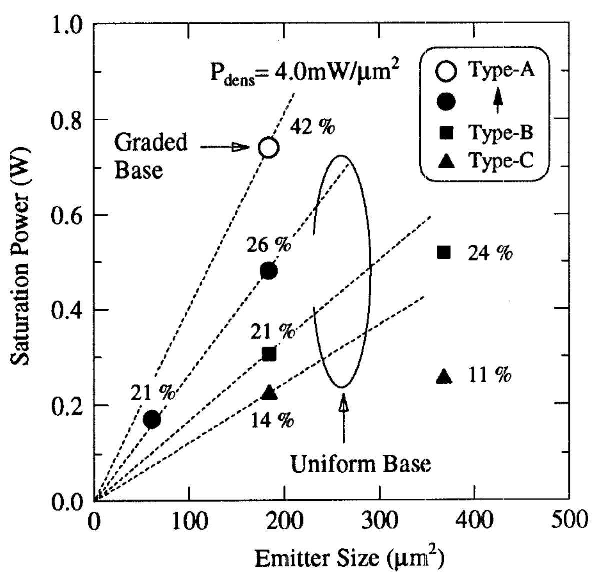

Fig. 7 Comparison of saturation power at 25-26 GHz for various types of CB cells. The corresponding power-added efficiencies are also shown.

The best power performance was obtained for the type-A cell (12-finger), which showed maximum output power of 480 and 740 mW for devices with a *uniform* and *graded* base, respectively. The latter output power translates into power density of 4.0 mW/μm^2, which compares well with the best values obtained in Ku or lower bands (Fig. 6). Another notable feature of the type-A cell is ideal power scaling. These results suggest that further power increase should be possible through scaling, with comparable gain and efficiency.

Power-added Efficiency: Fig. 8 shows that the maximum PAE of the common base (CB) type-A cell is 42%. The collector efficiency was 68 % which can be compared to the theoretical limit of 78.5 % for class-B operation. The record high PAE for power HBTs in near mmWave band (>25 GHz) is 20% improvement over that of conventional HBTs [5]. The difference is attributed to the via hole layout, which provides equal grounding conditions for each sub-cell (Fig. 2), as compared to the side-via design used in our previous work [5]. The reduced grounding inductance was more beneficial for the common emitter (CE) cell which showed about 10% PAE improvement over that of the CB cell. Nevertheless, the CE cell was discarded because much higher gain was obtained by using the CB cell [6, 7], particularly for large cells.

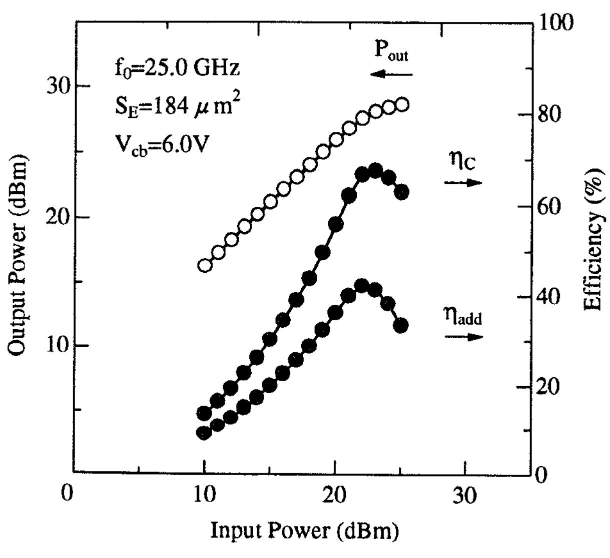

Fig. 8 Output power and power-added efficiency vs. input power for the CB type-A cell with 12 fingers.

SUMMARY

We demonstrated excellent power performance of AlGaAs/(In)GaAs HBTs at 24-26 GHz using epitaxial regrowth (high f_{max}) technology. The amplifier, which used 6 unit-cell chips, produced an outout power of 2.2 W with 19% PAE and 5 dB linear gain at 24 GHz. To further improve the efficiency and power density, various types of HBT cells were power-tested at 25-26 GHz. The results were a record high 42% PAE and 740 mW output power with a unit-cell (*single feed*) HBT chip. These results show the applicability of HBTs to high-power (>3W), high-efficiency (>40%) applications not only in X-bands or Ku-bands but also in near mmWave bands.

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REFERENCES

[1] W. Liu, A. Khatibzadeh, T. Henderson, S.-K. Fan and D. Davito, *IEEE MTT-S Technical Digest.*, p. 1477, 1993

[2] M. Salib, F. Ali, A. Gupta, B. Bayraktaroglu and D. Dawson, *IEEE Microwave and Guided Wave Lett.*, vol. 4, no. 10, 1994.

[3] N. L. Wang, W. J. Ho and J. A. Higgins, *IEEE Trans. on Microwave Theory Tech.*, vol. 42, No. 10, 1994.

[4] H. Shimawaki, Y. Amamiya, N. Furuhata and K. Honjo, *IEEE Trans. on Electron Devices*, vol. 42, no. 10, 1995

[5] C.-W.Kim, S. Tanaka, Y. Amamiya, N. Furuhata, H. Shimawaki, Y. Miyoshi, N. Goto and K. Honjo, *1995 IEEE GaAs IC Symp.*, p. 159

[6] N. L. Wang, W. J. Ho and J. A. Higgins, *IEEE Microwave and Guided Wave Lett.*, vol. 2, No. 10, 1992.

[7] D. Deakin, W. J. Ho, E. A. Sovero and J. A. Higgins, *1993 IEEE GaAs IC Symp.*, p. 371

[8] R. M. Wohlert, G. Jackson and M. G. Adlerstein, *IEEE MTT-S Technical Digest.*, p. 455, 1994