Ka-Band Power Performance of InP/InGaAs/InP Double Heterojunction Bipolar Transistors

Hin-Fai Chau, *Member, IEEE,* Hua-Quen Tserng, *Fellow, IEEE,* and Edward A. Beam, III, *Member, IEEE*

Abstract— **We report for the first time the Ka-band power performance of InP/InGaAs/InP DHBT's. A $2 \times 10\,\mu m^2$ common-emitter transistor delivered a continuous wave (CW) output power of 19.1 mW (1.91 W/mm power density), an associated gain of 5.3 dB, and a power-added efficiency (PAE) of 35.5% at 30 GHz. The maximum output power density was 2.34 W/mm and the peak associated gain was 6.6 dB. Under common-base operation, the maximum associated gain increased to 15.2 dB, but the maximum output power density and peak PAE dropped to 1.91 W/mm and 24.5%, respectively, at the same frequency.**

THE InP-based heterojunction bipolar transistor (HBT) technology has been progressing rapidly over the past few years. Both the current-gain cutoff frequency and maximum frequency of oscillation have broken the 200-GHz performance barrier [1]–[3]. The limitations of single HBT's (HBT's) arise from their low breakdown voltage and high output conductance, which limit their usefulness to low-voltage and low-power applications. Double HBT's (DHBT's) offer better output conductance and breakdown characteristics but require more careful base-collector heterojunction design. Too little InGaAs in the DHBT collector may lead to large saturation voltage and current blocking at low current densities. Too much InGaAs at the base-collector heterojunction results in high base-collector reverse saturation current and degradation of breakdown behavior [4]. Although no InP DHBT power amplifier has been reported to date, impressive microwave power results have been demonstrated in properly designed DHBT's with measured peak output power levels exceeding 2.0, 1.2, 0.62 W (4.3, 5.2, and 5.0 W/mm power density) at 4.3, 9, and 10 GHz, respectively, [5], [6]. We recently demonstrated that InP power DHBT's with small collector-emitter saturation voltage, large breakdown voltage and high maximum frequency of oscillation can be achieved by putting as little as 194 Å InGaAs in the >8300-Å-thick collector by carefully controlling the use of InGaAs in the collector and subcollector layers [7]. In this letter, we report on the first Ka-band power performance of these InP DHBT's.

The epitaxial structure of the InP/InGaAs/InP power DHBT consists of a 3000-Å n^+ InGaAs subcollector (1×10^{19} cm^{-3}), 8000-Å n^- InP collector (3×10^{16} cm^{-3}), 288-Å n^- InGaAs/InP superlattice grading layer (of which 50% is InGaAs), 50-Å n^- InGaAs spacer layer, 1000-Å p^+ InGaAs base (4×10^{19} cm^{-3}), 100-Å n InGaAs setback layer (1×10^{18} cm^{-3}), 900-Å n InP emitter (5×10^{17} cm^{-3}), and 100-Å n^+ InP and 1700-Å n^+ InGaAs emitter contact layers (both 1×10^{19} cm^{-3}). The transistor structure was grown by metalorganic molecular beam epitaxy (MOMBE) with the use of tertiarybutylarsine (TBA) and tertiarybutylphosphine (TBP) for the arsenic and phosphorus sources, respectively, and silicon tetrabromide ($SiBr_4$) and beryllium (Be) for n- and p-type doping, respectively [8].

Manuscript received September 19, 1995.

The authors are with Corporate Research & Development, Texas Instruments Inc., Dallas, TX 75243 USA.

Publisher Item Identifier S 1051-8207(96)02059-4.

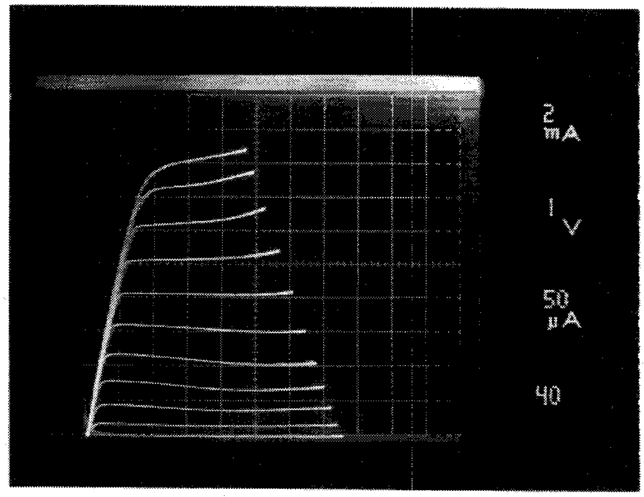

Fig. 1. Common-emitter I_C–V_{CE} characteristics of a $2 \times 10\,\mu m^2$ InP/InGaAs/InP DHBT.

Device fabrication began with the deposition of the emitter contact (Ti/Pt/Au), which acted as a natural mask during the base etch. The base etch was achieved by selectively removal of the InGaAs cap and InP emitter layers in a phosphoric acid-based ($H_3PO_4 : H_2O_2 : H_2O$) and hydrochloric acid-based ($HCl : H_3PO_4$) etchants, respectively. Owing to the emitter undercut formed in the base etch, the Ti/Pt/Au base metal was self-aligned to the emitter contact without shorting the emitter finger. A reactive ion etch (RIE) process based on CH_4/H_2 plasma chemistry was used to etch through the base and superlattice grading layers for the collector contact (AuGe/Ni/Au). Conventional mesa etching was used to isolate devices, and electroplated air-bridges were used to connect them to external coplanar pads and other circuit elements.

A good power transistor should exhibit high breakdown voltage, small V_{CE} offset voltage, and small V_{CE} saturation voltage. In addition, it is also important to avoid current blocking in DHBT's at low current densities. The current blocking in DHBT's is accompanied by current gain com-

1051–8207/96$05.00 © 1996 IEEE

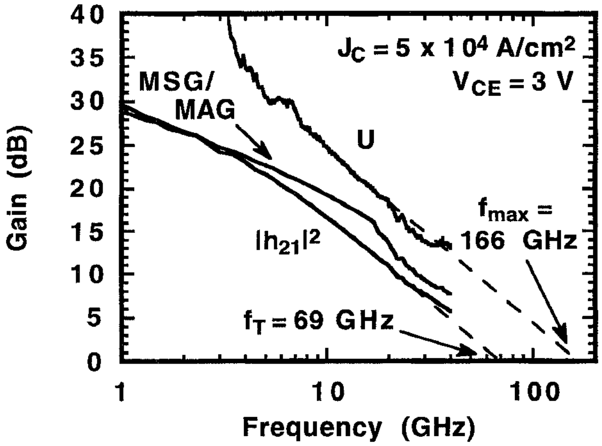

Fig. 2. Measured extrinsic RF characteristics of a 2 × 10 μm^2 common-emitter InP/InGaAs/InP DHBT.

pression. As shown in Fig. 1, the measured common-emitter I_C–V_{CE} characteristics of the completed 2 × 10 μm^2 power DHBT's show a very small V_{CE} offset voltage of only 85 mV and a V_{CE} saturation voltage of 1 V at 10 mA collector current (5 × 10^4 A/cm^2 current density). Current gain compression occurs at current larger than 15 mA (7.5 × 10^4 A/cm^2 current density). In spite of the use of a total of only 194-Å InGaAs in the collector, the V_{CE} saturation voltage in the power DHBT was small. The breakdown voltages BV_{CBO} and BV_{CEO} were 29 and 18 V, respectively.

On-wafer S-parameter measurements from 0.5–40.0 GHz indicated that the transistors have a f_T and $f_{\max}$ of 69 and 166 GHz, respectively, when they were biased at $V_{CE} = 3$ V and $I_C = 12.8$ mA (Fig. 2). This $f_{\max}$ value is the highest in any InP DHBT that has a BV_{CEO} greater than 8 V [7]. In comparison, our Ka-band GaAs HBT's typically have a f_T and $f_{\max}$ of 41 and 107 GHz, respectively, and a BV_{CBO} and BV_{CEO} of 24 and 17 V, respectively. The maximum oscillation frequencies $f_{\max}$ were extrapolated using the −6 dB/octave slope from the unilateral gain U. Theoretically, these extrapolated values of $f_{\max}$ should be equal to those extrapolated using −6 dB/octave slope from the maximum available gain $G_{\max}$ [9]–[11]. Numerical simulation, however, indicated that the maximum available gain could deviate from the linear −6 dB/octave slope as it crosses 0 dB [9]. It has also been pointed out that the best estimate of $f_{\max}$ is believed to result from the extrapolation of U because $G_{\max}$ decreases with frequency f somewhat more slowly than $1/f^2$ [11]. The maximum available gain $G_{\max}$ of the InP DHBT's at 30 GHz was 9.3 dB, which is also considerably higher than that in our conventional Ka-band GaAs power HBT's, which have a $G_{\max}$ of about 6.9 dB at the same frequency. The results indicate that the InP HBT technology offers higher cutoff frequency, higher maximum frequency of oscillation, higher maximum available gain, and larger breakdown voltages than the corresponding GaAs HBT's.

We have measured the Ka-band power performance of the InP power transistors. Fig. 3 presents the measured common-emitter and common-base results at 30 GHz. As Fig. 3(a) shows, the common-emitter 2 × 10 μm^2 transistor delivered 19.1-mW CW output power (1.91-W/mm output power density), 5.3-dB gain and 35.5% power-added-efficiency (PAE) at 1-dB compression. The collector efficiency was 50.2%. The maximum output power density and the peak associated gain measured were 2.34 W/mm and 6.6 dB, respectively. The average collector current increased from 4 to 10 mA when the RF input power was increased from −2.5 to 9.5 dBm. The average collector current increased with RF input power because the transistor was biased in class AB operation. Under the common-base operation, the maximum associated gain increased to 15.2 dB, but the maximum output power density and the peak PAE dropped to 1.91 W/mm and 24.5%, respectively, at the same frequency [Fig. 3(b)]. The reduced PAE in the common-base mode was due to the larger output-to-ground voltage drop (V_{CB}) and the nonnegligible input current (I_E). The maximum stable gain at 30 GHz was 14.2 dB in the common-base mode, but the stability factor k is less than unity throughout the entire frequency range used in the measurements. Tuning and matching were therefore found to be more difficult in the common-base transistors. In spite of the high breakdown voltage of the transistors, increasing

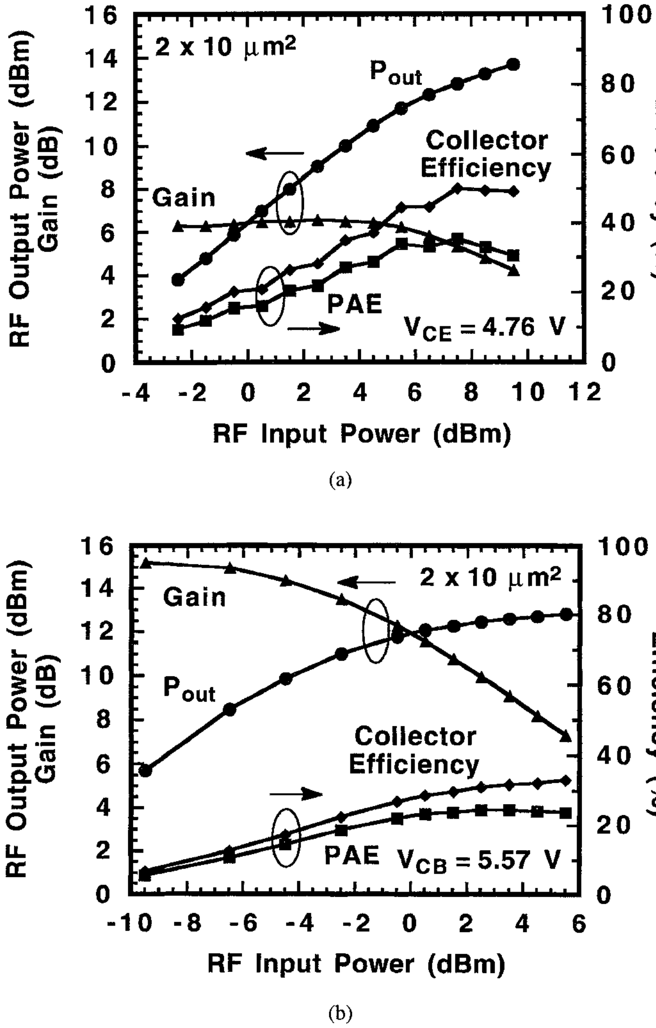

Fig. 3. Measured power performance of 2 × 10 μm^2 InP/InGaAs/InP DHBT's at 30 GHz. (a) Common emitter. (b) Common base.

the V_{CE} or V_{CB} bias voltage did not result in higher output power. The maximum output power appeared to be thermally limited and the power limiting mechanisms are currently being investigated.

In summary, we reported for the first time the Ka-band power performance of InP/InGaAs/InP DHBT's. The measured extrinsic $f_{\max}$ of 166 GHz was the highest in any DHBT that has a BV_{CEO} greater than 8 V. An output power density of 1.91 W/mm with an associated gain of 5.3 dB and a PAE of 35.5% were obtained at 30 GHz for a $2 \times 10\,\mu m^2$ common-emitter DHBT. Under common-base operation, the associated gain increased to 15.2 dB, but the PAE dropped to 24.5% at the same frequency.

ACKNOWLEDGMENT

The authors would like to thank D. Chasse, S. Duncan, S. F. Goodman, T. Session, and R. Smith for technical assistance.

REFERENCES

[1] J.-I. Song, K. B. Chough, C. J. Palmstrom, B. P. Van der Gaag, and W.-P. Hong, "Carbon-doped base InP/InGaAs HBT's with $f_T = 200$ GHz," in *IEEE Device Research Conf.*, 1994, paper IVB-5.

[2] H.-F. Chau and Y.-C. Kao, "High $f_{\max}$ InAlAs/InGaAs heterojunction bipolar transistors," in *IEEE IEDM Tech. Dig.*, 1993, pp. 783–786.

[3] S. Yamahata, K. Kurishima, H. Nakajima, T. Kobayashi, and Y. Matsuoka, "Ultra-high $f_{\max}$ and f_T InP/InGaAs double-heterojunction bipolar transistors with step-graded InGaAsP collector," in *IEEE GaAs IC Symp.*, 1994, pp. 345–348.

[4] H.-F. Chau, W. Liu, and E. A. Beam, III, "InP-based HBT's and their perspective for microwave applications," in *Proc. 7th Int. Conf. Indium Phosphide and Related Materials*, 1995, pp. 640–643 (invited paper).

[5] M. Hafizi, P. A. Macdonald, T. Liu, D. B. Rensch, and T. C. Cisco, "Microwave power performance of InP-based double heterojunction bipolar transistors for C- and X-band applications," in *IEEE MTT-S Dig.*, 1994, pp. 671–674.

[6] M. Hafizi, T. Liu, P. A. Macdonald, M. Lui, P. Chu, D. B. Rensch, W. E. Stanchina, and C. S. Wu, "High-performance microwave power AlInAs/GaInAs/InP double heterojunction bipolar transistors with compositionally graded base-collector junction," in *IEEE IEDM Tech. Dig.*, pp. 791–794, 1993.

[7] H.-F. Chau, W. Liu, and E. A. Beam, III, "InP-based heterojunction bipolar transistors: Recent advances and thermal properties," to appear in *Microwave and Optical Technol. Lett.* (invited paper).

[8] E. A. Beam, III and H.-F. Chau, "The application of $SiBr_4$ and CBr_4 doping in MOMBE for InP-based heterojunction bipolar transistor structures," in *5th Int. Conf. Chemical Beam Epitaxy and Related Growth Techniques*, 1995, paper TP3.

[9] B. Pejcinovic, T.-W. Tang, and D. H. Navon, "High-frequency characterization of heterojunction bipolar transistors using numerical simulation," *IEEE Trans. Electron Dev.*, vol. 36, no. 2, pp. 233–239, 1989.

[10] A. P. Laser and D. L. Pulfrey, "Reconciliation of methods for estimating $f_{\max}$ for microwave heterojunction transistors," *IEEE Trans. Electron Dev.*, vol. 38, no. 8, pp. 1685–1692, 1991.

[11] P. M. Asbeck *et al.*, "Heterojunction bipolar transistors for the microwave and millimeter-wave integrated circuits," *IEEE Trans. Electron Dev.*, vol. ED-34, no. 12, pp. 2571–2579, 1987.