Low-Power High-Speed Operation of Submicron InP–InGaAs SHBTs at 1 mA

Walid Hafez, Jie-Wei Lai, and Milton Feng, *Fellow, IEEE*

***Abstract*—Scaling of submicron InP–InGaAs HBTs is investigated for low-power high-speed applications in mixed signal circuits. Device performance for transistors fabricated with a 0.5–μm emitter width and varying emitter lengths are studied. The 0.5 μm × 2 μm devices yielded excellent low-current RF performance, with an $f_T = 173$ GHz and an $f_{\rm MAX} = 187$ GHz at 1 mA, the highest values reported for InP-based devices to date.**

***Index Terms*—Heterojunction bipolar transistors (HBTs).**

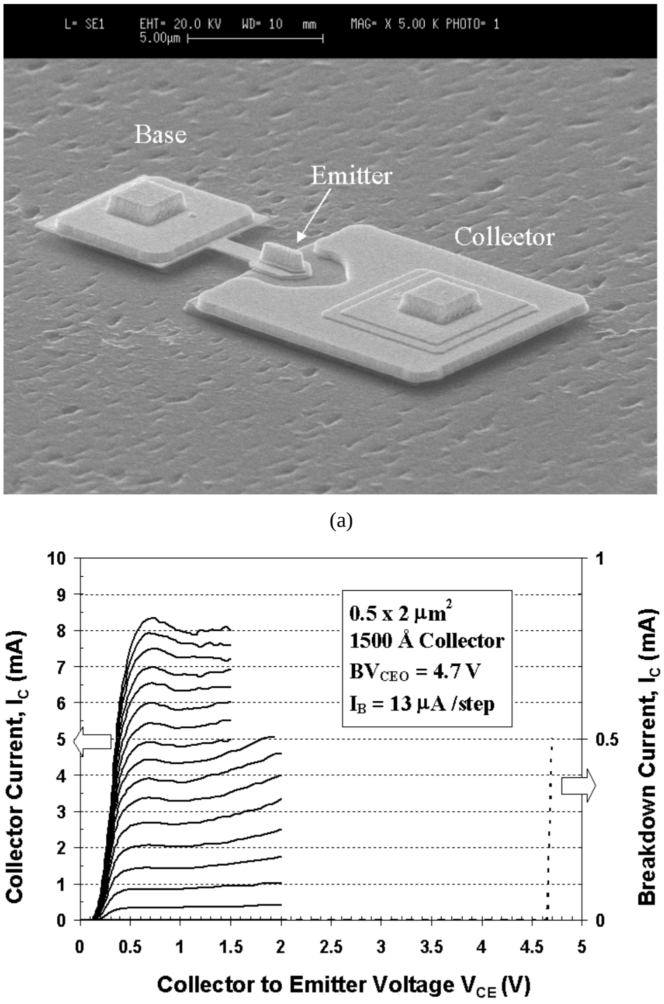
I. INTRODUCTION

SUBMICRON heterojunction bipolar transistors (HBTs) with high performance at low current levels are crucial to the development of high-speed high-density integrated circuits. Low-power consumption and better thermal management are driving the need for development of deep-submicron devices. This letter will present devices with record RF performance ($f_T = 173$ GHz, $f_{\rm MAX} = 187$ GHz) at 1 mA of collector current for InP-based devices. Comparisons of state-of-the-art low-power devices for both InP-based and SiGe HBTs are made.

II. LAYER STRUCTURE

The epitaxial structure is aggressively scaled and utilizes an 800-Å emitter structure, as well as a 300-Å base, Carbon doped to 5×10^{19} cm^{-3} and corresponding to a sheet resistance of 970 Ω/square. The base layer is compositionally graded from an Indium mole fraction of 0.5 to 0.53 to reduce the device transport time. A 1500-Å InGaAs collector, doped at 1×10^{16} cm^{-3}, is implemented to further reduce the transit time and increase the current cutoff frequency f_T. Devices were fabricated using a standard all wet-etch triple-mesa procedure as outlined in [1] and [2].

III. DC RESULTS



(a)

(b)

Fig. 1. (a) Fabricated 0.5×2 μm^2 device and (b) common emitter output characteristics for a 0.5×2 μm^2 InP–InGaAs SHBT.

Fig. 1(a) shows a SEM of a fabricated 0.5×2 μm^2 device. The common-emitter family of curves for the same device is shown in Fig. 1(b). Peak RF performance is achieved at a collector current of 5 mA ($J_C = 600$ kA/cm^2). The UIUC transistor has dimensions of 0.5 μm × 2 μm, however, lateral etching during processing reduces the physical device area to 0.83 μm^2, as determined by scanning-electron microscope during fabrication. The current densities reported are calculated taking this area reduction into consideration. It is also important to note that the minimal self-heating in the device, due to a small emitter area, allows operation above 1000 kA/cm^2 and corresponds to a collector current greater than 8 mA in Fig. 1. The dc gain β at 1 mA is 54. Idealities of the base and collector are 1.36 and 1.18, respectively. The collector-emitter breakdown $\rm BV_{CEO}$ is 4.7 V. An increase in $\rm BV_{CEO}$ for devices with shorter emitter lengths has been observed. The increase in emitter resistance of the shorter emitter length devices decreases the voltage drop across the base-emitter junction, thereby effectively increasing the breakdown of the device. For example, the $\rm BV_{CEO}$ is 3.7 V for 12 μm emitter length, and $\rm BV_{CEO}$ is 4.7 V for 2 μm length emitter length.

Manuscript received February 13, 2003; revised April 18, 2003. The review of this letter was arranged by Editor D. Ueda.

The authors are with the Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61871 USA.

Digital Object Identifier 10.1109/LED.2003.814008

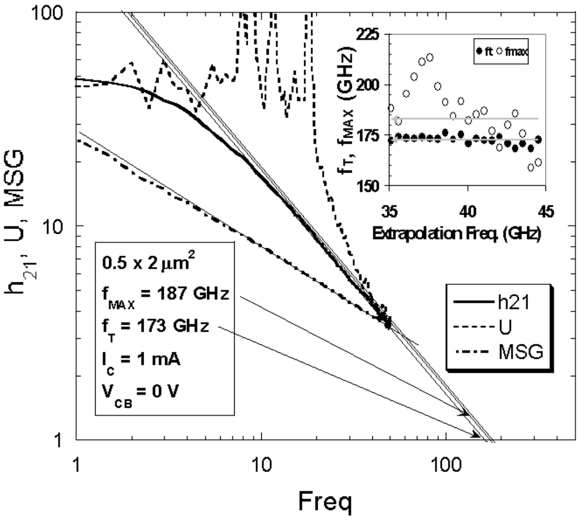


Fig. 2. Extrapolation of f_T and $f_{\rm MAX}$ for a 0.5 × 2 μm^2 device at $I_C = 1$ mA.

IV. RF RESULTS

The highest RF performance in the low-current region of operation is achieved in a 0.5 μm × 2 μm device. At 1 mA of collector current, the device yields an f_T of 173 GHz with a simultaneous $f_{\rm MAX}$ of 187 GHz at a $V_{\rm CE}$ of 0.86 V. At peak performance, an f_T of 310 GHz and an $f_{\rm MAX}$ of 275 GHz is achieved at a bias current of 5 mA ($J_C = 600$ kA/cm^2). A typical extrapolation of h_{21}, MSG, and U is shown in Fig. 2 at 1 mA of collector current. The value of f_T was taken from averaging -20 dB/decade slope of h_{21} between 35 and 45 GHz. We observe f_T remains constant and independent of the frequency where the extrapolation is made, as shown in the inset of Fig. 2. The value of $f_{\rm MAX}$ was obtained through two methods. The first method followed the same technique as f_T, with the averaging performed on the Mason's Unilateral Gain parameter U. The inset of Fig. 2 shows $f_{\rm MAX}$ varying from 160 to 215 GHz, contributing uncertainty to the final result of 187 GHz. The second method for extracting $f_{\rm MAX}$ was calculated using the maximum stable gain parameter MSG. For this extraction, the stability factor k was linearly extrapolated to find the corner frequency where the transistor becomes stable ($k = 1$ at 62 GHz). The MSG curve in Fig. 2 was extrapolated to this frequency, and beyond this frequency was fitted with a -20 dB/decade slope. This method yields an $f_{\rm MAX}$ of 190 GHz, in close agreement with the averaging technique described earlier [3].

A plot of f_T and $f_{\rm MAX}$ for varying emitter lengths from 2 μm to 12 μm at a fixed width (0.5 μm) is shown in Fig. 3. It is observed f_T shows a weak dependence on emitter length, and remains fairly constant for the larger devices. The highest extrinsic f_T occurs for a 0.5 μm × 16 μm device, and is measured at 382 GHz [4]. The large drop in extrinsic f_T of the 0.5 μm × 2 μm device, 310 GHz, is resulting from an increase in emitter resistance from the smaller emitter geometry. A much stronger dependence in $f_{\rm MAX}$ versus emitter length is observed; longer emitter lengths have a reduced power gain cutoff frequency due to higher base-collector capacitances, and more importantly higher base resistances as described in [4].

Table I shows a comparison of small geometry HBT devices and their associated low-current performance. In comparison to other InP based HBTs [5], the UIUC devices achieve the highest reported value of f_T (173 GHz) and $f_{\rm MAX}$ (187 GHz) at 1 mA. Fig. 4 shows collector current versus cutoff frequency for the 0.83 μm^2 UIUC device and the most recent 0.3 μm^2 IBM SiGe transistor [6]. The UIUC SHBT displays comparable performance to the IBM SiGe device, which is nearly three times smaller in area and running at over four times the current density of the UIUC device. For a SiGe device with a comparable emitter area of 1.1 μm^2 [7], the UIUC devices exhibit far superior f_T and $f_{\rm MAX}$, both at 1 mA and at peak performance. These results indicate that as a more mature submicron processing technology evolves, InP is the most suitable candidate

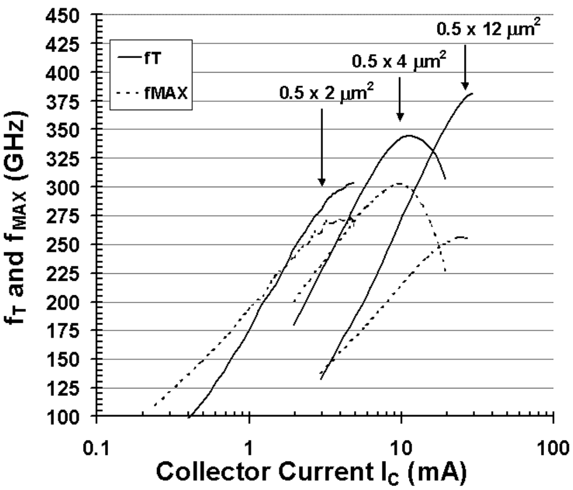


Fig. 3. f_T and $f_{\rm MAX}$ versus emitter length for 0.5 μm emitter width.

TABLE I
PERFORMANCE SUMMARY FOR CURRENT LOW-POWER BIPOLAR TECHNOLOGIES

Source	f_T@ 1 mA (GHz)	f_{MAX}@ 1 mA (GHz)	Peak f_T (GHz)	Associated f_{MAX} (GHz)	W_E x L_E (µm^2)	BV_{CEO} (V)
HRL InP SHBT [5]	160	Not Reported	162	250	0.5 x 1	> 2
IBM SiGe [6]	163	205	270	260	0.12 x 2.5	1.6
IBM SiGe [7]	120	55	210	90	0.22 x 5	1.8
UIUC InP SHBT	145	182	320	310	0.35 x 4	4.4
UIUC InP SHBT	173	187	310	275	0.5 x 2	4.7

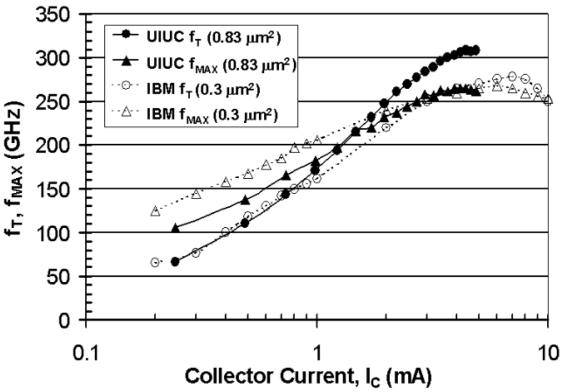


Fig. 4. I_C versus f_T and $f_{\rm MAX}$ for UIUC InP–InGaAs and IBM SiGe devices.

for supporting low-power high-speed applications as this material system has lower turn-on voltages, higher breakdowns, and higher speeds when compared with silicon-germanium.

V. CONCLUSION

SHBT transistors exhibiting excellent RF and dc performance at low current levels were fabricated using a vertically and laterally scaled submicron process. Reduction of the emitter length for a fixed emitter width results in a minor decrease in f_T and a stronger increase in f_{MAX}. Such devices exhibit sufficient RF performance to sustain 40 Gb/s performance with currents under 1 mA. Further lateral scaling of the emitter width should allow significantly higher performance.

ACKNOWLEDGMENT

The authors would like to thank F. Strolli from BAE System for the DARPA-TFAST program management support, as well as DARPA-TFAST program manager Dr. J. C. Zolper and ARL contract manager Dr. A. Hung for program support. Thanks also to Dr. D. Caruth (Xindium Technology, Inc.) for helpful discussions.

REFERENCES

[1] M. L. Hattendorf, Q. J. Hartmann, K. Richards, and M. Feng, “Submicron scaling of high-speed InP/InGaAs SHBT’s grown by MOCVD using carbon as the p-type dopant,” in *GaAs MANTECH Conf. Dig.*, 2002, pp. 255–258.

[2] W. Hafez, J. W. Lai, and M. Feng, “Sub-micron InP/InGaAs single heterojunction bipolar transistors with f_T of 377 GHz,” *IEEE Electron Device Lett.*, vol. 24, pp. 292–294, May 2003.

[3] M. Rohner, B. Willén, and H. Jäckel, “Sub-f_t gain resonance of InP/InGaAs-HBTs,” *IEEE Trans. Electron Devices*, vol. 49, pp. 213–220, Feb. 2002.

[4] W. Hafez, J. W. Lai, and M. Feng, “Record f_T and $f_T + f_{\mathrm{MAX}}$ performance of InP/InGaAs single heterojunction bipolar transistors,” *Electron. Lett.*, vol. 39, no. 10, pp. 811–813, May 2003.

[5] M. Sokolich, C. H. Fields, and M. Madhav, “Submicron AlInAs/InGaAs HBT with 160 GHz f_t at 1 mA collector current,” *IEEE Electron Device Lett.*, vol. 22, pp. 8–10, Jan., 2001.

[6] J. S. Rieh, B. Jagannathan, H. Chen, K. T. Schonenberg, D. Angell, A. Chinthakindi, J. Florkey, F. Golan, D. Greenberg, S.-J. Jeng, M. Khater, F. Pagette, C. Schnabel, P. Smith, A. Stricker, K. Vaed, R. Volant, D. Ahlgren, G. Freeman, K. Stein, and S. Subbanna, “SiGe HBT’s with cut-off frequency of 350 GHz,” in *IEDM Tech. Dig.*, 2002, pp. 771–774.

[7] S. J. Jeng, B. Jagannathan, J.-S. Rieh, J. Johnson, K. T. Schonenberg, D. Greenberg, A. Stricker, H. Chen, M. Khater, D. Ahlgren, G. Freeman, K. Stein, and S. Subbanna, “A 210-GHz f_T SiGe HBT with a nonself-aligned structure,” *IEEE Electron Device Lett.*, vol. 22, pp. 542–544, Nov. 2001.