Vertical Scaling of 0.25-μm Emitter InP/InGaAs Single Heterojunction Bipolar Transistors With $f_{\rm T}$ of 452 GHz

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***Abstract*—Vertical scaling of the epitaxial structure has allowed submicron InP/InGaAs-based single heterojunction bipolar transistors (SHBTs) to achieve record high-frequency performance. The 0.25×16 μm^2 transistors, featuring a 25-nm base and a 100-nm collector, display current gain cut-off frequencies $f_{\rm T}$ of 452 GHz. The devices operate at current densities above 1000 kA/cm^2 and have $\rm BV_{CEO}$ breakdowns of 2.1 V. A detailed analysis of device radio frequency (RF) parameters, and delay components with respect to scaling of the collector thickness is presented.**

***Index Terms*—Heterojunction bipolar transistors.**

I. INTRODUCTION

COMPOUND semiconductor single heterojunction bipolar transistors (SHBTs) have demonstrated record high-frequency performance through both submicron lateral scaling of the emitter width, and vertical scaling of the epitaxial structure [1]–[6]. Recent works at the University of Illinois at Urbana-Champaign (UIUC) have successfully demonstrated the highest current cut-off frequency with an $f_{\rm T}$ of 382 GHz on a 150-nm collector SHBT structure [1], [2]. Recognizing that the time delay limiting high-speed performance is still contributed by forward transit time, the most efficient way to enhance device $f_{\rm T}$ bandwidth is to scale down the epitaxial structure. However, the increase in current cut-off frequency by vertical scaling may come at the expense of $f_{\rm MAX}$ if parasitic capacitances are not carefully controlled, as well as a reduction in device breakdown voltage. In this paper, we report SHBT performance based on the novel lateral scaling of 0.25-μm emitter widths as well as a vertical scaling utilizing a 25-nm base and 100-nm collector structure. The $f_{\rm T}$ shows 452 GHz at a collector current density of 1063 kA/cm^2, the highest reported cut-off frequency of any bipolar transistor. These results support the promising potential of InP HBT technology for terahertz operation and for use in future high-speed applications.

II. LAYER STRUCTURE AND FABRICATION

High current cut-off frequencies in the devices are achieved with a vertically scaled epitaxial structure. The wafers were grown on Fe-doped semi-insulating (100) InP substrates by MBE. The layer structure consists of a 25-nm compositionally graded base, with an Indium mole fraction grading from of 0.53 to 0.50, and Carbon doped to $\rm p = 6 \times 10^{19}$ cm^{-3} ($\rm R_{sb} = 997$ Ω/sq), and grown on a 100-nm InGaAs collector doped at $\rm n = 1 \times 10^{16}$ cm^{-3}.

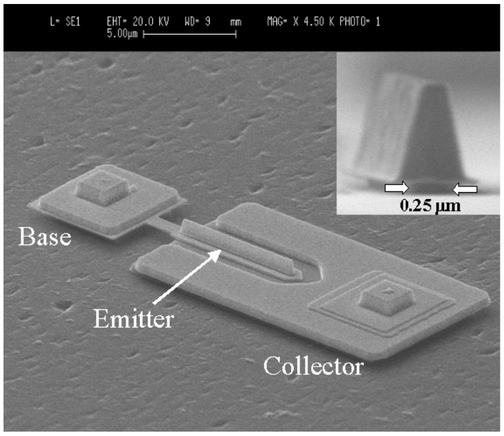

Fig. 1. Fabricated 0.25-μm × 8-μm InP/InGaAs SHBT before planarization.

The devices were fabricated using a standard mesa process as outlined in [7]. A μ-bridge is used to connect the base terminal to the intrinsic device to reduce parasitic capacitances. Emitters were defined using electron beam lithography, resulting in a minimum physical emitter width of 0.43-μm. The undercut during the emitter-base etch was controlled to 90 nm, yielding an intrinsic emitter width of 0.25-μm, as shown in the inset of Fig. 1. The self-aligned base metal consisted of a 62-nm Ti/Pt/Au e-beam evaporated metal stack. A scanning electron micrograph (SEM) image of a fabricated 0.25-μm × 8-μm device before planarization is shown in Fig. 1.

III. DC RESULTS

DC gain varies almost linearly from 20 to 40 between 1 μA and 1 mA, with β remaining constant at 40 above 1 mA. Base and collector ideality factors are 1.37, and 1.13, respectively. The common emitter output characteristics are show in Fig. 2, where the collector-emitter offset voltage $V_{\rm CE,offset}$ is approximately 0.165 V with a knee voltage of 0.6 V. The common-emitter breakdown voltage $\rm BV_{CEO}$ is 2.1 V. The DC Ic-Vce family curves are superior in output conductance and breakdown voltage to the state-of-the-art high-speed pseudomorphic high electron mobility transistor (PHEMT) device detailed in [8] and SiGe HBTs [9].

Manuscript received March 19, 2003; revised May 9, 2003. The review of this letter was arranged by Editor T. Mizutani.

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Digital Object Identifier 10.1109/LED.2003.814990

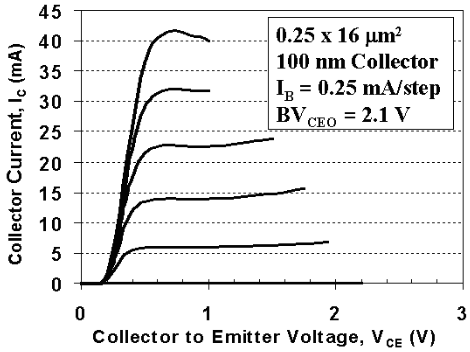
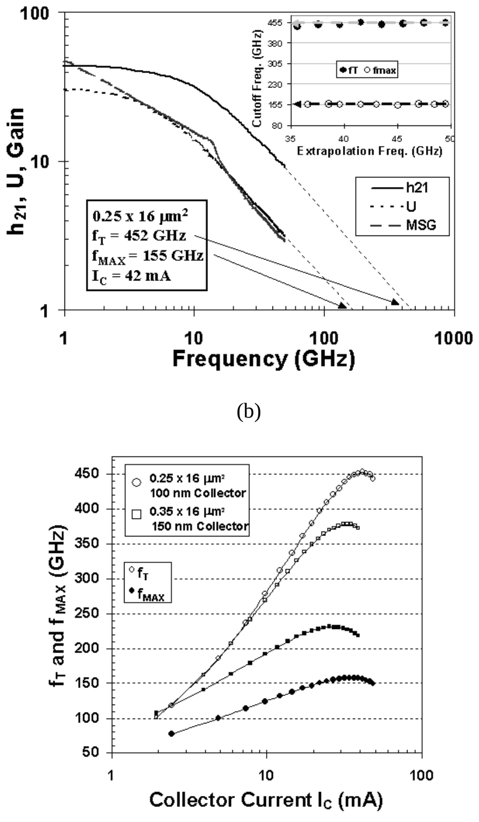


Fig. 2. Family of curve plots for a 0.25-μm × 16-μm device.



(b)

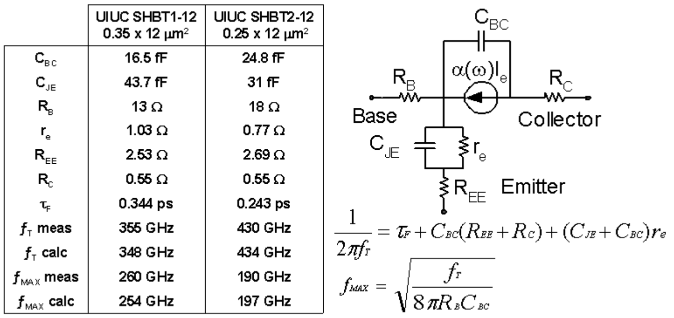
(a)

Fig. 3. (a) Extrapolation of $\mathrm{h}_{21}, \mathrm{U}$, and MSG/MAG and $f_{\mathrm{T}}, f_{\mathrm{MAX}}$ versus extraction frequency (inset) and (b) f_{T} and f_{MAX} and versus collector current for 150-nm and 100-nm collector devices.

TABLE I

UIUC HBT PERFORMANCE SUMMARY FOR 30-nm BASE/150-nm COLLECTOR (SHBT1) AND 25-nm BASE/100-nm COLLECTOR (SHBT2) DEVICES

Source	f_T (GHz)	f_{MAX} (GHz)	Jc (kA/cm^2)	W_E x L_E (μm)	BV_{CEO} (V)
UIUC InP SHBT1-8 [2]	363	310	667	0.35 x 8	3.7
UIUC InP SHBT1-12	355	260	635	0.35 x 12	3.7
UIUC InP SHBT2-4	345	251	1011	0.25 x 4	2.1
UIUC InP SHBT2-8	421	220	1236	0.25 x 8	2.1
UIUC InP SHBT2-12	430	190	1280	0.25 x 12	2.1
UIUC InP SHBT2-16	452	155	1063	0.25 x 16	2.1



	UIUC SHBT1-12 0.35 x 12 μm^2	UIUC SHBT2-12 0.25 x 12 μm^2
C_{BC}	16.5 fF	24.8 fF
C_{JE}	43.7 fF	31 fF
R_B	13 Ω	18 Ω
r_e	1.03 Ω	0.77 Ω
R_{EE}	2.53 Ω	2.69 Ω
R_C	0.55 Ω	0.55 Ω
τ_F	0.344 ps	0.243 ps
f_T meas	355 GHz	430 GHz
f_T calc	348 GHz	434 GHz
f_{MAX} meas	260 GHz	190 GHz
f_{MAX} calc	254 GHz	197 GHz

$$\frac{1}{2\pi f_T} = \tau_F + C_{BC}(R_{EE} + R_C) + (C_{JE} + C_{BC})r_e$$

$$f_{MAX} = \sqrt{\frac{f_T}{8\pi R_B C_{BC}}}$$

Fig. 4. Equivalent circuit with modeled delay terms for a 150-nm and 100-nm collector devices.

IV. RF RESULTS AND DISCUSSION

The HBTs were characterized with an HP8510C network analyzer from 0.5 to 50 GHz. On-wafer short-open-load-thru (SOLT) standards were used for the calibration routine. The current gain (h_{21}), Mason's unilateral gain (U), and the maximum stable gain (MSG) for a 0.25×16-$\mu\mathrm{m}^2$ HBT are shown in Fig. 3. Extrapolations were obtained by averaging the -20 dB/decade extrapolations from 40 to 50 GHz to minimize the effects of fluctuation in the RF measurements. Note the device becomes stable $(\mathrm{k} > 1)$ at 12.3 GHz, causing the MSG curve to transition to MAG and assume a -20 dB/decade slope. The dependence of f_{T} and f_{MAX} versus extrapolation frequency is shown in the inset of Fig. 3(a), note the cut-off frequency is independent of extraction frequency. The peak RF performance yields an f_{T} of 452 GHz and occurs at an Ic of 42 mA, corresponding to a Jc of 1063 kA/cm^2. A simultaneous f_{MAX} of 155 GHz is achieved at a V_{CB} of 0 V. The RF device performance has very little dependence on the collector-base voltage due to the thin collector layer. A plot of cut-off frequencies versus collector current is shown in Fig. 3(b) for 0.25×16 $\mu\mathrm{m}^2$ (100-nm collector) and 0.35×16 $\mu\mathrm{m}^2$ (150-nm collector) devices. HBT's with dimensions of 0.25×8 $\mu\mathrm{m}^2$ yield a simultaneous f_{T} and f_{MAX} of 421 and 220 GHz, respectively. A more complete RF device performance and collector current density comparison of UIUC HBTs with 30-nm base/150-nm collectors (SHBT1) and 25-nm base/100-nm collectors (SHBT2) with varying emitter lengths is summarized in Table I.

A comparison of two SHBT samples with different collector thicknesses clearly illustrates vertical scaling effects on device delay components. The 0.35×12 $\mu\mathrm{m}^2$ SHBT1-12 devices exhibit a peak f_{T} and f_{MAX} of 355 and 260 GHz, respectively, with modeled delay components detailed in Fig. 4. To allow a direct comparison, model parameters of a 0.25×12-$\mu\mathrm{m}^2$, SHBT2-12 device ($f_{\mathrm{T}} = 430$ GHz, $f_{\mathrm{MAX}} = 190$ GHz) were extracted. The forward transit time associated with the SHBT2-12 device was calculated to be $\tau_{\mathrm{F}} = 0.24$ ps, corresponding to a 30% decrease in transit time over the 30-nm base/150-nm collector device. The increase in the $\mathrm{R}_{\mathrm{B}} * \mathrm{C}_{\mathrm{BC}}$ charging delay of the SHBT2 devices is expected; this wafer experienced an increase in the C_{BC} component due to the thinner collector layer, as well as an increase in base resistance primarily due to a larger emitter undercut and a higher specific contact resistance. As a result, a significant degradation in f_{MAX} is observed for the SHBT2 devices as shown in Table I.

V. CONCLUSION

This paper reports InGaAs/InP SHBTs with current cut-off frequencies of 452 GHz: The highest reported for any bipolar transistor to date. The exceptional RF performance was achieved through vertical scaling of the epitaxial layer structure, thereby allowing a reduction of device transit time. As a result, the thin base and collector layers cause an increase in the $\mathrm{R_B} * \mathrm{C_{BC}}$ time constant, limiting the peak f_{MAX} performance. This analysis suggests that further vertical scaling of the epitaxial structure, combined with lateral device scaling, will allow devices with cut-off frequencies above 500 GHz while maintaining breakdown voltages greater than 1.5 V.

ACKNOWLEDGMENT

The authors would like to thank F. Strolli from BAE Systems for the DARPA-TFAST program management support, and DARPA-TFAST program manager Dr. J. C. Zolper and ARL contract manager Dr. A. Hung for program support.

REFERENCES

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

[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] C. Bolognesi, M. W. Dvorak, N. Matine, O. J. Pitts, and S. P. Watkins, "Ultrahigh performance staggered lineup ("Type-II") InP/GaAsSb/InP NpN double heterojunction bipolar transistors," *Jpn. J. Appl. Phys.*, vol. 41, pp. 1131–1135, 2002.

[4] M. Ida, K. Kurishima, and N. Watanabe, "Over 300 GHz f_{T} and f_{MAX} InP/InGaAs double heterojunction bipolar transistors with a thin pseudomorphic base," *IEEE Electron Device Lett.*, vol. 23, pp. 694–696, Dec. 2002.

[5] M. Sokolich, S. T. III, and C. H. Fields, "High speed and low power InAlAs/InGaAs heterojunction bipolar transistors for dense ultra high speed digital applications," in *IEDM Tech. Dig.*, 2001, pp. 35.5.1–35.5.4.

[6] A. Fujihara, Y. Ikenaga, H. Takahashi, M. Kawanaka, and S. Tanaka, "High-speed InP/InGaAs DHBT's with ballistic collector launcher structure," in *IEDM Tech. Dig.*, 2001, pp. 35.3.1–35.3.4.

[7] 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 DIG.*, 2002, pp. 255–258.

[8] Y. Yamashita, A. Endoh, K. Shinohara, K. Hikosaka, T. Matsui, S. Hiyamizu, and T. Mimura, "Pseudomorphic InAlAs/InGaAs HEMT's with an ultrahigh f_{T} of 562 GHz," *IEEE Electron Device Lett.*, vol. 23, pp. 573–575, Nov. 2002.

[9] 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 HBTs with cut-off frequency of 350 GHz," in *IEDM Tech. Dig.*, 2002, pp. 771–774.