

300 GHz InP/GaAsSb/InP Double HBTs with High Current Capability and $BV_{CEO} \geq 6$ V

M. W. Dvorak, *Student Member, IEEE*, C. R. Bolognesi, *Member, IEEE*, O. J. Pitts, and S. P. Watkins, *Member, IEEE*

Abstract—We report MOCVD-grown NpN InP/GaAsSb/InP abrupt double heterojunction bipolar transistors (DHBTs) with simultaneous values of f_T and f_{MAX} as high as 300 GHz for $J_C = 410$ kA/cm² at $V_{CE} = 1.8$ V. The devices maintain outstanding dynamic performances over a wide range of biases including the saturation mode. In this material system the p+ GaAsSb base conduction band edge lies 0.10–0.15 eV above the InP collector conduction band, thus favoring the use of nongraded base-collector designs without the current blocking effect found in conventional InP/GaInAs-based DHBTs. The 2000 Å InP collector provides good breakdown voltages of $BV_{CEO} = 6$ V and a small collector signal delay of ~ 0.23 ps. Thinner 1500 Å collectors allow operation at still higher currents with $f_T > 200$ GHz at $J_C = 650$ kA/cm².

Index Terms—HBTs, semiconductor heterojunctions.

I. INTRODUCTION

InP/GaInAs-BASED heterojunction bipolar transistors (HBTs) have demonstrated good microwave characteristics, but high cutoff frequencies are being achieved at the expense of low breakdown voltages because of the narrow gap collector. Wide energy gap Al_{0.48}In_{0.52}As or InP layers in double heterojunction bipolar transistors (DHBTs) can increase breakdown voltages by reducing impact ionization in the collector, but the introduction of a widegap material complicates the collector design because of current blocking resulting from the positive conduction band discontinuity between Ga_{0.47}In_{0.53}As and Al_{0.48}In_{0.52}As or InP: for an InP collector, a blocking barrier of ~ 0.25 eV must be overcome between the base and the collector. Various doping and/or compositional grading schemes have been developed to alleviate this blocking effect [1]–[3]. However, the specifics of any grading and/or doping schemes at the base/collector junction need to be considered carefully because they can have a dominant impact on DHBT performance at high current densities [4].

In contrast, the use of a GaAsSb base layer provides an elegant solution to the collector blocking effect plaguing GaInAs-based DHBT designs because the staggered band lineup at GaAsSb/InP heterojunctions allows unhindered injection of electrons from the GaAsSb base into the InP collector since the GaAs_{1-x}Sb_x conduction band lines up ~ 0.10 – 0.15 eV above the InP conduction band edge near

lattice-match at $x = 0.49$ [5], [6]. InP/GaAsSb DHBTs benefit from fundamental advantages: 1) the structure requires no graded transition layers at the collector- or emitter-base junctions, thus simplifying the growth of the epitaxial layers; and 2) C-doped GaAsSb features high doping efficiencies [7] and displays little or no H-passivation effects [8]. We previously reported on the excellent dc characteristics of InP/GaAsSb DHBTs [9], [10] and suggested that the microwave performance of earlier devices could be limited by base transit times [11]. In this work, we report the characteristics of thin base InP/GaAsSb/InP DHBTs with excellent dc and RF performances at record high current densities for III–V HBTs which are enabled by the nonblocking band lineup at the GaAsSb/InP B/C junction, and the high average electron velocity in the InP collector.

II. GROWTH AND DEVICE FABRICATION

DHBT structures were grown on nominally exact (001) SUMITOMO InP:Fe substrates in a horizontal low pressure MOCVD system equipped with a quartz chamber. Pd-diffused H₂ served as the carrier gas at a reactor pressure of 100 Torr. TMin, TEGa, TMSb, TBAs and TBP were the precursors. H₂S and CCl₄ were used for *n*- and *p*-type doping. A detailed study of the growth parameters and material properties has been presented elsewhere [7]. Device structures consist of a heavily doped 3000 Å InP/500 Å Ga_{0.47}In_{0.53}As subcollector, a 2000 Å InP collector (S: 3×10^{16} cm⁻³), a 200 (or 250) Å GaAs_{0.55}Sb_{0.45} base (C: 8×10^{19} cm⁻³), a 700 Å InP emitter (S: 3×10^{17} cm⁻³), and a heavily doped 500 Å InP/1000 Å Ga_{0.47}In_{0.53}As emitter cap. The typical base sheet resistance value determined by TLM measurements is $\rho_B = 1400$ (1000) Ω /sq. for a 200 (250) Å base. The slightly As-rich base layer with respect to the lattice-matched composition of GaAs_{0.51}Sb_{0.49} was used to reduce the “type-II” ΔE_C step at the E/B junction [6] and ease electron injection into the base layer. The base layer remains well below critical thickness and no negative side-effects due to strain have been detected in our devices.

Our devices were fabricated with an emitter-up triple mesa structure with a self-aligned base metallization extending 1.25 μ m on each side of the emitter metal stripe. Device fabrication relies exclusively on optical contact lithography and selective wet etching. Laterally etched undercut micro-air-bridges are used to contact the intrinsic emitter and base [12]: this approach enables one to minimize device parasitics despite the poor alignment registration of contact lithography, and would not be necessary in a stepper-based process. Typical

Manuscript received March 16, 2001; revised April 30, 2001. This work was supported by NSERC, Agilent Technologies, and Nortel Networks. The review of this letter was arranged by Editor D. Ueda.

The authors are with the Compound Semiconductor Device Laboratory (CSDL), School of Engineering Science, Department of Physics, Simon Fraser University, Burnaby, BC, Canada, V5A 1S6 (e-mail: colombo@ieee.org).

Publisher Item Identifier S 0741-3106(01)06645-9.

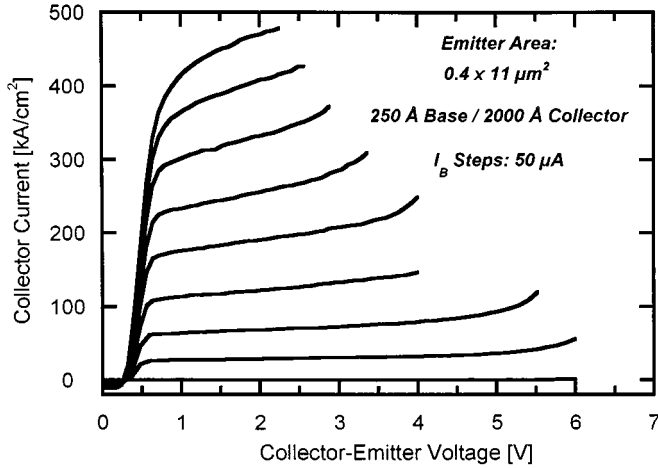


Fig. 1. Typical common-emitter characteristics for a small area $0.4 \times 11 \mu\text{m}^2$ emitter device with a 250 Å base and a 2000 Å InP collector.

emitter undercuts of $0.15 \mu\text{m}$ are achieved by taking advantage of the anisotropic etching properties of InP, while typical base contact undercuts are $0.75 \mu\text{m}$. The devices are not passivated nor heatsunk, and rely on evaporated airbridge interconnects for dc and RF probing. Typical base contact resistivities are $\rho_C \sim 2 \times 10^{-7} \Omega\text{-cm}^2$ as determined by TLM measurements. Device characteristics are stable over time despite prolonged RF testing at high current densities and/or storage in an air atmosphere for periods of several months. Further details on device fabrication will be published separately.

III. RESULTS AND DISCUSSION

A. DC Performance

Fig. 1 shows typical common-emitter characteristics for a small area $0.4 \times 11 \mu\text{m}^2$ emitter device with a 250 Å base. The transistor displays a common-emitter current gain $\beta = 40\text{--}50$ with a breakdown voltage $BV_{\text{CEO}} \geq 6 \text{ V}$ which can be attributed to the low electron multiplication coefficient in the 2000 Å InP collector layer. Transistors fabricated with a 200 Å base layer show dc characteristics qualitatively very similar to those shown in Fig. 1, but with a higher current gain of $\beta = 80$. Clearly, some gain can be traded off against higher base doping to further reduce the base sheet resistance: active C-doping levels as high as $2.5 \times 10^{20} \text{ cm}^{-3}$ are possible with MOCVD-grown GaAsSb [7]. The output conductance at high currents is not related to basewidth modulation (because of the very high doping level in the base), but is rather believed to due to a positive temperature coefficient of the current gain found in our devices (contrary to that of GaAs HBTs). Our transistors can operate at much higher J_C than conventional InP/GaInAs SHBTs and DHBTs: at similar current densities (say 100 kA/cm^2), our devices feature much higher Early voltages than GaInAs SHBTs of similar geometry and collector thickness. We recently provided a direct comparison of $I\text{--}V$ curves for InP/GaAsSb DHBTs and GaInAs SHBTs in [13].

B. Microwave Performance

On-wafer dc-40 GHz high frequency measurements in this work were performed with an HP8510 vector network analyzer

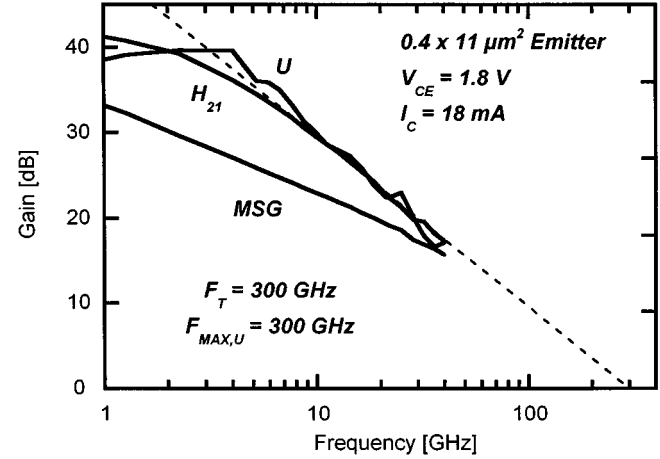


Fig. 2. Performance of a $0.4 \times 11 \mu\text{m}^2$ emitter device with a 200 Å thick base and 2000 Å InP collector with $f_T = 300 \text{ GHz}$ and $f_{\text{MAX}} = 300 \text{ GHz}$ obtained by extrapolating the current gain and Mason's unilateral power gain U at -20 dB/oct .

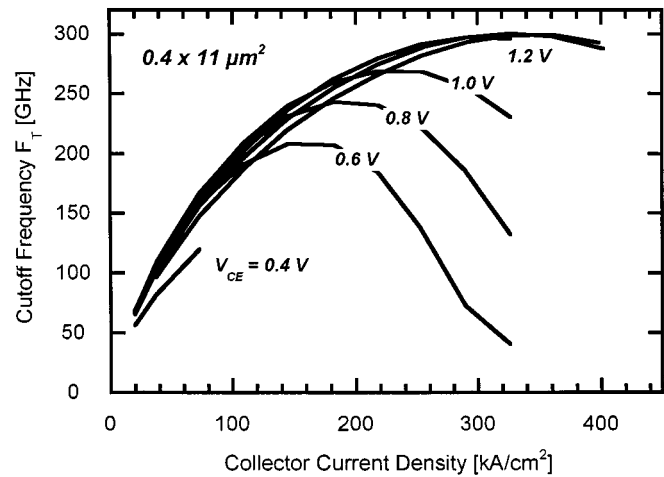


Fig. 3. Evolution of f_T with J_C for collector-emitter bias voltages $V_{\text{CE}} = 0.4$ to 1.8 V (steps of 0.2 V) for the 200 Å base and 2000 Å collector. The peak f_T of 300 GHz is reached at $J_C = 410 \text{ kA/cm}^2$ for $V_{\text{CE}} = 1.8 \text{ V}$.

and PicoProbe 40A coplanar waveguide probes. Fig. 2 shows the performance of a $0.4 \times 11 \mu\text{m}^2$ emitter device with a 200 Å thick base: the transistor shows $f_T = 300 \text{ GHz}$ and $f_{\text{MAX}} = 300 \text{ GHz}$ by extrapolating the current gain and Mason's unilateral power gain U with a -20 dB/oct roll-off. DHBTs fabricated with a 250 Å base and a 2000 Å collector featured peak cutoff frequencies of $f_T = 268 \text{ GHz}$ and $f_{\text{MAX}} > 300 \text{ GHz}$ for a $0.4 \times 11 \mu\text{m}^2$ emitter size.

Fig. 3 shows the evolution of f_T with J_C for various collector-emitter bias voltages for the 200 Å base. A peak f_T of 300 GHz is obtained at $J_C = 410 \text{ kA/cm}^2$. It must be emphasized that f_T remains well above 100 GHz even for a low collector bias of $V_{\text{CE}} = 0.4 \text{ V}$ which corresponds to operation in saturation mode. The excellent dynamic performance in saturation can be attributed to the confinement of holes in the base because the large $\Delta E_V = 0.7\text{--}0.8 \text{ eV}$ at the InP/GaAsSb interface prevents hole injection from the p+ GaAsSb base into the InP collector when the base/collector junction is forward biased. Independent measurements (performed at Nortel up to a frequency

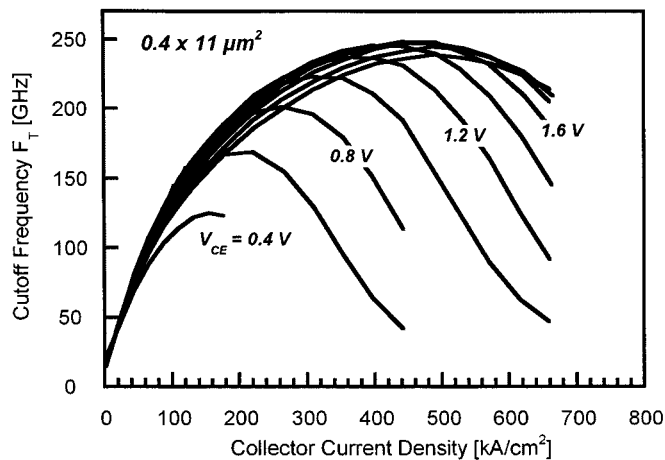


Fig. 4. Evolution of f_T with J_C for various collector-emitter bias voltages $V_{CE} = 0.4$ to 2.2 V (steps of 0.2 V) for a 250 Å base DHBT with a 1500 Å collector with $BV_{CEO} = 5$ V. The peak f_T of 250 GHz is reached at $J_C = 500$ kA/cm² for $V_{CE} = 1.6$ V.

of 80 GHz) revealed a peak f_T of 305 GHz by extrapolation of h_{21} data at -20 dB/dec from 80 GHz. Fig. 4 shows that devices fabricated with a 250 Å base and a 1500 Å InP collector ($BV_{CEO} = 5$ V) yield a peak $f_T = 250$ GHz at $V_{CE} = 1.6$ V and $J_C = 500$ kA/cm², with f_T remaining above 200 GHz up to 650 kA/cm². No classical base push-out can take place in the InP/GaAsSb system because of hole confinement in the base layer. The onset of f_T roll-off seen in Figs. 3 and 4 at very high J_C presumably occurs due to band flattening in the collector since its onset can be delayed by applying higher V_{CB} . We can estimate the average collector velocity by subtracting the base transit τ_B time (assuming diffusive transport with $D_{n,B} = 21$ cm²/s [13]) and the collector RC time constant (~ 0.02 ps) from the minimum delay τ_{\min} extrapolated to $1/I_C \rightarrow 0$ when plotting $1/2\pi f_T$ versus $1/I_C$: $\tau_{\min} = 0.35$ and 0.40 ps for the 200 and 250 Å bases, corresponding to an average collector velocity of $> 4.3 \times 10^7$ cm/s through the 2000 Å InP collector for both devices. This is consistent with the Monte Carlo results of Brennan and Hess [14] which show that higher electron velocities can be maintained over a wider range of biases in InP because of a greater intervalley separation ($\Delta E_{TL} = 0.59$ eV, $\Delta E_{TX} = 0.85$ eV) in comparison to GaAs ($\Delta E_{TL} = 0.29$ eV, $\Delta E_{TX} = 0.48$ eV).

IV. SUMMARY

InP/GaAsSb/InP DHBTs feature the best performance ever reported for a DHBT in any material system: the present devices largely overcome the huge speed advantage traditionally held by InP HEMTs [15] over InP-based HBTs [16] while maintaining good breakdown voltages and superior current drive capability. The use of a C-doped GaAsSb base layer enables the fabrication of ultrahigh-speed InP collector DHBTs without the additional complication of graded layers at the emitter-base and base-collector heterojunctions. The favorable band alignment in InP/GaAsSb DHBTs allows high collector current densities required for high-speed logic applications, and does away with the alloy potential problems associated with graded interfaces under

high J_C operation [4]. The resulting DHBTs can thus be operated at current densities approaching those found in high-performance SiGe/Si bipolar transistors [17] with the attendant reduction in dynamic emitter resistances and associated charging delays.

ACKNOWLEDGMENT

The authors thank T. W. MacElwee of Nortel for corroborating measurements.

REFERENCES

- [1] Y. Matsuoka and E. Sano, "InP/InGaAs double-heterostructure bipolar transistors for high-speed IC's and OEICs," *Solid State Electron.*, vol. 38, pp. 1703–1709, 1995.
- [2] E. F. Chor and C. J. Peng, "Composite step-graded collector of InP/InGaAs/InP DHBT for minimized carrier blocking," *Electron. Lett.*, vol. 32, pp. 1409–1410, 1996.
- [3] C. Nguyen, T. Liu, M. Chen, H.-C. Sun, and D. Rensch, "AlInAs/GaInAs/InP double heterojunction bipolar transistor with a novel base-collector design for power applications," *IEEE Electron Device Lett.*, vol. 17, pp. 133–135, 1996.
- [4] S. Tiwari and D. J. Frank, "Analysis of the operation of GaAlAs/GaAs HBT's," *IEEE Trans. Electron Devices*, vol. 36, pp. 2105–2121, 1989.
- [5] J. Hu, X. G. Xu, J. A. H. Stotz, S. P. Watkins, A. E. Curzon, M. L. W. Thewalt, N. Matine, and C. R. Bolognesi, "Type II photoluminescence and conduction band offsets of GaAsSb/InGaAs and GaAsSb/InP heterostructures grown by metalorganic vapor phase epitaxy," *Appl. Phys. Lett.*, vol. 73, pp. 2799–2801, 1998.
- [6] M. Peter, N. Herres, F. Fuchs, K. Winkler, K.-H. Bachem, and J. Wagner, "Band gaps and band offsets in strained GaAs_{1-y}Sb_y on InP grown by metalorganic chemical vapor deposition," *Appl. Phys. Lett.*, vol. 74, pp. 410–412, 1999.
- [7] S. P. Watkins, O. J. Pitts, C. Dale, X. G. Xu, M. W. Dvorak, N. Matine, and C. R. Bolognesi, "Heavily carbon-doped GaAsSb grown for HBT applications," *J. Cryst. Growth*, vol. 221, pp. 59–65, 2000.
- [8] B. T. McDermott, E. R. Gertner, S. Pittman, C. W. Seabury, and M. F. Chang, "Growth and doping of GaAsSb via metalorganic chemical vapor deposition for InP heterojunction bipolar transistors," *Appl. Phys. Lett.*, vol. 68, pp. 1386–1388, 1996.
- [9] N. Matine, M. W. Dvorak, C. R. Bolognesi, X. Xu, J. Hu, S. P. Watkins, and M. L. W. Thewalt, "Nearly ideal InP/GaAsSb/InP double heterojunction bipolar transistors with ballistically launched collector electrons," *Electron. Lett.*, vol. 34, pp. 1700–1702, 1998.
- [10] C. R. Bolognesi, N. Matine, M. W. Dvorak, X. G. Xu, J. Hu, and S. P. Watkins, "Non-blocking collector InP/GaAsSb/InP double heterojunction bipolar transistors with a staggered lineup base-collector junction," *IEEE Electron Device Lett.*, vol. 20, pp. 155–157, 1999.
- [11] C. R. Bolognesi, N. Matine, M. W. Dvorak, X. G. Xu, and S. P. Watkins, "InP/GaAsSb/InP DHBT's with high f_T and f_{MAX} for wireless communication applications," in *IEEE GaAs IC Symp.*, Monterey, CA, 1999, pp. 63–66.
- [12] M. W. Dvorak, N. Matine, C. R. Bolognesi, X. G. Xu, and S. P. Watkins, "Design and performance of InP/GaAsSb/InP double heterojunction bipolar transistors," *J. Vac. Sci. Technol. A*, vol. 18, pp. 761–764, 2000.
- [13] M. W. Dvorak, O. J. Pitts, S. P. Watkins, and C. R. Bolognesi, "Abrupt junction InP/GaAsSb/InP double heterojunction bipolar transistors with f_T as high as 250 GHz and $BV_{CEO} > 6$ V," in *IEDM Tech. Dig.*, 2000, pp. 178–181.
- [14] K. Brennan and K. Hess, "High field transport in GaAs, InP and InAs," *Solid State Electron.*, vol. 27, pp. 347–357, 1984.
- [15] Y. Yamashita, A. Endoh, M. Higashiwaki, K. Hikosaka, T. Mimura, S. Hiyamizu, and T. Matsui, "High f_T 50-nm-gate InAlAs/InGaAs high electron mobility transistors lattice-matched to InP substrates," *Jpn. J. Appl. Phys.*, vol. 39, pp. L838–L840, 2000.
- [16] Y. Matsuoka, S. Yamahata, K. Kurishima, and H. Ito, "Ultrahigh-speed InP/InGaAs double-heterostructure bipolar transistors and analyses of their operation," *Jpn. J. Appl. Phys.*, pt. 1, vol. 35, pp. 5646–5654, 1996.
- [17] K. Washio, R. Hayami, E. Ohue, K. Oda, M. Tanabe, H. Shimamoto, and M. Kondo, "67-GHz Static frequency divider using 0.2 μm self-aligned SiGe HBTs," *IEEE Trans. Microwave Theory Tech.*, vol. 49, pp. 3–8, Jan. 2001.