Enhancing the Device Performance of III-V Based Bipolar Transistors

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ABSTRACT

Superior DC and RF performance are obtained using InGaP/GaInAsN and InP/GaInAs double heterojunction bipolar transistors with compositionally graded base layers. By grading the base layer energy band-gap, we achieve nearly a 100% improvement in DC current gain and as much as a 15% increase in the unity gain cutoff frequency (f_t) relative to baseline constant-composition base layer devices. In InGaP/GaInAsN DHBTs, DC current gains as high as 250 and cutoff frequencies of 60 GHz are demonstrated for devices with a collector thickness of 400 nm and BV_{ceo} values of 8.4 Volts. Graded-base InP/InGaAs DHBTs with an f_t of 135 GHz are also demonstrated. Estimations of the f_t*BV_{ceo} figure-of-merit are used to compare performance of these devices to existing technologies.

INTRODUCTION

Within the last several years, GaAs-based heterojunction bipolar transistors (HBT) have become a mainstay device technology for realizing high performance integrated circuits in portable wireless and high-speed optical communication applications. Several research groups have been pursuing the development of lower turn-on voltage ($V_{be,ON}$) InGaP/GaInAsN double heterojunction bipolar transistors (DHBTs) as a means of enhancing the performance of GaAs-based devices [1]. At the same time, InP HBTs have gained considerable attention as an enabling technology for next generation OC-768 (40Gbit/sec) lightwave circuits [2]. However, both of these material technologies typically display degraded minority carrier properties compared to GaAs, reducing DC current gain (β) and potentially detracting from the frequency performance of the device. Manipulating the bandgap of the base layer (E_{gb}) in these devices provides an attractive pathway for addressing these unfavorable characteristics, thus extending and/or enhancing the performance of III-V based bipolar devices.

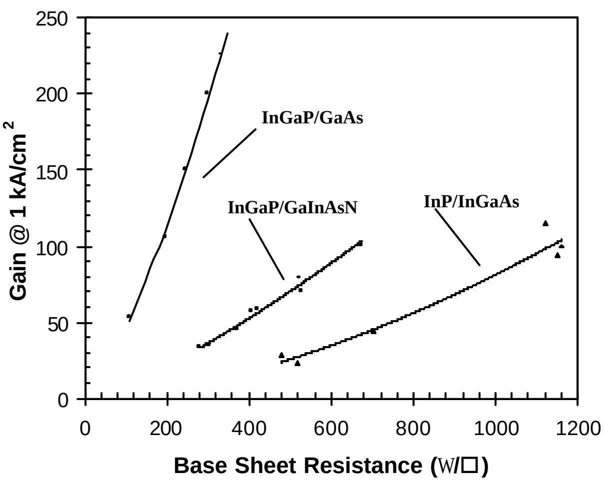

Figure 1: DC current gain as a function of base sheet resistance for InGaP/GaAs, InGaP/GaInAsN, and InP/InGaAs HBT structures with varying base thickness.

BANDGAP ENGINEERING: GRADED BASE

Figure 1 compares β as a function of base sheet resistance (R_{sb}) for HBTs grown in three different III-V material systems. Within each given material set, only the base layer thickness is altered. The reduction in β for both the InGaP/GaInAsN and InP/InGaAs technologies is significant, requiring a 5x to 8x increase in R_{sb} to achieve β values similar to typical InGaP/GaAs devices. Insertion of these technologies into existing real-world applications will likely require additional improvements in β while, at the same time, maintaining reasonably low R_{sb} values. Although the graded base concept is well understood and has been successfully exploited in Si_xGe_{1-x} HBT technologies [3], its application to III-V devices has been limited [4,5].

In the case of conventional HBTs with heavily doped constant composition base layers, DC current gain at high collector currents is dominated by neutral base recombination and follows the relationship:

$$\beta \propto v\tau / w_b \qquad (1)$$

where w_b is the base layer thickness and v and τ are the average electron velocity and the minority carrier lifetime, respectively. The unity gain cutoff frequency (f_t) can be expressed as:

$$f_t \propto 2\pi(\tau_b + \tau_{scl} + \tau_e + \tau_c)^{-1} \qquad (2)$$

where $\tau_b = w_b/v$ is the base transit time, τ_{scl} is the collector depletion region transient time, and τ_e and

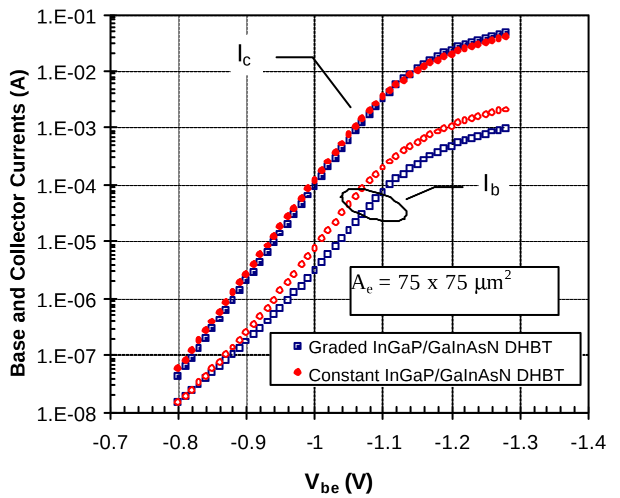

Figure 2: Gummel plots of constant and graded-base InGaP/GaInAsN/GaAs DHBT structures with similar base sheet resistance values (R_{sb} ~ 350 W/☐) and turn-on voltages (V_{be}~ 1.0 V @ 1.78 A/cm^2).

τ_c are the emitter and collector charging times, respectively. In an n-p-n bipolar transistor, grading the base layer energy-gap from a large value at the base/emitter junction to a smaller energy-gap at the base/collector interface produces a quasi-electric field that accelerates electrons across the base layer [6]. If the minority carrier lifetime and the base thickness are held constant, the increased velocity can lead to both improved frequency performance as well as increased DC current gain (i.e. Eq. 1 and 2).

In this paper, we report on our progress in incorporating graded base layers in both carbon-doped InGaP/GaInAsN and InP/InGaAs DHBTs. Samples were grown using LP-MOVPE in an Aixtron 2400 multiwafer production platform [1,2]. The grading of the base energy-gap was accomplished by linearly varying the In composition while keeping the doping level nearly constant. The difference in base energy-gap across the base (ΔE_{gb}) is estimated to be about 40 meV. In both material technologies, increases in DC current gains of up to 100% are observed. Moreover, we see a significant improvement in the f_t values of the graded-base structures compared to baseline samples with constant composition base layers.

GRADED InGaP/InGaAsN DHBTs

As previously reported, the insertion of reduced E_g GaInAsN into the base layer extends the applicability of GaAs-based HBTs by reducing the turn-on voltage [1]. In addition, the resulting DHBT structure significantly reduces the common emitter offset and knee voltages, as well as improves the DC current gain temperature stability relative to standard InGaP/GaAs HBTs. While reasonable performance for InGaP/GaInAsN DHBTs has been achieved [1], the best devices still exhibit gains considerably lower than that of standard InGaP/GaAs HBTs. Figure 2 compares the Gummel plots from constant and graded-base InGaP/GaInAsN DHBT structures. Each of the devices has comparable base sheet resistances and turn-on voltages. The neutral base (n=1) recombination current is substantially lower in the graded base structure due to the increased electron velocity in the base layer, leading to nearly a 2x improvement in peak DC current gain.

Small area device fabrication (A_e = 32 μm^2) and testing was performed at UCSD. The DC and RF characteristics of two devices were compared; a 60 nm thick (R_{sb} ~ 350 Ω/☐) GaInAsN base with constant composition and an 80 nm thick graded GaInAsN base (R_{sb} ~ 265 Ω/☐). For both samples the base doping was approximately 4 x 10^{19} cm^{-3}, the collector thickness was 400 nm, and the measured BV_{ceo} values were 8.3 and 8.4 V, respectively. The small area DC current gain of the graded base sample was 25-45 % higher than the constant composition sample in spite of the lower R_{sb}, indicating that the gain-to-base sheet resistance ratio is ~ 1.8x higher on this graded base sample. Peak incremental DC current gains (H_{FE}) greater than 250 were also measured on similar samples.

On-wafer RF probing was accomplished using an HP8510C parametric analyzer on 2-finger, 4 µm x 4 µm emitter area devices, and f_t was extrapolated using a 20 dB/decade slope of the small signal current gain (H_{21}). Figure 3 depicts the f_t dependence on the collector current density (J_c) for both structures. As J_c increases and τ_b begins to play a limiting role in the total transit time, the f_t of the graded base structure becomes notably larger than

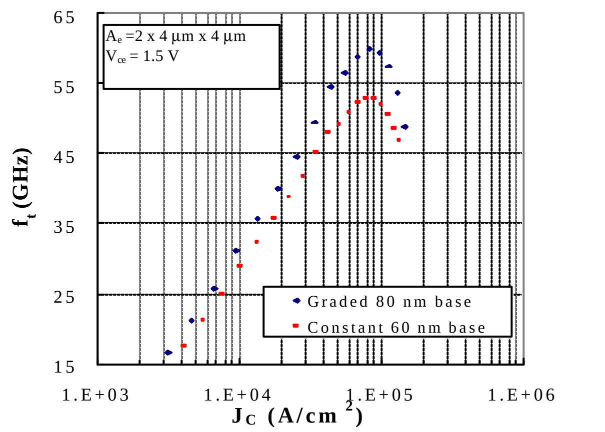

Figure 3: Extrapolated current gain cutoff frequency as a function of J_c for both a constant 60 nm and a graded 80 nm GaInAsN base DHBT structure.

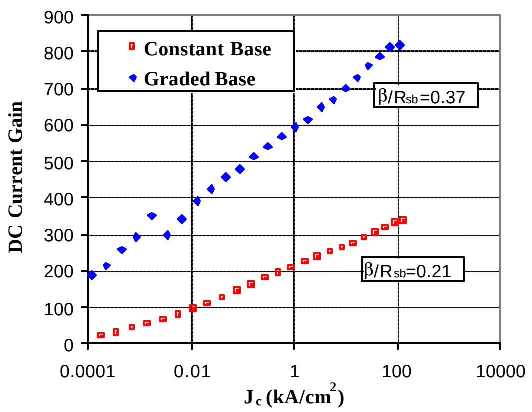

Figure 4: Beta versus collector current density for constant and graded-base InP/InGaAs DHBT structures. Base doping is ~ 2 x 10^{19} cm^{-3}.

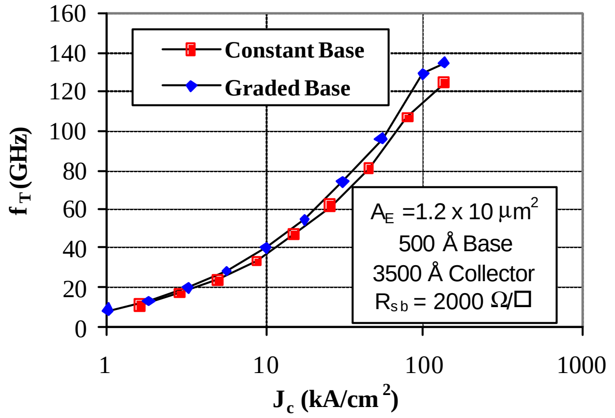

Figure 5: Extrapolated f_t as a function of J_c comparing constant and graded-base InP/GaInAs DHBT structures.

that of the constant composition structure (60 vs. 53 GHz) despite the greater base thickness of the former.

Fitting the experimental f_t data to analytical expressions for electron transit times suggests that the base transit time in the graded base devices has decreased by approximately 40% relative to the constant composition structures. A second set of devices, in which the base layers were the same thickness and BV_{ceo} ~12 V, yielded improvements in peak f_t values on the order of 15% [7].

GRADED InP/InGaAs DHBTs

InP DHBTs are being developed for lightwave applications, where device speed is the primary design parameter. However, circuit designers often require a minimum β value. Typically, for InP HBTs, β is no more than 1/8 that of conventional InGaP/GaAs HBTs for similar R_{sb} (Fig. 1). This suggests that a graded base may facilitate the introduction of InP HBT circuits. The use of the ternary InGaAs base material enables the lattice strain to be balanced while grading the base layer. This is accomplished by grading the composition from a tensile strain (large E_{gb}) at the base-emitter interface to a compressive strain (small E_{gb}) at the base-collector interface.

Small area InP DHBTs were fabricated and tested at Rockwell Science center, as reported elsewhere [8]. The emitter area was 1.2 µm x 10 µm and both DC and RF characteristics were measured. Figure 4 shows β as a function of current density, illustrating the increase in β for the graded base InP DHBT. The increase in β/R_{sb} of ~1.8 times is comparable to that seen in the GaInAsN DHBT structures. The dependence of f_t, extrapolated from the small signal current gain, on J_c for both constant and graded-base samples is depicted in Figure 5. The peak f_t increased 10% from 122 GHz for the constant composition device to 135 GHz for the graded-base structure.

RF TECHNOLOGY COMPARISON

To better compare the RF results of the constant and graded base structures to one another and to other HBT technologies, the peak f_t values from Figures 3 and 5 are plotted as a function of BV_{ceo} and compared to the peak or near peak f_t values of conventional HBTs quoted in the literature (see Figure 6). For each material system, a fairly wide distribution in the f_t values of the conventional HBT structures is expected, as this data was compiled from many groups using different epitaxial structures, device sizes, and test conditions. We have characterized the upper and lower bounds of current industry standards in the SiGe, GaAs, and InP material technologies using the Johnson figure-of-merit ($f_t \cdot BV_{ceo}$). While arguably limited in its applicability [9], the $f_t \cdot BV_{ceo}$ product nonetheless can provide an effective framework within which different HBT technologies can be compared.

Examination of Figure 6 indicates that the f_t of the constant composition GaInAsN and InP devices lie within the range expected for conventional HBTs of their respective material technologies. Furthermore, the graded base structures are notably improved, and with advanced layout and process techniques, appear poised to advance the Johnson limit for both InP and GaAs-based HBTs. In particular, the $f_t \cdot BV_{ceo}$ product of the graded InP DHBT approaches 1380 GHzV, while best graded GaInAsN device approaches 950 GHzV, exceeding conventional InP SHBT technology. Finally, we note that despite tremendous improvements in SiGe technology in recent years, optimized III-V technology remains 3 to 4 times better in terms of the Johnson $f_t \cdot BV_{ceo}$ product.

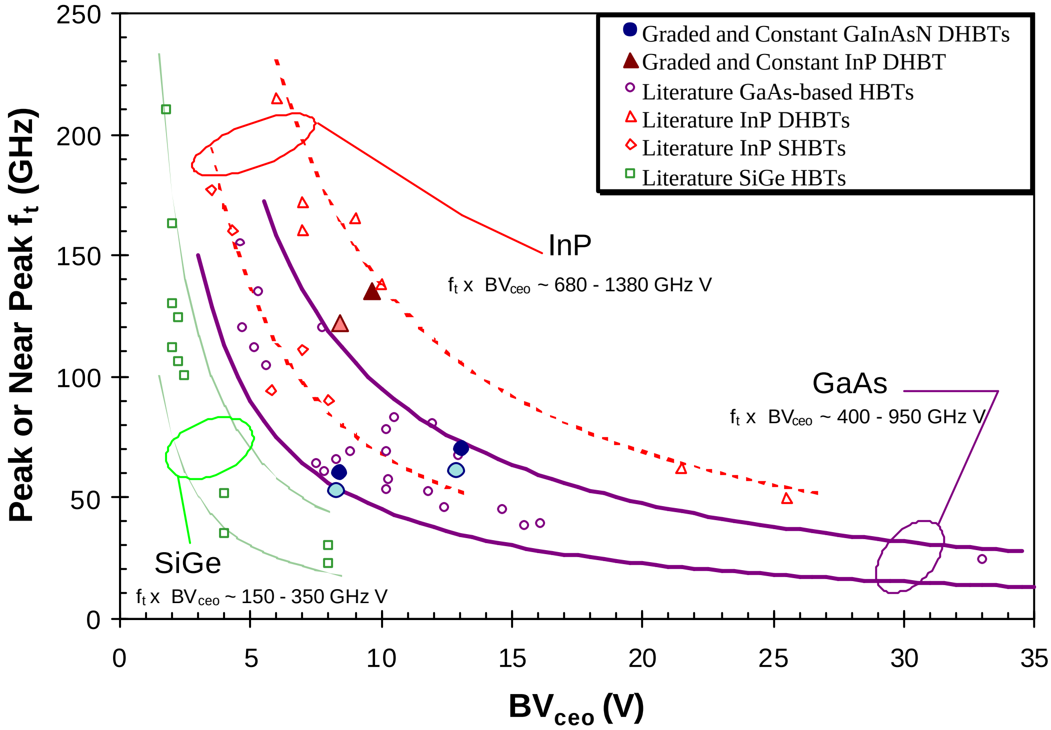

Figure 6: Peak or near-peak f_t values as a function of BV_{ceo} for the constant (shaded) and graded (solid) GaInAsN and InP structures, as well as a wide range of conventional HBTs in three materials systems taken from the literature. The solid and dashed lines represent constant f_t x BV_{ceo} products (Johnson figure-of-merit), and are given as a guide for the eye to characterize the range of current industry standards in each material system.

CONCLUSIONS

We have developed compositionally graded InGaP/GaInAsN and InP/GaInAs base DHBT structures which demonstrate improved DC current gain and frequency performance over that of comparable constant base composition devices. By adopting a band-gap engineered approach, the impact of reduced minority carrier lifetime in p-type GaInAsN and GaInAs, compared to conventional p-type GaAs, is mitigated. The decreased electron base transit time associated with the graded base leads to an approximately 1.7 to 2 times increase in the DC current gain and at least a 10% improvement in the cutoff frequency compared to similar constant composition DHBT devices.

ACKNOWLEDGEMENT

The authors would like to thank the AFRL/SNO at WPAFB for support of this work via STTR funding (contract # F33615-99-C-1510), and for the efforts of the entire GaAs Transistor Group at Kopin Corporation.

REFERNCES

[1] K. S. Stevens, R. E. Welser, P. M. Deluca, B. E. Landini, C. R. Lutz, and T. L. Wolfsdorf-Brenner, "Enhanced Performance GaAs-Based HBTs using a GaInNAs Base Layer," GAAS 2001 European Gallium Arsenide and Related III-V Compounds, Application Symposium, pp 17-20, London, England, 2001.

[2] P. M. Deluca, B. E. Landini, R. E. Welser, R. L Pierson, J. C. Li, and B. Brar, "Carbon Doped InP/InGaAs Heterojunction Bipolar Transistors Grown by MOCVD," GAAS 2001 European Gallium Arsenide and Related III-V Compounds Application Symposium, pp 29-32, London, England, 2001.

[3] G. L. Patton, D. L. Harame, J. M. C. Stork, B. S. Myerson, G. J. Scilla, and E. Ganin, "Graded-SiGe-base, poly-emitter heterojunction bipolar transistors." IEEE Electron Dev. Lett., 10, 534-536 (1989).

[4] D. A. Ahmari, M. T. Fresina, Q. J. Hartman, D. W. Barlage, P. J. Mares, M. Feng, and G. E. Stillman, "High-Speed InGaP/GaAs HBT's with a Strained $In_xGa_{1-x}As$ Base," IEEE Elec. Dev. Lett. **17**, 226-228 (1996).

[5] K.Kurishima, H.Nakajima, S.Yamahata, T.Kobayashi, and Y.Matsuoka, "Effects of a compositionally-graded $In_xGa_{1-x}As$ base in abrupt-emitter InP/InGaAs heterojunction bipolar transistors," Jpn. J. Appl. Phys. **1**, 1221-1227 (1995).

[6] H. Kroemer, "Heterostructure bipolar transistors: What should we build?," J. Vac. Sci. Technol. B1, 126-130 (1983).

[7] P. M. DeLuca, C. R. Lutz, R. E. Welser, T. Y. Chi, E. K Huang, R. J. Welty and P. M. Asbeck, "Implementation of Reduced Turn-on Voltage InGaP HBTs using Graded GaInAsN Base Regions," submitted to IEE Elec. Dev. Lett., May 2002.

[8] B.E.Landini, P. M. DeLuca, R. E. Welser, R. Pierson, P. Rowell, S. Newell, B. Brar, "Base Transport Characteristics of

InP DHBTs Grown by MOVPE," 14th IPRM Conference,
pp. 157-160, Stockholm, Sweden, 2002.
[9] K. K. Ng, M. R. Frei, and C. A. King, "Reevaluation of the f_tBV_{ceo} Limit on Si Bipolar Transistors," IEEE Trans. Elec. Dev., 45, 1854-1855 (1998).