GaInP/GaInAsN/GaAs N-p-N Bipolar Transistors: Influence of Base Layer Composition and Alloy Grading on Device Performance

Bryan D. Dickerson, Bradley J. Heath, and Louis J. Guido
Virginia Tech, Department of Material Science and Engineering, 213 Holden Hall, Blacksburg, VA 24061
Email: louis.guido@vt.edu; Tel: 540-231-3551; Fax: 540-231-8919

Kevin S. Stevens, Charles R. Lutz, Eric M. Rehder, and Roger E. Welser
Kopin Corporation, 695 Myles Standish Boulevard, Taunton, MA 02780

ABSTRACT

Data presented herein demonstrate that the DC current gain of GaInP/GaInAsN/GaAs DHBTs is almost independent of temperature over the range 225[T[475 K and is relatively insensitive to current density for J_c / 1 A/cm^2. Direct comparisons are made between DHBTs with different GaInAsN base alloy compositions and grading schemes and a high-performance GaInP/GaAs HBT.

INTRODUCTION

Heterojunction bipolar transistors are well suited for applications such as cellular phones that require highly linear power amplifiers. Moreover, GaAs-based HBT process technology is now mature with production volumes approaching 200 million units per year. As a consequence, improvements in materials properties and device structures that can be retrofitted into this robust manufacturing platform are very desirable. For example, lowering the base-emitter turn-on voltage would provide circuit designers with additional flexibility when specifying temperature controlled bias circuitry based on lithium-ion batteries. In addition, improvements in power added efficiency are possible by reducing the collector-emitter knee voltage. These objectives could be realized by lowering the energy band gap of the base and by forming a second (double) heterojunction between the base and collector. The challenge, however, is to reduce $V_{be,on}$ and $V_{ce,knee}$ without adversely impacting other important device parameters such as collector-emitter breakdown voltage, base sheet resistance, DC current gain, and power gain cutoff frequency.

Previous work has demonstrated the overall impact on device performance of constructing the base layer, in otherwise conventional GaAs-based HBT structures, from the GaInAsN material system [1-8]. The focus of the present investigation is on the temperature dependence of β and its stability at high collector current. Direct comparisons have been made, using a high-performance GaInP/GaAs HBT as the benchmark, between GaInP/GaInAsN/GaAs DHBTs with different base alloy compositions and grading schemes.

EXPERIMENT

The five transistors employed in this study fall into two distinct categories: one N-p-N GaInP/GaAs HBT and four N-p-N GaInP/GaInAsN/GaAs DHBTs. Among the four DHBT structures, one contains a GaInAsN base layer in which the alloy composition is linearly graded (Graded) with the widest energy band gap material at the BE junction and the narrowest band gap material at the BC junction. The other three DHBTs contain GaInAsN base layers with constant alloy compositions chosen to match the values at the BE junction (BEend), midpoint (MIDpt), and BC junction (BCend) of the graded base layer. The construction of the emitter and collector regions is nominally identical in all five samples ensuring comparable junction breakdown voltages and series resistances.

The HBT and DHBT structures were grown at Kopin Corporation using an OMVPE process that has been qualified for production [8]. Standard fabrication methods were employed to define square mesas with emitters ranging in length from 40 to 100 µm. Electrical measurements were made using a Keithley 4200 semiconductor parameter analyzer. The operating temperature of the device under test was controlled using a Joule-Thomson heater/refrigerator mounted in a vacuum microprobe station manufactured by MMR Technologies. Transistors were tested at heat-sink temperatures ranging from 225 to 600 K.

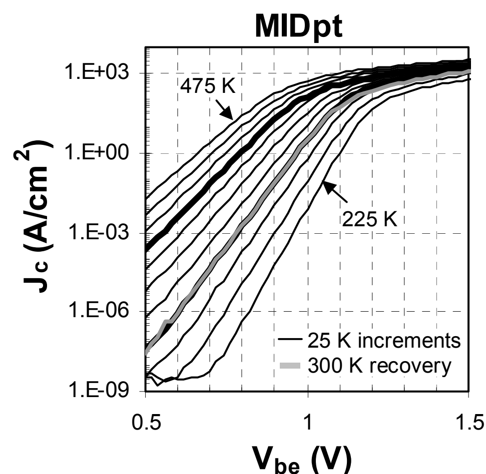

Figure 1: Collector current density versus base-emitter voltage at different temperatures for the MIDpt GaInAsN DHBT. The relevant parameters are base thickness = 44 nm, emitter length = 75 µm, and V_{bc} = -1 V.

Copyright 2003 GaAsMANTECH, Inc.

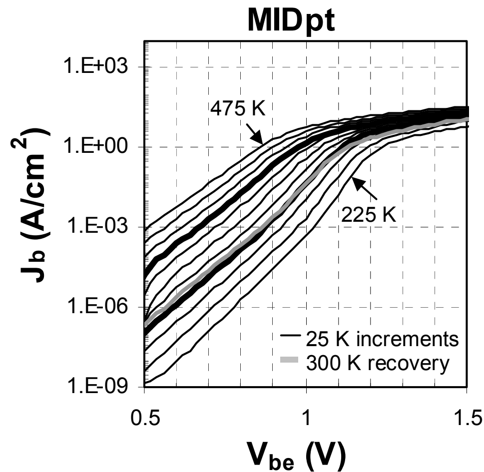

Figure 2: Base current density versus base-emitter voltage at different temperatures for the MIDpt GaInAsN DHBT. The relevant parameters are base thickness = 44 nm, emitter length = 75 µm, and V_{bc} = -1 V.

RESULTS

Figures 1 and 2 show the collector and base current density components, respectively, of Gummel plots measured over the range 225[T[475 K for the MIDpt GaInP/GaInAsN/GaAs DHBT. The J_c vs. V_{be} curves exhibit nearly ideal behavior over nine (three) orders of magnitude at 225 K (475 K). In contrast, the J_b vs. V_{be} curves must be considered in a piecewise manner. At T = 225 K with V_{be} [1 V (J_c [10^{-2} A/cm^2) the base current is dominated by an n ≅ 2 like component attributable to space charge recombination on the emitter side of the BE depletion region. However, for base-emitter voltage bias in the range 1[V_{be}[1.2 V (10^{-2}[J_c[10^1 A/cm^2) an n ≅ 1 like component begins to dominate the base current.

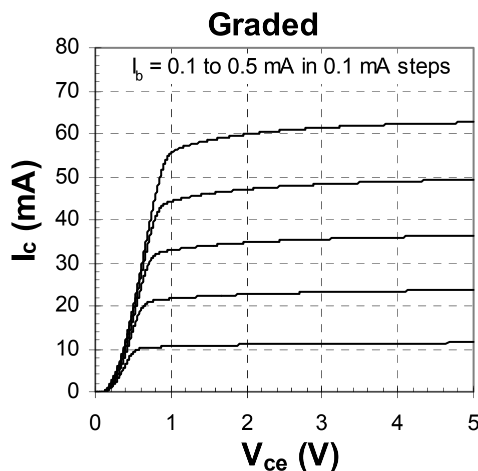

Figure 3: Common-emitter transistor output characteristics at 300 K for the Graded GaInAsN DHBT. The relevant parameters are base thickness = 47 nm and emitter length = 75 µm.

Figures 3 and 4 are plots of the common-emitter transistor output characteristics at 300 K for the Graded GaInP/GaInAsN/GaAs DHBT and GaInP/GaAs HBT, respectively. Note that the collector-emitter offset voltage is considerably smaller for the Graded DHBT than for the GaAs HBT. In addition, the Graded DHBT shows no evidence of negative differential resistance at collector currents in excess of 60 mA while the GaAs HBT clearly suffers from NDR over the same current range.

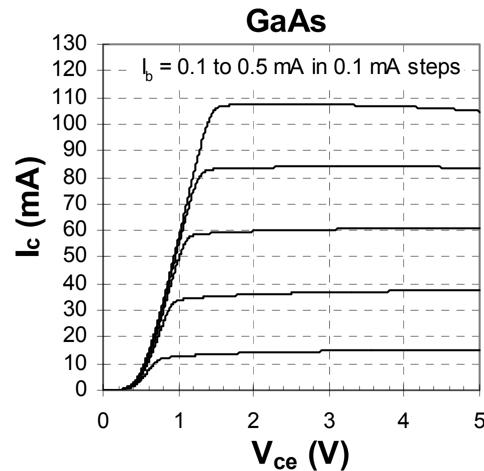

Figure 4: Common-emitter transistor output characteristics at 300 K for the GaAs HBT. The relevant parameters are base thickness = 50 nm and emitter length = 75 µm.

The data plotted in Figure 5 for the MIDpt GaInP/GaInAsN/GaAs DHBT demonstrate that β is almost independent of temperature for J_c/ 10 A/cm^2. Note, also, that β increases by only 20% as the collector current varies over two orders of magnitude. These trends are representative of the behavior observed for the BEend and Graded GaInP/GaInAsN/GaAs DHBTs as well – that is, the DC current gain is very stable with respect to changes in temperature and current density. The weak dependence of DC current gain on temperature is more clearly illustrated in Figure 6 in which each β(T) is normalized by the value measured at 27 8C. The normalized value of β for the GaInP/GaAs HBT drops by nearly 30% as the temperature increases from –50 to 250 8C. In contrast, the normalized values of β for the BEend, MIDpt, and Graded GaInP/GaInAsN/GaAs DHBTs exhibit a modest increase with temperature and an overall change of less than 10%. The BCend DHBT behaves in a distinctly different manner from all other samples in that β increases by more than 200% from –50 to 250 8C.

DISCUSSION

The device parameters in Table 1 demonstrate that the incorporation of a GaInAsN base layer causes a significant reduction in base-emitter turn-on voltage ($\Delta V_{be,on}$) and

collector-emitter knee voltage ($\Delta V_{ce,knee}$). As anticipated, the magnitudes of these voltage shifts increase as the energy band gap of the base narrows. Unfortunately, these attributes are accompanied by an abrupt decrease in β that is almost independent of alloy composition. Note, however, that the drop-off in β is partially offset by grading the energy band gap in the base, i.e., by incorporating a built-in electric field within the quasi-neutral region [9]. The average mobility-doping product for the GaInAsN alloys is still only about 80% of that for their GaAs counterparts. Thus, without further improvement, thicker base layers would be required to achieve similar values of R_{sb} in GaInP/GaInAsN/GaAs structures as compared to GaInP/GaAs HBTs.

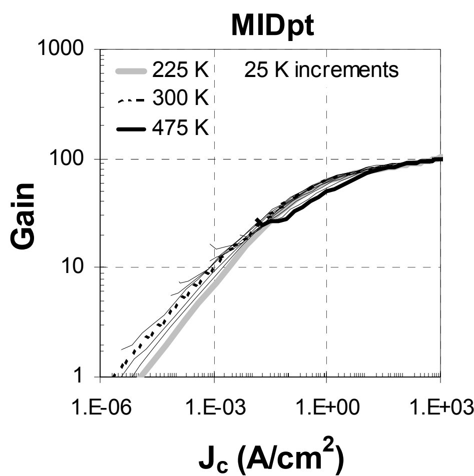

Figure 5: DC current gain versus collector current density at different temperatures for the MIDpt GaInAsN DHBT. The relevant parameters are base thickness = 44 nm, emitter length = 75 μm, and V_{bc} = -1 V.

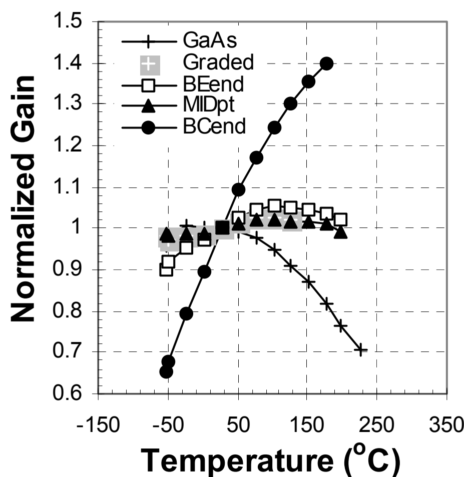

Figure 6: Normalized DC current gain at Jc = 200 A/cm^2 versus temperature for the high-performance GaAs HBT and all four GaInAsN DHBTs.

Previous work has shown that the ratio of β to R_{sb} is a useful indicator of material quality for transistors in which the base doping level is low enough such that Auger recombination in the neutral base does not limit current gain [10]. The symbol F_A is used herein to identify this figure of merit. Despite the significant drop-off in β for the GaInP/GaInAsN/GaAs structures, as compared to the high-performance GaInP/GaAs HBT, the values of F_A for the BEend, MIDpt, and Graded DHBTs are among the highest reported to date. Another useful indicator of device performance (F_B) is the fractional reduction in base-emitter turn-on voltage $\Delta V_{be,on}$(Alloy)/$V_{be,on}$(GaAs) divided by the fractional decrease in current gain Δβ(Alloy)/β(GaAs). A corresponding figure of merit (F_C) is used herein to track reductions in the collector-emitter knee voltage. Using F_A, F_B, and F_C as the basis of comparison, the Graded DHBT outperforms all three samples with constant GaInAsN alloy composition. Moreover, it compares favorably to other GaInAsN-based HBTs reported in the literature.

An important step in the continued development of GaInP/GaInAsN/GaAs DHBTs is to find the cause of the abrupt decrease in current gain. Gummel plots measured at 300 K in both the forward- and reverse-active biasing modes yield nearly ideal J_c vs. V_{be} characteristics over at least 6 orders of magnitude in collector current for all device structures under consideration. These findings demonstrate that J_c is limited by minority carrier electron transport within the base layers and not by the BE or BC hetero-junctions [11]. In addition, devices with emitter lengths greater than 40 μm exhibit "large-area" behavior; that is, the base current density is independent of emitter area. Thus, surface and contact recombination mechanisms may be ignored when analyzing the voltage and temperature dependences of the base current. The weak temperature dependence of β suggests that back injection of holes from the base into the emitter has been all but eliminated by the GaInP/GaInAsN heterojunction. These findings leave only an increase in space charge recombination (in the BE depletion region) or an increase in minority carrier recombination (in the neutral base) as possible explanations for the drop-off in current gain. In high-performance GaInP/GaAs HBTs, minority carrier recombination in the neutral base is the limiting factor in the overall expression for current gain when operating near 300 K at high collector current [10]. This component of the base current exhibits a weak dependence on temperature [12] and thus may explain our findings.

Since the base layer in the BCend DHBT contains the largest In and N mole fractions, stress relaxation might have occurred during growth via the introduction of misfit dislocations. If so, one might expect an increase in HSR recombination in the neutral base. The HSR recombination rate is a decreasing function of temperature and thus one might anticipate that the DC current gain would increase at higher temperatures consistent with our findings.

TABLE 1: STRUCTURAL, MATERIAL, AND DC DEVICE PARAMETERS FOR HBT AND DHBT STRUCTURES

Base Structure	W_b (nm)	$\mu_p p x 10^{21}$ ($cm^{-1}/V \cdot s$)	R_{sb} (Ω/sq)	J_c (n)	Max DC Gain (β)	BV_{ceo} (V)	$V_{be,on}$ (V)	$V_{ce,knee}$ (mV)	F_A	F_B	F_C
GaAs	50	3.25	385	1.013	208	17.5	1.076	910	0.546	---	---
BEend	47	2.49	535	1.034	94	20.5	1.012	734	0.176	0.125	0.353
MIDpt	44	2.72	523	1.048	102	18.8	0.986	692	0.195	0.178	0.470
BCend	47	2.22	600	1.033	42	19.0	0.973	N/A	0.070	0.087	N/A
Graded	47	2.49	534	1.032	117	17.7	0.992	707	0.219	0.192	0.510

Table 1: All experimental parameters were obtained from measurements taken at 300 K. Reported values of β, n, and $V_{be,on}$ were derived from Gummel plots taken with V_{bc} = -1 V. $V_{be,on}$ is defined as the applied voltage at the BE junction when $J_c = 1.78$ A/cm^2. Reported values of $V_{ce,knee}$ were derived from common-emitter transistor output characteristics. $V_{ce,knee}$ is defined as the collector-emitter voltage at which the 2nd derivative of the I_c vs. V_{ce} curve is a maximum (the I_b bias point was chosen such that I_c is roughly 35 mA for each device). The figures of merit F_A, F_B, and F_C are defined as follows: $F_A = \beta/R_{sb}$; $F_B = \Delta V_{be,on}(Alloy)/V_{be,on}(GaAs)$ divided by $\Delta\beta(Alloy)/\beta(GaAs)$; $F_C = \Delta V_{ce,knee}(Alloy)/V_{ce,knee}(GaAs)$ divided by $\Delta\beta(Alloy)/\beta(GaAs)$.

CONCLUSIONS

While GaInP/GaInAsN/GaAs DHBTs exhibit the anticipated reductions in $V_{be,on}$ and $V_{ce,knee}$, these benefits come at the expense of lower DC current gain relative to high-performance GaInP/GaAs HBTs. Improvements in DC current gain are possible by grading the GaInAsN alloy composition in the base layer. A wholly unexpected attribute of GaInP/GaInAsN/GaAs DHBTs is the excellent temperature stability of the DC current gain at high current density. This behavior manifests itself in a higher collector current threshold for the onset of NDR in the common-emitter transistor output characteristic as compared to conventional GaInP/GaAs HBTs.

REFERENCES

[1] N.Y. Li, P.C. Chang, A.G. Baca, X.M. Xie, P.R. Sharps, H.Q. Hou, "DC Characteristics of MOVPE Grown Npn InGaP/InGaAsN DHBTs," Electron. Lett. **36**, 81 (2000).

[2] P.C. Chang, A.G. Baca, N.Y. Li, X.M. Xie, H.Q. Hou, "InGaP/InGaAsN/GaAs Double-Heterojunction Bipolar Transistors," Appl. Phys. Lett. **76**, 2262 (2000).

[3] P.C. Chang, A.G. Baca, N.Y. Li, P.R. Sharps, H.Q. Hou, J.R. Laroche, F. Ren, "InGaAsN/AlGaAs P-n-p Heterojunction Bipolar Transistor," Appl. Phys. Lett. **76**, 2788 (2000).

[4] R.E. Welser, P.M. DeLuca, N. Pan, "Turn-On Voltage Investigation of GaAs-Based Bipolar Transistors with GaInAsN Base Layers," IEEE Electron. Dev. Lett. **21**, 554 (2000).

[5] R.J. Welty, H.P. Xin, K. Mochizuki, C.W. Tu, P.M. Asbeck, "GaAs/GaInNAs/GaAs NpN Double Heterojunction Bipolar Transistor with Low Turn-On Voltage," Solid-State Electron. **46**, 1 (2002).

[6] P.C. Chang, C. Monier, A.G. Baca, N.Y. Li, F. Newman, E. Armour, H.Q. Hou, "High-Speed InGaP/InGaAsN/GaAs NpN Double Heterojunction Bipolar Transistor with Low Turn-On Voltage," Solid-State Electron. **46**, 581 (2002).

[7] P.M. Asbeck, R.J. Welty, C.W. Tu, X.P.Xin, R.E. Welser, "Heterojunction Bipolar Transistors Implemented with GaInNAs Materials," Semicond. Sci. Technol. **17**, 898 (2002).

[8] P.M. DeLuca, C.R. Lutz, R.E. Welser, T.Y. Chi, E.K. Huang, R.J. Welty, P.M. Asbeck, "Implementation of Reduced Turn-on Voltage InGaP HBTs using Graded GaInAsN Base Regions," IEEE Electron. Dev. Lett. **23**, 582 (2002).

[9] H. Kroemer, "Heterostructure Bipolar Transistors; What Should We Build," J. Vac. Sci. Technol. B **2**, 126 (1983).

[10] R.E. Welser, N. Pan, D.P. Vu, P. Zampardi, B.T. McDermott, "Role of Neutral Base Recombination in High Gain AlGaAs/GaAs HBTs," IEEE Trans. Electron Devices **46**, 1599 (1999).

[11] W. Liu, S. Fang, T.S. Kim, E.A. Beam III, D.B. Davito, "Current Transport Mechanism in GaInP/GaAs Heterojunction Bipolar Transistors, IEEE Trans. Electron Devices **40**, 1378 (1993).

[12] C.M.S. Ng, P.A. Houston, H.K. Yow, "Analysis of the Temperature Dependence of Current Gain in Heterojunction Bipolar Transistors," IEEE Trans. Electron Devices **44**, 17 (1997).

ACRONYMS

HBT: heterojunction bipolar transistor
DHBT: double heterojunction bipolar transistor
OMVPE: organo-metallic vapor phase epitaxy
BE: base-emitter junction
BC: base-collector junction
F_A: DC current gain divided by base sheet resistance
F_B: $\Delta V_{be,on}(Alloy)/V_{be,on}(GaAs)$ divided by $\Delta\beta(Alloy)/\beta(GaAs)$
F_C: $\Delta V_{ce,knee}(Alloy)/V_{ce,knee}(GaAs)$ divided by $\Delta\beta(Alloy)/\beta(GaAs)$
NDR: negative differential resistance
HSR: Hall-Shockley-Read recombination
$V_{be,on}$: base-emitter turn-on voltage
$V_{ce,knee}$: collector-emitter knee voltage
$V_{ce,offset}$: collector-emitter offset voltage
BV_{ceo}: collector-emitter breakdown voltage
R_{sb}: base sheet resistance
β: DC current gain
f_{max}: power gain cutoff frequency
J_c: collector current density
J_b: base current density

Copyright 2003 GaAsMANTECH, Inc.