Base Layer Band Gap Engineering for III-V Bipolar Devices

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ABSTRACT

The dc current gain of InGaP/GaInAsN and InP/InGaAs DHBTs is increased by compositionally grading the energy-gap of the base layer. Graded InP/InGaAs DHBTs exhibit a 50% boost in current gain while InGaP/GaInAsN DHBTs exhibit up to a 100% increase. The use of graded base layers can increase flexibility in the design of DHBT structures for both InP and GaAs-based devices, by improving the dc current gain for a given base sheet resistance.

INTRODUCTION

Heterojunction bipolar transistor (HBT) integrated circuits (ICs) have developed into a key technology as power amplifiers for wireless handsets and high speed (>10 Gbit/s) circuits for fiber optic communication systems. Higher speed and lower turn-on voltages may be necessary for III-V HBTs to remain competitive in future circuit applications. InP/InGaAs DHBTs are being considered as an enabling technology for 40 Gbps lightwave circuits. InGaP/GaInAsN DHBTs are being pursued to enhance the GaAs platform by lowering the turn-on voltage. However, both material technologies suffer from low dc current gains relative to GaAs-based HBTs. Engineering the base layer band gap may provide significant benefits in extending the applications of current GaAs technologies and facilitating the introduction of InP circuits.

In this work, we report on the effects of grading the energy-gap of the base layer (E_{gb}) in both InGaP/GaInAsN and InP/InGaAs double heterojunction bipolar transistors (DHBTs). Carbon-doped DHBT device wafers were grown using low pressure MOVPE in an Aixtron 2400 multiwafer production system. Large area devices (75 µm x 75 µm) were fabricated using a simple wet-etching process and tested in the common base configuration using an HP4145 parametric analyzer.

Gain vs. Base Sheet Resistance Comparison

Figure 1 compares dc current gain (β) as a function of base sheet resistance (R_{sb}) for three different III-V HBT material technologies. Typical InGaP/GaAs SHBTs are compared to InGaP/GaInAsN (GaInAsN) and InP/InGaAs (InP) DHBTs structures. For all three materials only the base thickness was varied. The reduction in β for the GaInAsN and InP technologies is substantial. For example, to achieve a β of 100, GaInAsN and InP require R_{sb} values 5x and 8x, respectively, that of GaAs. In order to facilitate the introduction of dilute nitrides and InP in many applications, improvements in β may be necessary. In this paper, we attempt to maximize current gain by incorporating a graded base into InGaP/GaInAsN and InP/InGaAs DHBT structures.

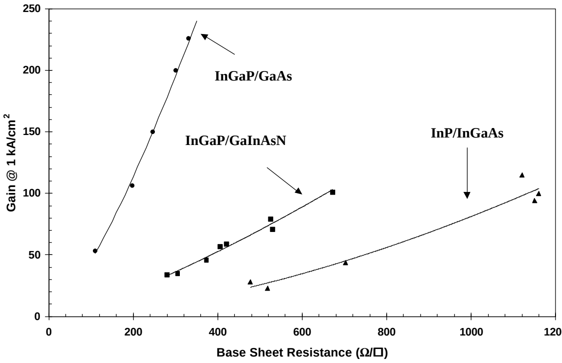

Figure 1 DC current gain as a function of base sheet resistance from InGaP/GaAs, InGaP/GaInAsN, and InP/InGaAs HBT structures with varying base thicknesses.

Graded Base Concept

The concept of grading the base layer is well known in bipolar technologies [1]. Graded Si_xGe_{1-x} HBT devices result in significantly reduced base transit times, which has opened up significant new opportunities for Si technologies [2]. While demonstrated in the laboratory, this technique has been slow to incorporate into III-V designs [3,4]. This delay has been the result of a reliance on the excellent material characteristics of GaAs HBTs and the difficulty in controlling the base layer doping while compositionally grading the base.

Grading the energy-gap of the base layer from a larger E_{gb} at the base-emitter interface to a smaller E_{gb} at the base-collector interface introduces a quasielectric field, which accelerates electrons across the base in an npn bipolar device. The electric field increases the electron velocity in the base, decreasing the base transit time for improved RF performance and increased β. The dc current gain, in the case of HBTs with heavily doped base layers, is limited by bulk recombination in the neutral base (n=1) [5,6]. The dc current gain can be estimated by:

$$\beta \cong \upsilon\tau/w_b$$

where υ is the average minority carrier velocity in the base, τ is the minority carrier lifetime in the base and w_b is the base thickness. In the case of graded base HBTs, the minority carrier lifetime and base thickness are held constant, resulting in a significant increase in β due to the increased electron velocity. This analysis assumes that the grading does not significantly alter the minority carrier lifetime in the base. In the case of constant composition GaInAsN and InGaAs base layers, τ is reduced relative to GaAs. The reduction in lifetime may be the result of ternary and quaternary base material. Proper base layer E_{gb} engineering combines improved β performance, preserving compatability with circuits and designs based on InGaP/GaAs materials, and the enhanced features intrinsic in these advanced material systems.

InGaP/GaInAsN DHBTs

Traditional InGaP/GaAs HBTs have higher turn-on voltages compared to competing SiGe bipolar technologies due to the higher GaAs base layer E_{gb}. By adding both In and N to GaAs, the E_{gb} can be reduced while minimizing lattice strain, resulting in significant turn-on voltage reduction. InGaP/GaInAsN DHBTs have previously demonstrated reasonable DC and RF performance [7-10]. However, even for the best GaInAsN material, the dc current gain is typically a factor of 5 lower than standard InGaP/GaAs HBTs with similar base sheet resistances (Figure 1).

A comparison of base currents from a constant and graded base InGaP/GaInAsN DHBT (Figure 2) illustrates that β can be increased by a factor of 2 with comparable turn-on voltage and base sheet resistance. Comparable turn-on voltages ensure that the collector current has not significantly changed. Similar R_{sb} values are necessary due to the strong dependence of β on R_{sb}. The neutral base component (n=1) of the base current is significantly lower in the graded base structure. This reduction in neutral base recombination can be explained by the increased electron velocity produced by the quasielectric field in the graded base structure.

Figure 3 compares β as a function of base sheet resistance for similar constant and graded base InGaP/GaInAsN DHBT structures with varying base thickness. The increase in β/R_{sb} for graded base structures is readily apparent. The β/R_{sb} of the baseline InGaP/GaInAsN DHBT depends on the growth conditions utilized and the specific details of the overall structure. The graded base structure typically results in a 50 to 100% increase in β/R_{sb}.

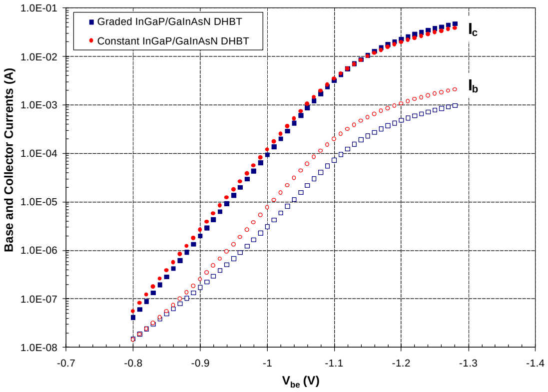

Figure 2 Gummel plots from a constant and a graded E_{gb} InGaP/GaInAsN HBT structure with comparable base layer growth conditions, turn-on voltages (V_{be} ~ 1.00 V @ 1E-4 A) and base sheet resistances (R_{sb} ~ 350 $\Omega/\square$).

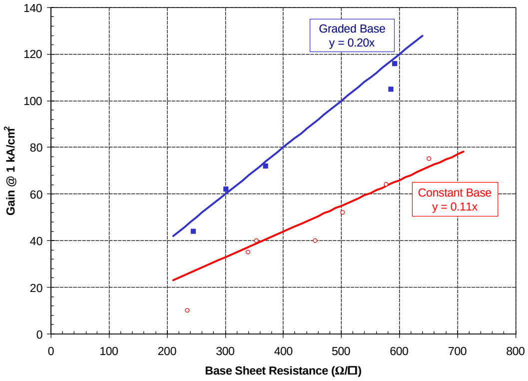

Figure 3: DC current gain as a function of base sheet resistance for constant and graded base InGaP/GaInAsN DHBTs. The dc current gain is measured at J_c = 1 kA/cm^2 on large area 75 μm x 75 μm emitter devices. The solid lines are linear fits used as a guide to the eye, and represent β/R_{sb} of 0.11 and 0.20.

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, β for InP HBTs is no more than 1/8 that of InGaP/GaAs HBTs for similar R_{sb} (Fig. 1). This suggests that a graded base could facilitate the introduction of InP circuits. The ternary base material, InGaAs, enables the lattice strain to be offset while grading the base layer. This is accomplished by grading the composition from a compressive strain (large E_{gb}) at the base-emitter interface to a tensile strain (small E_{gb}) at the base-collector interface. The InP/InGaAs DHBT structure in this work consisted of (from the top surface) a highly doped n$^+$-InGaAs contact layer, a highly doped 500 Å thick InP (1x10^{19} cm^{-3}) emitter cap, a 500 Å thick InP (3x10^{17} cm^{-3}) emitter, and a 700 Å thick C-InGaAs (2x10^{19}) base layer. This was followed by a 2000 Å thick InP (3x10^{16} cm^{-3}) collector and a 4000Å thick InGaAs (1x10^{19} cm^{-3}) subcollector.

Gummel plots from constant and graded base InP/InGaAs DHBTs with comparable turn-on voltage and base sheet resistance (Figure 4) demonstrate that the neutral base component (n=1) of I_b has been suppressed in the graded base structure as with the InGaP/GaInAsN DHBTs. Figure 5 shows β as a function of current density, illustrating the increase in β for the graded base DHBT. Electrons spend less time in the graded base as a result of the increased electron velocity, which reduces the opportunities to recombine.

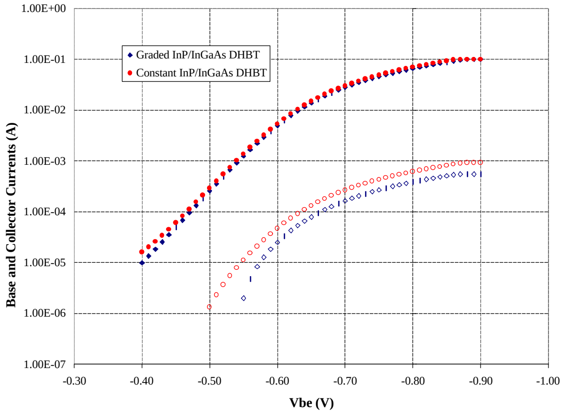

Figure 4: Gummel plots from a constant and a graded E_{gb} InP/InGaAs HBT structure with comparable base layer growth conditions, turn-on voltages (V_{be} ~ 0.47 V @ 1E-4 A) and base sheet resistances (R_{sb} ~ 1000 $\Omega/\square$).

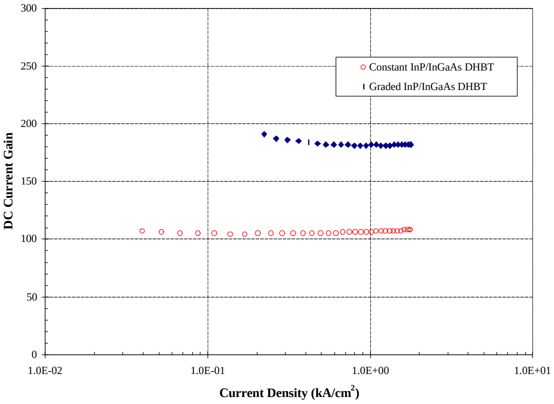

Figure 5: DC current gain versus collector current density for the two transistor structures in Figure 4.

Figure 6 compares β as a function of R_{sb} from constant and graded base InP/InGaAs DHBT structures with varying base thickness. The structures compared were identical, with the exception of the base grading. The base was linearly graded across the entire thickness of the base layer. As in the case of InGaP/GaInAsN DHBTs, the increase in gain-to-base sheet resistance ratio is readily apparent across a wide range of R_{sb} values. The graded base structure typically results in a 60% increase in β/R_{sb}. It should be noted that β for the InP/InGaAs has an R_{sb}-squared dependence instead of the linear dependence of GaAs HBTs.

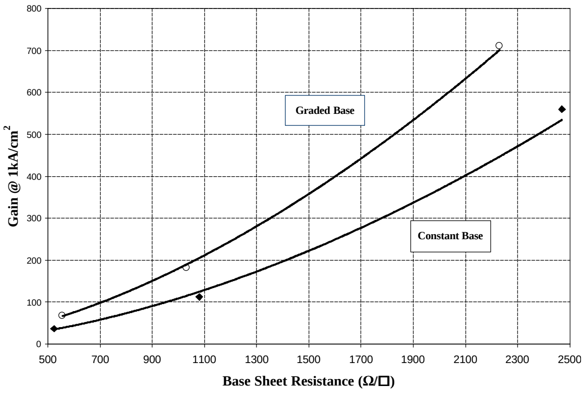

Figure 6: DC current gain as a function of base sheet resistance from constant and graded base InP/InGaAs DHBTs. The solid lines are fits used as a guide to the eye.

CONCLUSIONS

The use of graded base layers results in increased flexibility in the design of InGaP/GaInAsN and InP/InGaAs DHBTs by improving the dc current gain for a given base sheet resistance. In both cases the current gain is typically increased by 50–100% in graded base structures. In addition, graded base layers can be expected to enhance RF performance by reducing base transit times by an amount commensurate with the increase in current gain.

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