Pathway for HBT Turn-on Voltage Reduction on a GaAs Platform

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ABSTRACT

The fundamental lower limit on the turn-on voltage of GaAs-based bipolar transistors is reduced with the use of a low energy-gap base material, GaInAsN. A 115 mV reduction in the turn-on voltage over a wide range of base sheet resistance values (250 to 850 Ω/☐) is established relative to both GaAs BJTs and conventional InGaP/GaAs HBTs with optimized base-emitter interfaces. InGaP/GaInAsN DHBTs structures with high p-type doping levels (~ $3x10^{19}$ cm^{-3}) and acceptable DC and RF characteristics (β_{max} ~ 75, f_t ~ 64 GHz) are demonstrated. The reduction in turn-on V_{be} enabled by lattice-matched GaInAsN base layers should permit improved management of the voltage budget, and enhance the overall performance, of both wired and wireless GaAs-based RF circuits.

INTRODUCTION

GaAs-based heterojunction bipolar transistor (HBT) integrated circuits (ICs) have developed into a key technology for a variety of applications, particularly as power amplifiers for wireless handsets and high speed (>10 Gbit/s) circuits for fiber optic communication systems [1]. However, one of the difficulties designers encounter applying this technology to increasingly complex circuits is the limited number of transistors that can be stacked within a given power supply rail, constrained either by standard fixed voltage supplies or by battery output. GaAs-based power amplifier circuit designs are particularly limited in terms of bias circuit behavior and on-chip logic integration [2]. As a result, there is significant motivation to decrease the turn-on voltage of each transistor.

Traditional AlGaAs/GaAs and InGaP/GaAs HBTs suffer from high turn-on voltages relative to competing SiGe and InP bipolar technologies because of the higher GaAs base layer energy gap (E_{gb}) and, to a lesser extent, the impact of a conduction band spike at the base-emitter interface. In this work, we report on our progress in developing high performance InGaP/GaInAsN double heterojunction bipolar transistors (DHBTs). Turn-on voltage reduction is achieved in these structures by simultaneously lowering the energy-gap of the base layer and minimizing the impact of the conduction band spikes. Numerous laboratories have demonstrated that the energy-gap of GaInAs decreases substantially when small amounts of N are incorporated into the material [3,4]. More important, GaInAsN alloys can be grown lattice-matched to GaAs because In and N have opposing strain effects on the lattice (Figure 1). GaInAsN alloys thus provide a practical pathway for reducing HBT turn-on voltage on a GaAs platform by relieving the problems of excess strain. While still an immature material system, the bandgap engineering enabled by GaInAsN is being aggressively developed for a variety of device applications, including laser diodes, multijunction solar cells, HBTs and HEMTs [3-8]. Described below are our current results and general approach for exploiting the GaInAsN material system to enhance the performance of GaAs-based HBTs.

TURN-ON V_{be} AND BASE SHEET RESISTANCE (R_{sb})

Ideally, the turn-on voltage of bipolar transistors, defined as the base-emitter voltage (V_{be}) required to achieve a certain fixed collector current density (J_c), is governed by the material properties of the base layer (including R_{sb} and E_{gb}). However, a spike in the conduction band at the emitter-base interface of an HBT can block electron transport, thus limiting collector current and effectively raising the turn-on voltage. By comparing the current characteristics of several different types of GaAs-based bipolar transistor

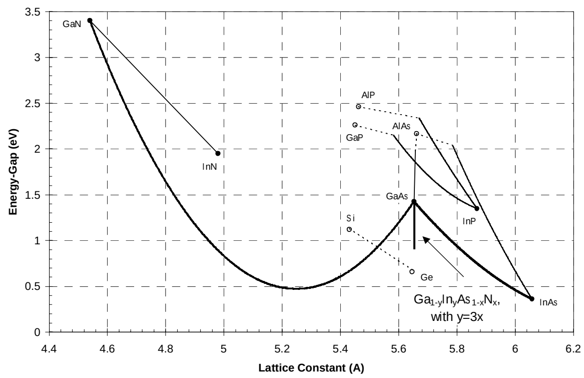

Fig. 1. Energy-gap vs. lattice constant for common III-V semiconductors including GaAsN. Highlighted are the GaAsN and GaInAs ternaries, as well as the lattice-matched GaInAsN quaternary.

structures, including GaAs emitter BJTs with no conduction band spike, we have established the fundamental lower limit of the turn-on voltage that can be achieved using GaAs in the base layer [7]. To further quantify changes, the turn-on voltage can be expressed as a logarithmic function of R_{sb}:

$$V_{be} = -(kT/q)\ln[R_{sb}] + V_o \qquad (1)$$

where V_o is dependent principally upon E_{gb} and J_c. As seen in Figure 2, the turn-on V_{be} of both the InGaP/GaAs HBTs and the GaAs emitter/GaAs base BJTs qualitatively exhibit the same ideal logarithmic dependence on R_{sb}. This data provides a base line for analyzing the collector current characteristics of InGaP/GaInAsN DHBTs.

The basic InGaP/GaInAsN DHBT device structures explored in this work are identical to standard InGaP/GaAs HBTs except for the addition of In and N to the base layer, as described in Reference [7]. All samples have MOCVD-grown, C-doped base layers varying between 1.5-4.5x10^{19} cm^{-3} in doping and 500-1500 Å in thickness, resulting in R_{sb} values between 100 and 850 Ω/☐. The electrical and structural properties of the GaInAsN base layer are determined directly from the InGaP/GaInAsN DHBT structure by a combination of transistor measurements, Polaron C-V profiles, photoluminescence (PL) signals, and double crystal x-ray diffraction spectrum [9]. Large area devices (L = 75 µm x 75 µm) are fabricated using a simple wet-etching process and tested in the common base and common emitter configurations. Our basic experimental approach for developing InGaP/GaInAsN

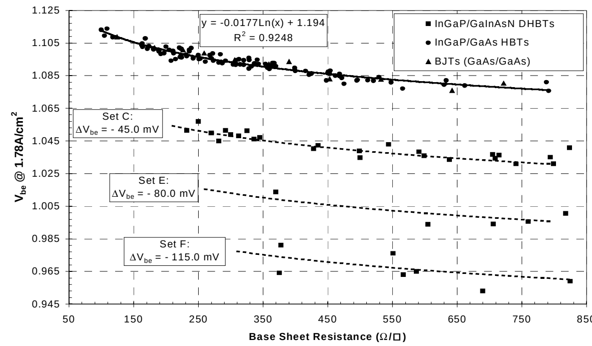

Fig. 2. Turn-on V_{be} (@ J_c = 1.78A/cm^2) as a function of R_{sb} for standard InGaP/GaAs HBTs and GaAs/GaAs BJTs, as well as Set C, Set E, and Set F InGaP/GaInAsN DHBTs. The solid line represents a logarithmic fit to the InGaP/GaAs HBT data, while the dashed lines are a 45.0, 80.0 and 115.0 mV reduction to the fit, used as a guide for the eye for the Set C, Set E, and Set F InGaP/GaInAsN data.

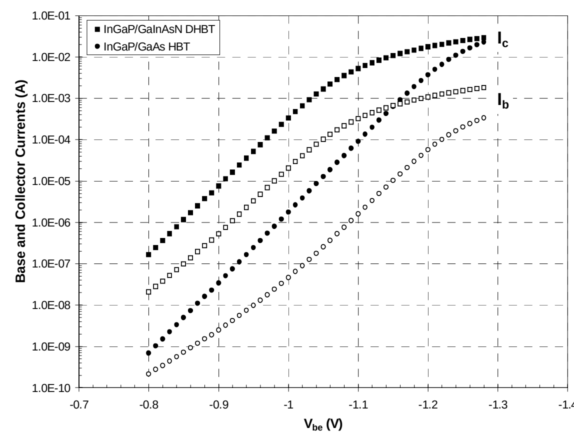

Fig. 3. Large area (75 µm x 75 µm) Gummel plots from a Set F InGaP/GaInAsN DHBT and a conventional InGaP/GaAs HBT. The collector currents are the solid shapes, the base currents open shapes. Differences in the turnover of the collector currents at higher bias can be attributed to current crowding effects.

DHBTs is iterative in nature and focuses on obtaining both high p-type base doping levels and acceptable dc current gain characteristics. Using standard 4x10^{19} cm^{-3} p-type GaAs base layers as a base line, we add small amounts of In and N, optimize the growth for maximum doping and dc current gain, and then incrementally increase both the In and N levels. Separate sets (e.g. A through F) of InGaP/GaInAsN DHBTs are thus defined, each characterized by an average reduction in turn-on voltage (ΔV_{be}) relative to GaAs BJTs of similar R_{sb}. Figure 2 illustrates the turn-on voltage reduction

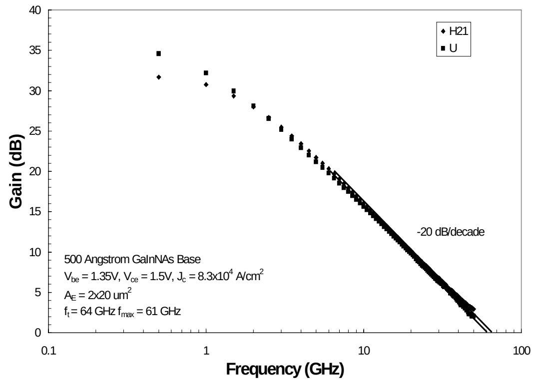

Fig. 4. RF results from a 2 µm x 20 µm device on a Set C InGaP/GaInAsN DHBT. The extrapolated f_t and f_{max} are 64 GHz and 61 GHz. The measurements were taken at V_{be} = 1.35 V, V_{ce} = 1.5 V, and J_c = 83 kA/cm^2.

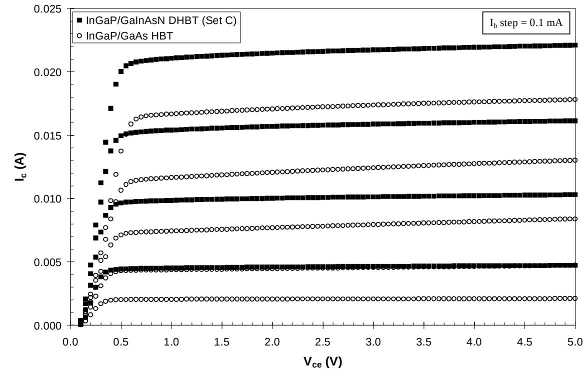

Fig. 5. Common emitter characteristics from a large area (75 µm x 75 µm) Set C InGaP/GaInAsN DHBT (R_{sb} ~ 312 Ω/☐) and a standard InGaP/GaAs HBT (R_{sb} ~ 124 Ω/☐).

achieved in our latest sets of InGaP/GaInAsN DHBTs relative to other GaAs-based bipolar structures. The turn-on V_{be} of the InGaP/GaInAsN DHBTs follows the logarithmic dependence on R_{sb} expected from Equation (1), but the entire curve shifts downward by an amount (45.0, 80.0, and 115.0 mV in the Set C, E, and F samples) related to the reduction in E_{gb}, as expected from Equation (1) and confirmed by PL measurements.

DC AND RF CHARACTERISTICS

Comparison of the collector currents from a Set F InGaP/GaInAsN DHBT and a conventional InGaP/GaAs HBT illustrates that over a 150 mV reduction in turn-on V_{be} can be obtained for five decades of collector current, corresponding to a two order of magnitude increase in J_c for a fixed V_{be}, as seen in Figure 3, by lowering E_{gb} and increasing R_{sb}. DC current gains (β) of greater than 10 are also achieved over four decades of current for most structures. The maximum dc current gain scales with base sheet resistance as expected, and can exceed 75 in all InGaP/GaInAsN sets (e.g. β ~ 75 @ R_{sb} ~ 683 Ω/☐, Set F).

Small area devices were processed on the Set C InGaP/GaInAsN structures using an advanced airbridge process. Emitter fingers were 2 microns wide and the length ranged from 2 to 20 microns. On-wafer RF testing was performed using an HP8510C from 0.5-50 GHz. Pad parasitics were de-embedded using open and short structures. The f_t and f_{max} were extrapolated using –20 dB/decade slopes of the small signal current gain (H_{21}) and unilateral gain (U), and were found to be 64 and 61 GHz respectively (Figure 4). This is comparable to the f_t and f_{max} achieved in a GaAs-based HBT with a similar BV_{cbo} of 14.7 V.

Controlling the conduction band spike at both the base-emitter and base-collector interfaces is essential for optimizing the dc and rf properties of these InGaP/GaInAsN DHBTs. Conduction band spikes at both junctions generally appear to be minimized on our structures, as characterized by a variety of methods. For example, the collector currents exhibit near ideal n=1 behavior, and forward and reverse Gummel plots overlay (see Figure 2 of Reference [9]). The knee and offset voltages are comparable, if not superior, to standard InGaP/GaAs HBTs (Figure 5). The temperature characteristics of the dc current gain and collector current are also comparable, if not superior, in stability to standard InGaP/GaAs HBTs.

POTENTIAL BENEFITS: STABILITY, RELIABILITY, POWER ADDED EFFICIENCY, AND SPEED

While the reduction in turn-on V_{be} achieved in InGaP/GaInAsN DHBTs can directly benefit the management of the voltage budget on both wired and wireless GaAs-based RF circuits, there are a number of additional performance enhancements worth noting which could result with these structures. Lowering the turn-on V_{be} to achieve a target J_c alters the relative magnitude of the various base current components in a GaAs-based HBT. In particular, the relative magnitudes of the reverse hole injection and space charge recombination components are suppressed as the neutral base recombination component of the base current increases in proportion to the collector current

(Figure 3) [10]. DC current gain stability as a function of both temperature and applied bias has been previously shown to rely critically on the relative magnitudes of these base current components [11]. Improvements in long term device reliability have also been associated with a reduction in turn-on V_{be} [12]. By extending the arguments given by Mochizuki *et al.* in Reference [13], a reduction in offset and knee voltages, and hence an increase in power added efficiency, may also be expected with an optimized InGaP/GaInAsN DHBT structure. By increasing the n=1 component of the base-collector forward bias current relative to the n=2 component, better symmetry between the forward diode currents can be achieved. Finally, strain-free, graded energy-gap GaInAsN base structures may be reasonably expected to enhance RF performance in GaAs-based HBTs by decreasing the base transit time [14].

SUMMARY

We have demonstrated that the turn-on V_{be} of GaAs-based HBTs can be reduced below that of GaAs BJTs by using an InGaP/GaInAsN DHBT structure. Turn-on V_{be} reductions over 150 mV are achieved through two key steps. The base-emitter interface is first optimized to suppress the conduction band spike, as is currently done in state-of-the-art InGaP/GaAs and AlGaAs/GaAs HBTs. Further reduction in V_{be} is then accomplished by lowering E_{gb}. By adding both In and N to the base layer, E_{gb} can be reduced while minimizing strain in the base layer. With proper growth optimization, we have achieved a two order of magnitude increase in J_c while maintaining high base doping and acceptable dc and rf characteristics. These results clearly indicate the potential of GaInAsN alloys for lowering the turn-on voltage in GaAs-based HBTs.

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