Enhanced Performance GaAs-Based HBTs using a GaInNAs Base Layer

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ABSTRACT

GaInNAs base layers are enabling performance enhancements over standard GaAs-based HBTs, while preserving the cost effective GaAs platform. We have demonstrated InGaP/GaInNAs HBTs which offer 115 mV lower operating voltage, improved diode symmetry for reduced $V_{CE,offset}$ and V_{knee}, and superior gain temperature stability as compared with standard InGaP/GaAs HBTs. These enhancements have been realized while simultaneously preserving DC current gain and base doping (β ~ 80, R_{sb} ~ 530 $\Omega/\square$, base thickness ~ 500 Å, base doping ~ 4×10^{19} cm^{2}) at the high levels necessary for commercial applications. GaInNAs enables these performance enhancements due to a lower energy gap which advantageously alters relative magnitudes of the collector and various base current components in an HBT.

INTRODUCTION

GaAs-based heterojunction bipolar transistor (HBT) integrated circuits 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. However, there is ever increasing demand for performance enhancements to the basic GaAs-based HBT. Increased handset circuit complexity, higher efficiency and lower power dissipation for extended battery lifetime, faster fiber optic bit rates, and improved robustness are some of the motivating issues. The relevant device performance enhancements include lower minimum operating voltage, improved gain stability, greater reliability at increased current densities, lower $V_{CE,offset}$ and V_{knee}, and shorter transit times. Manipulating the relative magnitudes of the collector and various base current components in a GaAs-based HBT will help realize most all these improvements.

To first order, there are five current components for state of the art GaAs-based HBTs operating in active mode. One component describes the collector current (I_C) and the other four comprise the base current (I_B). The collector current is simply the base-emitter forward biased diode diffusion current, which is exponentially dependent on the base-emitter voltage (V_{be}). The base current is composed of space charge recombination (I_{SC}), neutral base recombination (I_{NB}), reverse hole injection (I_{RHI}), and surface recombination (I_{SR}) currents. By manipulating these currents, several device enhancements can be realized. Increasing I_C for fixed V_{be} lowers the operating voltage of the HBT. This also reduces the relative contribution of I_{SC}, I_{SR} and I_{RHI} to I_B, thereby improving gain stability and reliability [1,2]. Matching current for the base-emitter and base-collector junctions at the same forward bias (V_{be} and V_{bc}, respectively), minimizes the offset voltage ($V_{CE,offset}$) and knee voltage (V_{knee}). These reductions should allow for improved PAE [3,4].

The current component adjustments described above can be achieved by lowering the base layer energy gap ($E_{g,b}$), while taking care to minimize the impact of conduction band spikes. These adjustments, in turn, result in device performance enhancements. To achieve this, while at the same time preserving the cost effective GaAs platform, we substitute p^+-GaInNAs for p^+-GaAs as the HBT base layer. Numerous laboratories have demonstrated that the energy-gap of GaInAs decreases substantially when small amounts of N are incorporated into the material [5,6]. More importantly, GaInNAs alloys can be grown lattice-matched to GaAs because In and N have opposing strain effects on the lattice (N adds tensile strain, In compressive). Using this quaternary system, it should also be possible to engineer a strain-free graded E_g base layer, thereby enhancing the frequency performance of the device. The bandgap engineering enabled by GaInNAs is being aggressively developed for a variety of device applications, including laser diodes, multijunction solar cells, HBTs and HEMTs [5-10]. In this report, we present our current results for exploiting the GaInNAs material system to enhance the performance of GaAs-based HBTs.

EXPERIMENT

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 elsewhere [9]. All samples have MOCVD-grown, C-doped base layers varying between 1.5-6x10^{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 [11]. 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.

RESULTS AND DISCUSSION

Our basic approach for developing InGaP/GaInAsN 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, thereby lowering $E_{g,b}$. Separate sets (e.g. A through F) of InGaP/GaInNAs DHBTs are thus defined as having different $E_{g,b}$.

Using the GaInNAs base layer approach, we have achieved turn-on voltage reductions up to 115 mV relative to other GaAs-based bipolar structures. This is illustrated in Figure 1, which shows the V_{be} required to achieve a certain fixed collector current density (J_C) as a function of base sheet resistance (R_{sb}). Standard InGaP/GaAs HBTs and GaAs/GaAs BJT data are included to establish the fundamental lower limit of the turn-on voltage that can be achieved using a GaAs base layer [9]. To help quantify turn-on voltage reductions, a solid line is included and indicates a logarithmic fit to this data. Three sets of InGaP/GaInNAs DHBT data are fitted by the same logarithmic dependence on R_{sb}, allowing for a V_{be} shift due to bandgap narrowing. These fits show 45, 80, and 115 mV reductions in turn-on voltage for the three sets of InGaP/GaInNAs DHBTs. Comparison of J_C vs. V_{be} shows this turn-on reduction is maintained for over five decades of current, corresponding to a two order of magnitude increase in J_C for a fixed V_{be}.

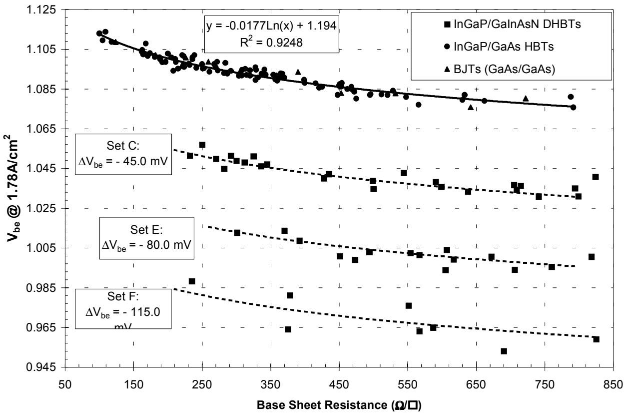

Fig. 1. Turn-on V_{be} (@ J_C = 1.78A/cm^2) as a function of R_{sb} for standard InGaP/GaAs HBTs and GaAs/GaAs BJTs. Also shown are data for 3 sets of InGaP/GaInNAs DHBTs, sets C, E, and F, each with different ΔV_{be}. The solid line represents a logarithmic fit to the InGaP/GaAs HBT data. The dashed lines represent 45.0, 80.0 and 115.0 mV reductions to the same logarithmic fit and are used as a guide for the eye.

Increased I_C for a given V_{be} lessens the asymmetry of the base-emitter / base-collector diode pair. For the wide bandgap InGaP emitter HBTs under consideration here (no conduction band spikes), I_{BEF} is dominated by the diffusion current (n = 1) exponential term which is highly sensitive to $E_{g,b}$. However, the forward biased base-collector diode current (I_{BCF}) is dominated by the recombination current (n = 2) exponential term which is governed largely by the collector properties and is insensitive to the heavily doped base layer properties, including $E_{g,b}$ [4]. The net result is that lowering $E_{g,b}$ using p^+ GaInNAs, improves the symmetry of the base-emitter / base-collector diode pair of the HBT. This should lower $V_{CE,offset}$ (and by extension V_{knee}) since its value is related to the difference between V_{be} and V_{bc} where $I_{BEF} = I_{BCF}$ [4].

Figure 2 shows the base-emitter (I_{BEF}) and base-collector (I_{BCF}) currents as a function of diode forward bias for a large area (75 μm x 75 μm) InGaP/GaInNAs (set E) DHBT and a standard InGaP/GaAs HBT. As expected, the InGaP/GaInNAs HBT data show reduced $V_{be} - V_{bc}$ difference for fixed forward biased diode current.

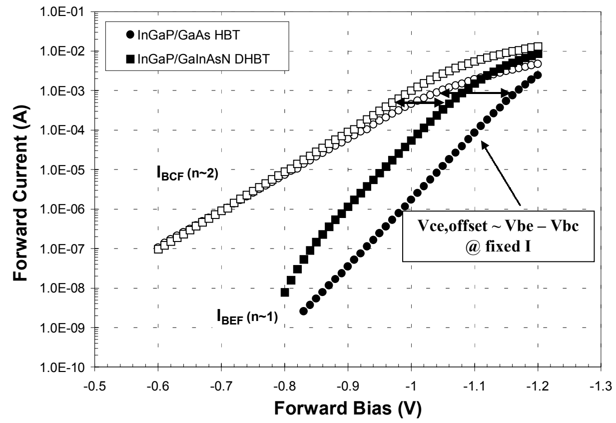

Fig. 2. Base-emitter (I_{BEF}) and base-collector (I_{BCF}) currents as a function of diode forward bias for a large area (75 μm x 75 μm) InGaP/GaInNAs (set E) DHBT and a standard InGaP/GaAs HBT.

Figure 3 shows the common emitter characteristics for a large area InGaP/GaInNAs DHBT exhibiting $V_{CE,offset}$ ~ 100 mV. This is slightly lower than we typically obtain for InGaP/GaAs HBTs. It should be noted that an unoptimized device geometry contributes significantly to $V_{CE,offset}$ of these devices. The base-collector interface must be well engineered due to the presence of a conduction band discontinuity between the p^+ GaInNAs base and n –GaAs collector. The high output impedance of this InGaP/GaInNAs HBT (Fig. 3) indicates the lack of a conduction band spike at the base-collector interface.

The data presented above demonstrate properly engineered InGaP/GaInNAs (lower $E_{g,b}$) HBTs give increased I_C for a given V_{be}, as compared to InGaP/GaAs HBTs. Reduced $E_{g,b}$ and increased I_C (through a corresponding increase of I_{NB}) reduce the relative contribution of I_{SC}, I_{SR} and I_{RHI} to I_B [1,2]. Since I_{RHI} is extremely temperature sensitive, reducing its contribution to I_B should improve gain temperature stability of the device [12,13].

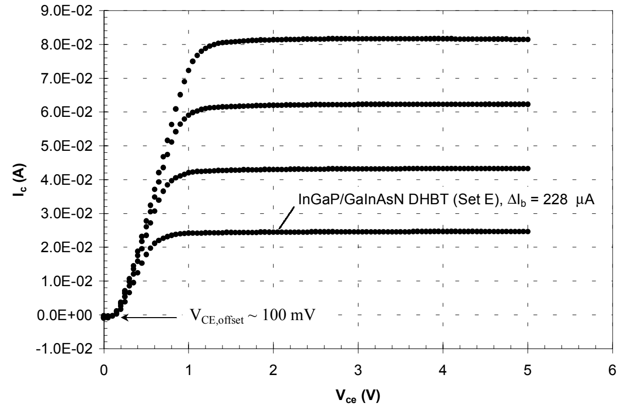

Fig. 3. Common emitter characteristics for a large area (75 μm x 75 μm) InGaP/GaInNAs (set E) DHBT ($V_{CE,offset}$ ~ 100 mV).

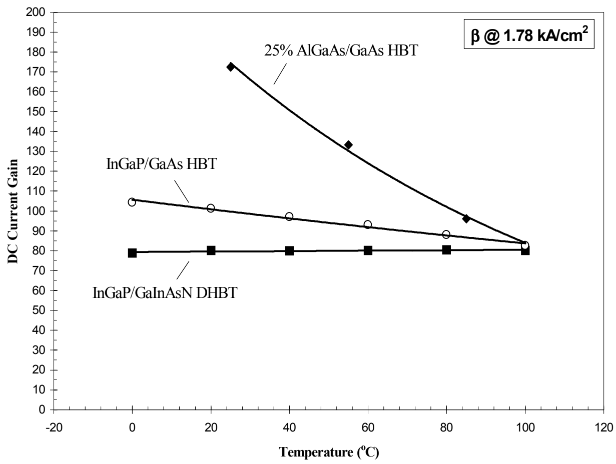

Fig. 4. DC Current gain (β) as a function of temperature for a 25%AlGaAs/GaAs HBT, an InGaP/GaAs HBT, and an InGaP/GaInNAs (ΔV_{be} = -100 mV, Rsb ~ 530 Ω/□, $thick_{base}$ = 500 Å) DHBT.

Figure 4 shows DC current gain as a function of temperature which illustrates the superior gain temperature stability of InGaP/GaInNAs HBTs as compared to InGaP/GaAs and 25%AlGaAs/GaAs HBTs. InGaP/GaAs HBTs exhibit superior gain temperature stability compared to 25%AlGaAs/GaAs HBTs due to the larger hole barrier. The larger hole barrier is a result of the larger band gap of InGaP as compared to 25%AlGaAs [13]. This hole barrier is increased further via the reduced $E_{g,b}$ of GaInNAs as compared to GaAs. Additionally, the temperature dependence of the minority carrier lifetime in the GaInNAs base may be less than for a GaAs base [7]. For the InGaP/GaInNAs HBTs, these two mechanisms likely explain the absence of DC current gain temperature dependence over all current densities and temperatures measured in this study (Fig. 5).

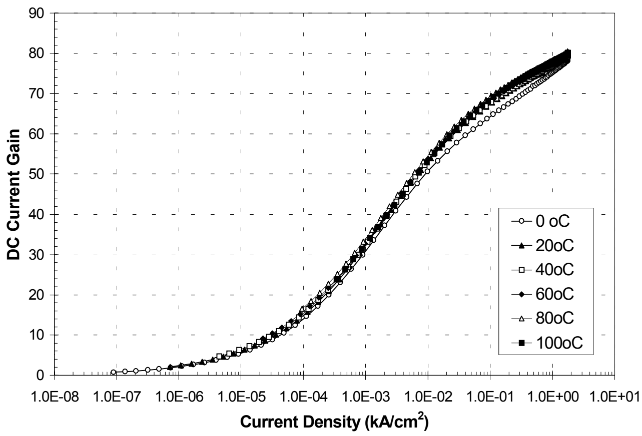

Fig. 5. DC Current gain (β) as a function of current density for an InGaP/GaInNAs (ΔV_{be} = -100 mV, Rsb ~ 530 Ω/□, $thick_{base}$ = 500 Å) DHBT for a range of temperatures.

CONCLUSIONS

Performance enhancements to the standard GaAs-based HBT are feasible through alterations to the relative magnitudes of the collector and various base current components. GaInNAs base layers allow these current manipulations and realize these sought after improvements through reducing $E_{g,b}$. To date, we have demonstrated InGaP/GaInNAs HBTs which offer 115 mV lower operating voltage, improved diode symmetry for reduced $V_{CE,offset}$ and V_{knee}, and superior gain temperature stability as compared with standard InGaP/GaAs HBTs. These enhancements have been realized while simultaneously preserving DC current gains and base doping levels (β ~ 80, R_{sb} ~ 530 Ω/□, base thickness ~ 500 Å, base doping ~ 4×10^{19} cm^2) which are useful for practical applications. Significant improvements in these and other performance enhancements are expected as growth of this new material system matures.

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