GaAs Heterojunction Bipolar Transistor Emitter Design

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ABSTRACT

We demonstrate that GaAs-based HBTs with very low base currents at both low and high injection levels can be achieved using either $Al_{0.35}Ga_{0.65}As$ or InGaP in the emitter with the proper optimization of structure and growth. We observe an order of magnitude reduction in space charge recombination current as the Al composition, and hence the energy-gap, of the emitter increases from 25% (1.77 eV) to 35% (1.89 eV). AlGaAs/GaAs HBTs with approximately 35% Al have the same energy-gap as InGaP and exhibit comparable space charge recombination in large area devices (L = 75 x 75 μm^2). Moreover, this reduction in the space charge recombination in $Al_{0.35}Ga_{0.65}As$/GaAs HBTs can be achieved while maintaining a low turn-on voltage and high DC current gain over a wide range of current densities. Small area devices (L = 1.4 x 3 μm^2) fabricated with an $Al_{0.35}Ga_{0.65}As$ emitter and a base sheet resistance of 330 Ω/☐ exhibit very high DC current gain at all bias levels, with a DC current gain exceeding 140 @ 25 A/cm^2 and a peak DC current gain of 210 @ 26 kA/cm^2. The temperature dependence of the peak DC current gain is significantly improved over a similar structure with a 25% AlGaAs emitter. The RF performance of the 35% AlGaAs structure is also comparable to the 25% structure, with an f_t of 34 GHz and an f_{max} of 55 GHz.

INTRODUCTION

GaAs-based Heterojunction Bipolar Transistors (HBTs) operating as high power amplifiers are gaining wide acceptance in the commercial wireless communications market. At the present time, several high volume GaAs-based HBT production programs use AlGaAs in the emitter layer. However, InGaP has received considerable attention as an emitter layer material for GaAs-based HBTs because of a number of device performance improvements over standard AlGaAs structures. These improvements include enhanced temperature stability, higher DC current gain at low bias, and increased reliability at high junction temperatures and high current densities [1-4]. In this paper we will report on the impact of the emitter layer design on both large area and small area device characteristics. This work will focus on determining the specific properties of InGaP HBTs which lead to the enhanced device performance. We will show that GaAs-based HBTs with very low base current at all injection levels, excellent temperature stability, and good RF performance can be achieved using either $Al_{0.35}Ga_{0.65}As$ or InGaP as the emitter.

LARGE AREA DEVICE RESULTS

In this work, the DC characteristics of large area HBTs (L = 75 x 75 μm^2) have been used as important figures of merit reflecting the material properties of the epitaxial layers [5]. One of the key features in the large area device characteristics of InGaP HBTs is a low base current at low injection levels [2]. The Gummel plots overlaid in Figure 1 (a) include results from typical $Al_{0.25}Ga_{0.75}As$/GaAs and InGaP/GaAs HBTs. The base current at base-emitter voltages (V_{be}) below 1 V is significantly higher in the 25% AlGaAs emitter sample, leading to a relatively high cross-over point between the base and collector currents. The high DC current gain at low V_{be} in InGaP/GaAs HBTs relative to AlGaAs/GaAs HBTs has typically been attributed to a higher defect density in AlGaAs. However, we show here that this difference may instead be largely due to differences in energy-gap and interfacial layer thickness between typical $Al_{0.25}Ga_{0.75}As$/GaAs and InGaP/GaAs HBTs.

Several different physical mechanisms contribute to the base current of a GaAs-based HBT. At low bias, n=2 components of the base current dominate. In the absence of periphery effects (surface recombination),

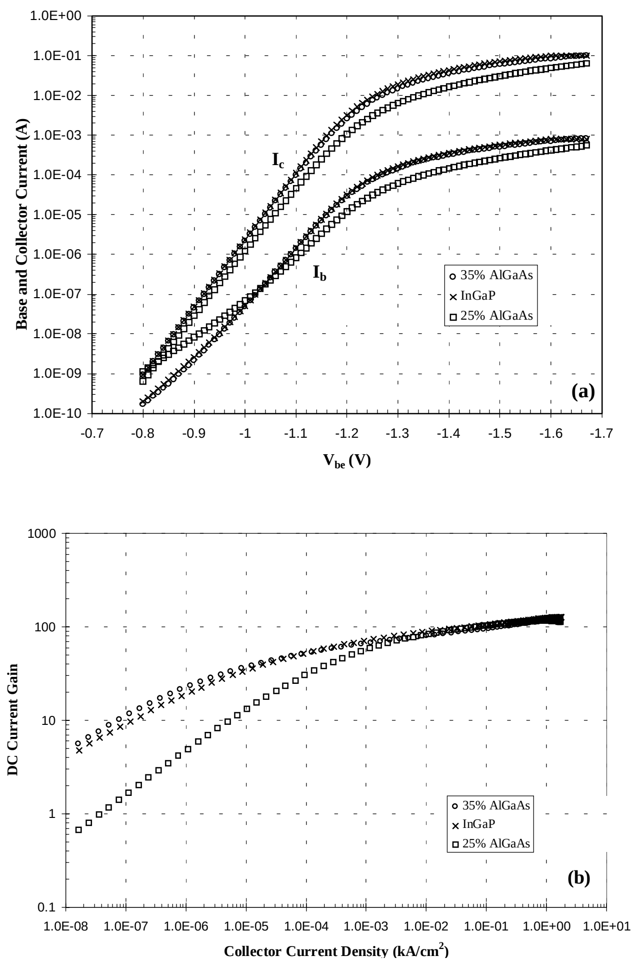

Fig. 1. Gummel plots (a) and DC current gain versus current density curves (b) from large area devices (75 x 75 μm^2) on three samples with different emitter structures and 4E19 cm^{-3} base layers ($R_B \sim 250\ \Omega/\square$). Note the base current at low injection levels ($V_{be} < -0.9$ V) for the 35% AlGaAs emitter is nearly an order of magnitude lower than the 25% AlGaAs structure and comparable to the InGaP emitter.

the primary n=2 base current component is space charge recombination. Assuming an abrupt junction where one side is doped much more heavily than the other, as is the case at the base-emitter junction, then the space-charge recombination component of the base current is dominated by recombination in the emitter. By rewriting the intrinsic doping level in terms of energy gap, the space charge recombination constant ($I_{b1} = I_{scr}\exp(qV_{be}/2kT)$ can be related to the trap density (N_t) and the effective emitter energy-gap (E_{gE}) [6]:

$$I_{scr} \propto N_t \exp(-E_{gE}/2kT).$$

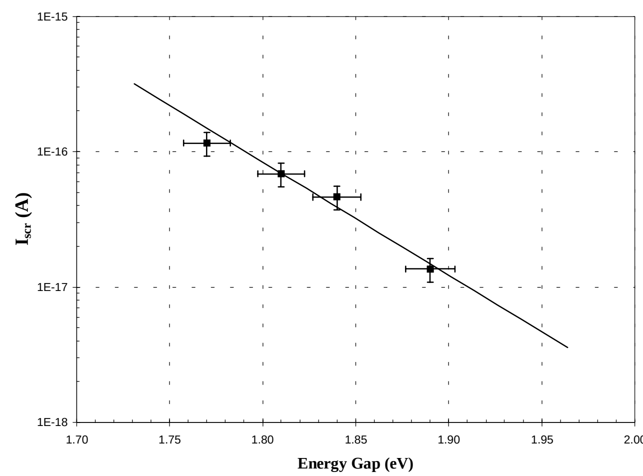

Fig. 2. Extrapolated space charge recombination component of the base current ($I_{b1} = I_{scr} \exp(qV_{be}/2kT)$ as a function of the energy-gap of the AlGaAs in the emitter. The solid line is a fit to the data assuming the basic expression for I_{scr} found in the text.

The effective emitter energy-gap is equal to the emitter energy-gap if the interface is abrupt, and less if it is graded. By fitting the base current as a sum of components, we have observed an order of magnitude reduction in space charge recombination current as the Al composition, and hence the energy-gap, of the emitter increased from 25% (1.77 eV) to 35% (1.89 eV). Figure 2 shows the extrapolated space charge recombination current as a function of emitter energy gap. The solid line represents calculated values derived from a basic expression for space charge recombination in the emitter with a constant trap density [6,7]. The close fit to the experimental data suggests that the trap density is not significantly increasing with composition in these samples.

AlGaAs/GaAs HBTs with approximately 35% Al have the same energy-gap as lattice-matched InGaP and exhibit comparable space charge recombination. As seen in Figure 1 (a), the Gummel plot of an optimized 35% AlGaAs emitter structure is nearly identical to that of a typical InGaP HBT. The base current is actually slightly lower than the InGaP sample, and the DC current gain at low V_{be} is almost an order of magnitude higher than the 25% AlGaAs structure in both the 35% AlGaAs and InGaP emitter structures (Figure 1 (b)). When viewed on a linear scale, the gain versus current density curves from Figure 1 (b) reveal another difference between the low and high energy-gap emitter structures. The DC current gain of the 35% AlGaAs

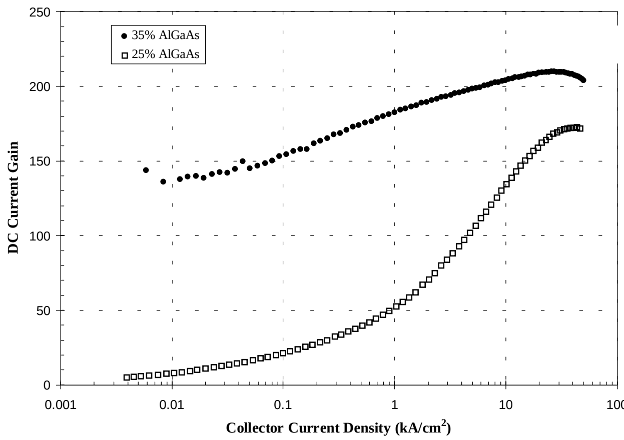

Fig. 3. Gain versus current density from small area devices (1.4 x 3 μm^2) on two wafers with different Al composition in the emitter. The gain at low current density is significantly improved with the higher energy-gap emitter.

sample does not roll over like the 25% AlGaAs sample, but instead continues to increase with current density similar to that observed in InGaP/GaAs HBT.

The reduction in the space charge recombination in the 35% AlGaAs structure has been achieved without increasing the turn-on voltage. The growth of high Al composition emitters usually results in a significant conduction band spike which lowers the collector current and thus increases the device turn-on voltage. To overcome the conduction band spike problem, the composition has typically been graded over several hundred Angstroms at the base-emitter junction, which can offset the advantages of the higher energy-gap in the emitter [8]. By optimizing the interface growth conditions, we have been able to reduce the conduction band spike with a very minimal compositional ramp. Thus, with the proper design and growth, AlGaAs/GaAs and InGaP/GaAs HBTs can be made to exhibit similar Gummel plots at both high and low injection levels in large area devices.

SMALL AREA DEVICE RESULTS

To confirm the conclusions drawn from the large area device characteristics, small area devices (L = 1.4 x 3 μm^2) have been fabricated and tested on a wafer with an optimized 35% AlGaAs emitter. The small area device characteristics of the 35% AlGaAs structure have been compared to a standard 25% AlGaAs emitter structure with similar base thickness and doping

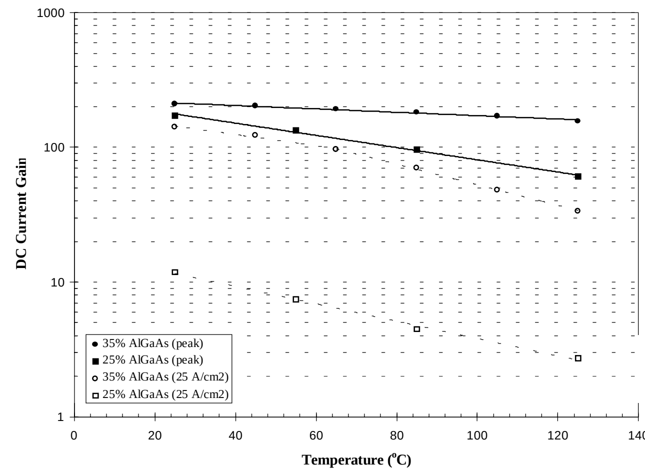

Fig. 4. Dependence of DC current gain on temperature in small area devices (1.4 x 3 μm^2) on two wafers with different Al composition in the emitter. The solid points are for peak gain, the open points for the gain at a fixed collector current density of 25 A/cm^2. The line are exponential fits to the data used as a guide for the eye.

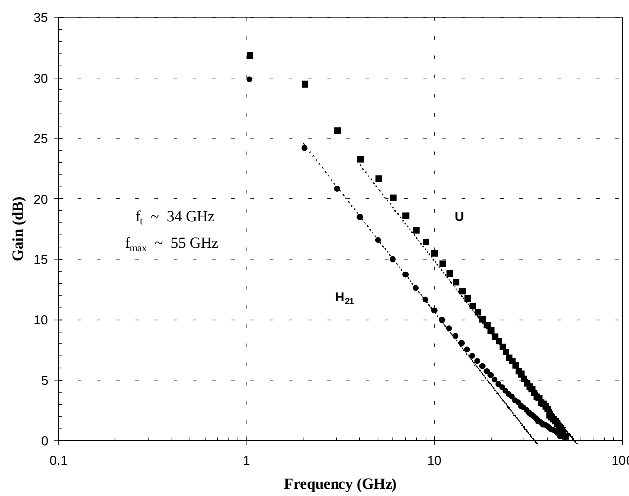

Fig. 5. RF results from a 1.4 x 3 μm^2 device on the 35% AlGaAs structure. The extrapolated f_t and f_{max} are 34 and 55 GHz. The measurements were taken at V_{ce} = 1.5 V and I_c = 2 mA.

(p_b ~ 4E19 cm^{-3}, w_b ~ 500 Å) and overall peak DC current gain. The device wafers were grown in a production MOCVD system and processed in a large volume fabrication line. The high DC current gain at low V_{be} seen in large area devices translated to the small area devices, indicating that the ledge was properly depleted and that space charge recombination intrinsic to the emitter material remains a limiting factor at low V_{be}. As shown in Figure 3, the DC current gain of the 35%

AlGaAs emitter structure is over 150 at current densities as low as 100 A/cm^2, whereas the DC current gain of the 25% AlGaAs structure is under 25.

A large improvement in the temperature stability of the DC current gain was observed in the devices with the 35% AlGaAs emitter structure. The peak DC current gain of a standard $Al_{0.25}Ga_{0.75}As$ structure dropped over 64% from 172 at room temperature to 61 at 125 ^oC (Figure 3). On the other hand, the peak DC current gain of the $Al_{0.35}Ga_{0.65}As$ structure dropped around 25% from 210 at room temperature to 157 at 125 ^oC. This compares favorably with previously published InGaP results, where the DC current gain for an InGaP structure with lower overall peak DC current gain decreased by 15% at 125 ^oC [4]. We have observed a 26% reduction in the peak DC current gain of an InGaP structure tested under the same conditions as those shown in Figure 4, with the DC current gain dropping from 155 at room temperature to 115 at 125 ^oC. The DC current gain stability of the 35% AlGaAs structure at lower current densities, where space charge recombination dominates, was not significantly improved, as has been observed in InGaP HBTs [1]. The RF performance showed an f_t of 34 GHz and a f_{max} of 52 GHz, which is comparable to that observed in an $Al_{0.25}Ga_{0.75}As$ HBT of similar structure (Figure 5). In summary, the small area device results suggest that AlGaAs emitters are capable of producing similar results to InGaP emitter structures with proper growth and structure optimization.

CONCLUSIONS

We have investigated the impact of the emitter energy-gap and the base-emitter interface on the large area device characteristics of GaAs-based HBTs. We have observed an order of magnitude reduction in space charge recombination as the energy-gap of the emitter increases from 1.77 eV to 1.89 eV in AlGaAs/GaAs HBTs. With the properly engineered base-emitter interface, this low emitter space charge recombination can be achieved while still maintaining a high collector current density and corresponding low turn-on voltage. The large area device characteristics of an optimized $Al_{0.35}Ga_{0.65}As$/GaAs HBT are quite similar to those of a typical InGaP/GaAs HBT. The DC current gain of small area devices with the optimized $Al_{0.35}Ga_{0.65}As$ structure also show superior DC current gains at low current density (25 A/cm^2), with a seven-fold increase over $Al_{0.25}Ga_{0.75}As$ emitter HBT structures. The higher emitter energy gap $Al_{0.35}Ga_{0.65}As$ structure exhibits significantly better temperature stability than $Al_{0.25}Ga_{0.75}As$ structures, with the peak DC current gain dropping only 25% at 125 ^oC compared to 64%. These improvements in the device performance of $Al_{0.35}Ga_{0.65}As$/GaAs structures have been achieved without sacrificing the RF performance, which exhibits an f_t of 34 GHz and an f_{max} of 55 GHz.

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