Ledge Design of InGaP Emitter GaAs Based HBTs

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ABSTRACT

A wide range of emitter composition, thickness, and doping is studied via dc current gain measurements on large area GaAs based heterojunction bipolar transistors (HBTs) at both room and elevated temperatures. InGaP emitters offer the widest thickness and doping design window in terms of dc peak current gain, as compared with AlGaAs emitters. Remarkably, a 50 Å InGaP emitter HBT retains 50% gain of a more standard 500 Å emitter device. For state-of-the-art HBTs, a degraded peak gain is argued to be caused by an increased reverse hole injection current (I_{RHI}). In light of previously published results which implicate I_{RHI} as a mechanism for materials limited HBT reliability, we suggest dc current gain measurements on large-area HBTs give meaningful insights into the long term reliability of the structure. Specifically, the wider emitter thickness and doping design window offered by an InGaP emitter HBT could apply to reliability as well as to the demonstrated gain stability.

INTRODUCTION

Proper emitter ledge design is critical for obtaining reliable, small area, high power HBTs. A thick or heavily doped ledge will not pinch off sufficiently, resulting in poor device reliability. *Ma et al*. propose a ledge monitor which will detect this undesirable situation prior to reliability measurements [1]. Conversely, too thin or lightly doped of an emitter ledge may result in both degraded initial dc characteristics and poor long term device reliability. In this work, we explore the impact of emitter material, thickness, and doping on the dc current gain characteristics of large area HBTs at both room temperature and at elevated temperatures. AlGaAs/GaAs HBTs exhibit significant drops in peak dc current gain and gain roll over at higher current densities as either emitter thickness or doping is decreased below 500 Å or 2×10^{17} cm^{-3}. InGaP/GaAs HBTs are much less sensitive to emitter thickness and doping variations, exhibiting good room temperature dc characteristics for thickness down to 100 Å or doping as low as 3×10^{16} cm^{-3}. However, dc current gain measurements at elevated temperatures (60 ºC and 100 ºC) are more sensitive to changes in InGaP emitter structure. The observed changes in dc current gain characteristics with emitter design and temperature are discussed in terms of changes in the reverse hole injection component of the base current, which has been identified as a possible driving force controlling in the long term reliability of HBTs [2,3]. We suggest that the characterization of the initial dc characteristics at room and elevated temperatures may be used as a tool for the design of the optimal InGaP emitter ledge.

EXPERIMENT

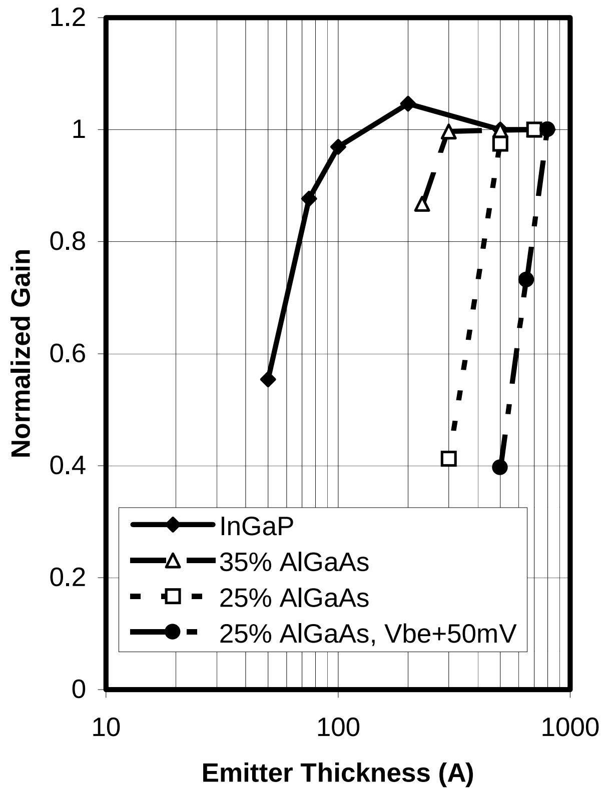
The devices used in this work were fabricated from HBT wafers grown in a low-pressure MOCVD system. These large area devices (L = 75 μm $\times$ 75 μm) were fabricated using a simple wet-etching process and tested in the common base configuration. The maximum collector current density attainable for our measurement and device setup is 1.78 kA/cm^2. The emitter composition, thickness, and doping were varied while the remainder of the layers was kept constant. The emitters are 50 Å to 800 Å thick InGaP, $Al_{0.35}Ga_{0.65}As$, or $Al_{0.25}Ga_{0.75}As$, silicon doped between 3×10^{16} cm^{-3} and 1×10^{18} cm^{-3}. The composition of the $Al_{0.35}Ga_{0.65}As$ was chosen to match the 1.89eV room temperature energy gap of partially disordered InGaP [4]. The turn-on voltage for all devices was controlled via the growth of the emitter-base interface to affect the conduction band spike [5]. All turn-on voltages are at the theoretical minimum unless otherwise noted [6]. The complete HBT layer structure consists of an n^+-GaAs:Si subcollector, an n-GaAs:Si collector, a p-GaAs:C base, an n-type emitter (as described above), an n^+-GaAs:Si emitter cap and an n^+-InGaAs contact layer.

To screen out the affects of moderate changes in base sheet resistance and to highlight comparisons between different emitter compositions, thicknesses, and doping levels, dc current gain obtained from the various HBT structures is normalized as $G_n = (G/R_{s,b})/(G_c/R_{s,b,c})$, where G_n is the normalized dc current gain, G is the dc current gain, $R_{s,b}$ is the base sheet resistance, G_c is the dc current gain of the control sample, and $R_{s,b,c}$ is the base sheet resistance of the control sample.

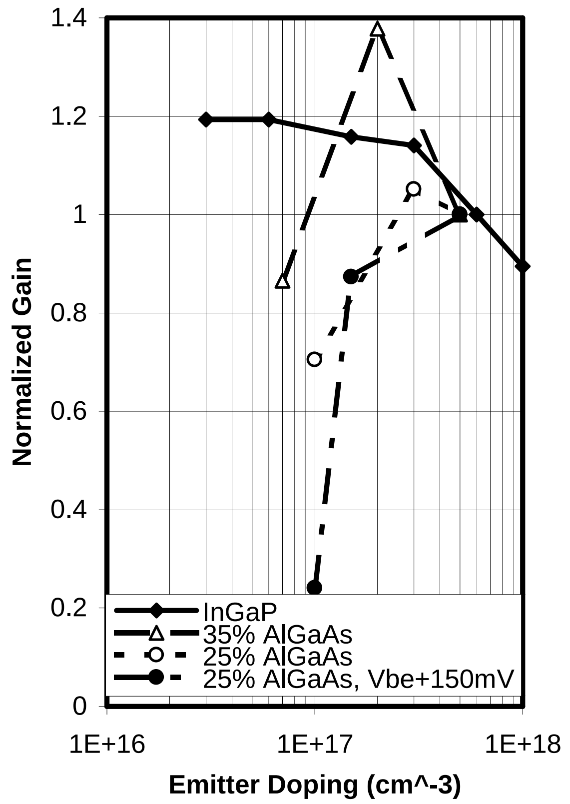
RESULTS

Figures 1a and 1b compare normalized peak dc current gain versus thickness and doping for InGaP, 35% AlGaAs, and 25% AlGaAs emitters HBTs. The InGaP emitter HBT exhibits constant dc gain over significantly wider thickness and doping ranges than do any of the AlGaAs emitter HBTs. The 35% AlGaAs emitter HBT offers a wider thickness and doping window than does the 25% AlGaAs emitter HBT. A rough interpolation and extrapolation of the data suggests that a 50 Å InGaP emitter, a 170Å 35% AlGaAs emitter, and a 330 Å 25% AlGaAs emitter yield the same gain degradation (50%) relative to thicker emitter HBTs. Similarly, low doped 25% AlGaAs emitter HBTs show the most dc current gain degradation and low doped InGaP emitter HBTs show the least. In fact, there is no room temperature gain degradation for the lowest doped (3×10^{16} cm^{-3}) InGaP emitter HBT examined in this study.

Turn-on voltage clearly plays a role in gain degradation, as shown by the 25% AlGaAs emitter HBT data. The higher turn-on voltage devices exhibit worse dc current gain degradation for thin and low doped emitters than do the minimized turn-on devices.



a)



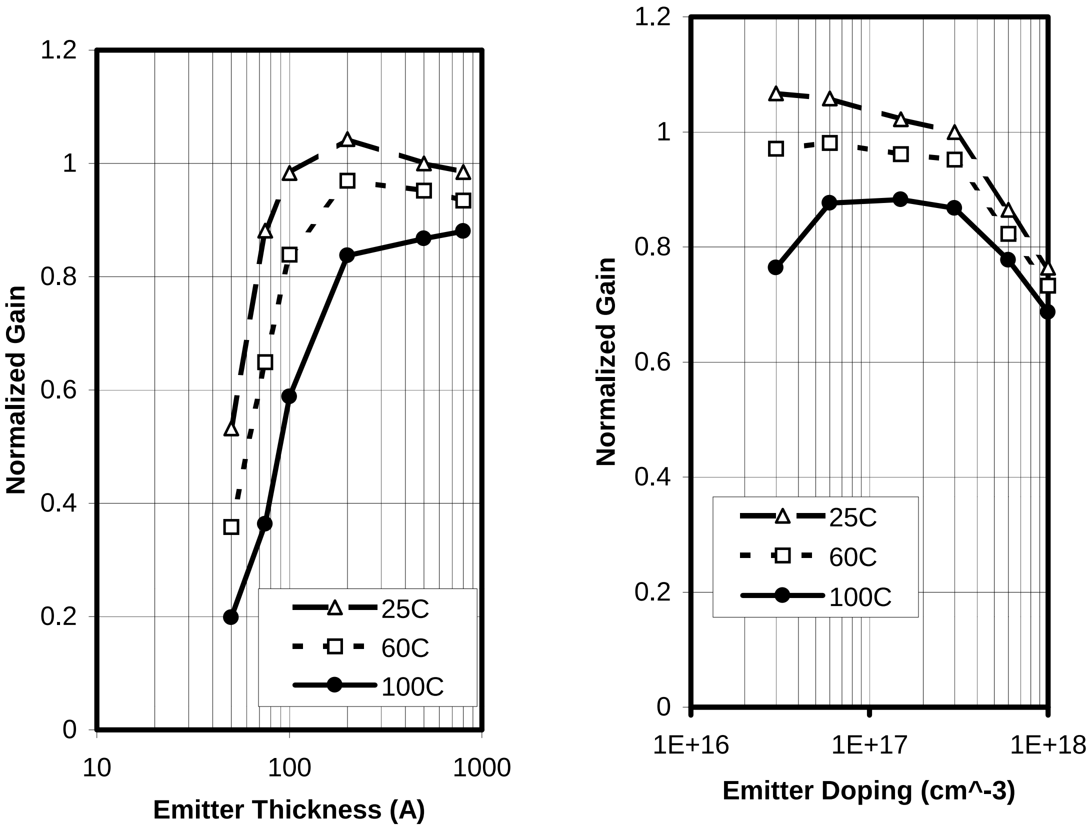
b)

Figure 1 Room temperature normalized peak dc current gain versus (a) emitter thickness and (b) emitter doping. For (a) The emitter doping level is 4×10^{17} cm^{-3}, and for (b) the emitter thicknesses range from 500 Å to 1300 Å for the four data sets.

There is also an emitter composition dependence visible in the gain versus collector current data for these HBTs. Specifically, none of the InGaP emitter HBTs showed any gain roll over at high current densities. Of the 35% AlGaAs samples, only the thinnest (230Å) sample exhibited roll over. Of the 25% AlGaAs minimized turn-on samples, both the thinnest (300 Å) and the lowest doped (1×10^{17} cm^{-3}) exhibited roll over. With the exception of the 1300 Å, 5×10^{17} cm^{-3} emitter device, all the 25% AlGaAs high turn-on HBTs showed roll over.

Figures 2a and 2b show variable temperature characteristics of the dc current gain versus InGaP emitter thickness and doping. These elevated temperature measurements magnify the deficiencies of the thinnest and lowest doped emitters for InGaP/GaAs HBTs. In particular, InGaP/GaAs devices with emitters thinner than 200 Å or doped less than 1×10^{17} cm^{-3} have degraded variable temperature dc current gain relative to thicker or more heavily doped emitter structures.

Whereas no dc current gain roll over is present in the InGaP emitter HBT room temperature data, some is clearly visible in the elevated temperature data. Specifically, the two lowest doped InGaP emitters exhibited clear roll over at high current densities.



a) b)

Figure 2 Variable temperature normalized peak dc current gain versus (a) InGaP emitter thickness and (b) InGaP emitter doping. For (a) the emitter doping is 4×10^{17} cm^{-3}, and for (b) the emitter thickness is 500 Å.

DISCUSSION

The base current (I_b) of a GaAs-based HBT is composed of several different components, including space charge recombination, neutral base recombination (I_{NBR}), reverse hole injection (I_{RHI}), and surface recombination [7]. The hole injection component is suppressed by the wide energy-gap emitter in an HBT due to an increase in the hole barrier height. In sufficiently thick emitter structures, the hole barrier height is related to emitter energy gap and the Fermi levels in the base and emitter layers, not the valence band offset (ΔE_v). Because the reverse hole injection current is highly temperature sensitive, elevated temperatures, either from internal heating at high current densities (gain roll over) or external heating (variable temperature gain studies), further degrade dc gain [8]. Consistent with the energy gap (and not ΔE_v) dependence of the reverse hole injection current, it has been previously shown that the dc gain variable temperature stability of a properly grown $Al_{0.35}Ga_{0.65}As$ emitter HBT is equivalent to that of an InGaP emitter HBT [4].

However, when the emitter side of the base-emitter junction depletion region extends beyond the emitter into the n^+-GaAs emitter cap layer, due a to thin and/or lightly doped emitter, the base-emitter hole barrier will be reduced from its maximum possible (partially depleted emitter) value. This leads to an increase in the reverse hole injection current, which in turn reduces the overall gain. In this regime, unlike the case of a partially depleted emitter, ΔE_v plays an increasingly important role in determining the hole barrier height as emitter thickness and doping decrease. Hole barrier reduction in general explains degraded gain for thinner and lower doped emitter HBTs (Fig. 1). Furthermore, the superior gain stability versus various emitter parameters (Fig. 1), of the InGaP emitter HBT over the 35% AlGaAs emitter HBT over the 25% AlGaAs emitter HBT is due to the decreasing valence band discontinuities with GaAs

Elevated temperatures serve to increase the sensitivity of the dc current gain measurement to the deleterious effect of a reduced hole barrier, by increasing the ratio of reverse hole injection current to base current. Hence the variable temperature gain data in Fig. 2 highlights the reduced gain stability and therefore higher reverse hole injection current of the thinner and lower doped InGaP emitter HBTs.

It should be noted that for the thinnest InGaP emitter (50 Å and 75 Å) HBTs in this study, there are at least three possible sources of the increased base-emitter hole current as evidenced by the dc current gain degradation. These are: a) a reverse hole injection current over the hole barrier as discussed above, b) a tunneling current through the hole barrier which is likely dominated by the InGaP valence band discontinuity with the GaAs emitter cap and c) a reduced hole barrier (compared to the theoretical size) due to possible mixing at the interfaces to an extent that the composition of the entire thin emitter is compromised.

For state-of-the art GaAs based HBTs, neutral base recombination and reverse hole injection dominate the base current at high bias / peak dc gain [3,4]. Under these conditions, I_{RHI} contributes significantly more to I_b for a high turn-on V_{be} device than for a low turn-on V_{be} device. This is because I_{NBR} is proportional to the collector current (I_c), whereas I_{RHI} is exponentially dependent on V_{be} [3]. This can explain the inferior gain stability versus emitter thickness and doping of the high turn-on V_{be} 25% AlGaAs HBT (Fig. 1). For comparable high bias I_c and therefore gain, I_{RHI} is significantly greater than for the low turn-on V_{be} 25% AlGaAs HBT. Therefore a smaller reduction in the hole barrier (via thickness or doping reduction) is enough to increase I_{RHI} sufficiently to degrade the gain noticeably.

CONCLUSIONS

The previous data and observations argue that dc current gain measurements of large area HBTs gives significant information about the injection of holes from the base to the emitter. This hole current data correlates with the superior reliability of InGaP emitter HBTs over 25%AlGaAs emitter HBTs [2,9,10] and with the improved reliability of low turn-on V_{be} AlGaAs emitter devices over high turn-on AlGaAs devices [3]. Furthermore, a model has been proposed elsewhere [3] in which materials limited reliability is controlled by the generation of defects in the emitter depletion region via a recombination enhanced defect reaction process involving an electron, a hole and a previously existing non-radiative recombination center. If correct, this model suggests that the key to controlling and engineering the materials-related limit on the long term reliability of GaAs-based HBTs lies not only in reducing the initial trap density, but in reducing the reverse hole injection component of the base current. Working from this model, we suggest dc current gain measurements on large-area HBTs can give meaningful insights into the materials limited long term reliability of the structure. Specifically, the wider emitter thickness and doping design window offered by an InGaP emitter HBT could apply to reliability as well as to the demonstrated gain stability.

REFERENCES

[1] P. Ma, P. Zampardi, L. Zhang, M. F. Chang; Determining the Effectiveness of HBT Emitter Ledge Passivation by Using an On-Ledge Schottky Diode Potentiometer; 1999; IEEE Electron Device Lett.; 20; 460-462.

[2] T. S. Low, C. P. Hutchinson, P. C. Canfield, T. S. Shirley, R. E. Yeats, J. S. C. Chang, G. K. Essilfile, M. K. Culver, W. C. Whiteley, D. C. D'Avanzo, N. Pan, J. Elliot, C. Lutz; Migration from an AlGaAs to an InGaP Emitter HBT IC Process for Improved Reliability; 1998; GaAs IC Symp.; 153-156.

[3] R. E. Welser, M. Chaplin, C. R. Lutz, N. Pan; Base Current Investigation of the Long-Term Reliability of GaAs-Based HBTs; 2000; GaAs MANTECH; 145-148.

[4] R. E. Welser, N. Pan, C. R. Lutz, D. P. Vu, P. J. Zampardi, R. L. Pierson, B. T. McDermott; High Performance $Al_{0.35}Ga_{0.65}As$/GaAs HBT's; 2000; IEEE Electron Device Lett.; 21; 196-199.

[5] W. Liu et al.; Current Transport Mechanism in GaInP/GaAs Heterojunction Bipolar Transistors; 1993; IEEE Trans. Electron Devices; 40; 1378.

[6] R. E. Welser, N. Pan; Turn-on Voltage Investigation of GaAs-based Bipolar Transistors with $Ga_{1-x}In_xAs_{1-y}N_y$ Base Layers; to be published.

[7] P. M. Asbeck, M.-C. F. Chang, K. C. Wang, D. L. Miller; ; 1990; Introduction to Semiconductor Technology: GaAs and Related Compounds; .

[8] C.-M. S. Ng, P. A. Houston, H.-K. Yow; Analysis of the Temperature Dependence of Current Gain in Heterojunction Bipolar Transistors; 1997; IEEE Trans. Electron Devices; 44; 17-24.

[9] N. Pan, J. Elliot, M. Knowles, D. P. Vu, K. Kishimoto, J. K. Twynam, H. Sato, M. T. Fresina, G. E. Stillman; High Reliability InGaP/GaAs HBT; 1998; IEEE Electron Device Lett.; 19; 115-117.

[10] O. Ueda, A. Kawano, T. Takahashi, T. Tomioka, T. Fujii, S. Sasa; Current Status of Reliability of InGaP/GaAs HBTs; 1997; Solid-State Elect; 41; 1605-1610.