Transient Characteristics of InGaP/GaAs/AlGaAs Double Heterojunction Bipolar Transistors

C.R. Lutz, R. E. Welser, and N. Pan

Kopin Corporation
695 Myles Standish Blvd. Taunton, Ma 02780 email : clutz@kopin.com Tel: 508-824-6696

K. M. Lau and C. F. Musante

ECE Department, University of Massachusetts, Amherst, Ma 01003

ABSTRACT

Both the electrical characteristics and optical properties of the base layer in InGaP/C-GaAs/AlGaAs double heterojunction bipolar transistors (DHBT's) are investigated to facilitate a better understanding of the mechanisms governing the short term transient electrical performance observed in HBT devices. The double heterojunction design is highly attractive for photoluminescence measurements of the base layer since electrons can be better confined. Differences in the burn-in related transient of the dc-current gain are observed and lead to dramatic increases when collector current densities approach 200-500 A/cm^2 in large area ($A_E = 75 \times 75\ \mu m^2$) devices measured at room temperature. In general, samples possessing high dc current gain-to-base sheet resistance (β/R_s^{base}) ratios tend to exhibit the largest degree of dc current gain shift. We also observe a marked dependence in the 77 °K photoluminescence (PL) intensity originating from the base layers of these samples. The intensity dependence is strongly correlated to the dc-current gain performance in large area devices. Samples with the highest gain-to-base sheet resistance ratios demonstrated PL intensities that were 25% higher than identical structures exhibiting significantly lower gains. Furthermore, the hydrogen concentration in the base layer—incorporated during growth and usually implicated in the origin of the burn-in phenomena—remains constant in spite of the observed differences in the burn-in characteristics. This result suggests that the underlying physical mechanisms of the burn-in effect occurring during this process may be more complex than originally recognized.

INTRODUCTION

High performance GaAs-based heterojunction bipolar transistors (HBT's) continue to be attractive candidates for insertion into a wide array of microwave and optical communications systems. The high power added efficiencies, exceptional linearity, good noise performance, small device size, and power handling capability demonstrated by state of the art HBT's make them the "device of choice" for many circuit designers developing cutting-edge millimeter wave integrated circuits (MMICs) for demanding wireless applications.

Exceptional long-term reliability of carbon-doped InGaP emitter HBT's have recently been reported by a number of groups [1-4]. In the course of conducting such studies, it has been observed that many of these devices experienced a marked, burn-in related, increase of the dc-current gain after the initial bias stressing [5-8]. This burn-in effect generally occurs within the first several minutes of device operation and has been universally ascribed to hydrogen either unintentionally incorporated in the base layer during crystal growth, or introduced during device fabrication. However, to date no clear evidence has been presented which elucidate the fundamental mechanisms involved, nor satisfactorily explains the role of hydrogen pertaining to burn-in related processes occurring during the initial testing of the HBT.

This burn-in phenomenon does not pose serious problems for current generation power amplifiers and MMICs since devices can be tested to mitigate the burn-in effects. However, as advanced wireless integrated circuits become more complex and the number of transistors required to realize the more sophisticated functionality increase, there is a growing need to minimize any initial transient effects.

THE BURN-IN EFFECT IN LARGE AREA HBTs: DC ELECTRICAL CHARACTERISTICS

In this work, a series of InGaP/C-GaAs/AlGaAs double heterojunction bipolar transistors (DHBT's) exhibiting differing degrees of burn-in related gain transients in large area devices are investigated. Device wafers were grown using low pressure MOCVD. The p-type base layer was doped with carbon using intrinsic doping. The layering sequence featured a standard highly doped n^+-InGaAs contact layer followed by a 1000 Å thick GaAs (4×10^{18} cm^{-3}) cap layer; a 500 Å thick lattice matched InGaP emitter (3×10^{17} cm^{-3}), and a 700 Å thick C-GaAs base layer. This was followed by a thin AlGaAs graded layer and a delta-doped region which were used to reduce the conduction band spike at the base/collector junction. The collector layers were composed of a 6500 Å thick $Al_{0.2}Ga_{0.8}As$ (2×10^{16} cm^{-3}) collector, a 150 Å thick GaAs (1×10^{16} cm^{-3}) layer, and a 4500 Å GaAs subcollector (5×10^{18} cm^{-3}), respectively.

Large area (75 x 75 μm^2 emitter size) HBT's were fabricated and the dc characteristics measured using an HP 4145 parameter analyzer. Table I presents measured values of standard electrical parameters on devices that showed different degrees of initial burn-in effect. The dc current gain values were obtained after 5 sweeps of the curve tracer. The dc current gain β/R_s^{base} ratios (a figure of merit for HBT's), with nominal base sheet resistance values of 250 ohms/square ($p = 4 \times 10^{19}$ cm^{-3}), ranged from 0.33 to 0.16.

Table 1: DC parameters from three large-area DHBT devices that exhibit differing amounts of burn-in related dc current gain shift. Note that the only significant change is in the dc-current gain.

Device	A	B	C
BV_{CBO}	28.5	28.5	28.7
BV_{BEO}	7.8	7.8	8.2
$R_s^{emitter}$	32	31	36
R_s^{base}	243	240	244
β(@J_c= 200 A/ cm^2)	74	65	35
β(@ J_c= 1 kA/ cm^2)	79	70	39
β(@ J_c= 1.78 kA/cm^2)	81	72	40
V_{BE} @ 100uA (75X75)	1.1	1.1	1.102
β(1 kA/ cm^2)/R_s^{base}	0.325	0.290	0.158

Figure 1 shows the dc-current gain versus collector current density for two of the three samples. These curves illustrate the degree of variation that was observed in the burn-in behavior for typical HBT samples. In each case, two curves from a single device are plotted, depicting dc current gain for the first and fifth traces of the HP4145 analyzer. During the initial measurement, the dc current gain abruptly increases as the collector current density approaches 200-500 A/cm^2. Eventually the dc current gain reaches a stable profile after several successive traces beyond which no significant changes are observed.

The first device, shown in Figure 1a, has the highest dc-current gain in the series and exhibits the greatest amount of dc current gain shift during the burn-in phase. A 45% increase in the dc-current gain occurs at a current density of about 100A/cm^2. Even more substantial changes, amounting to more than 70%, have been observed in single heterojunction bipolar transistors (SHBT's) which exhibited higher β/R_s^{base} values. The growth conditions for the second and third samples were varied to achieve a reduced level of gain shift, as demonstrated in Figure 1b. Under these conditions the β/R_s^{base} ratio decreases considerably.

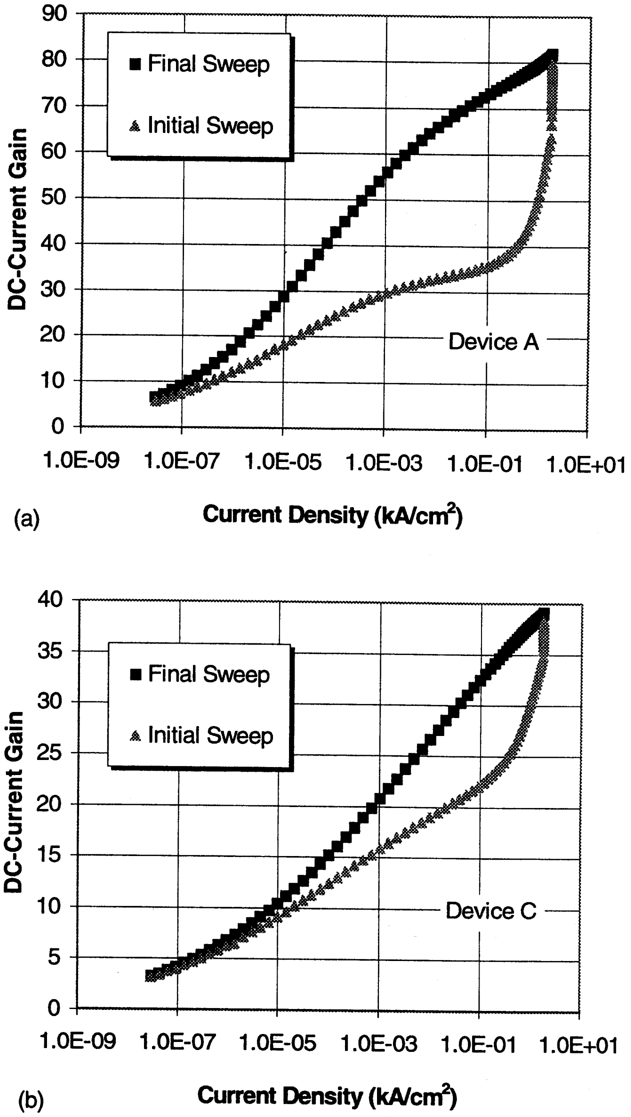

Figure 1: Plot of dc-current gain vs. collector current density for two DHBTs. The initial measurement (triangles) exhibits depressed gains relative to subsequent measurements on the same device. After the fifth sweep (squares) the gain curve reaches a stable profile. (a): Device optimized for high current gain exhibiting the largest amount of burn-in. (b): Device in which growth conditions were adjusted to reduce burn-in induced gain shift.

Shown in Figure 2 is the Gummel plot of Device A that was presented in Figure 1. Plotted are the base and collector currents of both the initial and final traces from the HP 4145 analyzer as a function of the voltage applied to the

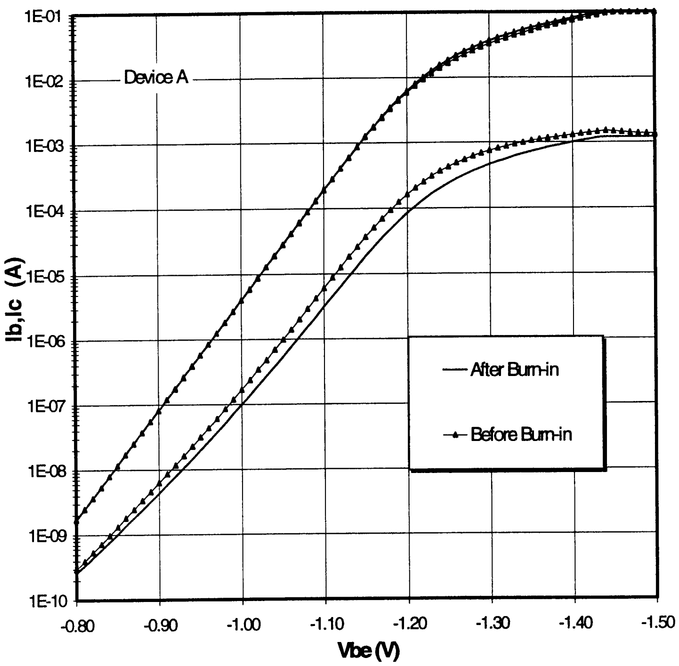

Figure 2: Gummel plots for Device A, highlighting differences in the magnitude of the burn-in induced changes. Solid lines represent the initial data from the pre-stressed devices. Note that in each device the burn-in process is accompanied by a substantial decrease in the base current of the HBT. No change is observed in the collector currents.

base/emitter junction. As suggested by the relative consistency of the turn-on voltage (V_{be}) in the large-area device data in Table I, there is little difference in collector currents in the range of samples investigated. This indicates that no appreciable change takes place in the base/emitter interface as a result of the different growth conditions employed. Moreover, in any single device the collector currents between successive traces are identical within measurement error.

In contrast, the base current decreases significantly during bias stressing and accounts for the entirety of the observed burn-in induced dc current gain shift. The majority of this change occurs at higher biases where neutral base recombination is the dominant base current term [9]. As suggested by Henderson, the observed changes in the base current indicate that the minority carrier lifetime (τ_e) in the base layer changes after the initial application of a current stress [8] and thus both an as-grown and post-stress τ_e should be defined. The gain transients are less severe in samples B and C, but qualitatively behave the same as sample A. The changes seen in τ_e have been previously attributed to H_2 incorporation in the base layer.

PHOTOLUMENESCENCE ASSEMENT OF BASE LAYER QUALITY

The double heterostructure design is ideally suited for studying changes in the crystalline quality of the base material through the application of low temperature photoluminescence (PL) measurements. This is a consequence of the higher bandgap of the emitter and collector layers relative to the GaAs base, leading to enhanced electron carrier confinement and hence radiative recombination within the base region. Although many previous experiments aimed at correlating PL signatures to HBT device parameters have been attempted [10], they have all relied on conventional HBT designs without electron confinement in the base layer, making it difficult to establish the quality of the base layer.

Unprocessed wafers were first prepared by etching away the InGaAs and GaAs cap layers with the intention of eliminating any extraneous absorption of the emitted luminescence signals of interest. The samples were mounted in a dewar, cooled, and pumped with the 514 nm line from an Argon ion laser. The collected light was dispersed by a 0.75 m spectrometer and detected with a thermoelectrically cooled GaAs(Cs) photomultiplier tube. The 77 °K PL signature from the base region for three of the samples is shown in Figure 3. A direct correlation is observed between the PL intensity and the magnitude of the final dc-current gain in the associated HBT after bias-stressing.

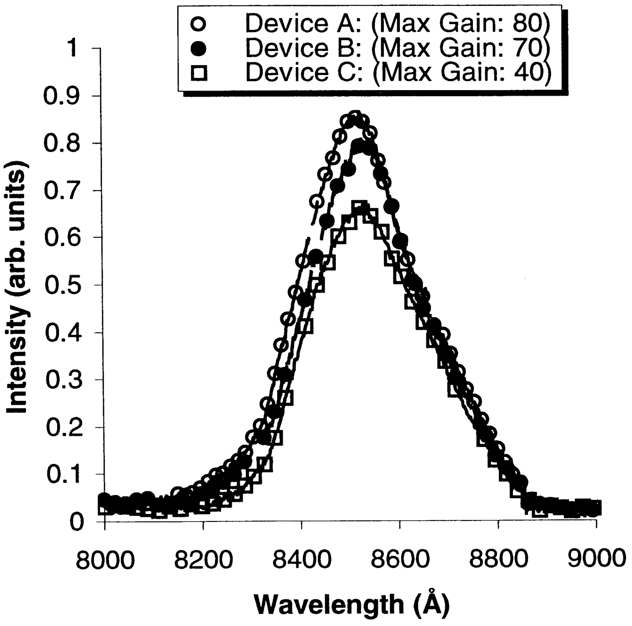

Figure 3: The 77 °K PL spectra from the base region of three devices grown under differing conditions. The device with the lowest PL intensity exhibited the smallest burn-in induced gain shift. The base sheet resistance for all three devices was 250 Ohms/sq.

THE IMPACT OF HYDROGEN

Different physical mechanisms can play a role in controlling the dc-current gain both before and after bias-stressing the device. For instance, the short-term increase in gain observed in unpassivated small area devices can be attributed to passivation of defects in the extrinsic base by H^+ [5-7]. Kawano et al. discussed the role of H^+ implantation on device burn-in, noting that hydrogen did not impact the long-term reliability of HBT's [6]. On the other hand, increases in dc current gain seen in large-area devices [8], where the emitter periphery effects are negligible, must arise from mechanisms other than annihilation of recombination sites in the extrinsic base region.

Clearly, the minority carrier lifetime of the base layer in the samples discussed here is altered by the growth conditions employed and presumably contributes to the observed disparity in the burn-in behavior. If hydrogen does indeed play a dominate role in determining the burn-in characteristics in HBT's, one may reasonably expect to find some difference in the amount of atomic hydrogen incorporated in the base region of these devices during growth. As shown in Figure 4 for unprocessed material, the secondary ion mass spectroscopy (SIMS) profile for both carbon and hydrogen in the base region are indistinguishable between samples A and C. This result suggests the possibility that mechanisms other than C-H dissociation or neutralization of hydrogen related recombination centers might also be operative in processes associated with short-term electrically induced burn-in phenomena in C-GaAs based HBT's.

CONCLUSIONS

The DHBT structure discussed in this work is an ideal vehicle for investigating the mechanisms associated with the short-term burn-in phenomena seen in many HBT's. A careful review of the literature suggests there are several physically distinct phenomena in GaAs-based HBT's that can lead to burn-in effects. We have presented preliminary results from a series of devices in which the dc-current gain burn-in characteristics were intentionally varied. DC current gain was observed to increase dramatically as the collector current density approached the 200-500 A/cm^2 range. The change was primarily attributed to changes in the base current. The largest degree of change was observed in samples that exhibited high β/R_s^{base} figures of merit. A marked dependence in the 77 °K PL spectra from the base layers in these samples also noted. This trend was strongly correlated with the gain performance in the HBT, consistent with the observed reduction in the minority carrier recombination rate of the base layer.

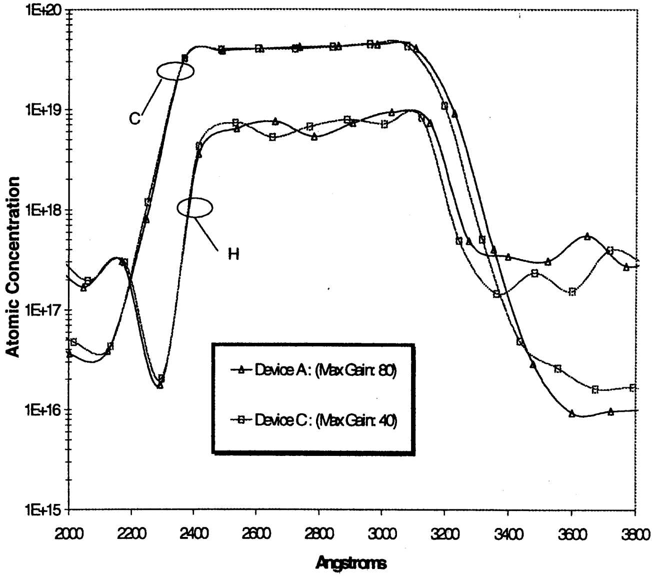

Figure 4: SIMS profile of carbon and hydrogen in the base layer of high and low gain samples. Note that the concentration of both species remains unchanged in the two samples. Hydrogen concentrations are estimated to be approximately 6.8 x 10^{18} cm^{-3}, which is typical.

ACKNOWDEGMENTS

The authors are indebted to Jesse Rodriques for the device processing and electrical characterization of the HBT's. We are also grateful for the technical support and helpful discussions of Paul Deluca.

REFERENCES

[1] T. S. Low, C. P. Hutchinson, P. C. Canfield, T. S. Shirley, R. E. Yeats, J. S. C. Chang, G. K. Essilfie, M. K. Culver, W. C. Whiteley, D. C. D'Avanzo, N. Pan, J. Elliot, and C. R. Lutz, GaAs IC Symp. (1998).

[2] N. Pan, J. Elliott, M. Knowles, D. P. Vu, K. Kishimoto, J. K. Twynam, H. Sato, M. T. Fresina, and G. E. Stillman, IEEE Electron Device Letters **19**, 115 (1998).

[3] O. Ueda, A. Kawano, T. Takahahi, T. Tomioka, T. Fujii, and S. Sasa, Solid-State Electronics **41**, 1605 (1997).

[4] C. Beaulieu, B. Beggs, J. Bennett, J. P. D. Cook, L. Hobbs, T. Lester, B. Oliver, and R. K. Surridge, Proc. GaAs Reliability Workshop 11 (1996).

[5] M. Borgarino, R. Plana, S. Delage, F. Fantini, and J. Graffeuil, IEEE Trans. Electron Dev., **46**, 10, 1999

[6] A. Kawano, K. Imanishi, T. Tomioka, T. Iwai, K. Ishii, and Y. Yamaguchi, Solid-State Electronics, **42**, 2057, 1998.

[7] N. Bovolon, R. Schultheis, J. Muller, P. Zwicknagl, and E. Zanoni, IEEE ED, **19**, 469, 1998

[8] T. Henderson, V. Ley, T. Kim, T. Moise, and D. Hill, IDEM Tech Dig., pp203-206, 1996c

[9] R. E. Welser, N. Pan, D. P. Vu, P. J. Zampardi, and B. T. McDermott, IEEE Trans. Electron Devices **46**, 1599 (1999).

[10] Z. Lu, A. Majerfeld, P. Wright, and L. Yang, IEEE J. Selected Topics in Quant. Elec., **1**, 1030,1995