Investigations on Initial Beta Drift During Reliability Test for MOCVD Grown C-doped InGaP/GaAs HBTs

Lance Rushing, Catherine Luo and Peter Zampardi
Skyworks Solutions Inc., 2427 W. Hillcrest Drive, Newbury Park, CA91320
Email: Catherine.Luo@Skyworksinc.com, Phone: 805-480-4553
Barbara Landini, Kevin Stevens, Charles Lutz and Roger Welser
Kopin Corporation, 695 Myles Standish Blvd, Taunton, MA 02780
Email: Roger_Welser@Kopin.com, Phone: 508-824-6696

***Abstract* --- We report on investigations of the initial drift in DC current gain, or beta (β), during the early stages of reliability testing of MOCVD-grown carbon doped InGaP/GaAs HBTs. The β drift is compared for different HBT structures with varying burn-in percentages. Competing mechanisms are observed in which β can either increase or decrease during the initial stages of reliability testing. This β drift behavior is found to depend upon both the β burn-in percentage and the hydrogen concentration in the base. Hydrogen-related defect mechanisms are found to adequately explain the observed β decreases, while non-hydrogen related recombination reduction mechanisms must be considered to account for the β increases observed during the initial stages of reliability testing.**

Keywords: *HBT, reliability, beta burn-in, beta drift*

INTRODUCTION

GaAs heterojunction bipolar transistors (HBTs) are important devices for wireless communication applications. Many GaAs HBTs are grown by the metal-organic chemical vapor deposition (MOCVD) technique, using carbon as the p-type dopant for the base layer. A DC beta "burn-in" effect is typically observed in such GaAs HBTs. This burn-in effect is characterized by an instantaneous and finite increase in the DC current gain of the HBT devices after biasing at normal measurement or operating conditions. Various explanations have been proposed to explain this effect, such as the annihilation of hydrogen related recombination centers in the base layer [1] or hydrogen passivation at the extrinsic base surface or in the emitter region.[2,3]

GaAs HBTs exhibit three typical modes during reliability testing:[4,5] (1) initial β drift, which occurs after the first few hours of stress, (2) relatively stable β extending over some period of time and (3) sudden β degradation when the devices catastrophically fail. The behavior of the initial β drift during reliability testing is also believed to be related to the presence of hydrogen incorporated into the HBT structure during epitaxial growth (via MOCVD) or device processing.[6,7,8] However, unlike the β burn-in effect in which β always increases, we observe that this initial β drift during the early stages of reliability testing can be either an increase or a decrease for different HBTs with varying burn-in. In this paper, we report on the relationship between the initial β drift and the β burn-in percentage of different InGaP/GaAs HBTs. Both hydrogen and non-hydrogen related mechanisms are proposed to account for the observed β drift behaviors of structures with differing burn-in and hydrogen concentrations.

EXPERIMENTAL

The InGaP/GaAs HBT epitaxial wafers were grown at Kopin Corporation using an Aixtron MOCVD system. HBT structures with varying β burn-in were grown. HBT devices with emitter areas of 56μm^2 were then processed at Skyworks, and packaged into a custom-built test system for electrical/thermal reliability stress testing.[9] Identical device processing and test procedures were used for all HBT structures. The hydrogen concentration in the HBT layers was measured on unprocessed wafer pieces using Secondary Ion Mass Spectroscopy (SIMS).

The HBTs were characterized by forward Gummel measurements and base-emitter/base-collector diode I-V measurements using a semiconductor parameter analyzer. A β burn-in percentage was calculated to quantify the HBT DC β burn-in effect. The burn-in percentage was defined using the first (β_1) and final (fifth, β_5) bias measurement as: $(\beta_5 - \beta_1)/(\beta_5)$ at 100A/cm^2 collector current density (J_c) on 75μmX75μm emitter area transistors. The β drift during reliability testing was quantified as $(\beta_{final}-\beta_{initial})/(\beta_{initial})$ on 56μm^2 emitter area devices at J_c of 25kA/cm^2. The initial beta ($\beta_{initial}$) was measured at 0 hour stress, post burn-in, while the final beta (β_{final}) was taken after 50 hours of stress time. The detailed reliability test setup and procedures have been previously reported.[9] The stress conditions used in this study are 25KA/cm^2 emitter current density and 200^{o}C case temperature (~305^{o}C junction temperature). The electrical/thermal stress was interrupted periodically to allow device characterization to be performed at room temperature.

RESULTS AND DISCUSSIONS

InGaP/GaAs HBTs with different epitaxial layer structures and properties were investigated in this study. Table 1 summarizes the HBT structural details and their corresponding β burn-in and initial β drift percentages. The β drift percentages are average values derived from measuring multiple devices from the same HBT wafer. Fig. 1 depicts the correlation between the β burn-in and the initial β drift percentages for these HBTs. Even for HBTs with slightly different base and emitter structures, it is observed that the larger the β burn-in, the larger the β decrease during reliability testing. The β becomes more stable, or β even increases, as the β burn-in percentage decreases.

Our data indicates that the base layer properties have a large impact on the initial β drift during reliability testing. HBTs with β/R_b(base sheet resistance) of 0.55 and a burn-in value of 66% (structure A) exhibit an average 20% β decrease during initial reliability testing, while the same structure with β/R_b=0.4 and a burn-in value of 39% (structure A2) has an average β increase of 3%. This behavior appears to be independent of base thickness, since structures B and B2 exhibit a similar behavior as that of structures A and A2. High β/R_b HBTs with a reduced burn-in of 31% (structure A1) demonstrate only a 2% β decrease. Further reduction in burn-in for low β/R_b wafers (structure B3, burn-in = 10%) results in an 8% β increase. Although structures C and C1 have different emitter cap doping, they exhibit similar β burn-in and initial β drift behavior as structures A and A1. Changing the InGaP emitter ordering (B1) and altering the emitter / emitter cap interface (A3 and A4) have minimal effects on the relationship between β burn-in and initial β drift.

Sample	Description	Beta Burn-in	Initial Beta Drift During Rel
A	Nominal base thickness, beta/R_b=0.55	66%	-20%
A1	Structure A with low beta burn-in	31%	-2%
A2	Structure A with beta/R_b =0.4	39%	3%
A3	Structure A with type I emitter/emitter cap interface	69%	-12%
A4	Structure A with type II emitter/emitter cap interface	58%	-10%
B	Thick base, beta/R_b =0.4	47%	5%
B1	Structure B with ordered InGaP emitter	38%	6%
B2	Structure B with beta/R_b =0.55	67%	-18%
B3	Structure B with low burn-in	10%	8%
C	Structure A with different emitter cap doping	78%	-25%
C1	Structure C with low beta burn-in	33%	3%

Table 1: Summary of the HBT structures and their beta burn-in and initial beta drift percentage.

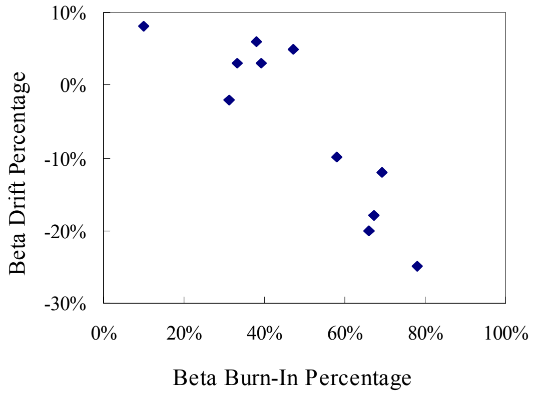

Figure 1: Correlation of beta burn-in vs. initial beta drift.

We measured the hydrogen concentration in the base layer for these various HBTs. Figure 2 shows the base layer hydrogen concentration versus β burn-in and β drift percentages for selected HBTs in Table 1. It is observed that the base layer hydrogen concentration correlates almost linearly with both the β burn-in and the initial β drift percentages. This correlation indicates that both the β burn-in and initial β drift during reliability testing are related to the hydrogen concentration in the base layer of these HBTs.

From the literature, hydrogen may be incorporated into the HBT base in a number of different ways, including: 1) as a meta-stable hydrogen/As antisite trap complex[1], 2) as an isolated hydrogen donor and 3) as a neutral hydrogen-carbon complex due to hydrogen passivation of the carbon acceptor[10]. Our burn-in results appear consistent with the theory that the DC burn-in β increase is caused by the annihilation of hydrogen-related traps,

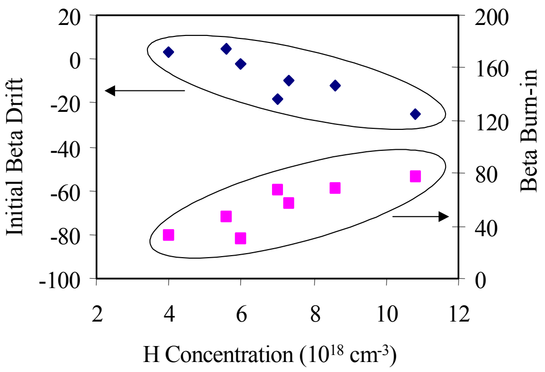

Figure 2: Correlation of base layer H concentration with beta burn-in and initial beta drift.

such as hydrogen/As antisite traps or other metastable traps, during electron injection into the base.[1] We note that the collector current (I_c) remains stable during burn-in, while the base current (I_b) with ideality factor (n) of 1 decreases. The observed decrease in base current can be attributed to a reduction in neutral base recombination, since reverse hole injection current is negligible for InGaP emitters, as is extrinsic base surface recombination current in large emitter area (75μmX75μm) transistors. It implies that changes in defect trap density, which appear proportional in density to the as-grown hydrogen concentration, govern the magnitude of the burn-in.

After the initial β burn in, β is then observed to drift further during the initial stages of reliability testing. Since this β drift occurs during high current and temperature reliability stress, it is reasonable to assume that the process(es) responsible for this β drift requires higher activation energies than that of β burn-in effect. The depassivation of C-H complexes in the base layer has been proposed as a mechanism explaining both HBT long term and short term β degradation.[10,6,7,8]. The decomposition of C-H complexes re-activates the carbon acceptors, effectively increasing the base doping. We typically observe a small, rapid decrease in I_c (i.e. increasing Vbe) with stress time, consistent with higher active doping. Higher active doping, as well as traps created during decomposition, can increase the base recombination current, decreasing β. Hence a C-H decomplexing mechanism could account for the β decrease during the initial stages of reliability testing observed for our high burn-in HBTs with large hydrogen concentrations in the base layer. However, this mechanism cannot adequately explain the β increase observed in low burn-in.

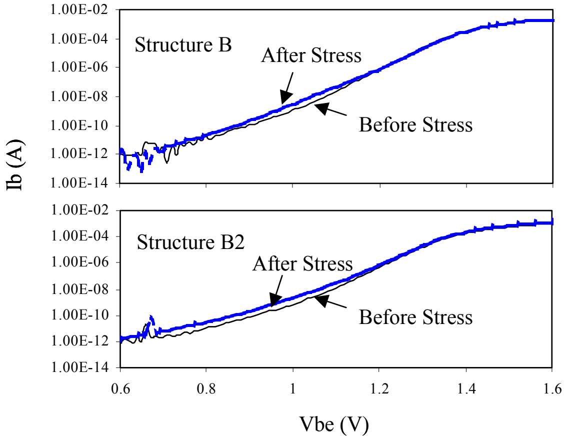

Figure 3: Ib vs. Vbe for structures B and B2 before and after stress.

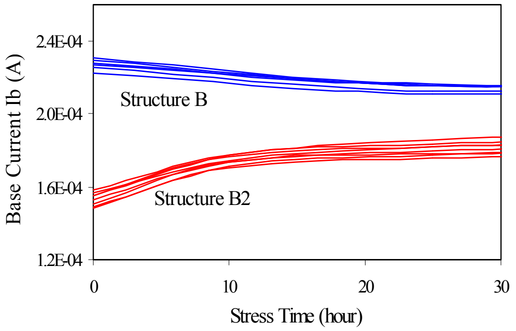

Figure 4: Ib vs. stress time for structures B and B2 at Jc = 25KA/cm^2 .

In order to better understand the mechanism of initial β drift for HBTs with different burn-in percentages, we examined the base current behavior with current/temperature stress. Fig. 3 shows I_b versus V_{be} at 0 hour and after 10 hours stress for structures B (burn-in = 47%) and B2 (burn-in = 67%). Structures B and B2 both exhibit a slight I_b increase in the low bias (n=2) region, but the I_b in the high bias region (n=1) increases for structure B2 and decreases for structure B. This I_b behavior progresses in time as shown in Fig. 4, which plots I_b vs. stress time for the same two devices at J_c of 25KA/cm^2. These changes in n=1 I_b behavior correlate with the observed increase in β over time of 5% for structure B, and decrease in β over time of 18% for structure B2. For a well ledge-passivated HBT, the extrinsic base surface recombination current is relatively small, and the base current is dominated by the base bulk recombination in the high bias region (n=1). Our results indicate that there are competing mechanisms driving the change in n=1 base bulk recombination current that account for the different β drifts measured for HBTs with varying burn-in percentages.

Based on our experimental results, we propose that, in addition to the C-H complex decomposition, there is a competing mechanism responsible for the recombination current reduction in the base after reliability stress. The fact that I_b initially decreases in low burn-in HBTs with low hydrogen concentrations in the base suggests that this competing mechanism may not be hydrogen related. We speculate that this β increase could be due to other possibly non-hydrogen related intrinsic defect reductions that occur during the early stages of reliability testing after the initial burn-in of the device. For HBTs with high burn-in and high base layer hydrogen incorporation, C-H complex depassivation may be the dominating mechanism responsible for the observed β decrease after reliability stress. In contrast, for low burn-in HBTs with low hydrogen concentrations in the base, the annihilation of other recombination centers, potentially non-hydrogen related, may be the dominant mechanism responsible for the observed β increase after reliability stress. Further study is required to fully understand this defect reduction process in low burn-in, low hydrogen HBTs.

CONCLUSION

We have investigated the behavior of the initial β drift during reliability testing and its correlation with β burn-in effect in InGaP/GaAs HBTs. Our study indicates that the β drift is related to the β burn-in percentage, even for slightly different HBT structures. HBTs with larger burn-in percentages are found to have higher hydrogen concentrations in the base layer, and a larger initial β decrease after reliability stress. Lower burn-in HBTs have lower hydrogen concentrations in the base, and show relatively stable or even increasing β after stress. Annihilation of a meta-stable hydrogen/As antisite trap or other traps is thought to adequately account for the β burn-in effect. C-H complex depassivation in the base layer is thought to be at least partially responsible for the initial β decrease during reliability test observed in high burn-in devices. A recombination reduction process, possibly non-hydrogen related, is proposed as a competing mechanism to account for the initial beta increase observed in low burn-in devices. The exact mechanism of this defect reduction process requires further investigation.

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Acronym:

HBT: Heterojunction Bipolar Transistor
Beta, β: DC current gain
R_b: Base Sheet Resistance
I_b: Base current
I_c: Collector current
J_c: Collector current density
V_{be}: Base-emitter turn-on voltage
n: Ideality factor