Base Current Investigation of the Long-Term Reliability of GaAs-Based HBTs

R. E. Welser, M. Chaplin, C. R. Lutz, and N. Pan
Kopin Corporation, 695 Myles Standish Blvd, Taunton, MA 02780
Phone: (508) 824-6696 email: rwelser@kopin.com

A. Gupta, B. Veasel, and A. Ezis
Northrop Grumman, 1212 Winterson & W. Nursery Roads, Linthicum, MD 21090

ABSTRACT

We observe a 5x increase in the time to failure of $Al_{0.28}Ga_{0.72}As$/GaAs HBTs with lower V_{be} turn-on voltages. Degradation in dc current gain is used as the criteria for failure analysis. Standard four-finger 1.7 μm x 19.7 μm devices both stressed and tested at a junction temperature of 260 °C and a collector current density of 48.5 kA/cm^2 exhibit a MTTF under 400 hours. Devices from wafers of identical structure except for a 53 mV lower turn-on voltage (@ J_c = 1.78 A/cm^2) have a MTTF in excess of 2000 hours. These results are simulated using a simple Gummel plot model for the various base current components in a well passivated device. An expression consistent with a recombination enhanced defect formation process is used to quantify an increase in trap density within the emitter-base depletion region. The general features of previously reported reliability results, such as the observed 10x difference in MTTF between AlGaAs and InGaP emitter HBTs, can also be simulated using the model discussed in this work.

INTRODUCTION

The reliability of GaAs-based heterojunction bipolar transistors (HBTs) is an ongoing subject of discussion, research, and debate [1-6]. The long-term reliability of GaAs-based HBTs with AlGaAs emitters has proven sufficient for a number of commercial applications, such as power amplifier circuits in L-band mobile phones. InGaP emitters exhibit a longer mean time to failure (MTTF), opening new commercial applications, such as microwave instrumentation and OC-192 fiber optic circuits [1,5]. Understanding the many physical processes which can impact and limit device reliability is essential for process control in current manufacturing programs and for developing even higher reliability devices for future generations of HBT circuits. Degradation of dc current gain is the most common failure mechanism reported in state-of-the-art GaAs-based HBTs. In this work, we focus on the material properties and physical processes which may set the upper limit on device reliability. We present experimental data which indicates that the turn-on voltage can have a significant impact on the reliability of $Al_{0.28}Ga_{0.72}As$/GaAs HBTs. This experimental data, coupled with suggestions from the literature, is used to construct a Gummel plot based model which can simulate both present and previously published results. DC current gain degradation is assumed to result exclusively from an increase in the n=2 space charge recombination component of the base current (I_{SCR}). A generic recombination enhanced defect reaction (REDR), involving a two-carrier, electron-hole capture process which results in the creation of a new defect, is used to quantify increases in I_{SCR}.

IMPACT OF TURN-ON VOLTAGE

The scatter plot in Figure 1 depicts the change in dc current gain with time on the best ten devices from two distinct lots of epitaxial $Al_{0.28}Ga_{0.72}As$/GaAs HBT wafers. The wafers, which were processed and tested together, are identical in structure, except that in one case the base-emitter interface is better optimized, leading to a 53 mV reduction in the turn-on voltage (V_{be} @ J_c = 1.78 A/cm^2). The simulated and experimental room temperature Gummel plots from four-finger, 1.7 μm x 19.7 μm devices on these two lots of wafers are shown in Figure 2. The base currents are nearly identical, but the collector currents differ by a factor of 6x due to differences in the effective height of the conduction band spike at the $Al_{0.28}Ga_{0.72}As$/GaAs interface [7-8]. The wafers with the lower V_{be} yielded devices which both have a higher overall dc current gain at elevated junction temperatures, and survive five times longer than devices on the higher V_{be} wafers.

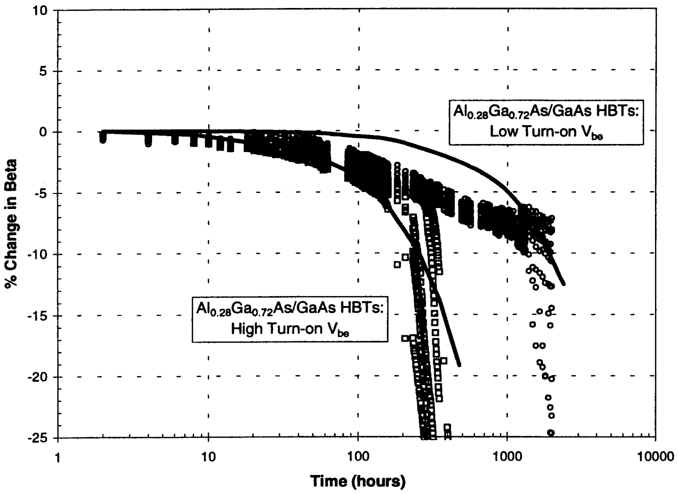

Fig. 1. Percent change in dc current gain (beta) on ten devices from each of two different sets of $Al_{0.28}Ga_{0.72}As/GaAs$ HBT wafers differing in turn-on voltage. Both stress and test conditions were T_j = 260°C, $J_c = 48.5$ kA/cm^2, and $V_{ce} = 7.0$V on four finger, 1.7 μm x 19.7 μm devices. The solid lines are simulated results from the model described in the text. The time to failure increased from under 400 hours to over 2000 hours on the lower V_{be} wafers.

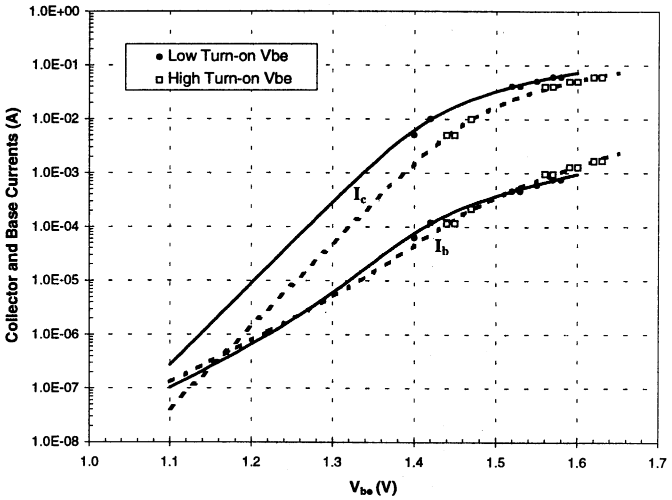

Fig. 2. Experimental (solid circles and open squares) and simulated (solid and dashed lines) room temperature Gummel plots from the four finger, 1.7 μm x 19.7 μm devices on the two sets of $Al_{0.28}Ga_{0.72}As/GaAs$ HBT lots showing a 5x difference in MTTF. Both lots of wafers are MOCVD-grown C-doped 4E19 cm^{-3} base layer structures (R_B ~ 240 Ω/□) with 11,000 Å thick collector layers. The simulations result from the model depicted in Fig. 3.

MODEL FOR DEGRADATION OF DC CURRENT GAIN

Numerous laboratories have reported that the degradation in dc current gain observed in state-of-the-art GaAs-based HBTs results principally from an increase in the n=2 components of the base current for both AlGaAs and InGaP emitter structures [1,3]. Any model for HBT device reliability needs to begin with a more detailed understanding of the base and collector currents. The base current (I_b) of a GaAs-based HBT is composed of several different components, including space charge recombination (I_{SCR}), neutral base recombination (I_{NBR}), reverse hole injection (I_{RHI}), and surface recombination [9]. Previously, we have used a basic device model to analyze the Gummel plots of large area devices in which surface recombination mechanisms can be ignored [8,10]. In this device model, the collector current is fit by a simple diode equation, and the base current is the sum of the first three components listed above. For this work, we assume the same basic model can be applied to the passivated, four finger 1.7 μm x 19.7 μm devices used for reliability testing. Gummel plots for small area devices can then be simulated based upon large area device measurements and analysis simply by scaling the device area (A). Figure 3 illustrates the current components used to simulate the collector and base currents in these devices. The three principal base current components considered here differ in both their voltage (n=1 vs. n=2) and temperature (E_a) dependencies. Note also that some of the pre-exponential terms shown in Figure 3 also have exponential temperature dependencies, such as the collector saturation current (I_o) and the intrinsic carrier concentration in the emitter (n_{ie}) [8,11]. At room

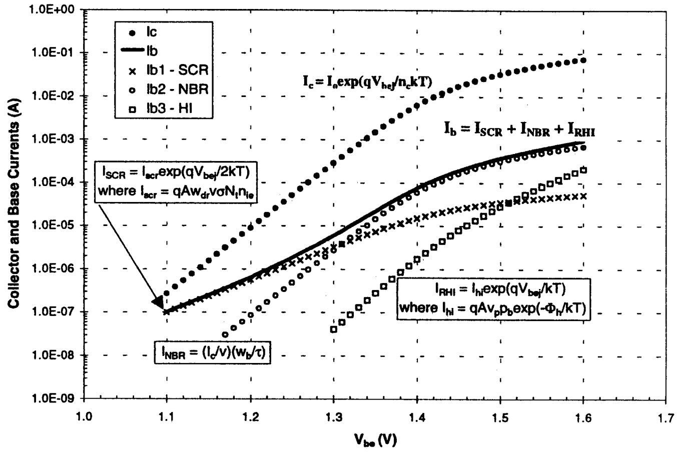

Fig. 3. Simulated room temperature Gummel plot of the low turn-on voltage $Al_{0.28}Ga_{0.72}As/GaAs$ HBT showing the current components assumed to be most relevant. Note that V_{bej} is the internal voltage across the base-emitter junction, w_b and p_b are the base thickness and doping, Φ_h is the effective hole barrier height, and N_t is the trap density within the space charge region of the base-emitter junction. See references for further details [8,10].

temperature, I_{SCR} is the most significant base current component at low bias, whereas I_{NBR} and I_{RHI} dominate at high bias in the simulated low turn-on V_{be} device shown in Figure 3. Because I_{NBR} is proportional to I_c, I_{NBR} plays a less dominant role in the high turn-on V_{be} (i.e. low I_c) devices.

In a comparison of the reliability of InGaP/GaAs and AlGaAs/GaAs HBT circuits, Low *et al.* observed a similar activation energy, but demonstrated a 10x improvement in the MTTF of InGaP/GaAs HBTs [1]. In accordance with previous reports, the authors also observed that the degradation in dc current gain results primarily from a large increase in an n=2 component of the base current. The authors further suggest that recombination enhanced defect formation within the space charge region of the emitter-base junction may be responsible for the observed increase in the n=2 base current.

We note here that an increase in I_{SCR} (assumed to be the primary n=2 base current component) can qualitatively account for the commonly reported changes in Gummel plots after high-temperature, high-current density stress [1,3]. Figure 4 shows simulated Gummel plots in which the only variable changed is the magnitude of the I_{SCR} pre-factor (I_{scr}). Since the collector current is unchanged, the dc current gain is simply inversely proportional to the base current at each bias point. A 600x change in I_{scr} has a negligible impact on the dc current gain at the high current densities typically used to assess reliability (J_c = 48.5 kA/cm^2). However, a 5000x increase in I_{scr} results in a significant decrease in the dc current gain, even at high J_c.

Recombination enhanced defect reactions (REDRs) encompass a large number of diffusion, dissociation, and annihilation processes whose reaction rates are increased as a result of the energy liberated during electronic transitions [12]. REDRs are found to be responsible for the creation of non-radiative recombination centers which degrade the light output in LEDs and laser diodes, and Henderson has previously suggested REDRs could be responsible for the degradation of GaAs-based HBTs as well [6]. In this work, we apply the concept of REDRs to model the increase in the trap density within the base-emitter space charge region (N_t). As seen in Figures 3 and 4, increases in N_t result in increases in I_{SCR}, the n=2 base current component assumed to drive to the observed degradation in dc current gain in the longest-lived GaAs-based HBTs. We further assume that defect formation within the depletion region is a REDR process involving an electron, a hole and a previously existing non-radiative recombination center. The density of non-radiative recombination centers within the space charge region (i.e. N_t) then increases exponentially with time (t) by a factor (F) which is proportional to the product of the electron-hole recombination rate and the defect formation constant [13]. Specifically, we find:

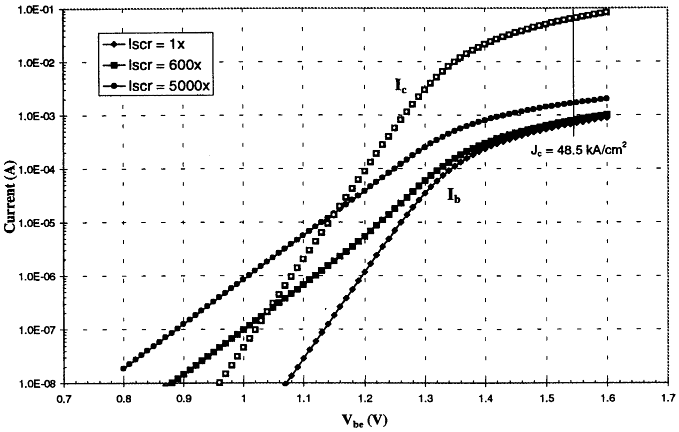

Fig. 4. Simulated room temperature Gummel plots showing the impact of an increase in the I_{SCR} component on the base current. The current density at which dc current gain is monitored is marked.

$$N_t(t) = N_{to} \exp(Ft) \qquad (1)$$

$$F \propto J_c\, J_{RHI} \exp(-E_{RE}/kT_j) \qquad (2)$$

where N_{to} is the initial trap density, E_{RE} is the recombination enhanced defect formation energy, J_c and J_{RHI} are the collector and reverse hole injection current densities under stress conditions, and T_j is the stress junction temperature.

In using Equations 1 and 2 to analyze the reliability results shown in Figure 1, J_{RHI} clearly plays a prominent role. The hole injection component of the base current is proportional to the effective hole barrier height (Φ_h) and the internal voltage across the base-emitter junction (V_{bej}):

$$J_{RHI} \propto \exp(-\Phi_h/kT) \exp(qV_{bej}/kT). \qquad (3)$$

At the stress conditions of J_c = 48.5 kA/cm^2 and T_j = 260 °C, we calculate that J_{RHI} decreases from 3.5 kA/cm^2 on the high turn-on devices to 0.5 kA/cm^2 for the low turn-on $Al_{0.28}Ga_{0.72}As$/GaAs HBTs discussed in Figs. 1 and 2. In these samples, the difference in J_{RHI} is due to the different voltages (V_{bej}) needed to achieve the fixed J_c used for the stress test. With these different J_{RHI} values, Equation 1 can be used to compute how N_t

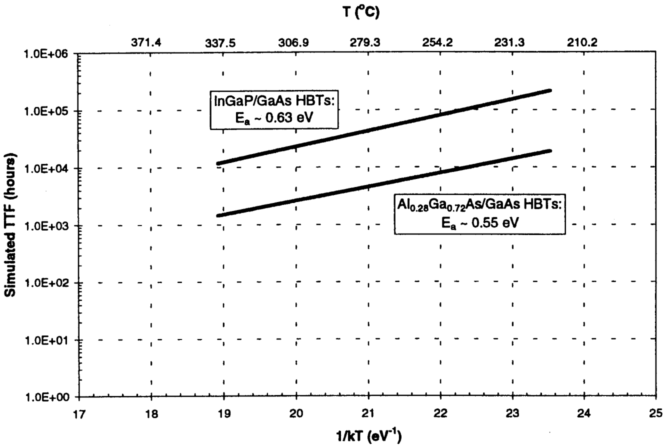

Fig. 5. Simulated time to failure (TTF) of $Al_{0.28}Ga_{0.72}$/GaAs and InGaP/GaAs HBTs using the model discussed in the text. The simulated Gummel plots were derived from large area device results, and we assume $J_c = 48.5$ kA/cm^2 under stress and $E_{RE} = 0.45$ eV.

changes with time for each set of devices. Gummel plots corresponding to different times are then simulated. The solid lines in Figure 1 show the resulting differences in the % change of the dc current gain. In these particular devices, the simulations do not perfectly match the shape of the experimental data, but the 5x difference in MTTF is reasonably approximated. We note again that the model proposed here represents a materials-related limiting factor on the reliability.

A 10x difference in the MTTF between AlGaAs and InGaP emitter HBTs can also be simulated using the REDR-based model for $N_t(t)$ discussed above. Large area device (L = 75 x 75 μm^2) results from optimized $Al_{0.28}Ga_{0.72}As$/GaAs and InGaP/GaAs HBTs were used as a starting point to simulate small area Gummel plots and to determine N_{to}. J_{RHI} was computed for the same stress conditions discussed in Figure 1, as well as for a number of different T_j, assuming E_{RE}=0.45 eV (arbitrarily chosen). Because of its larger emitter energy gap (and hence hole barrier), J_{RHI} is roughly 8x lower on the InGaP/GaAs HBTs under stress conditions. The simulated TTF for the two types of devices was computed using the same algorithm discussed above. The results are shown in Figure 5. We note that, for this choice of E_{RE}, the simulated activation energies governing degradation are comparable to those reported by Low *et al.* [1].

CONCLUSIONS

We have modeled the degradation in dc current gain observed in state-of-the-art GaAs-based HBTs. Starting with an initial simulated Gummel plot, degradation is assumed to occur due to an increase in N_t, the trap density in the emitter-base space charge region. This increase in N_t is quantified with an expression consistent with a REDR process involving electron-hole recombination at existing trap sites within the depletion region. Using this model, we are able to simulate not only the observed 5x difference in the MTTF of $Al_{0.28}Ga_{0.72}As$/GaAs HBTs with different turn-on V_{be}, but also the 10x difference in MTTF previously reported to exist between AlGaAs and InGaP emitter structures. 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 J_{RHI} by lowering the turn-on voltage and increasing the hole barrier height (i.e. wider emitter energy-gap).

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