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

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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 $\mu$m x 19.7 $\mu$m devices both stressed and tested at a junction temperature of 260 $^\circ$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 (@ $I_c = 1.78$ 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 ($V_{be}$ @ $I_c = 1.78$ A/cm$^2$). The simulated and experimental room temperature Gummel plots from four-finger, 1.7 $\mu$m x 19.7 $\mu$m 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.
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 $\mu$m x 19.7 $\mu$m 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 currents considered here differ in both their voltage ($n=1$ vs. $n=2$) and temperature ($E_g$) 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 ($I_C$) and the intrinsic carrier concentration in the emitter ($n_i$) [8,11].
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 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:

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

$$F \propto J_c J_{RHI} \exp(-E_{RE}/kT)$$ (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 ($\Phi_h$) and the internal voltage across the base-emitter junction ($V_{BE}$):

$$J_{RHI} \propto \exp(-\Phi_h/e) \exp(qV_{BE}/kT)$$ (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 ($V_{BE}$) 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 $N_t$
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) discussed above. Large area device (L = 75 x 75 μm²) results from optimized Al0.28Ga0.72As/GaAs and InGaP/GaAs HBTs were used as a starting point to simulate small area Gummel plots and to determine N0. J_{RH} was computed for the same stress conditions discussed in Figure 1, as well as for a number of different Tj, assuming E_{BE}=0.45 eV (arbitrarily chosen). Because of its larger emitter energy gap (and hence hole barrier), J_{RH} 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_{BE}, 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, the trap density in the emitter-base space charge region. This increase in N 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 Al0.28Ga0.72As/GaAs HBTs with different turn-on Vbe, 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_{RH} by lowering the turn-on voltage and increasing the hole barrier height (i.e. wider emitter energy-gap).

REFERENCES


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