Reliability Evaluation of InGaAsN for PA Handset Applications

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Abstract

An initial assessment of the reliability of InGaP/InGaAsN transistors was investigated in order to evaluate this new material system for cell phone applications. The investigation consisted of single temperature HTOL with a modest case temperature 200°C, V_{ce} of 5.0V, and a current density of 25kA/cm^2. InGaP/InGaAsN variants and InGaP/GaAs controls were stressed at the same time. The failure mode for both the InGaP/InGaAsN and InGaP/GaAs transistors was identified through IV characterization as Beta degradation due to an increase in I_b. All other device parameters are stable. The Beta degradation data was used to construct a probability plot. The InGaP/InGaAsN transistors had greater or comparable reliability to the control population, thus indicating that this material has sufficient reliability for cell phone applications.

INTRODUCTION

InGaAsN material has been receiving a great deal of attention for its potential applications in both optical and electronic devices [1]. In particular, the lower band-gap and device turn-on, when used as the base on an HBT, provide additional margin for handset PA designs. However, in current commercial applications, reliability is a primary concern of handset customers

The InGaAsN material system grown on GaAs is often a strained material (lattice mis-matched) system. Theoretically, this places a strain limit on how thick this layer can be before dislocations form that will dramatically degrade the device characteristics and reduce the device reliability [2]. Hence, a thorough understanding of device reliability over a range of base thicknesses is critical for both device design and understanding the manufacturing tolerance of this material system.

In this feasibility study, we evaluate the reliability of this new technology. This evaluation is designed to provide forward knowledge of the reliability and confidence that the lifetimes are sufficient for cell phone applications. To accomplish this, devices from this new technology with a range of base thicknesses and controls from a qualified technology (InGaP/GaAs) were subjected to single temperature HTOL. By comparing the lifetimes of a sufficiently sized population through the use of a lognormal probability plot, we provide confidence that the technology has sufficient reliability.

EXPERIMENTAL

Since this material system is strained, there is a limit to how thick the base layer can be grown. Calculations show that this value is theoretically close to 900 Å. However, work in other systems show that this theoretical limit can be violated [3]. Also, early tests in our laboratory with this material showed a high degree of instantaneous burn-in. As a result of these two factors, we studied devices with 500 Å and 900 Å base thickness possessing both high and low burn-in.

The Gummel plots for the different variants are shown in Figure 1. While this is not a characterization report we note the lower V_{be} turn-on and no abnormalities in series resistance, gain, or leakage. An InGaP/GaAs Gummel plot is shown for reference.

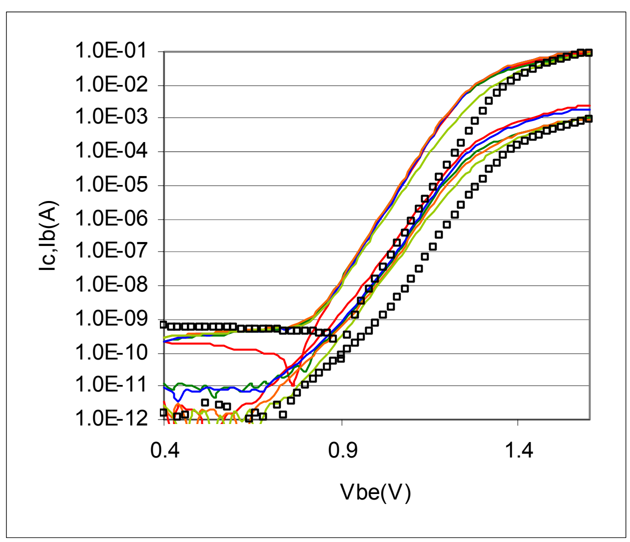

Fig 1. Gummel plots for InGaP/GaAs HBT's, shown in squares, and InGaP/InGaAsN variants shown in lines.

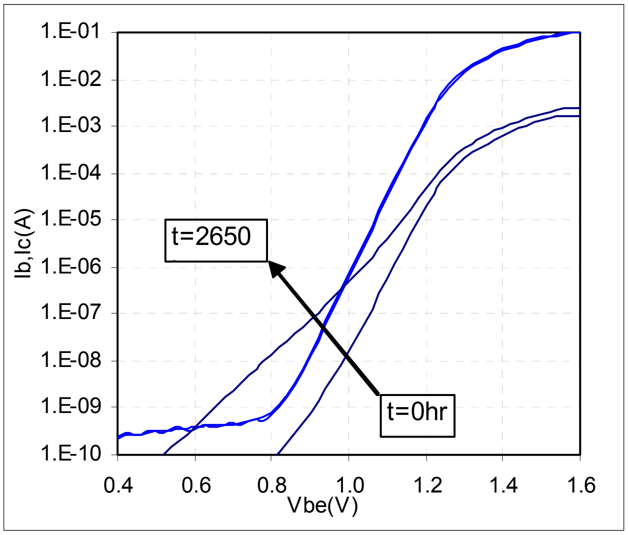

Fig. 2: Gummel plot for Typical InGaP/InGaAsN showing fundamental failure mode as Beta degradation due to degradation in I_b.

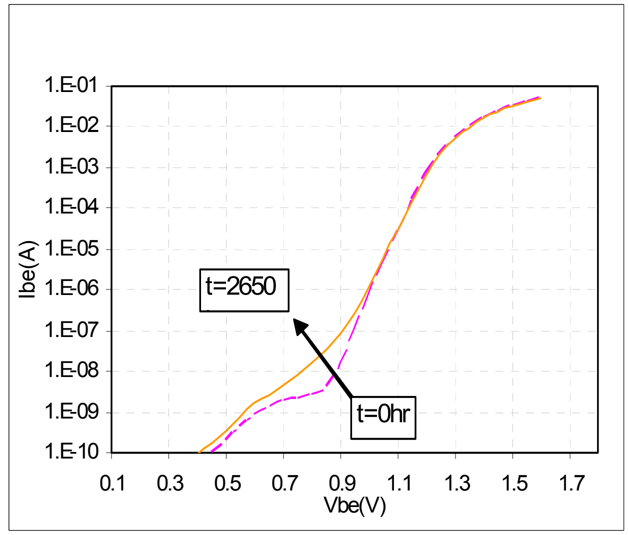

Fig. 3: Typical forward BE diode for InGaP/InGaAsN transistor showing degradation in I_b.

Transistor level HTOL was performed much in the same fashion as reported previously [4]. Thirty-two transistors per test cell were stressed at a modest case temperature of 200°C, V_{ce} of 5.0V, and a current density of 25kA/cm^2. The bias circuits maintain constant emitter current stress resulting in constant junction temperature. Junction temperature is typically characterized using the method described by B.Yeats [5]. The primary transistor failure mode identified in this study is Beta degradation and is characterized by an increase of I_b as a function of stress time and is shown in Figure 2. Note from the Gummel plot that I_b is the only degrading parameter and that I_c, R_e, and V_{be} are quite stable. Note also that the base ideality factor is close to 1 before stress, indicating quasi-neutral base recombination, and evolves to a value of 2, indicating space charge recombination. This is evident by the change in slope of I_b over stress time and is indicative of the classic failure mode for carbon doped HBTs. Reviewing the forward diodes curves in Figure 3 and 4 for a typical transistor further substantiates beta degradation due to an increase in I_b. The forward Base-Emitter diode curve shows the degradation in I_b at low bias while the forward Base-Collector curve shows a stable I_c. In summary, the failure mechanism for InGaAsN transistor is beta degradation and is similar to InGaP transistors from the same facility. as previously reported [4].

The typical Beta degradation for devices from this study is shown in Figure 5 for both low and standard burn-in. The vendor defines burn-in as the change in I_b from the Gummel plot from the first measurement to the 5th measurement. During the reliability tests, the burn-in affects the "initial Beta drift as described in the following statements. Figure 5

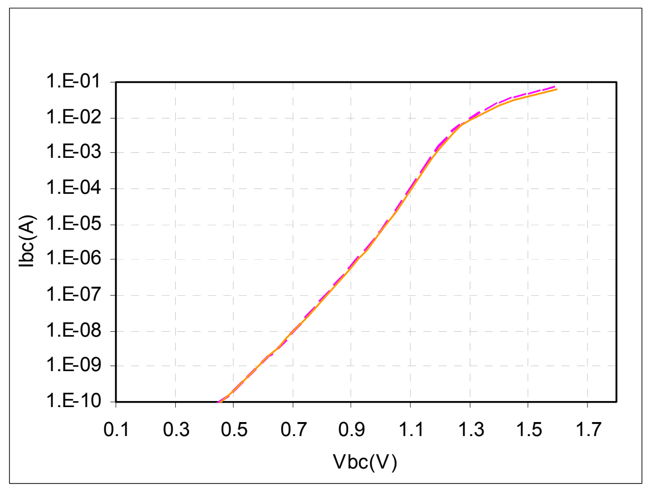

Fig. 4: Typical forward BC diode for InGaP/InGaAsN transistor showing stable I_c for length of stress test.

shows the three typical regions of Beta degradation. The first, is a drift period where Beta drifts up or down depending on

whether the material has low or standard burn in. The first region is followed by a second stable period with little or no change in Beta. A rapid drop in beta characterizes the third and final region. The failure criteria is defined as a 50% degradation in DC gain (Beta) in order to capture the sudden beta degradation mode.

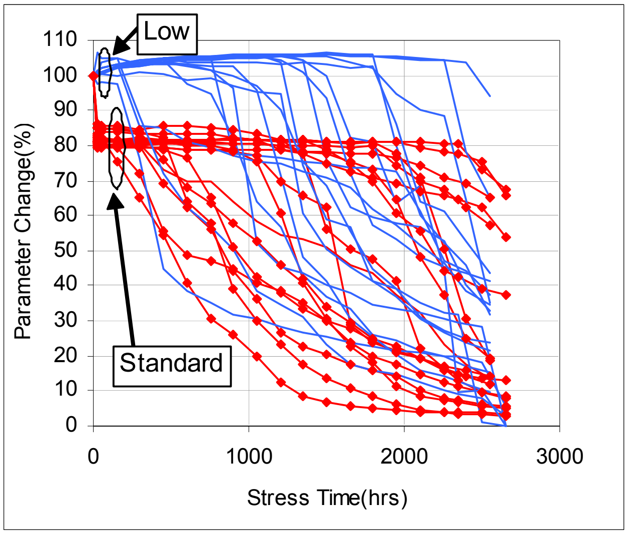

Fig. 5: Normalized Beta degradation for typical InGaP/InGaAsN transistors for both standard and low burn-in material.

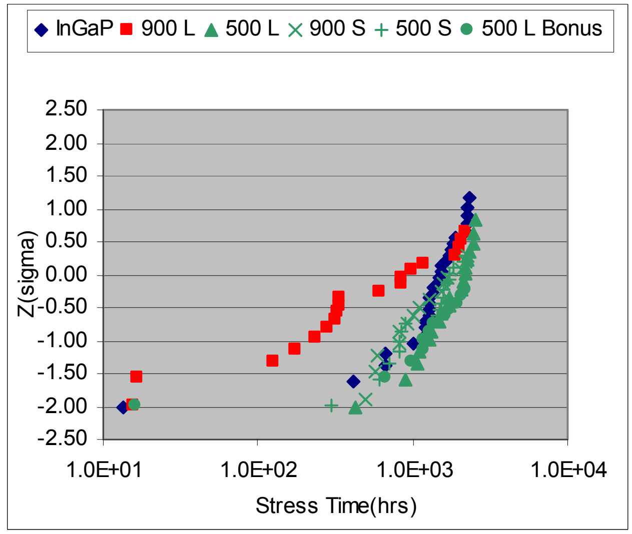

Fig. 6: Cumulative failures transformed into linear space for control and InGaP/InGaAsN variants. Z=0 is equivalent to MTTF. The number in the legend indicates the base thickness and the letters S and L denote standard or low burn-in material.

RESULTS AND DISCUSSION

Poor Man's Probability Plot

At Skyworks, probability plots are automatically generated after each read-point. The probability plot gives an indication of what the cumulative failures will look like. A probability plot of lifetime is quite easy to construct by transforming the times into normal space [6]. First, the exact time to failure is approximated by interpolating the beta drift between two read-points (remember 50% degradation is the failure criteria). These failure times are then screened for non-stress failures algorithmically and suspended. The failure times are then sorted and ranked (suspended values are also ranked) [6,7]. Next, the probability is found by calculating the inverse standard normal function of the ranks. The "inverse" values are plotted versus log failure times (or failure times on a log scale) . Thus, "ta da" the poor man's cumulative failures plot.

Cumulative Failures

The cumulative failures for the controls and each variant are shown in Figure 6. In the legend, the variants are denoted by the base thickness and the letters S and L denote standard or low burn-in. Most of the variants have similar reliability to the control. This is indicated by both MTTF (Mean Time to Failure) and sigma. On the Z-axis MTTF is equivalent to Z=0. Sigma, the lognormal shape parameter, is related to the inverse slope of the line and indicates the amount of spread in time. Thus, our variants have comparable lifetime and variation. Now, clearly the 900 Å low burn-in variant has considerably lower MTTF indicating a possible strain limit. We also note another sample with the same base thickness but much better reliability indicating the necessity for further exploration. As a side topic, note the MTTF differences between standard and low burn-in wafers (ignoring our wafer 900 L outlier). Clearly the standard wafers have slightly lower lifetime. There has been much internal debate as to whether lower burn-in wafers have longer lifetime because there is no 20% initial drift, which "contradicts" with the assumption of sudden beta degradation. So, from Figure 6, we see that the lifetime is lower but comparable and thus conclude that sudden beta degradation is the dominant mechanism and that the initial drift is a subordinate mechanism. This is also clear from Figure 5, where the low burn-in devices start with higher normalized Beta but have sudden degradation in a similar time scale as the standard burn-in devices.

Conservative Use Lifetime Estimation

To convince ourselves further, we decided to process subsequent wafers and stress them in order to generate a trend. These wafers have not yet finished (approximately 70% complete) but the cumulative failures are shown in Figure 7. The cumulative failures for our InGaP process are also shown. The InGaP population consists of over 942 transistors across 4 years and includes good and bad lots. Clearly, the sigma associated with production populations is much larger than those reported in more controlled experiments [4]. The wear-out populations for both material types are identified by the straight line. We typically isolate the wear-out population for device level data since the infant failure populations are more accurately identified by Product Reliability tests. This is because these test typically run at a lower temperature and involve the whole circuit (much more accurate representation of the failure mode!). Of course, one must be careful and product level test must include a

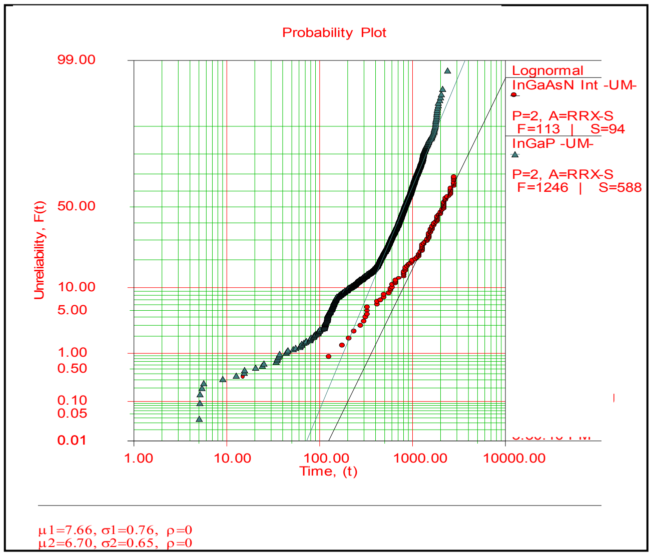

Fig. 7: Cumulative failures for our InGaP production with 942 transistors across 4 years with good and bad lots included compared to the preliminary InGaAsN population. The wear-out populations for both material types are isolated and identified by the straight lines.

sufficient number of parts (at Skyworks, product level tests usually consist of 3*77 parts per test).

The trends from Figure 7, with conservative sigmas, are used to generate reliability metrics. For cell phone applications the customer is much more interested in T0.1% (time to 0.1% failures) as opposed to MTTF (Mean Time to Failure) or T50%. Furthermore, since we did not initiate any acceleration factor studies we want a lower bound. For the lower bound we use an activation energy of 0.65eV which is typical for AlGaAs based devices. For an upper bound, we use an activation energy of 0.97 which was previously reported for our InGaP process [4]. The metrics are shown in Table I. Clearly the lower bound for both material types exceeds our internal device level reliability requirement for T0.1% (wear-out population) greater than 10,000 hours at 140C Tj.

CONCLUSIONS

Devices from a new technology incorporating strained InGaAsN were subjected to single temperature HTOL. Results are encouraging and show that most of the variants investigated have comparable reliability to the controls. Very conservative lifetime estimates give further confidence of acceptable reliability (clearly if multi stress studies would be necessary to estimate acceleration factors). Conservative techniques include using large sets of data over large periods of time, using Ea=0.65eV, and finally calculating T0.1% instead of T50%. The end result is that the material is reliable for cell phone applications over a large, and desirable, base thickness range.

TABLE I
Conservative Estimate of Use Lifetime at V_{ce}=5.0V, J_e=0.25kA/cm^2, and T_j=140C.

Type	Ea	T50%(hrs)	T0.1%(hrs)
InGaP	0.97	2.19E+06	2.10E+05
InGaP	0.65	1.49E+05	1.43E+04
InGaAsN	0.97	5.73E+06	7.69E+05
InGaAsN	0.65	1.49E+05	2.00E+04

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ACRONYMS

HTOL: High Temperature Operating Life
HBT: Heterojunction Bipolar Transistor
T0.1%: Time to 0.1% failures
T50%: Time to 50% failures
MTTF: Mean Time to Failure