Determination of Reliability on MOCVD Grown InGaP/GaAs HBT's under both Thermal and Current Acceleration Stresses

Kevin T. Feng, Lance Rushing, Phil Canfield*, and Larry Flores
Reliability Dept., Conexant Systems, Inc.
2427 W. Hillcrest Dr., Newbury Park, CA 91320
kevin.feng@conexant.com
*InPhi Corp., Westlake Village, CA 91361

Abstract – Conexant's reliability infrastructure was utilized to determine the reliability of next generation InGaP/GaAs heterojunction bipolar transistors (HBT's). The investigated InGaP HBT's were subjected to stresses at three junction temperatures and three current densities, in order to extract both thermal and current acceleration factors. The primary failure mode we identified for all stress conditions is sudden Beta degradation characterized by an increase of base current over time. The thermal activation energy was extracted to be 0.97eV for Beta degradation. The current acceleration of transistor lifetime is modeled as a power law relationship and we have extracted a square root dependence of lifetime on current density.

I. Introduction

Quantifying reliability of new technologies is a critical requirement of process development and subsequent transfer to manufacturing. Analysis of the acceleration factors and failure modes is used to extrapolate lifetime, determine maximum safe operating conditions, and obtain the intrinsic failure rate. To aid the quantification of reliability metrics, Conexant has built a state-of-art transistor reliability infrastructure to conduct high temperature operating life tests (HTOL). This reliability infrastructure has been utilized to characterize the reliability of next generation, production InGaP/GaAs heterojunction bipolar transistors (HBT's), monitor the current production AlGaAs HBT technology, to qualify HBT epitaxial reactors, and evaluate potential foundry partners.

InGaP/GaAs HBT's are highly attractive devices for high-power microwave amplifiers and high-speed telecom circuits as a potential replacement for AlGaAs/GaAs HBT products. The most significant advantage of InGaP/GaAs HBT's is the superior transistor reliability compared to AlGaAs/GaAs HBT's as demonstrated by multiple companies. The large valence band discontinuity of InGaP/GaAs heterojunction reduces hole ejection from the base to emitter, resulting in reduces space-charge recombination. InGaP/GaAs HBT's may be suitable for high current density and high power gain applications due to its excellent reliability under high current stress. However, the reported thermal activation energy for InGaP HBT ranges from 0.60eV to 1.8eV, giving tremendous discrepancy in extrapolated lifetime at operating condition [1-5]. The difference in reported activation energies may be related to different failure modes. Whether the activation energy extracted from accelerated life tests can be extrapolated to operating conditions depends on whether the same failure modes that are observed in the reliability life tests will dominate at actual use conditions. Moreover, little work has been done to characterize the current acceleration factor for InGaP/GaAs HBT's in order to obtain the current operating limit in terms of reliability.

In this work, we fully investigate the reliability of InGaP/GaAs HBT's fabricated in Conexant's high volume 4-inch wafer facility. The degradation characteristics of InGaP HBT's under both temperature and current acceleration were quantified allowing extraction of both thermal and current acceleration factors.

II. Reliability Infrastructure

Conexant has built a specialized HTOL infrastructure to conduct reliability evaluations. The infrastructure is very flexible, allows testing of large sample sizes, and testing at high temperatures for faster turn around. The HTOL test systems are custom built as is the software data acquisition and instrument control. The data acquisition software allows easy storage and analysis necessary to analyze the large volume of data generated.

The custom built HTOL test systems were designed around the fixture concept as opposed to the oven concept. The system consists of an insulated thermal mass with package fixturing, interconnects for measurements and biasing, and a thermal source with control. Two 40-pin packages with 16 transistors each are clamped into the thermal mass. Heat conduction as opposed to convection or radiation is used to heat the devices under test. The packages are connected through the insulation to a bias board at ambient. Thus, lower temperature circuitry can be used which increases reliability and decreases cost. For HBT HTOL testing, the transistors are bonded in a common collector configuration designed to maintain constant emitter current stress, therefore constant junction temperature during testing. Finally, the bias board is wired with connections to enable insitu electrical measurements. Thus, the packages do not have to be removed from the HTOL system for read point measurements.

Currently, Conexant has 80 HTOL systems, which equates to a capacity of 2560 transistors. This results in a large volume of data (single read point of one HTOL system generates 96 curves). Thus, efficient and powerful software tools are necessary to analyze the data. At Conexant, we developed custom software tools that allow automated test and data storage. Also, we have software tools that automatically compile and trend stored data. The compilation includes device curves and parameters. Finally, the software will automatically identify failures subsequent to specification of a failure criterion. This criterion is currently defined as a 50% reduction in Beta in order to capture the sudden Beta degradation mode.

III. InGaP/GaAs HBT Reliability

Conexant's InGaP/GaAs HBT process uses on MOCVD epitaxial wafers from commercial suppliers. The epi structure is rather conventional and critical layers affecting transistor performance are adjusted depending on the intended application. The fabricated InGaP/GaAs HBT's have an emitter area of $56\mu m^2$.

In order to extract both thermal and current acceleration factors, the InGaP HBT's were subjected to stresses at three junction temperatures and three current densities, illustrated in Figure 1. The junction temperatures were characterized on transistors mounted in packages and in the HTOL test system using electrical methods described by B. Yeats [6]. The junction temperatures for these tests were kept constant for the three different current density stresses by adjusting V_{ce}'s, to maintain a constant power density.

A. Thermal acceleration

Figure 2 shows the normalized DC Beta degradation of the $56\mu m^2$ InGaP/GaAs HBT's as a function of stress time at T_j=305°C and J_c=25kA/cm^2. It is noted that after initial Beta drop, which we believe is due to hydrogen-carbon complex dissociation, the InGaP HBT's show a stable Beta region, followed by a sudden Beta drop. The only transistor failure mode observed in Conexant's InGaP/GaAs HBTs, for all stress conditions, is Beta degradation. This degradation is characterized by an increase of I_b with increasing stress time.

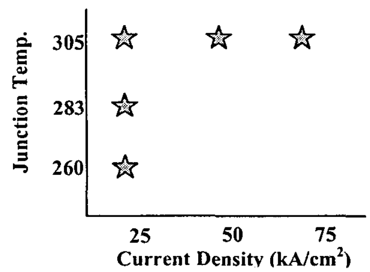

Fig. 1 InGaP HBT stress conditions.

Figure 3 shows the forward Gummel plots for an InGaP HBT before and after stress. The base current ideality factor, n_b has increased from unity before stressing, to nearly 2.0 as stress time increases, consistent with an increase in space charge recombination current. Figure 4 shows a typical forward B-E junction I-V. The junction IV characteristics display an increase in current at low bias as the stress time increases which is correlated to the increase in I_b observed in the Gummel plots. The Base-Collector junction exhibits very stable behavior during stress testing as shown in the forward B-C junction I-V measurements in Fig. 5. Lack of change in the collector current at high current densities in the Gummel plots indicates that the non-alloy emitter contact used in our InGaP HBTs is very stable.

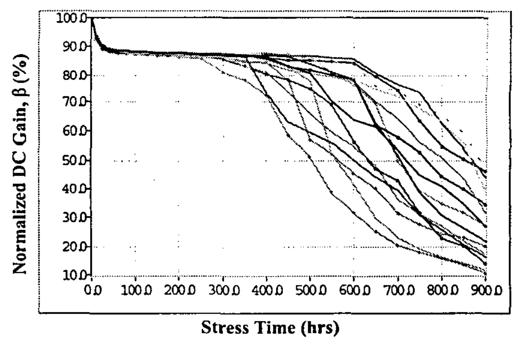

Fig 2. Normalized Beta degradation of a $56\mu m^2$ InGaP HBT's stressed at T_j=305°C and J_c=25kA/cm^2.

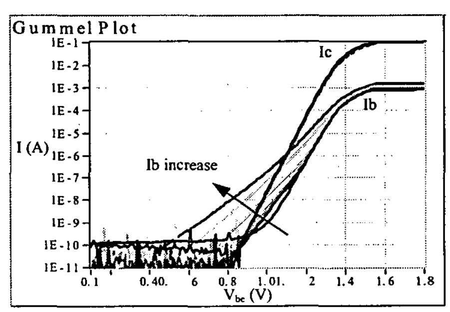

Fig. 3.Typical Gummel plots of an InGaP/GaAs HBT before stress and after 850hrs stress at T_j=305°C and J_c=25kA/cm^2.

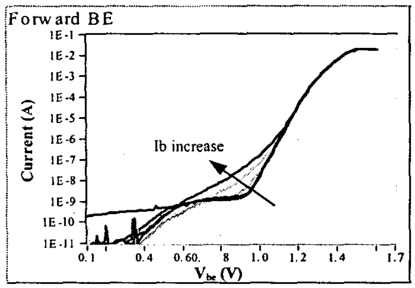

Fig.4. Typical Base-Emitter Junction forward I-V measurement for an InGaP/GaAs HBT before stress and after 850hrs stress at T_j=305°C and J_e=25kA/cm^2.

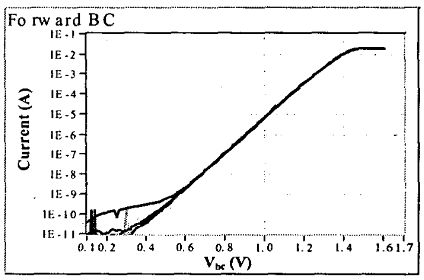

Fig. 5. Typical Base-Collector Junction forward I-V measurement for an InGaP/GaAs HBT before stress and after 850hrs stress at T_j=305°C and J_e=25kA/cm^2.

A lognormal distribution has been used to fit the cumulative failures for different junction temperature stresses and the plots are shown in Fig. 6. The similar sigma from each stress indicates that the failure mode and the failure distribution are the same, which is important for thermal activation energy extraction. The thermal activation energy for our InGaP HBT's was extracted to be 0.97eV from the Arrhenius model.

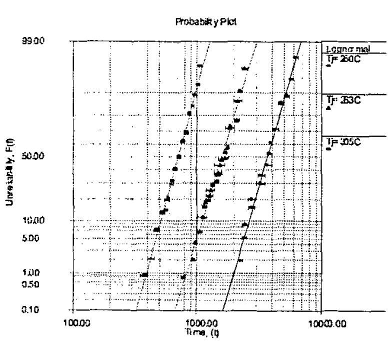

Fig.6. Cumulative failure distributions for InGaP/GaAs HBT's stressed at T_j=305, 283, and 260°C.

We have also compared Conexant InGaP HBTs with the InGaP HBT's processed by another vendor. Limited number of samples limited the evaluation to three-temperatures. The Gummel plots of the vendor supplied InGaP HBTs are shown in Figure 7. Mixed failure modes were observed for both Beta degradation, characterized by an increase of I_b over time, and Emitter resistance degradation, characterized by a decrease of I_c at high current density. Careful analysis allowed separation those two failure modes, giving a high activation energy of 1.5eV for emitter contact degradation, and a low activation energy of 0.72eV for beta degradation. This high activation energy observed for emitter resistance drift is consistent with metal diffusion process and indicates that the emitter resistance changes are related to the emitter/metal semiconductor contact metallurgy. We believe the MTTF extrapolated from low activation energy for beta degradation is more suitable prediction of device lifetime. Figure 8 shows the comparison of Arrhenius plots for the different failure modes.

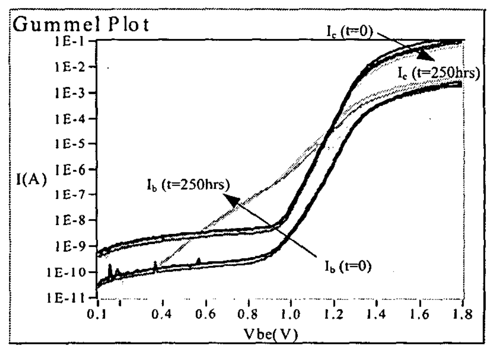

Fig. 7 The Gummel plots show mixed failure modes for an immature InGaP HBT stressed at T_j=305°C and J_e=25kA/cm^2.

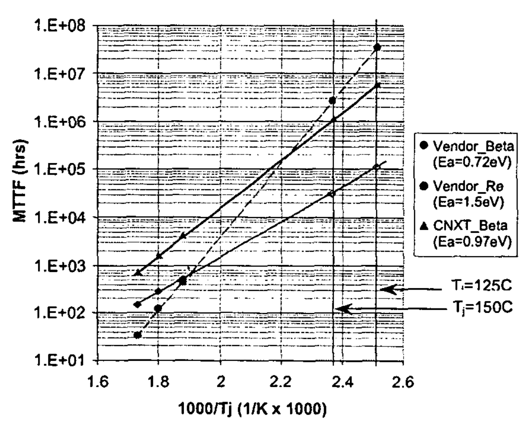

Fig. 8 Arrhenius plots of MTTF vs. junction temperature, T_j, for Conexant's InGaP HBT's, compared to InGaP HBT's provided by an external source.

B. Current Acceleration

The current acceleration factor, n is extracted from the power law dependence of lifetime on current density J_c, The Conexant InGaP HBT's were evaluated for transistors processed on starting wafers from two different epi vendors. MTTF as a function of current density is plotted in Figure 9. The current acceleration factor, n is exacted to be 0.46 for one epi vendor and 0.51 for other epi vendor, respectively, which is nearly square root dependent. A J^2 dependence was observed in recombination-enhanced defect reaction systems for AlGaAs/GaAs HBT's [7]. The difference in current acceleration factors has a profound affect on high-speed circuits that must operate at higher current densities to meet performance requirements.

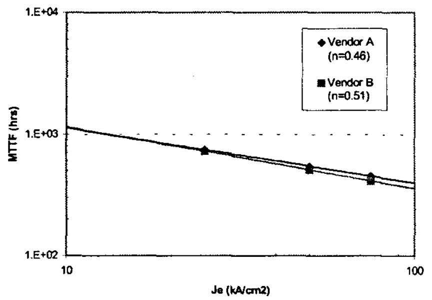

Fig. 9. The measured MTTF's vs. stressed emitter current densities for InGaP/GaAs HBT's

IV. Discussion

Based on the extracted thermal and current acceleration factors, the extrapolated useful lifetime, over a range of operating junction temperatures, is calculated for different current densities shown in Figure 10. This figure demonstrates that the InGaP HBT's can provide sufficient lifetime margins, even for potentially high current and high junction temperature applications. Practical limitations such as the total power dissipation in circuits and the available supply voltage become more significant limitations in many applications. This behavior highlights the large difference between reliability considerations for power amplifiers compared to optical networking circuits. In many lightwave circuits, the transistor V_{ce} is limited to 1-2 Volts, while for power amplifiers under full power operation, the RMS voltage on the collector can be well above 4.2 Volts (the peak voltage can exceed 20 volts under mismatch conditions for some amplifiers). Another factor that can affect maximum operating current density is thermal resistance of the technology, thus lowering the thermal resistance is imperative in order to fully utilizing the current density potential of InGaP.

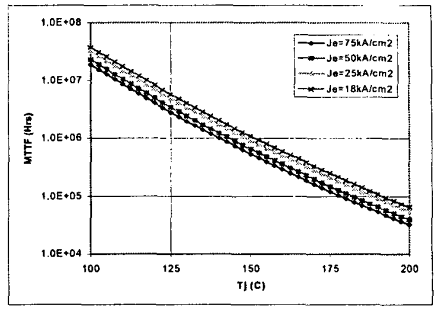

Fig. 10 The extrapolated lifetime vs. operating junction temperatures under different current densities.

V. Conclusions

We have fully utilized the reliability infrastructure built in Conexant to determine the reliability of next generation InGaP/GaAs heterojunction bipolar transistors (HBT's). The investigated InGaP HBT's were subjected to accelerated tests at multiple junction temperatures and current densities. The primary failure mode we identified for all stress conditions is sudden Beta degradation characterized by an increase of base current as stress time increases. The thermal activation energy was extracted to be 0.97eV for Beta degradation. The current acceleration of transistor lifetime is modeled as a power law relationship and we have extracted a square root dependence of lifetime on current density, which compares with an approximate square law result reported on AlGaAs HBT's. We also demonstrated that having the right infrastructure and data analysis is neccessary to identify appropriate failure modes and extract right acceleration factors and lifetime.

ACKNOWLEDGMENTS

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Outline

- **Introduction**
  - Reliability "Philosophy"
- **Reliability Infrastructure at Conexant**
  - Equipment and Capacity
- **Reliability Activities at Conexant**
  - Monitor, Qualify and Study
- **Reliability Process Flow**
- **InGaP Reliability**
  - Test Plan
  - Sudden and Mixed Mode Beta Degradation
    - Data Analysis for Thermal Acceleration
    - Data Analysis for Current Acceleration for Sudden Beta Degradation
  - Lifetime
- **Comments and Summary**

Reliability Challenges for New Technologies

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- Quantifying reliability is usually the last step of development;
- Reliability work takes a long time;
- Results can be confusing and difficult to interpret;
- Extrapolation can exacerbate the uncertainty inherent to reliability predictions to absurd and meaningless extremes;
- Design appropriate acceleration tests to extract meaningful reliability data.

Infrastructure

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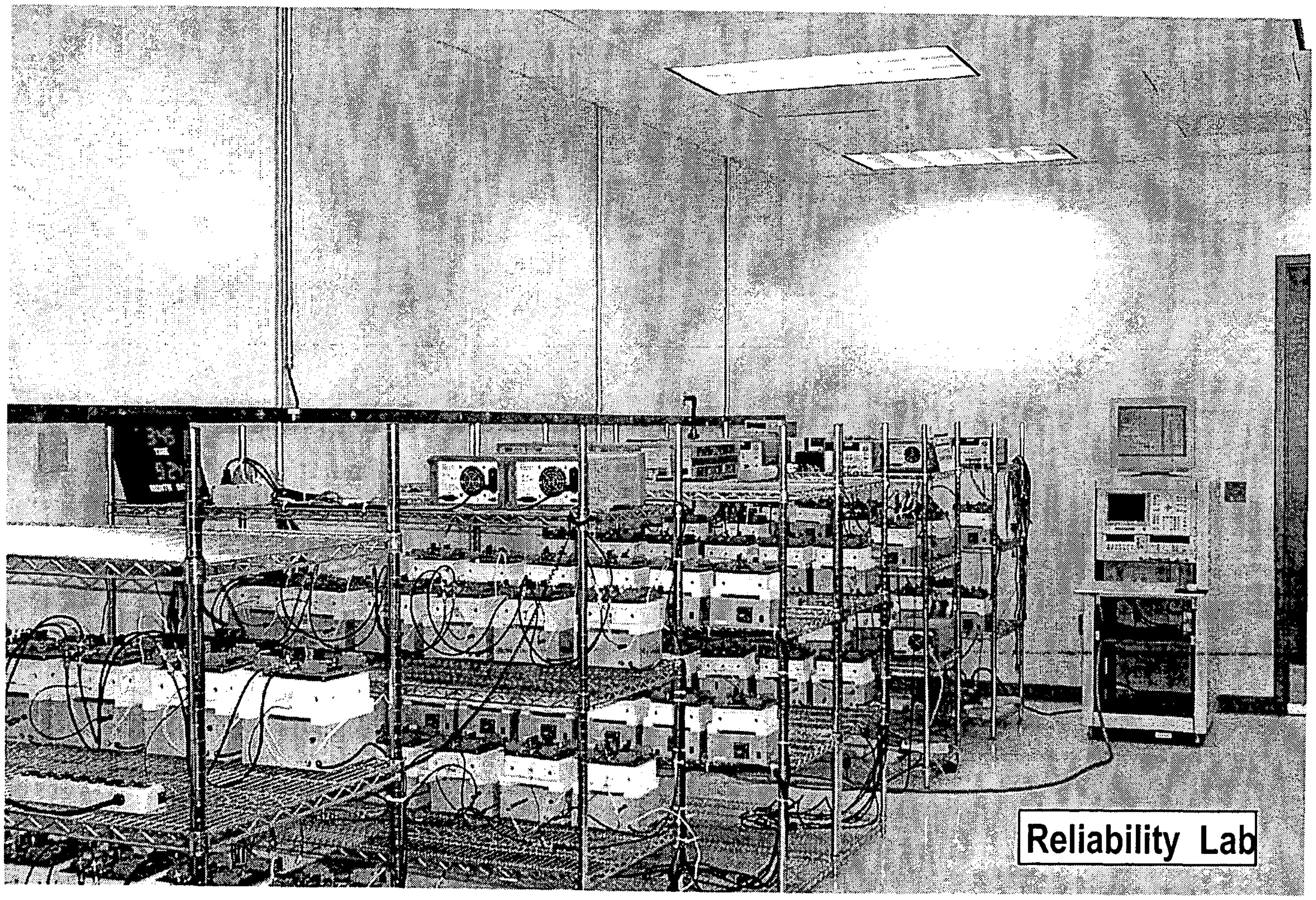

Reliability Lab

Infrastructure

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- **Custom Fixturing**
  - Temperature Range 25C- 240C
  - Adjustable Bias Conditions
- **Equipment**
  - Parameter Analyzer and Switch Matrix
  - Automated Electrical Measurements, data storage and extraction, and curve and parameter compilation
- **Capacity**
  - 32 device per fixture
  - 80 fixtures
  - 2560 devices

Activities

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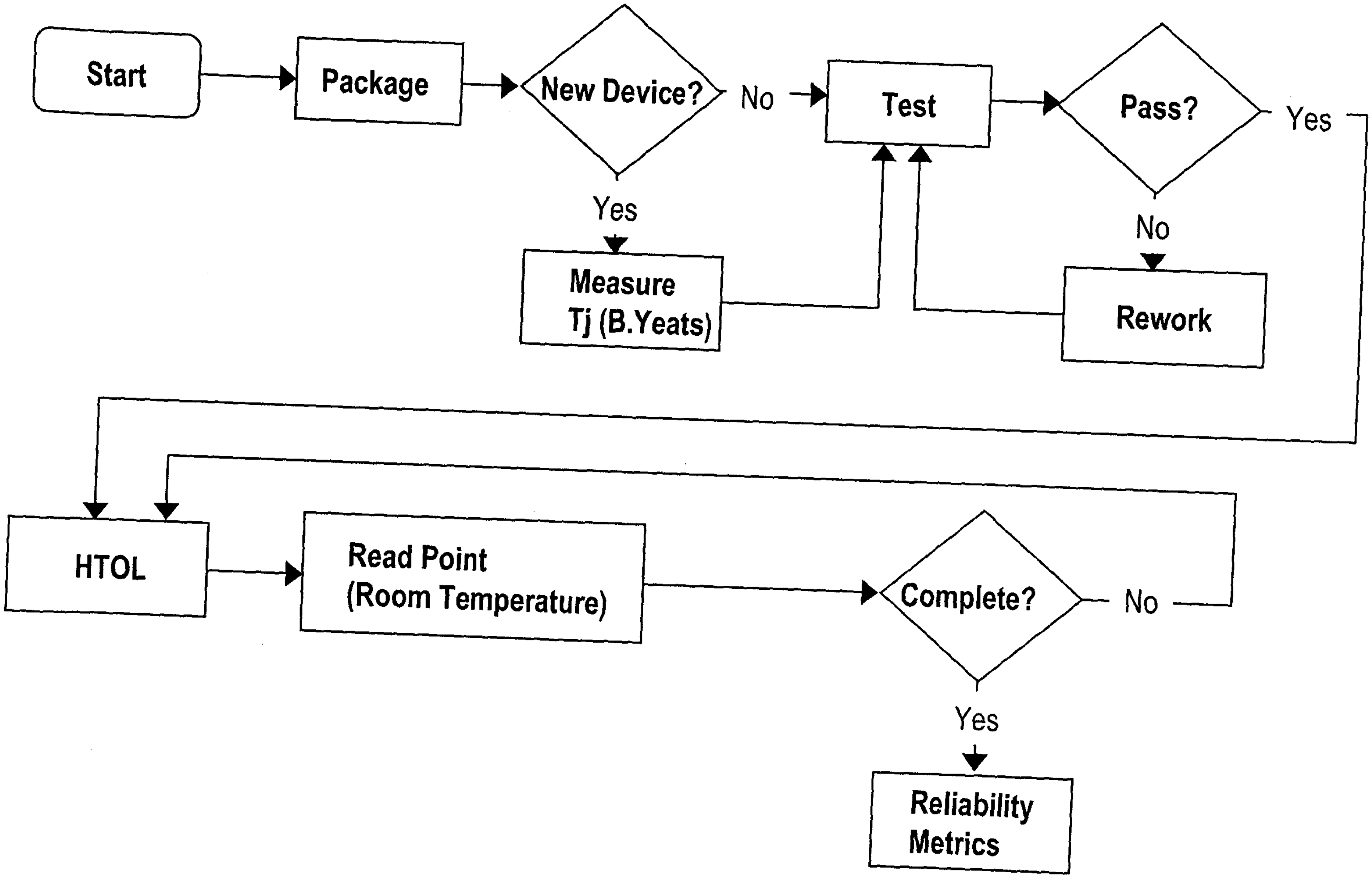
- **Monitor**
  - Trend Process Reliability
  - Trend Epi Reliability
- **Qualify**
  - Epi Vendors
  - Foundry Vendors
- **Study**
  - Both Thermal and Current Acceleration Factors
  - Affect of Epi Material Design
  - Affect of Device Structure

Reliability Process Flow



InGaP HBT Reliability Test Plan

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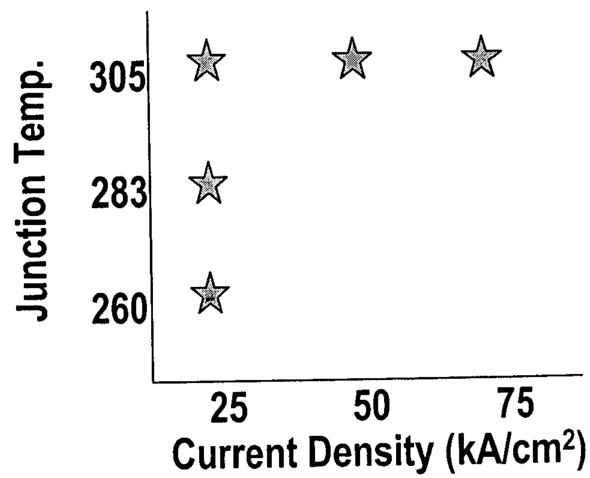
- **Three Temperatures at Same Je**
  - Activation Energy (Thermal Acceleration Factor)
- **Three Current Densities at Same Junction Temperature**
  - Current Density Acceleration Factor
  - Maximum Operating Current Density
- **Lifetime at Operating Temperature and Current Density**
- **Total 480 Transistors**



Beta Degradation

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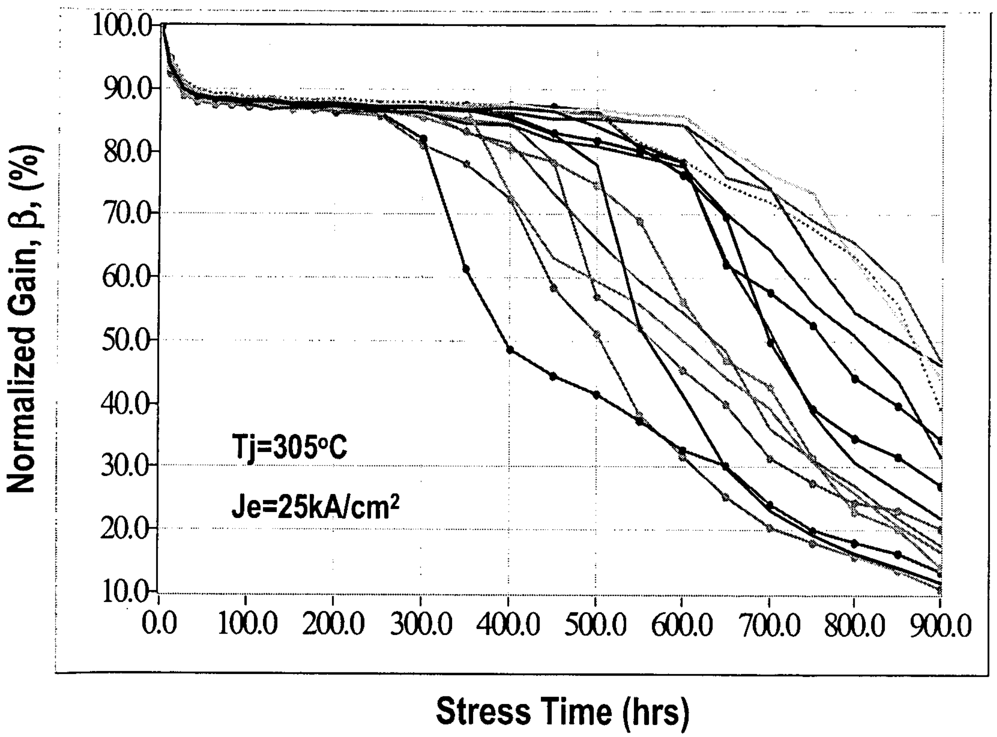

- **Three Degradation Zones**
  - Initial Beta drop due to Hydrogen burn-in effects
  - Stable
  - Sudden Beta Degradation

Degradation of I-V curves

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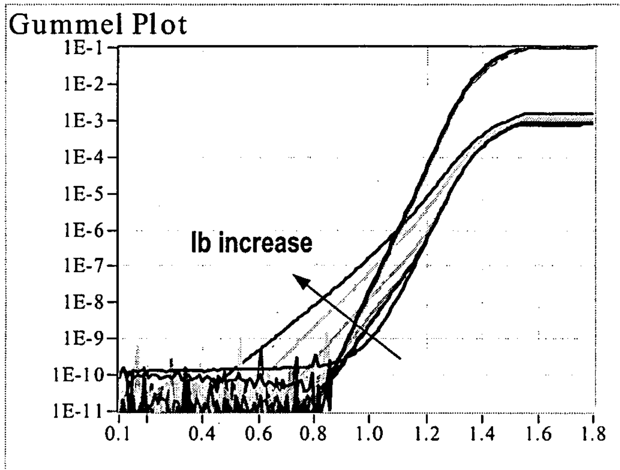
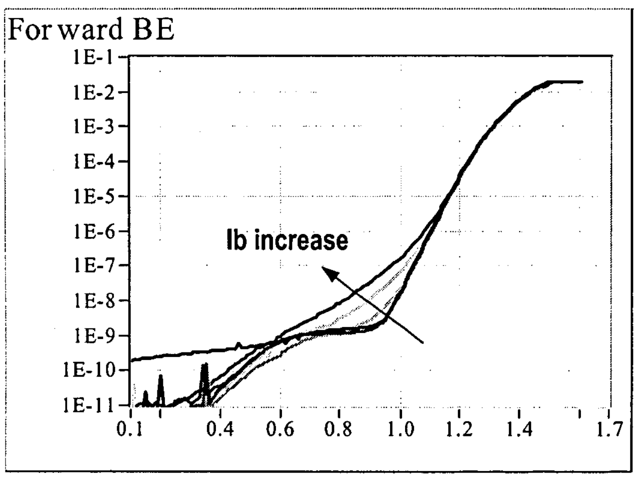
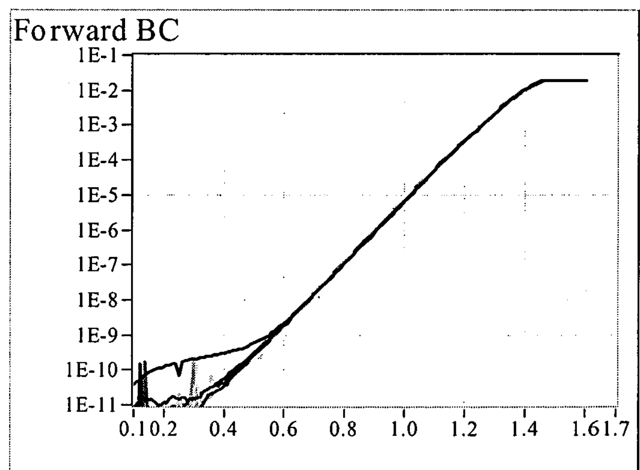


- Beta degradation characterized by increase in Ib
- Stable Re
- Main failure mode is the same for all stresses.





Cumulative Failures:Temperature Acceleration

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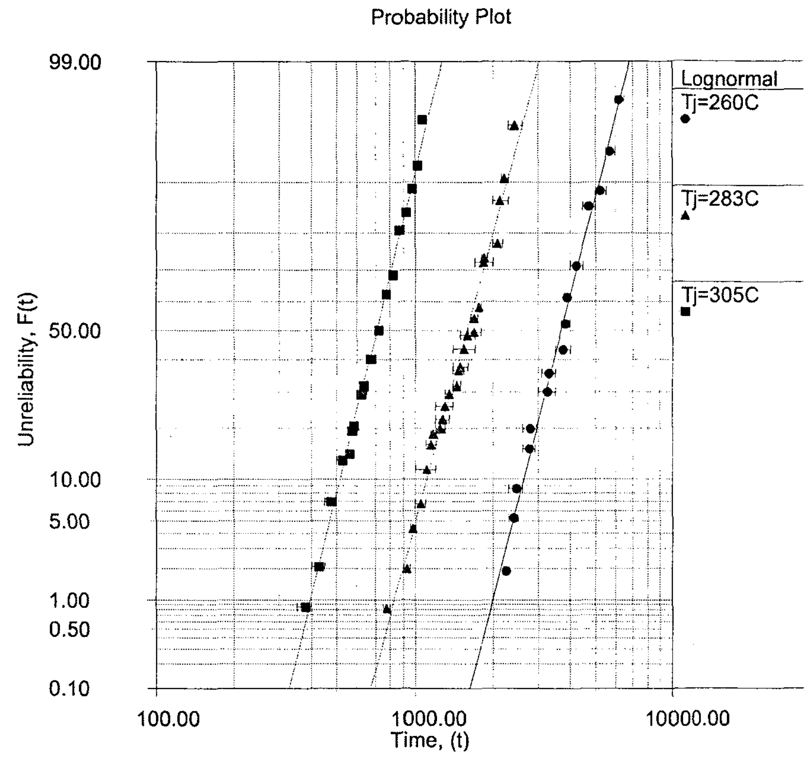

$\mu1=8.21$, $\sigma1=0.27$, $\rho=0.99$
$\mu2=7.37$, $\sigma2=0.28$, $\rho=0.99$
$\mu3=6.57$, $\sigma3=0.25$, $\rho=1.00$

- Three Temperatures
- Same slope (sigma) indicates same population at all temp.

Data Analysis for Mixed Failure Modes

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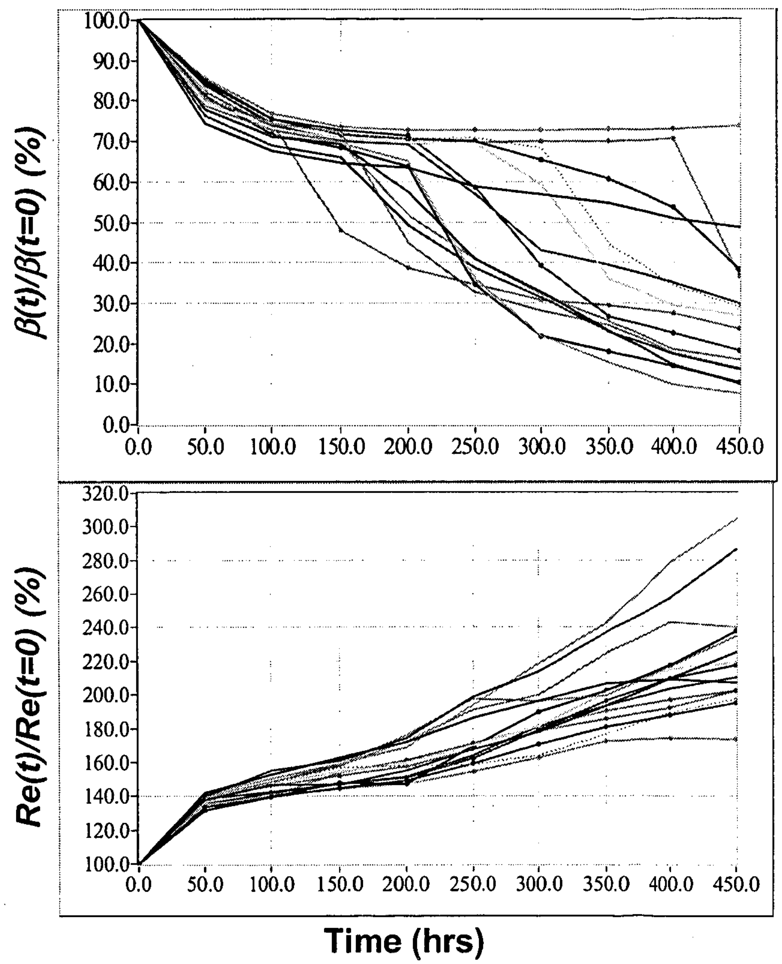
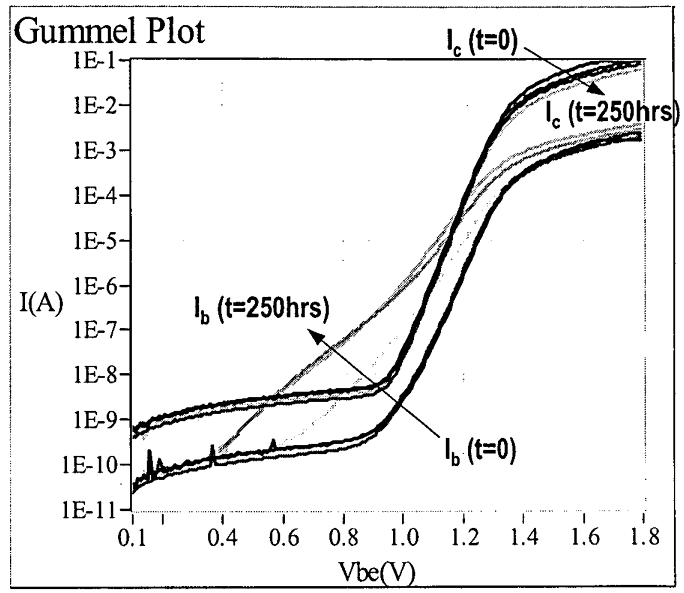
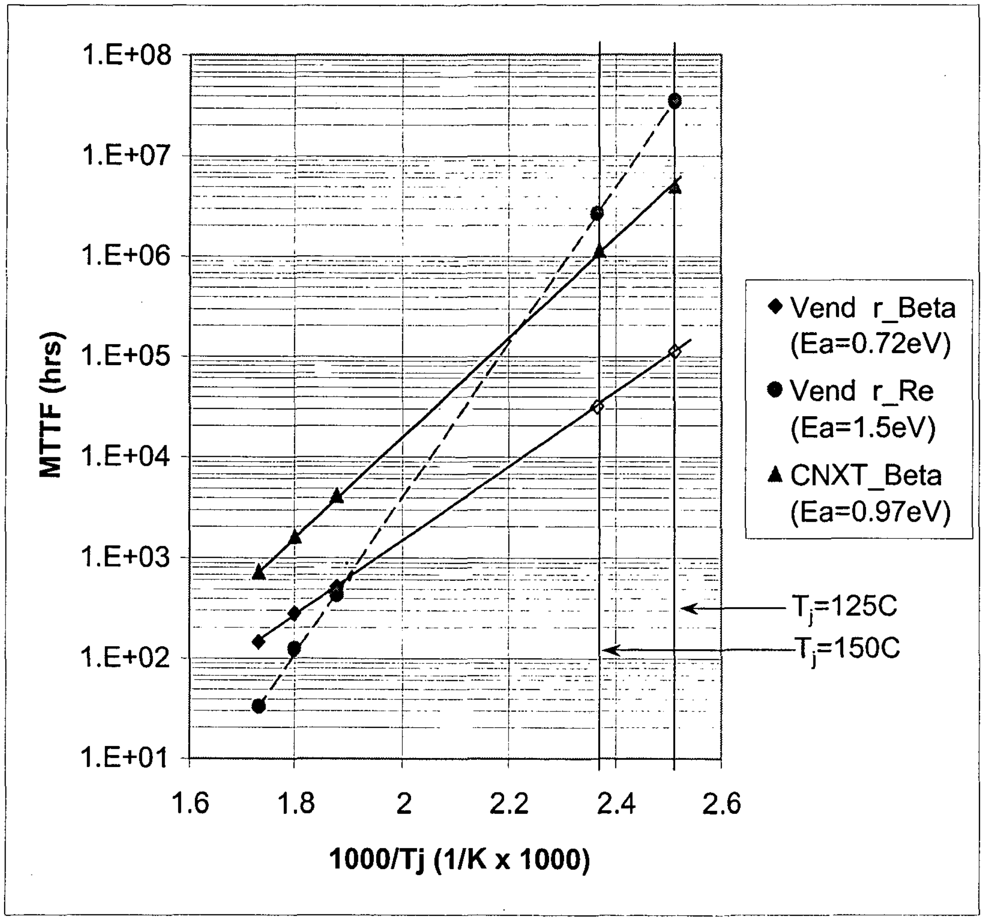




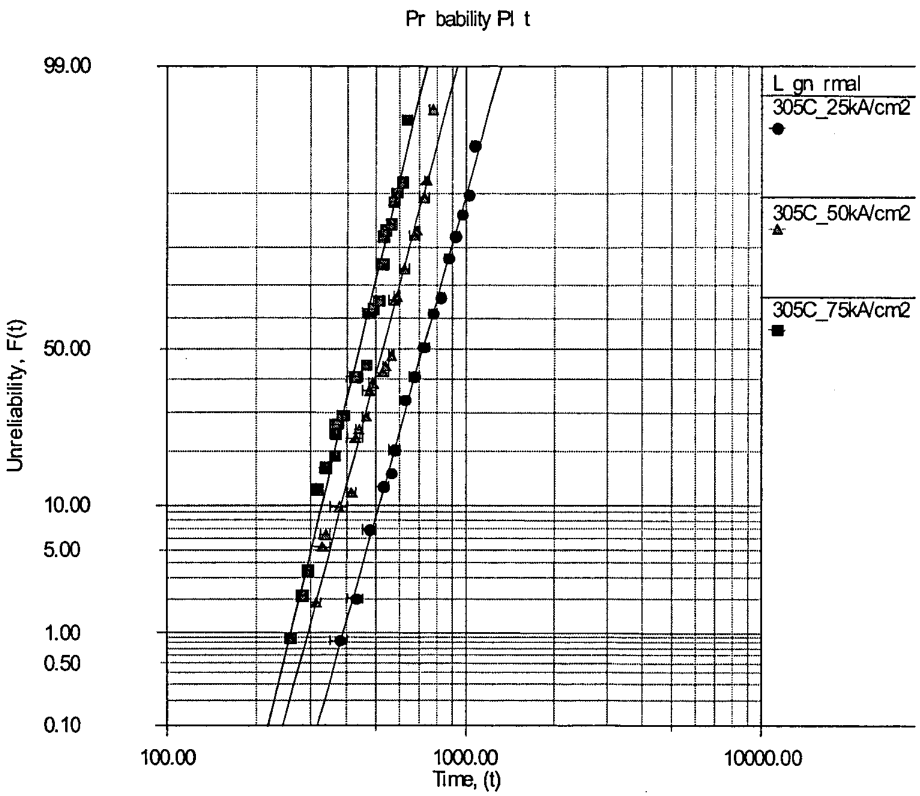
- Beta and Re degradation modes mixed for Vendor InGaP HBTs

Activation Energy Extraction



- Separate Beta and Re degradation modes
- Different activation energy Ea's extracted
- MTTF extrapolated by Beta degradation mode is more suitable at operating temperature

Cumulative Failures: Current Acceleration



$\mu 1=6.58, \sigma 1=0.26, \rho=1.00$
$\mu 2=6.26, \sigma 2=0.25, \rho=0.99$
$\mu 3=6.09, \sigma 3=0.23, \rho=0.99$

- **Three Current Densities**
  - Slope(Sigma) indicates same population at three densities
  - Slope also indicates same population as temperature

Current Acceleration

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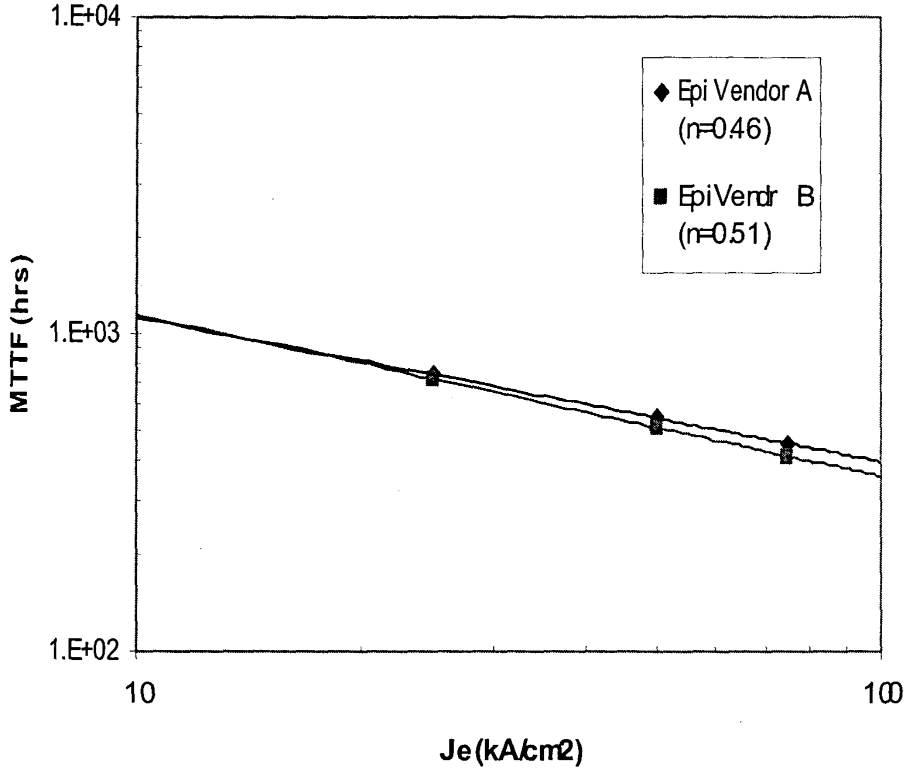

- InGaP current Acceleration approximately square root dependent

Lifetime

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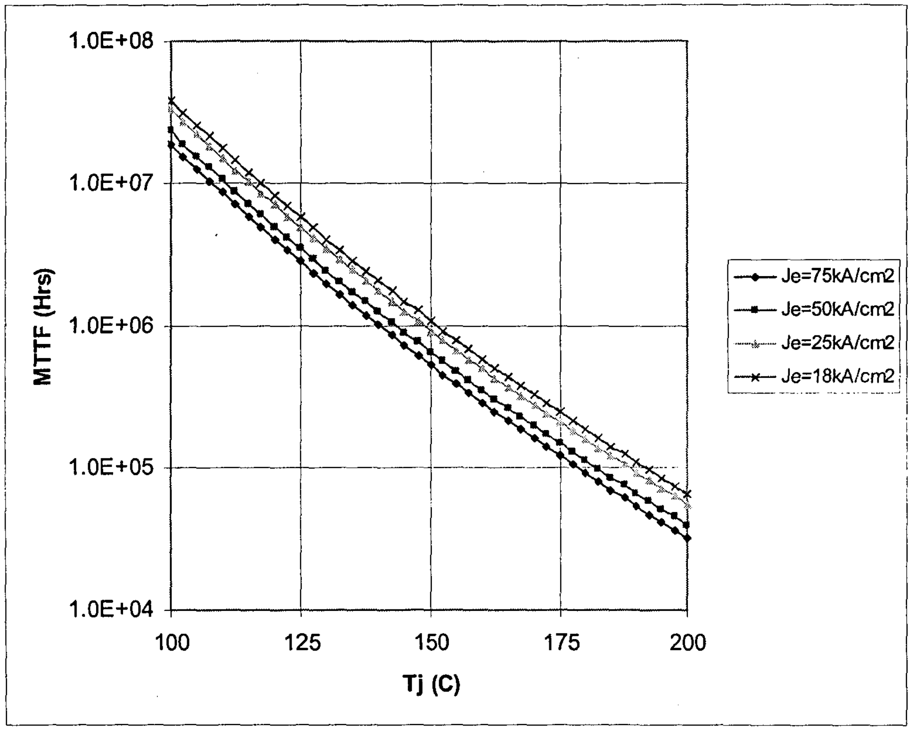

- Lifetime Estimate
  $E_a \sim 0.97$eV
  $n \sim 0.5$
- Lifetime~10^6hrs (>100yrs) at 125C

Comments

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- **Beware High Activation Energy**
  - Indicates failure mode may not be fundamental failure mode (ie. Emitter contact vs Beta degradation)
  - High activation energy failure modes are related to metal diffusion (a high activation energy process). Thus, failure modes with high activation energy can be identified by shifts in metal contact associated parameters (ie Ic and Re)
- **Understand Failure Mode**
  - Fundamental failure mode has been identified as sudden Beta degradation due to increase in Base current (NOT Emitter degradation or Base dopant out-diffusion)
  - Collector current and Re should be stable

InGaP HBT Reliability Summary

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- **Some surprises worth noting**
  - Activation energy, Ea ~ 0.97 eV
  - Current acceleration, n~0.5
- **Several key success factors worth emphasizing**
  - Having the right infrastructure is key
  - Starting reliability on first development lots helped establish base line and insure success in the qualification
  - Application of reliability fundamentals