A SURVEY OF HETEROJUNCTION BIPOLAR TRANSISTOR (HBT) DEVICE RELIABILITY

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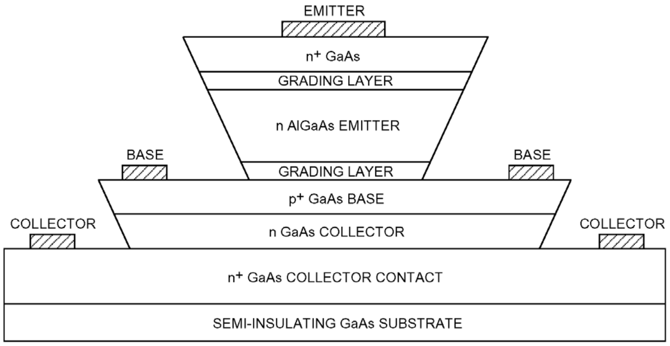
INTRODUCTION

Heterojunction Bipolar Transistor (HBT) technology has become a major player in wireless communication, power amplifier, mixer, and frequency synthesizer applications. HBTs extend the advantages of silicon bipolar transistors to significantly higher frequencies. Since the mid-1980s, HBT technology development has focussed on reducing cost and improving reliability which, in turn, led to numerous commercial products, such as prescalers, gate arrays, digital-to-analog converters, mux/demux chip sets, logarithmic amplifiers, RF chip sets for CDMA wireless communication systems, and power amplifiers for cellular communications. They have become a natural choice for very high frequency military applications requiring a high current drive, high transconductance, high voltage handling capability, low noise oscillator, and uniform threshold voltage. Emerging HBT technologies allow the integration of a large quantity of high performance RF circuits and high speed digital circuits on a single chip.

This paper provides an overview of HBT device reliability issues.

EARLY HBT DEVICES



CROSS SECTION OF AN EXAMPLE ALGAAS HBT[i]

Early HBTs used an AlGaAs emitter structure and a beryllium base dopant. While this technology achieved enhanced performance and cost goals, AlGaAs HBTs were plagued with reliability and processing problems. The two predominant problems with this technology are the following:

1. The beryllium dopant is unstable and diffuses into the emitter region. Elevated junction temperatures and higher operating current densities accelerate this diffusion resulting in DC current gain degradation. This problem was overcome by substituting the beryllium base dopant with the larger and more stable carbon atom. A problem remained, however, with gain degradation due to the surface effects associated with recombination-enhanced defect reactions (REDRs).[1]
2. The base access surface near the emitter-base junction of the AlGaAs HBT is relatively unstable. This requires a careful surface passivation technique (ledge passivation) to reduce surface recombination effects. This surface effect increases base current and further degrades current gain.

Studies show that turn-on voltage (Vbe) has a major effect on AlGaAs HBT reliability. Wafers with a lower Vbe yield devices with higher overall DC current gain at elevated junction temperatures and survive five times longer than those from wafers with a higher Vbe. Wafers where the base-emitter interface is better optimized exhibit this reduction in turn-on voltage.

Applications that generate higher current density across the emitter junction further aggravate current gain degradation in AlGaAs HBT devices. Applications in high-temperature environments and those requiring continuous current flow are particularly vulnerable to these problems.

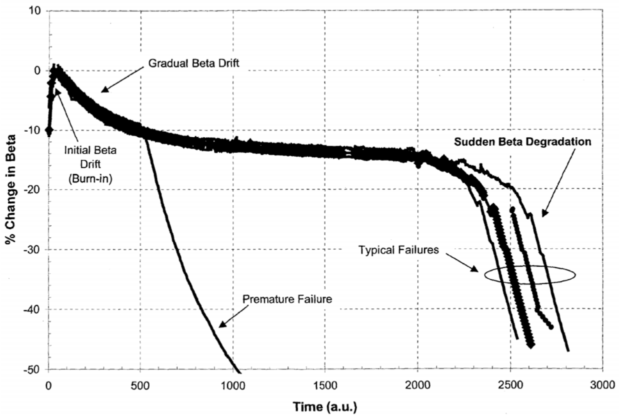


ILLUSTRATION OF ALGAAS HBT GAIN DEGREDATION[ii]

AlGaAs HBT technology matured over the last decade due to the significant and steady progress made in reliability improvements. Device fabrication, however, remains a major factor in achieving a reliable device. The emitter-base heterojunction of AlGaAs HBTs must be graded for proper device operation. Preparing this junction is an art practiced in a unique way by each material supplier. To make matters worse, each device manufacturer produces AlGaAs HBTs with significant fabrication variations. Factors introduced by details of the fabrication method and the materials growth often confuse the assessment of device reliability. As a result, the constituents of factors limiting the reliability of AlGaAs HBTs are not clearly assessed.

Researchers report recent improvements in AlGaAs HBT device level design and fabrication methods that substantially reduce device sensitivity to gain degradation resulting in improved mean-time-to-failure (MTTF) performance. Incorporating a passivating emitter ledge, for example, significantly enhances MTTF. New measurement

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[i] JPL Publication 96-25

[ii] Welser and Deluca, 2001 GaAs Reliability Workshop

techniques allow device manufacturers to assess passivation ledge characteristics, optimize ledge design and implement early screens for potential reliability or process related device degradation.

CURRENT AND EMERGING HBT TECHNOLOGIES

Newer compound semiconductor technologies used in HBT devices have overcome the major reliability and processing problems associated with AlGaAs. The InGaP emitter structure, for example, has been shown to offer a robust solution to the reliability issues of AlGaAs structures. Several researchers report that InGaP emitter structures have an order of magnitude higher MTTF than AlGaAs. The new generation of InGaP HBT emitter structures has several advantages, such as a highly reproducible manufacturing process, tighter DC and RF parameter distributions, and smaller die. Other researchers report success in producing InP-based HBT devices with yield and reliability comparable to newer GaAs-based HBT processes. Newer techniques for assessing the reliability of HBTs show great promise for assessing device lifetimes. These techniques, which use high bias currents to accelerate aging, are effective for routine device qualification and for assessing suitability of processing or material changes.

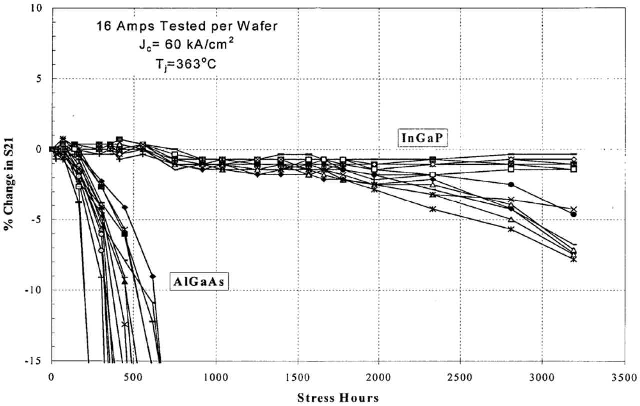

ILLUSTRATION OF ALGAAS VS INGAP HBT GAIN DEGRADATION [iii]

In the silicon world, Si/SiGe heterostructures allow the integration of a large quantity of high performance RF and high speed digital circuits. SiGe HBTs can operate at speeds previously attainable only with gallium-arsenide and enjoy the advantage of being manufactured in existing silicon fabs using standard tool sets. Combining the SiGe HBT with CMOS and a suite of passive elements and transmission lines enables a wide variety of applications on a single chip with a very high level of integration.

The main reliability concern for SiGe HBTs is the robustness of the base-emitter junction to hot carriers which introduce current gain degradation. Degradation of bipolar current gain under emitter-base junction reverse-bias has been investigated extensively in the past decade. This degradation is a sensitive function of voltage due to the exponential collector dependence of both avalanche carrier generation and of interface state creation. The negative effects of avalanche can be reduced by a small decrease in operating voltage. Thus, researchers conclude that this avalanche-induced hot carrier degradation is not likely to become a significant limit for future devices scaled for high speed performance.

Current research indicates that SiGe HBT BiCMOS technology developed for the analog and mixed signal communication circuit implementations provides reliable operation with ample safety margins for products operating at high temperatures. Researchers report that current gain shifts of SiGe BiCMOS HBTs fall within the spread of the pre-stress current gain distribution for conventional bipolar technologies, and that most of the bipolar circuits are insensitive to this level of current gain fluctuations. Researchers also report that SiGe BiCMOS HBT's exhibit excellent radiation hardness, thus offer promise as a high-speed, low-cost alternative for applications requiring some level of radiation tolerance.

Though limited reports exist in the literature, researchers previously reported gradual degradation of DC current gain and microwave performance in boron-doped SiGe HBTs and attributed this degradation to recombination-enhanced impurity diffusion (REID), a particular case of a REDR. Subsequent evaluations, however, do not support this conclusion.[2]

SUMMARY

AlGaAs HBTs present the greatest risk to military and aerospace applications due to reliability and processing problems causing long-term current gain degradation. Applications in high-temperature environments and those requiring continuous current flow are particularly vulnerable.

HBT products applying newer compound semiconductor technologies (e.g. InGaP, InP, SiGe) have overcome the major reliability and processing problems associated with AlGaAs. While the gain performance of these newer technologies satisfy the operating life requirements of the telecommunications industry, performance over long term operating life times associated with some DoD and aerospace applications has not yet been widely published in peer reviewed technical literature. While researchers report some progress, industry standard methods do not yet exist to estimate HBT device lifetimes with respect to current gain degradation. DoD and NASA studies to evaluate these newer technologies for long term operating life are underway, but reports from these studies are not yet available. For equipment applications with long operating life requirements, data generated from device manufacturer operating life testing may be required to perform an application risk assessment.

[iii] Low et al, 1998 GaAs IC Symposium

[1] ***Recombination-Enhanced Defect Reaction (REDR)***

Several authors associate the sudden and catastrophic DC current gain degradation of GaAs-based HBTs with a recombination-enhanced defect reaction (REDR) process. REDRs encompass a large number of diffusion, disassociation, and annihilation processes whose reaction rates increase as a result of the energy liberated during electronic transitions. While a complete understanding of the physical mechanisms controlling GaAs-based HBT reliability has yet to emerge, a REDR process leading to an exponential increase in trap density within the base-emitter depletion region can reasonably describe the sudden beta degradation typically seen as the failure mode in many GaAs-based HBTs. Though hydrogen may play a partial role in the initial and gradual beta drifts seen in some stress tests, it appears irrelevant to REDR driven sudden beta degradation.

Researchers report activation energies (Ea) for this failure mechanism as low as 0.35eV. It is possible that during conventional life tests (with junction temperatures from 200°C to 300°C), other high-Ea phenomena occur first, the tests are subsequently stopped, and the low-Ea phenomena are not observed. Conventional life tests, therefore, may fail to characterize the mechanism that will actually occur first at the low temperature of typical applications, and may result in greatly overestimating device reliability.

Key parameters governing the REDR process include the junction temperature and stress current applied during testing, and the reverse hole injection of the base current. Any non-uniformity in starting defect density, current density, or temperature (or, more generally, any disturbance to a uniform V_{bej}) can significantly accelerate degradation.

For a comprehensive discussion of the recombination-enhanced defect reaction mechanism and HBT reliability, refer to ...

> William Liu, "Handbook of III-V Heterojunction Bipolar Transistors," Wiley, 1998, (ISBN 0471249041)

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[2] ***Recombination-Enhanced Impurity Diffusion (REID)***

The recombination-enhanced impurity diffusion (REID) mechanism is a particular case of a recombination-enhanced defect reaction (REDR). In the REID mechanism, the recombination of injected minority carriers causes the annihilation of nonradiative recombination centers which is then followed by the emission of a defect. The REID process has been widely observed in Be-doped GaAs base regions of GaAs/AlGaAs HBTs.

The following paper reports that REID causes gradual degradation of DC current gain and microwave performance of boron-doped SiGe HBTs.

> Ma, Z.; Bhattacharya, P.; Rieh, J-S; Ponchak, G.E.; Alterovitz, S.A.; Croke, E.T.; "Reliability of Microwave SiGe/Si Heterojunction Bipolar Transistors", IEEE Microwave and Wireless Components Letters, Vol.11 Iss.10 , Oct 2001, pp.401-403

Although these experimental results were obtained from SiGe/Si HBTs with high Ge content, these researchers concluded they can be generalized to most boron-doped SiGe/Si HBTs.

Recent discussions with one of the researchers, however, revealed that results included in this paper were based on small data set from devices processed in an academic research facility. A large accumulated reliability data set subsequently processed by an established production foundry does not support the idea of REID. Parts of these results are published in the following paper.

> Rieh, J.-S.; Watson, K.; Guarin, F.; Yang, Z.; Wang, P.-C.; Joseph, A.; Freeman, G.; Subbanna, S. "Wafer Level Forward Current Reliability Analysis of 120GHz Production SiGe HBTs Under Accelerated Current Stress," 40th Annual Reliability Physics Symposium Proceedings, 2002, pp.184-188

This researcher attributes the lack of a signature of REID in SiGe HBTs to the bonding between the host atoms (Si) and dopants (B) in SiGe HBT's, which is far stronger than those in III-V HBT's. Moving dopant atoms requires more energy than generated from carrier recombination for Si-based bipolar devices.

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