HIGH-RELIABILITY GaAs HBT MONOLITHIC MICROWAVE AMPLIFIER

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ABSTRACT

High-reliability performance of an X-band high-intercept MMIC amplifier fabricated using a production GaAs/AlGaAs HBT process technology is reported. Operating at 20kA/cm^2 quiescent collector current density, the single-stage balanced amplifier with on-chip regulation has a projected median-time-to-failure (MTF) of 4x10^7 hours at a 125°C junction temperature. MTF was determined by three-temperature constant-stress accelerated lifetest using $|\Delta S21|>1.0$dB as the failure criterion. Additionally, an activation energy (Ea) of 1.2 eV and log-standard deviation (σ) of 0.7 was measured. This is the first report of HBT reliability based on small-signal microwave characteristics of HBT MMIC amplifiers under lifetest.

INTRODUCTION

State-of-the-art performance in electronic and communication systems has been achieved largely through advances in III-V semiconductor technology including GaAs/AlGaAs Heterojunction Bipolar Transistor (HBT) process technology. GaAs HBT has been demonstrated to have inherent advantages in performance over its silicon counterparts, GaAs MESFET and HEMT technologies [1-2]. GaAs HBTs have found insertion into cutting-edge space/defense applications and more recently into high-volume, low-cost commercial applications such as wireless communication. With GaAs HBT becoming a preferred technology for system enhancement or next generation system design, demonstration of a reliable technology establishes TRW's production GaAs HBT process as a mature technology for providing reliable, high-performance integrated circuits (ICs) at low cost and high yield to both the space/defense and commercial markets.

In this paper, we present an advancement in the state of GaAs/AlGaAs HBT technology by demonstrating high-reliability HBT microwave amplifiers and investigating the stability of small-signal microwave characteristics of HBTs, an aspect different from previously published HBT reliability data [3-7]. In addition, this study is a higher complexity MMIC-level reliability test that allows assessment of HBT, passive component, metal and interconnect reliability. In contrast, published reliability data of GaAs and InP based HBTs have been mostly based on discrete device tests only. The presented data benefits the microwave community by demonstrating a reliable and robust HBT technology, a critical factor in wide-spread acceptance of HBTs for microwave applications.

PROCESS TECHNOLOGY

TRW's standard GaAs/AlGaAs HBT production process features Npn HBT devices grown on semi-insulating GaAs substrates by solid source molecular beam epitaxy (MBE). The HBT device features include: 1400Å 1x10^{19} cm^{-3} Be doped base layer; 1200Å wide gap emitter layer of $Al_{0.3}Ga_{0.7}As$ with a 300Å $Al_xGa_{1-x}As$ grading on both sides; and 850Å graded InGaAs emitter cap. Silicon is used as the n-type dopant. Figure 1 shows the MBE profile of the Npn device.

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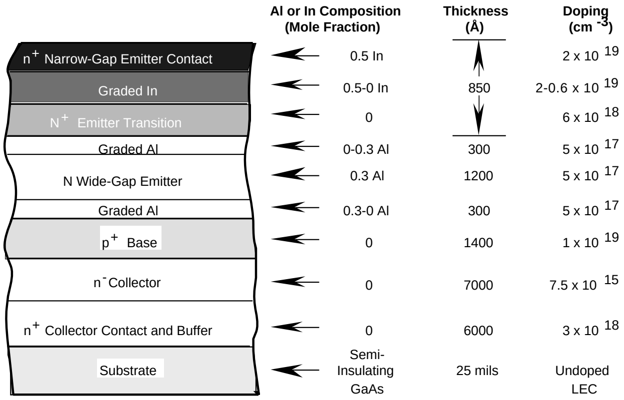

Figure 1. MBE profile for standard GaAs/AlGaAs Npn HBT structure. Be and Si are the p-type and n-type dopant, respectively. Graded InGaAs emitter cap provides stable low resistance contact. Figure is not to scale.

The production process uses a self-aligned base ohmic metal (SABM) fabrication process that aligns the base ohmic contact to the emitter mesa edge. The emitter and base mesa are formed by wet etch, and boron implantation provides device isolation. AuBe/Pd/Au, AuGe/Ni/Ti/Au and refractory Ti/Pt/Au metalization are used for the base, collector and emitter ohmic contact, respectively.

Other key process features include Schottky diodes, PIN diodes, 100Ω/sq NiCr thin film resistors (TFR), metal-insulator-metal (MIM) capacitors, multiple interconnect levels, backside ground vias and SiN glassivation. In this process, Schottky and PIN diodes can be integrated with HBTs without added process complexity due to the common MBE material profile shared between these device structures. All processed wafers are subjected to in-process screening that includes process control monitor testing for process conformance, 48-hour unbiased stabilization bake at 240°C, RF and DC electrical test, and visual inspection.

STANDARD EVALUATION CIRCUIT

The MMIC design selected for this lifetest is the 59HIA, a single-stage, balanced amplifier with on-chip regulation operating over 5-9 GHz with a typical gain of 11dB. Under normal operating conditions, the RF transistors operate at 20kA/cm^2 collector current density (Jc) with NiCr TFRs operating at 3000kA/cm^2. The 59HIA incorporates two regulators with each regulator biasing a single RF HBT at 24mA while operating on a low 2mA, 0.5V bias overhead. A microphotograph of the 59HIA is shown in Figure 2.

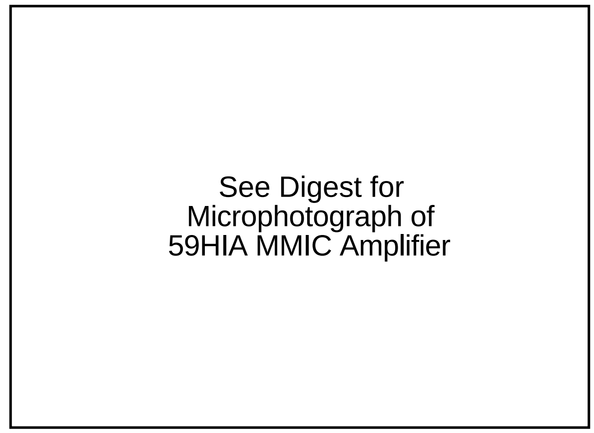

Figure 2. Microphotograph of a 59HIA MMIC, a single-stage balanced amplifier with on-chip regulation. Operates over 5-9 GHz with typical gain of 11dB. Chip size is 3.0mm x 4.0mm.

RELIABILITY TESTING

At TRW, HBT reliability assessment is determined by three temperature constant stress lifetesting where aging of discrete components and ICs is accelerated at elevated temperatures under full DC bias. Three temperature constant stress lifetest is an effective methodology for semiconductor reliability testing and is used to determine factors such as failure distribution, median-time-to-failure (MTF) and activation energy (Ea) based on the Arrhenius life-temperature relationship. These factors allow the user to estimate device or IC lifetime and failure rate at the user-specified operating temperatures.

For IC or MMIC reliability testing, proper selection of a Standard Evaluation Circuit (SEC) and its failure criteria are essential to demonstrate and fully evaluate the reliability of a technology. The 59HIA was selected as a SEC for its higher than normal MMIC complexity and for it's design function of X-band amplification, a common function implemented with GaAs HBTs.

For this lifetest, a total of 59 MMICs were randomly selected across 16 wafers from 3 standard process lots. The wafers originated from 3 different LEC GaAs boules. All 16 wafers passed in-process electrical, stabilization bake and visual screening requirements. The MMICs were assembled by standard methodology using silver epoxy and 0.0007” Au wirebond on 16-pin DIP carriers. Following assembly and prior to lifetest, all parts were screened with a 125°C biased burn-in for 320 hours. Lifetest was conducted at ambient temperatures of 240, 255 and 270°C. At elevated temperature, the MMICs were DC biased with the critical RF HBTs operating at Jc=20kA/cm^2 and Vce=3.5V. Automated RF and DC measurements were performed at room temperature at set intervals throughout the lifetest. For this lifetest, the failure criterion was set as a 1.0dB degradation in S21 gain at 7GHz from pre-lifetest level.

RESULTS

Over 22000 hours at elevated temperatures have been accumulated during this test. During lifetest, S21 characteristics decrease gradually and evenly across the bandwidth, indicating the well-behaved manner in which the HBTs age over time and temperature. The S21 characteristic of a representative 59HIA stressed at 240°C is shown in Figure 3. Interpolated failure time for this representative MMIC was 647 hours.

Lifetest failures exhibit a log-normal behavior with temperature-independent log-standard deviation (σ). The lifetest failure distribution is plotted on a log-normal scale in Figure 4. Measured σ was 0.7. Figure 5 is an Arrhenius life-temperature model based on the median failure time measured at each lifetest temperature. Junction temperature rise has been factored into Figure 5. The Arrhenius model projects a MTF of 4x10^7 hours at a 125°C junction temperature with an Ea=1.2eV. At a 125°C junction temperature, a maximum instantaneous failure rate of <10^{-6} FITs (failures per billion device hours) has been calculated for a 10-year mission life.

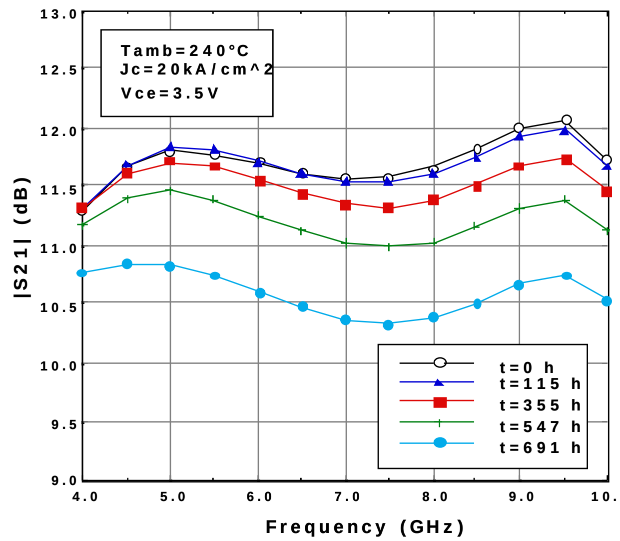

Figure 3. Room temperature S21 characteristic of a typical 59HIA subjected to a 240°C biased lifetest. While under lifetest, the 59HIA was biased at Jc= 20kA/cm^2 and Vce=3.5V. Over time, S21 decreases gradually and evenly across the 5-9 GHz design bandwidth

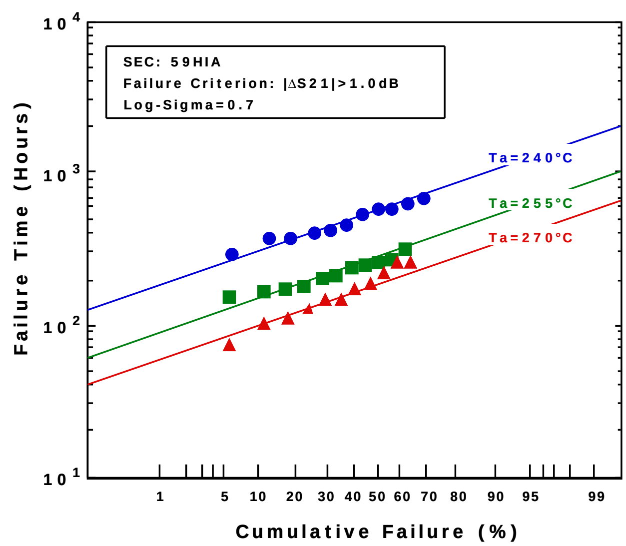

Figure 4. Lifetest failure distribution plotted on a log-normal scale. The 59HIA exhibits a well-behaved log-normal distribution with σ=0.7. The low σ measured over 16 wafers from a 3 lot, 3 boule matrix demonstrate the excellent material and process uniformity achieved by this technology. Ta is the ambient temperature.

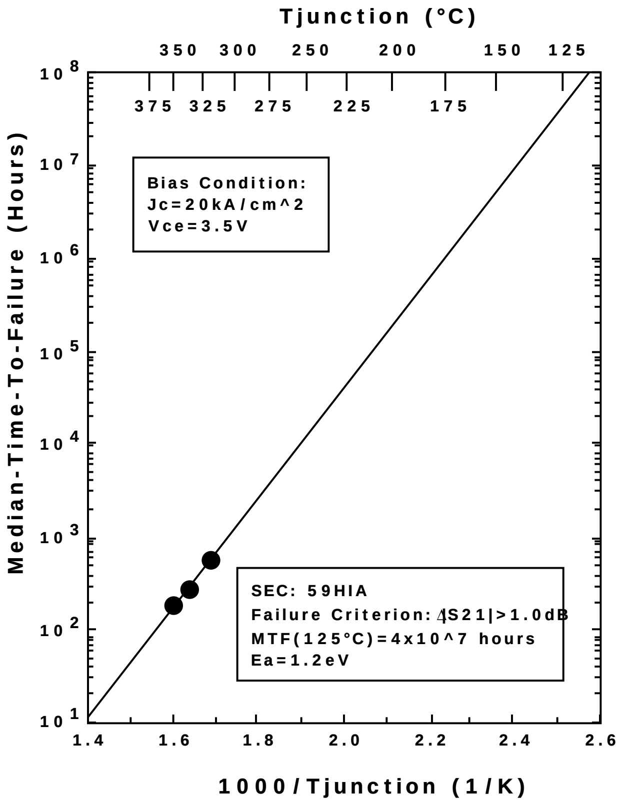

Figure 5. Arrhenius life-temperature model for 59HIA amplifier operating at Jc=20 kA/cm^2 and Vce=3.5V. Projected median-time-to-failure (MTF) is $4x10^7$ hours at a 125°C junction temperature.

SUMMARY

Fundamental reliability of the MBE-based production GaAs HBT process technology is demonstrated by lifetesting a 59HIA MMIC amplifier with a resulting median-time-to-failure of $4x10^7$ hours at a 125°C junction temperature and a measured activation energy of 1.2eV. The low σ measured over a 16 wafer, 3 process lot, 3 substrate boule population demonstrates the excellent material and process uniformity achieved by this technology.

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