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Invited

High Volume Production of Heterojunction Bipolar Transistors

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We have developed the first commercial heterojunction bipolar transistor production line based on GaAs-AlGaAs-InGaAs HBT material grown by molecular beam epitaxy. We have demonstrated sustained high-yield production of HBT integrated circuits for commercial applications using MBE growth and processing techniques originally developed for high-reliability applications. As a result, we are currently shipping over 500,000 commercial HBT chips per month built using MBE material that combines both low cost and high reliability. TRW HBT parts such as cellular power amplifiers, CDMA chip sets, Darlington gain blocks, and A/D convertors are now inserted in high volume commercial products such as cellular phones, digital radio systems, local area networks, and digital oscilloscopes. HBT MMICs allow these products to achieve functions and performance never before available for consumer applications.

1. INTRODUCTION

Heterojunction bipolar transistors have held the promise of improved microwave performance compared to MESFET or HEMT devices for over a decade. HBTs have been demonstrated that clearly show the inherent bipolar advantages of low 1/f noise, high Early voltage, and highly linear output characteristics. HBTs can be made using extremely small die sizes using standard optical lithography, making them ideally suited for high volume microwave and digital applications. However, in spite of their potential performance, yield, and cost advantages, HBTs have not been commercially available. Unexpected producability and reliability problems have so far stood in the way of a commercially available HBT product. We report here our development of a high-yield, high-volume commercial HBT production line based on MBE grown material originally developed for high reliability applications. These HBT parts are now being inserted into commercial products such as digital radio and telephone systems, and cellular power amplifiers.

2. DEVICE DESIGN

The epitaxial profile used for TRW's commercial HBT products is shown in Fig. 1. The profile is optimized for real world performance, and has been shown to have good performance from dc to 20 GHz for both analog and digital applications. A thick 700 nm collector provides high breakdown voltage BVceo >10V, Early voltage Va >800V, and extremely linear output characteristics with a very high third intercept point IP3 = 38 dBm at 12 GHz. The wide 140 nm base is easily contacted using a modest Be doping $p=1x10^{19}$ cm^{-3}. The emitter uses an InGaAs contact silicon doped at $n=2x10^{19}$ cm^{-3}. The InGaAs contact provides low emitter resistance using TiPtAu contacts, and is important for both good Vbe matching and emitter contact reliability. The 30% AlGaAs emitter is graded on both sides, for both minimum Vbe and good Vbe matching, which is typically < 1 mV at Ic = 1mA. Devices with 2x10 μm^2 emitter area have cutoff frequency ft = 22 GHz, fmax = 55 GHz, and current gain ß >100 at Ic = 4 mA = 20 kA/cm^2, ideal for commercial parts.

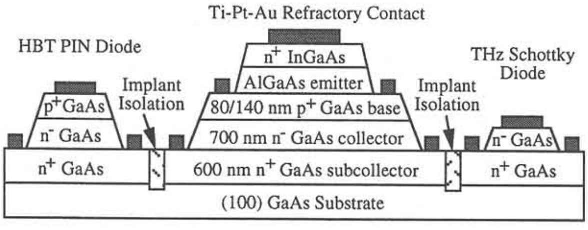

Fig. 1. Schematic diagram of commercial HBT epitaxial profile.

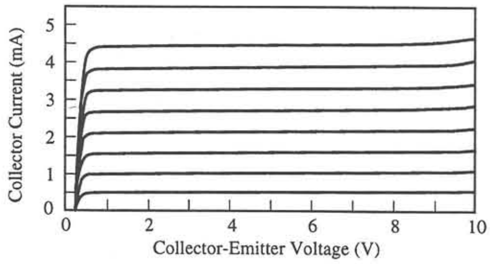

Fig. 2. Current-voltage characteristics of typical 2x10 μm^2 HBT.

Fig. 3. Resistivity map of typical HBT wafer. Resistivity range min to max is 1.5%, standard deviation is 0.4%.

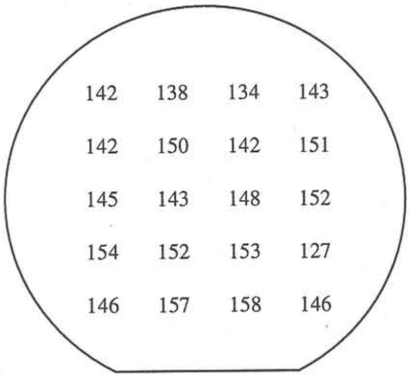

Fig. 4. Current gain ß map of typical HBT wafer. <ß> = 146 ± 8 (± 5%)

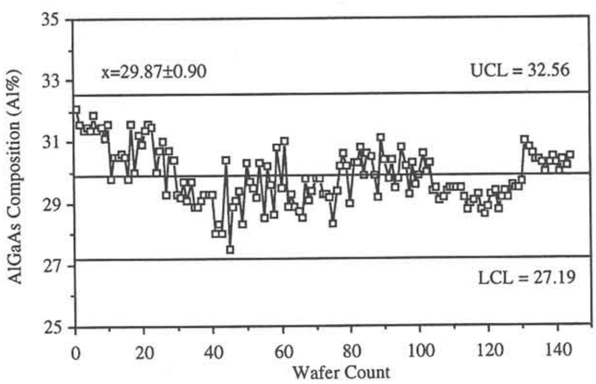

Fig. 5. SPC chart of AlGaAs composition as determined by photoreflectance.

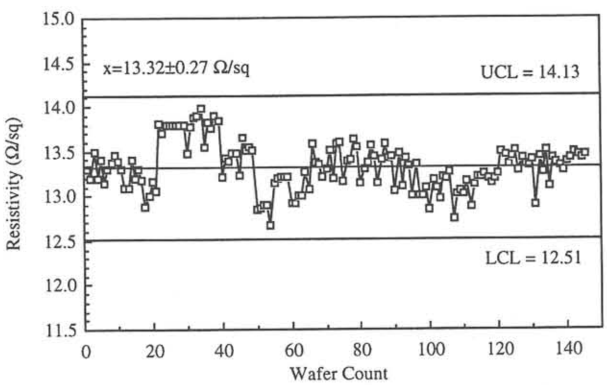

Fig. 6. SPC chart of resistivity as determined by noncontact eddy current mapping.

3. MBE GROWTH

We have observed that HBT yield, performance, and reliability are driven by the epitaxial material used for device production. We use an MBE-based HBT production line due to the demonstrated ability of MBE to provide uniform, reproducible, and reliable HBT epitaxial material. This in turn enables the HBT process to be optimized without the uncertainties associated with epitaxial material variability. The control and reproducibility of HBT material properties such as minority carrier lifetime, layer thickness, AlGaAs and InGaAs alloy composition, alloy grading profiles, dopant incorporation characteristics, dopant concentration, and surface morphology are essential to obtaining reproducibility of the HBT process. The resistivity distribution of a typical HBT wafer is shown in Fig. 3, as measured using noncontact eddy current mapping. The total max-min variation is 0.22 Ω/sq, or 1.5%. The standard deviation of the resistivity variation is 0.4%. Alloy and thickness uniformities are simiar in their distribution patterns, allowing for uniform etching characteristics. Uniform etch depths are essential for uniform ß distribution. A typical ß map shown in Fig. 4 has max-min ß variation across the 76.2 mm wafer of 8, for a total range of ß = 146±8.

4. STATISTICAL PROCESS CONTROL

Reproducible HBT MBE material is fundamental to obtaining a reproducible HBT process. We use SPC as a tool to track the essential HBT material parameters such as alloy composition, resistivity, thickness, and doping levels. The AlGaAs alloy composition is determined on every device wafer using photoreflectance, a noncontact measurement technique. A typical AlGaAs alloy SPC chart for a 145 wafer production run is shown in Fig. 5. The AlGaAs emitter thickness is determined based on a target composition of 30%. Variations from target composition can result in emitter thickness variations that can affect the etch targets, thus affecting breakdown, ß, and base resistance. This crucial parameter is tightly controlled to an alloy standard deviation of 0.9%.

A typical HBT resistivity SPC chart is shown in Fig. 5. The resistivity measured here is dominated by the subcollector, but yields information on every HBT wafer regarding overall doping levels. We are typically able to control this parameter with a standard deviation of 2%. Feedback using daily measurements on every device wafer provides an effective method for this level of control.

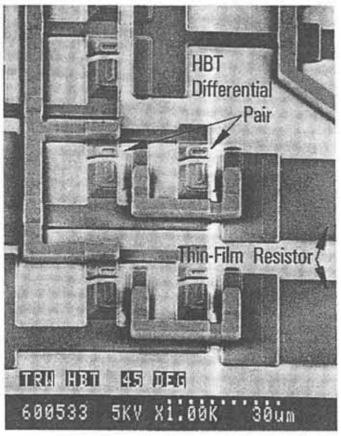

Fig. 7. Scanning electron micrograph of portion of SDLA.

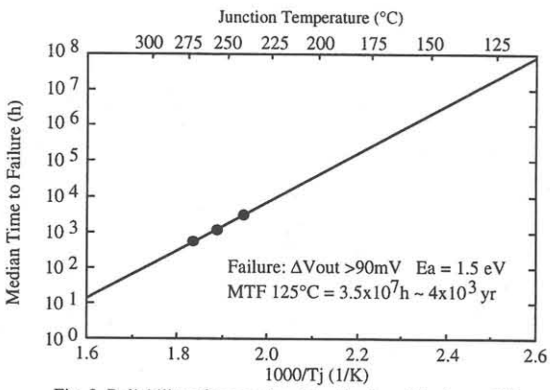

Fig. 8. Reliability of successive detection logarithmic amplifier.

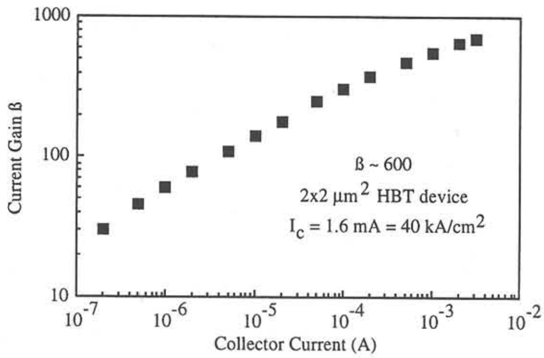

Fig. 9. Current gain ß versus Ic for digital HBT process.

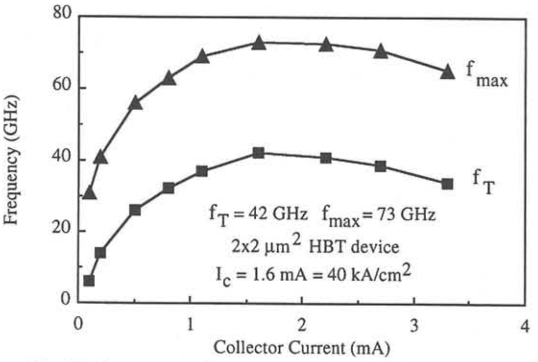

Fig. 10. Frequency performance versus Ic for digital HBT process.

5. HBT RELIABILITY

We have made extensive measurements of the reliability of our Be-doped MBE grown HBTs. Be doping can yield extremely reliable HBT material, provided that the MBE material is grown such that the Be is incorporated as a substitutional dopant rather than as an interstitial impurity. Over the past 5 years TRW has performed over 10^6 hours of elevated-temperature reliability testing of our HBT devices and circuits. We have found the reliability of these parts to be reproducible, with consistent active energies and lifetimes obtained on every lot tested to date since 1990. We have consistently measured HBT discrete device lifetimes of $>10^8$ h at junction temperatures of 125°C. We have also obtained reliability results on HBT integrated circuits. The successive detection logarithmic amp is used as the standard evaluation circuit for these tests. A micrograph of a portion of this circuit is shown in Fig. 7. This high performance MMIC has 216 HBTs, plus capacitors, thin film resistors, and backside vias, and provides 80 dB of dynamic range from 0.4 to 1.5 GHz. The failure criterea is a 90 mV change in the video output at -30 dBm input power, a stringent requirement that is affected by changes in ß, Re, Vbe, and passive component values. The MTF measured at a maximum HBT current density of 20 kA/cm2 and 125°C junction temperature was $>10^7$ h, with an activation energy of 1.5 eV and a sigma of 0.8, as shown in Fig. 8. The junction rise is < 20°C. Despite the negative reports concerning Be doping in non-optimized MBE material, no other growth or doping technique has yet been reported that provides this level of device and circuit reliability.

6. NEXT GENERATION DEVICES

We have developed a new HBT process that provides considerably more device performance than our current commercial process. This process has been optimized for digital applications, but applies equally well to microwave analog circuits. The HBT profile is nearly identical to our baseline profile, except the base thickness has been reduced to 80 nm. Typical for this process is B > 500 for Ic = 40 kA/cm2, as shown in Fig. 9. fT = 42 GHz and fmax = 73 GHz at the same current density, as shown in Fig. 10. This high ß process is ideally suited for high speed digital requirements.

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