Extended Abstracts of the 22nd (1990 International) Conference on Solid State Devices and Materials, Sendai, 1990, pp. 43-46 **B-2-1**

Invited

GaAs Heterojunction Bipolar Transistor (HBT) Device and IC Technology for High-Performance Analog/Microwave, Digital, and A/D Conversion Applications

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This paper discusses the GaAs/AlGaAs N-p-n heterojunction bipolar transistor (GaAs HBT) technology and circuit applications where the GaAs HBT offers unique advantages over advanced Si bipolar and GaAs-related field-effect transistor approaches. Key issues in device/IC fabrication, device performance, and circuit applications are addressed. A 2-3 μm emitter self-aligned HBT IC fabrication process based on molecular-beam epitaxy (TRW) is used as a vehicle to demonstrate basic technology capabilities. These include dc to 20 GHz analog/microwave, 6-17 GHz digital, 0.3-3 GHz analog/digital conversion, and monolithically-combined functions for insertion into future military and commercial signal processing systems.

1. INTRODUCTION

The GaAs/AlGaAs heterojunction bipolar transistor (GaAs HBT) designed for high frequency non-saturating operation offers intrinsic advantages over advanced Si bipolar and GaAs-related MESFETs and HEMTs for many wideband analog, microwave, digital, analog/digital (A/D) conversion, and monolithically-combined functions. The GaAs HBT is extending the bipolar's performance into the microwave/millimeter-wave regime with $f_T \approx 100$ GHz and $f_{max} > 200$ GHz[1]) using relaxed 1-2 μm emitters, higher linearity[2]), and the benefits of a semi-insulating substrate for integrated circuits. It also has the inherent bipolar advantages over GaAs FETs including better device threshold matching, higher transconductance, lower trapping effects, and higher-efficiency output power.

The objective of this paper is to address the key GaAs HBT technology issues in epitaxy, device/IC processing, device performance, and circuit functions that are important for insertion into future electronic systems.

2. GaAs HBT/IC FABRICATION TECHNOLOGY

The most mature GaAs/AlGaAs HBT approach is the N-p-n, emitter-up single heterojunction using molecular-beam epitaxial (MBE) growth with n-type Si and p-type Be doping, and mesa etching to access the active layers. Fabrication processes are optimized for various circuit functions (Fig. 1). The tradeoffs are in the operational frequency, dc current gain ß, breakdown voltage, device/IC fabrication complexity, and power consumption determined by epitaxial profile and processing designs.

The key to the HBT technology is the epitaxial growth and doping control. High f_T, f_{max}, and dc ß are achieved through reduction of transit times, parasitic resistances and capacitances, and recombination effects by

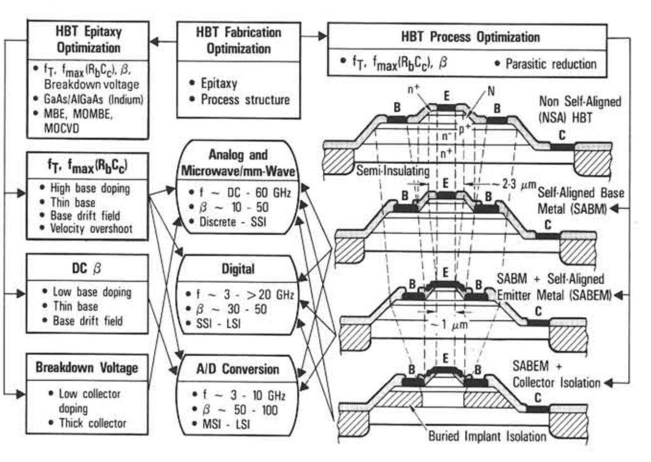

Fig. 1 GaAs HBT epitaxial growth and device process structures for optimized IC functions.

implementing combinations of very high base doping, thin base layer, base grading (Al or doping), and thin collector, including velocity overshoot designs (Fig. 2). With these structures, proper p-base dopant incorporation (substitutional Be rather than interstitial Be^+) and N-p junction placement (which determines the base-emitter turn-on voltage V_{BE}) are critical in minimizing Be redistribution during growth and in high-temperature biased-device operation, as well as maximizing dc ß (Fig. 3). GaAs HBT epitaxy based on metal-organic MBE (MOMBE) and chemical vapor deposition (MOCVD) are attractive since relatively immobile p-type carbon doping can be used. MOCVD also offers high throughput batch growth and surface morphology comparable to Si. However, further development is needed with the GaAs MOMBE and MOCVD epitaxial technologies.

Device and IC processing trade off high frequency performance, dc ß, power consumption, output power, and integration complexity. High frequencies are achieved by reducing parasitic base resistance and collector capacitance (Fig. 1) but usually at the expense of dc ß and yield. The etched-mesa HBT approach is preferred because epitaxial-planar techniques require p-dopant diffusion/implantation which tends to degrade the N-p junction. With proper p-dopant profile control, the dc ß of mesa-type GaAs HBTs is determined mainly by surface and bulk recombination. The use of a passivating depleted emitter AlGaAs layer on the exposed GaAs base-emitter region and lower p-dopant levels appear to be important in achieving high dc ß≈100-200. In IC applications, microwave functions require minimal HBTs and dc ß (≈10-30) but demand more complex device and circuit processing for low parasitics and input/output matching. At the other extreme A/D ICs require the highest dc ß (≈50-100) and LSI integration with laser-trimmable thin-film resistors and Schottky diodes for fast sampling switches.

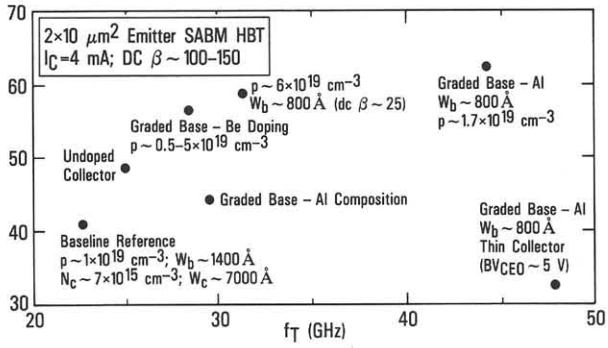

Fig. 2 f_T and f_{max} of 2x10 μm² emitter SABM HBTs for enhanced MBE structures.

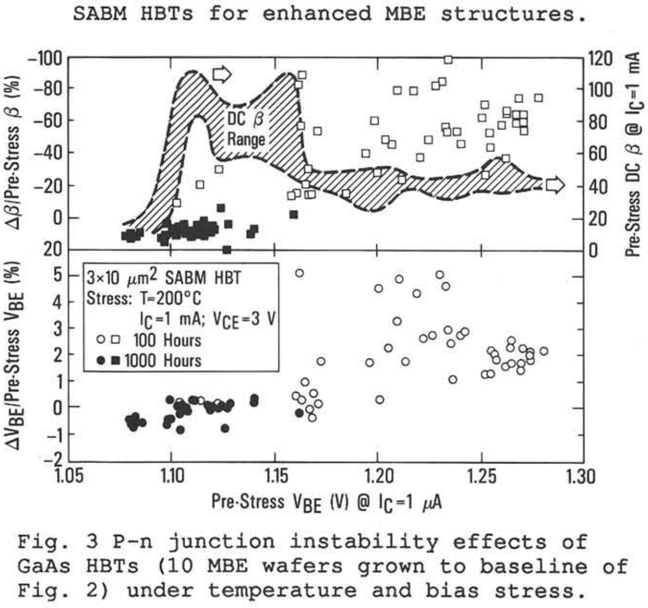

Fig. 3 P-n junction instability effects of GaAs HBTs (10 MBE wafers grown to baseline of Fig. 2) under temperature and bias stress.

3. GaAs HBT DEVICE PERFORMANCE

While enhanced GaAs HBT epitaxial and device design structures permit technology benchmarks, a simplified baseline MBE growth structure (Fig. 2) and a 2-3 μm emitter, partially self-aligned base ohmic metal (SABM) HBT (Fig. 1) are used to establish basic technology capabilities. These include high dc/RF performance, versatility in IC functions, and demonstrated device/IC reliability and producibility; the baseline MBE SABM HBT/IC process has been transferred to a pilot production line. It will be the basis for the device and IC discussions to follow.

Key HBT features include simultaneous dc ß≈50-100, Early voltage >800 V (Fig. 4), V_{BE} matching <2 mV, and f_T, f_{max}≈20-40 GHz. The small dc ß rolloff combined with high f_T, f_{max} at low collector currents (Fig. 5) satisfy the low power requirements of high-speed A/D and digital ICs. The Early voltage is naturally high for HBTs (≈10-20 times higher than Si bipolars) due to the high base doping which

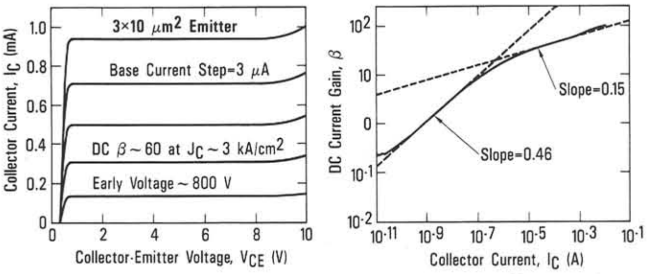

Fig. 4 Dc characteristics of 3x10 μm² emitter SABM HBT (baseline MBE profile of Fig. 2).

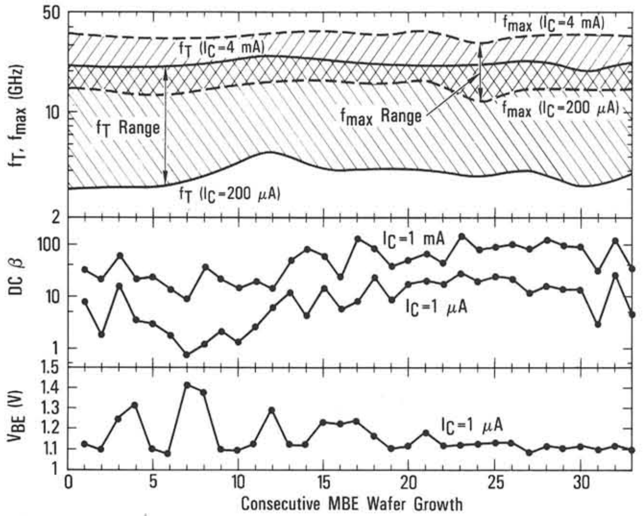

Fig. 5 V_{BE}, dc ß, f_T, f_{max} of 3x10 μm² emitter SABM HBTs (baseline MBE profile of Fig. 2).

minimizes basewidth modulation and the output conductance slope. This leads to high device linearity, a measure being the 3rd-order intermodulation intercept point (IP3) per input dc power which is significantly higher than GaAs MESFETs and HEMTs (Table 1).

Other GaAs HBT features lead to many circuit advantages. As a vertical device, its reduced trapping effects compared to GaAs FETs lead to lower phase (1/f and g-r) noise in high frequency oscillators[2),3)] and dividers. Alternatively, the GaAs HBT's relatively high surface-state density (Fermi-level pinning), combined with SiN passivation (which traps both negative and positive charges), the high-doped

12 GHz Performance							
TRW Device Structure	DC Power (mW)	Minimum Noise Figure (dB)	Gain (dB)	P_{out} 1 dB Comp. (dBm)	Power-Added Efficiency 1 dB Comp. (%)	IP3 (dBm)	Linearity Figure of Merit Ratio IP3 (mW) / DC Power (mW)
MESFET 0.5 × 300 μm² Gate	141 (3 V, 47 mA)	3.5	7.0	14.6	20	23.2	1.5
HEMT 0.25 × 200 μm² T-Gate	45 (3 V, 15 mA)	0.6	13.5	10.2	23	19.9	2.2
HBT 3 × 60 μm² Emitter	72 (3 V, 24 mA)	4.9	7.0	13.9	34	35.0	43.9

Table 1 Device technology comparison of 3rd-order intermodulation intercept point (IP3) (GaAs SABM HBT with baseline MBE of Fig. 2).

n^+ collector ohmic buffer layer, and inter-device implant isolation make it extremely radiation hard with respect to total dose, neutron, and dose rate effects[2)].

4. CIRCUIT APPLICATIONS

The GaAs HBT IC technology has established unique advantages in certain analog/microwave, digital, A/D conversion, and monolithically-combined functions. The results in this section are based mainly on TRW's baseline MBE 2-3 μm SABM HBT IC process discussed earlier.

Analog/Microwave. The GaAs HBTs are attractive for linear, nonlinear, wide dynamic range, and low phase noise functions from dc to >20 GHz. For less demanding broadband microwave performance, compact Si bipolar analog circuit design techniques can be applied. Examples are direct-coupled feedback amplifiers (Fig. 6), logarithmic and limiting amplifiers, and four-quadrant multipliers and mixers[2)] with significant improvement in gain-bandwidth over advanced Si bipolar and in fabrication simplicity over GaAs MESFETs. More stringent broadband performance requires passive component matching techniques. One example is a 5-11 GHz high-linearity/low-dc-power amplifier (Fig. 7) with an IP3(mW)/dc power (mW) figure-of-merit ratio of 13.5, which is a factor of 2-3 better than MESFETs and HEMTs. In high power applications, the push has been towards 10 and 20 GHz (phased-array radar) with impressive results achieved at ≈8-

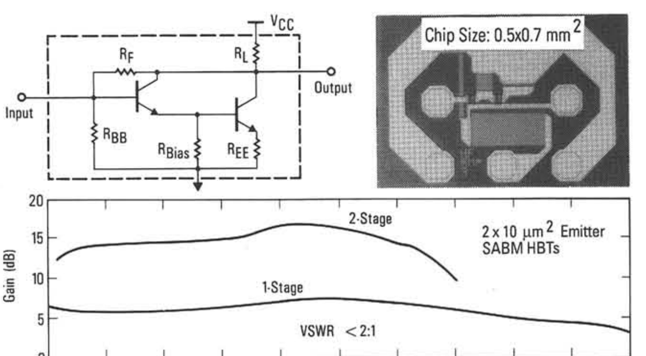

Fig. 6 GaAs HBT broadband direct-coupled feedback amplifiers to 20 GHz using analog design techniques.

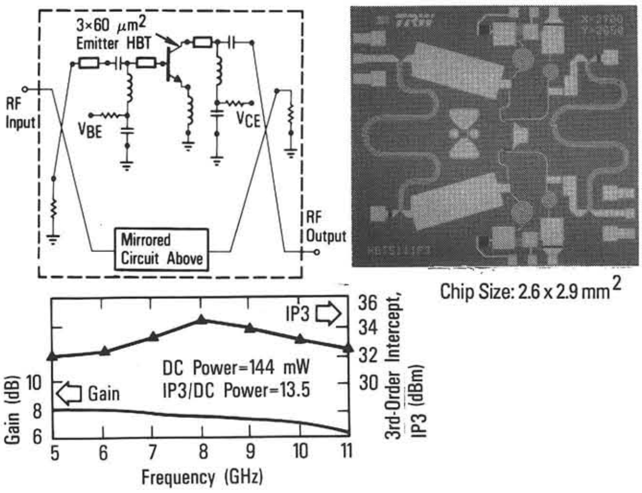

Fig. 7 GaAs HBT 5-11 GHz balanced amplifier designed for high linearity with low dc power using microwave matching technique.

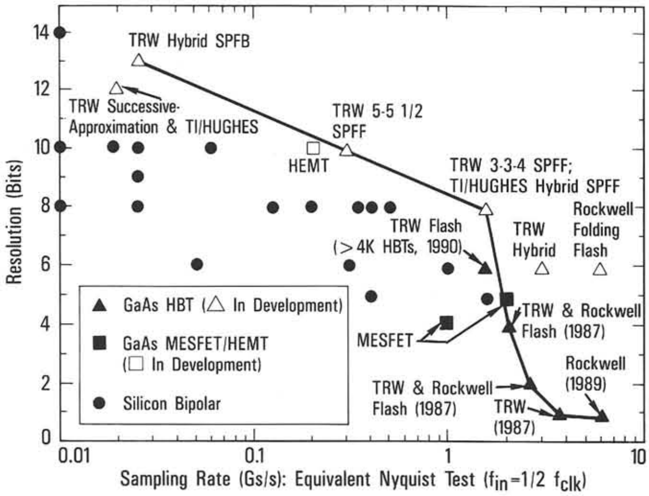

Fig. 8 Competing A/D converter technologies.

10 GHz[4),5)] (e.g. 6.4 W/mm emitter with >60 percent efficiency in common-base, class B)[5)].

Digital. Digital HBT ICs impact robust, high-speed/low-power applications. The HBT in non-saturating topologies (ECL/CML) is power driven, however its extra speed margin can be traded off for lower power. Key applications include fixed[6)] and variable modulus dividers[2)] operating from 3-35 GHz for frequency down-conversion and phase-locked loop synthesizers, and fiber-optic interface circuits operating at ≈10-20 Gb/s rates, beyond the projected capabilities of advanced Si bipolar.

A/D Conversion. A/D conversion functions are the most demanding from the point of high dc ß≈50-100, high f_T and f_{max} at low collector current (I_C≈50-500 μA), and high circuit complexity. The GaAs HBT is impacting the higher bandwidth sampling rates ≈0.3 to >3 GHz with 6 to 10-bit resolution (Fig. 8). With presently limited integration complexity (6-bit flash ADC with ≈4000 HBTs), reduced transistor count ADC architectures such as series-parallel feed-forward and feedback techniques are used to achieve higher performance. For these ADC topologies the GaAs HBT IC process offers an ultra-fast, Schottky-diode-based sample-and-hold unavailable in Si bipolar approaches.

Monolithically-Combined Microwave and Digital. The same 2-3 μm emitter MBE SABM HBT IC process used to achieve dc to 20 GHz analog/microwave performance has been used to demonstrate 6-17 GHz digital and 0.3-3 GHz A/D conversion functions. It is thus attractive for single-chip analog conditioning and digital processing of microwave signals.

5. SUMMARY AND CONCLUSIONS

The GaAs/AlGaAs N-p-n HBT device and IC technology is designed to complement advanced Si bipolars and GaAs FETs in achieving more efficient system functions. A relaxed 2-3 μm emitter SABM process and simplified MBE growth profile offer many performance advantages over present and projected alternative device technologies. The GaAs HBT's future in niche applications as well as its expanding role will be assured through significant growth potentials in epitaxy, processing, and design.

6. ACKNOWLEDGMENT

The authors thank the many technical and support staff for contributions to this work.

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