High-Efficiency GaInP/GaAs HBT MMIC Power Amplifier with up to 9 W Output Power at 10 GHz

Klaus Riepe, Helmut Leier, Ulrich Seiler, Anita Marten, and Hardy Sledzik

Abstract—**Monolithic power amplifiers using adequately ballasted high-efficiency GaInP/GaAs heterojunction bipolar transistors (HBT's) have been designed, fabricated, and tested. A maximum output power of 9 W with a power-added efficiency (PAE) of 42% and peak power-added efficiencies of 45% have been achieved at 10 GHz under critical long pulse conditions (pulse width = 100 μs, duty cycle = 10%). To our knowledge these results represent the best performance of any GaInP/GaAs HBT MMIC power amplifier considering efficiency, output power, operation frequency, and pulse conditions.**

I. Introduction

The GaInP/GaAs HBT is now well accepted as a serious competitor to the conventional AlGaAs/GaAs HBT. The major interest in GaInP/GaAs HBT's stem from the manufacturing advantages compared to AlGaAs/GaAs HBT's. The latter requires delicate base etch monitoring during fabrication, whereas GaInP/GaAs HBT's can be structured in a highly selective etch process that allows easy and economic fabrication. Excellent dc and RF results have been demonstrated for GaInP/GaAs HBT's [1]–[3]. Low phase-noise Ka-band oscillators have already been realized [4].

Recently, the GaInP/GaAs HBT technology has also been applied to monolithic power amplifiers. Under short pulse conditions (pulse width = 10 μs, duty cycle = 10%) an amplifier with an output power of 5.3 W and a PAE of 34% at 9.5 GHz and an amplifier with 9.9 W output power and 33% PAE at 8.5 GHz have yet been realized [5], [6].

In this letter, we report on the fabrication and performance of monolithic power amplifiers that are designed for long pulse and CW operation. The MMIC's deliver state-of-the-art performance with respect to efficiency, output power, operation frequency, and pulse conditions of any GaAs-based HBT power amplifier [7]–[9].

II. GaInP/GaAs HBT Technology

The processed 3-in. wafers incorporate an InGaAs cap and a highly carbon-doped base layer with a thickness of 100 nm and a doping level of $5 \times 10^{19}\text{cm}^{-3}$. The 1-$\mu$m-thick GaAs collector is doped at $2 \times 10^{16}\text{cm}^{-3}$. The dc current gain ($\beta$) is typically 25 resulting in a breakdown voltage (BV_{CEO}) of ~20 V.

The HBT process utilizes a conventional mesa approach and a self-aligned base metallization with respect to the emitter stripe. Standard optical contact lithography, selective wet etching, and deep high-dose proton isolation are applied. Nonalloyed TiPtAu is used for the emitter and base contacts. GeNiAu is applied as subcollector contact. The emitter fingers are adequately ballasted with 11 Ω per finger to suppress completely the current gain collapse effect. The backsides of the wafers are thinned to a thickness of 100 μm. Subsequently the via-holes are formed for emitter grounding by dry etching.

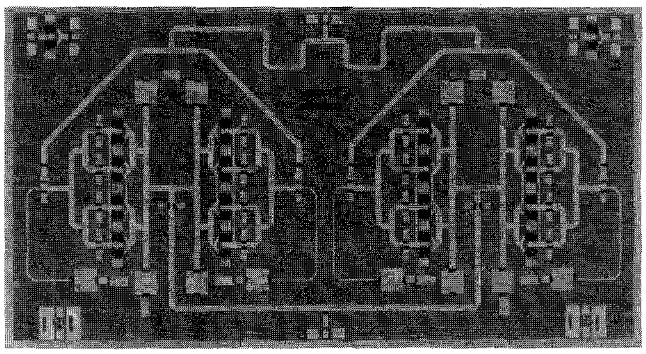

Fig. 1. A photograph of a X-band GaInP/GaAs HBT MMIC power amplifier. The chip size is 8 mm by 4 mm.

III. Circuit Design

A photograph of a fabricated single-stage HBT MMIC power amplifier is shown in Fig. 1. The chip incorporates 128 emitter fingers, each having an area of $2 \times 30\ \mu\text{m}^2$. The overall emitter area of 7680 μm^2 allows high output power levels with moderate power and current densities ($j = 2 \times 10^4$ A/cm^2). This is an important aspect since there is some evidence that reliability of HBT devices strongly depend on current density [10].

The power amplifier design is based on a temperature-dependent large-signal HBT model fitted to measured small-signal S-parameters as well as dc characteristics. For circuit simulation LIBRA$^{\text{TM}}$ (HP-EEsof) and an electromagnetic simulator (SONNET software) are used. The amplifier design is checked by Rollet's as well as Nyquist's stability criterion to avoid even and odd mode oscillations.

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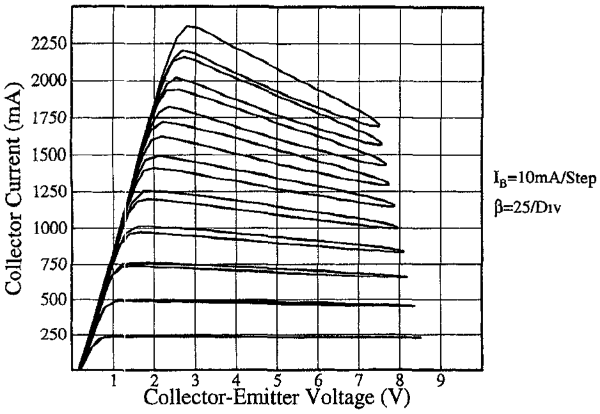

Fig. 2. Measured I-V characteristic of a power amplifier with 16 unit-cells. Each unit-cell has eight emitter fingers with an emitter area of $2 \times 30\,\mu m^2$.

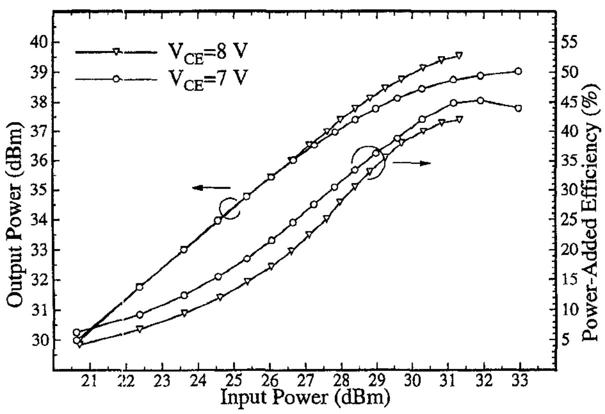

Fig. 3. Output powers and power-added efficiencies versus input power for a typical power amplifier. The curves are traced at different collector biases of $V_{CE} = 7$ V and $V_{CE} = 8$ V, respectively ($f = 10$ GHz, pulse width = 100 μs, duty cycle = 10%).

To improve the amplifier stability resistive losses are added to the base bias networks.

IV. Circuit Performance

Single-finger HBT's show maximum frequencies of oscillation (f_{max}) of 130 GHz. The 8-finger HBT power unit-cells have a f_{max} of 50 GHz and a maximum available gain (MAG) of 13 dB at 10 GHz ($V_{CE} = 8.5$ V, $j = 2 \times 10^4$ A/cm^2). The unit-cell delivers typically 0.5–0.6 W CW output power with a PAE of 60%. The thermal resistance of the unit-cell at 20°C is estimated to 130 K/W at a power density of 1 W/mm.

Fig. 2 shows a typical on-wafer measured I-V characteristic (measured with a Tektronix 370A curve tracer) of a power amplifier demonstrating the stable dc operation of this amplifier. The series resistance of ~1 Ωis mainly determined by the needle access resistance.

For large-signal analysis the chips are mounted in a test fixture. All measurements are carried out without any external tuning. The power-added efficiencies are calculated considering the power dissipation in the collector terminals as well as the base terminals.

Fig. 3 illustrates the power performance at 10 GHz under long pulse (pulse width = 100 μs, duty cycle = 10%) conditions. At 7 V collector bias a maximum output power of 8 W is reached with a PAE of 44%. The peak power-added efficiency is 45% at 7.7 W with 7 dB gain. At a collector bias of 8 V the amplifier delivers 9 W output power with a PAE of 42% and a gain of 8 dB. Under CW conditions the amplifier delivers 7.5 W, a PAE of 39%, and a gain of 6 dB at 10 GHz (see Fig. 4).

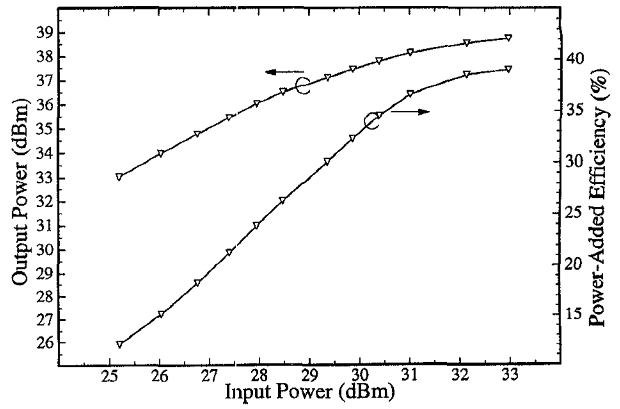

Fig. 4. Measured CW output power and power-added efficiency as a function of input power at 10 GHz of a typical power amplifier. The collector bias is 7 V.

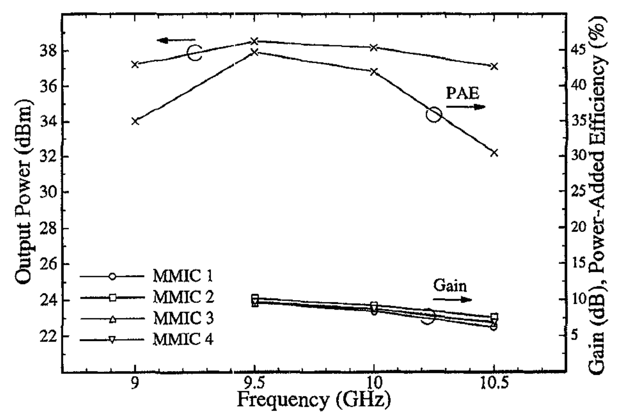

Fig. 5. Output power and PAE versus frequency of a power amplifier at an input power level of 30 dBm. Also shown are measured gains versus frequency of several power amplifiers at an output power of 5 W (pulse width = 100 μs, duty cycle = 10%, V_{CE} = 7 V).

Fig. 5 shows the frequency dependence of output power and PAE for a power amplifier at an input power level of 30 dBm. The highest output powers and efficiencies are obtained between 9.5 and 10 GHz. The variation of gains in the 9-10.5 GHz range for 4 MMIC chips are also shown in Fig. 5. At an output power level of 5 W the gains of the single-stage amplifiers are between 9.5 and 10.5 dB at 9.5 GHz. The decrease of gain at higher frequencies is mainly due to the intrinsic RF behavior of the basic-cell.

Amplifier yields of 50% averaged over several wafers have been obtained demonstrating the high manufacturing level of GaInP/GaAs-based HBT MMIC power amplifiers.

V. Conclusion

In conclusion, we have demonstrated high-efficiency and high-power X-band amplifiers based on a well established and optimized GaInP/GaAs heterojunction bipolar transistor technology. Maximum output powers of up to 9 W and peak power-added efficiencies of 45% have been measured at 10 GHz under critical long pulse conditions.

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