First Demonstration of High-Power GaInP/GaAs HBT MMIC Power Amplifier With 9.9 W Output Power at X-Band

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***Abstract*—We report for the first time the large-signal power performance of a MMIC amplifier based on GaInP/GaAs HBT's. A output power of 9.9 W and power-added efficiency of more than 30% are measured at X-band. These results compare favorably with those measured from AlGaAs/GaAs HBT's, demonstrating that GaInP/GaAs HBT's are suitable for microwave power applications.**

I. Introduction

HETEROJUNCTION bipolar transistors (HBT's) based on the $Ga_{0.5}In_{0.5}P$/GaAs material system have received considerable attention because simple wet etchants offer nearly infinite selectivity of etching away the GaInP emitter and stopping at the GaAs base [1]. This allows the fabrication of GaInP HBT's to be truly manufacturable and reproducible, unlike the AlGaAs HBT process, which requires some form of monitoring during the base etch [2]. To date, large-signal powers of 2.8, 2.0, and 0.6 W were obtained at 3, 10, and 12 GHz, respectively [3]–[5]. These results demonstrate that GaInP/GaAs HBT's have comparable large-signal performance to the more conventional AlGaAs/GaAs HBT's. However, these results were obtained from discrete power transistors with total emitter area equal or less than 600 μm^2. In this work, we report the first MMIC amplifier results measured from HBT's based on the GaInP/GaAs material system. A large-signal output power level of 9.9 W and power-added efficiencies greater than 33% are obtained at X-band. This result is especially remarkable in that it demonstrates the GaInP HBT, which has significant processing advantages over AlGaAs HBT [1]–[5], is suitable for MMIC power applications.

The result differs from an AlGaAs HBT result [6]. Firstly, the GaInP HBT is fully ballasted. It guarantees unconditional thermal stability whereas the AlGaAs HBT was unballasted and prone to sudden device breakdown due to thermal effects [7]. In addition, the GaInP HBT is produced from a truly manufacturable and reproducible process as a result of selective base etching. This is contrasted with the AlGaAs HBT that was fabricated with engineering monitoring during the entire base etch process.

The GaInP/GaAs wafer was grown by metal-organic chemical vapor deposition (MOCVD). The epitaxial structure consists of a 2000-Å n-GaAs cap layer doped at 5×10^{18} cm^{-3}, a 1000-Å n-GaInP active emitter layer doped at 2×10^{17} cm^{-3}, an 800-Å p-GaAs base layer doped with carbon at 3×10^{19} cm^{-3}, a 1-μm n-GaAs collector layer doped at 1×10^{16} cm^{-3}, and a 1-μm n-GaAs subcollector doped at 3×10^{18} cm^{-3}. The devices were fabricated using Texas Instruments' self-aligned HBT process, except for an etching step to remove the GaInP emitter [3]. The knee voltage measured from the common-emitter I–V characteristics is ~0.8 V and the dc current gain values are about 10. The emitter-collector breakdown voltage (BV_{ceo}) is ~20 V and the base-collector junction breakdown voltage (BV_{cbo}) is 35 V. The small-signal performance of a 2×60 μm^2 GaInP/GaAs HBT was also measured. At an operating collector current density of 2.1×10^4 A/cm^2 and a collector-emitter bias of 2 V, the values of f_T and $f_{\max}$ extrapolated using a 20-dB/decade slope are 25 and 90 GHz, respectively.

Each unit cell, which forms the fundamental unit of the amplifier, has 400 μm emitter length and is fully ballasted to ensure unconditional thermal stability. The collapse of current gain reported in unballasted transistors is not observed in the measured I–V characteristics between 0 and 20 V of collector bias [7]. The unit cell, in common-emitter configuration, is designed to produce minimum 1 W ouput power in the 8.5–10.5 GHz band. The details of the power performance of the unit cell were described [2], [8].

The amplifier was designed from both the large-signal load-pull and small-signal S-parameter measurements, as well as the modeling of the unit cells. The input stage of this two stage amplifier consists of four unit cells, whereas the output stage is composed of 12 unit cells connected in parallel. A schematic of the circuit is identical to that reported for a previous version of this circuit [6], except for the removal of some resistances in the interstage. A photograph of the 2-stage amplifier circuit, occupying a total area of 4.5×4.5 mm^2, is shown in Fig. 1. The circuit was designed to be unconditionally stable at all frequencies and drive levels. Both the interstage and the input stage matching circuits have lossy characteristics at the subharmoinc frequencies (2–6 GHz) to prevent spurious modes. A two-dimensional electromagnetic design tool was used in the design of the signal distribution manifolds in all of the matching circuits [9].

The rf yield on unit cell approaches 100%. The yield on the MMIC cicuit is 24%, a comparable value as that from AlGaAs MMIC circuit based on similar fabrication process.

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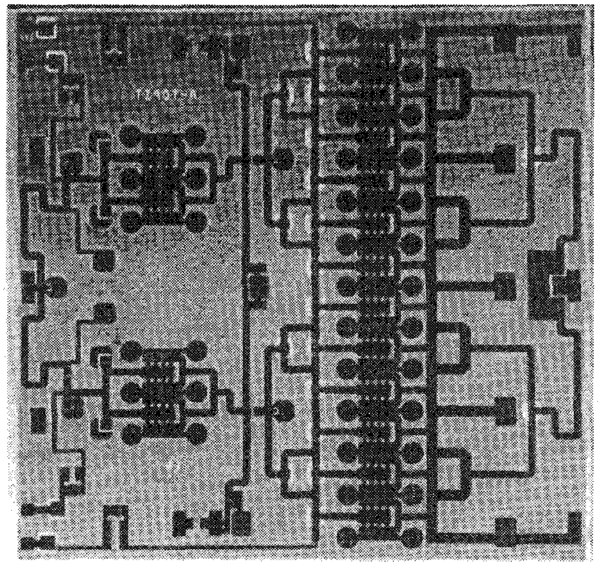

Fig. 1. Photograph of the amplifier chip, which occupies an area of 4.5×4.4 mm^2.

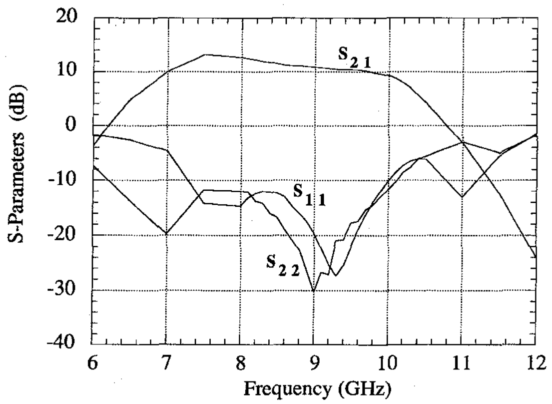

Fig. 2. Measured small-signal parameters of the GaInP/GaAs HBT amplifier circuit.

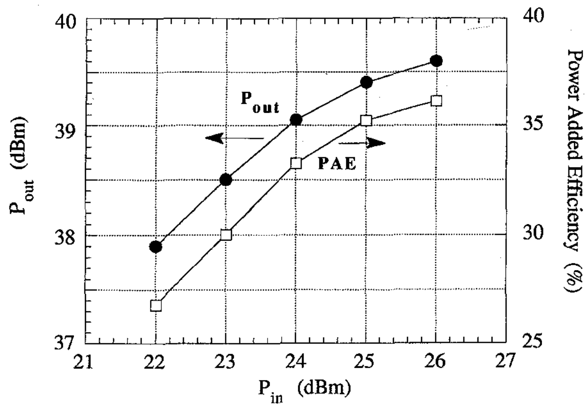

Fig. 3. Measured output power and power-added efficiency as a function of the input power for a typical amplifier circuit.

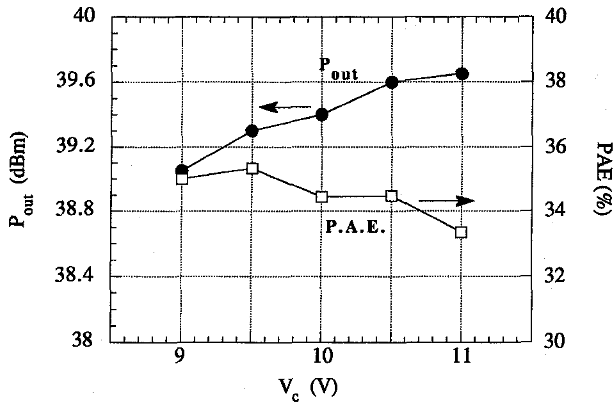

Fig. 4. Measured output power of a typical amplifier circuit as a function of collector bias. The input power was maintained at 26 dBm.

The circuit yield is believed to be limited by the use of contact lithography. However, because of the availability of selective etches to remove the GaInP emitter to reach the GaAs base layer, it is expected that the GaInP MMIC circuit yield would eventually surpass that of AlGaAs MMIC. Fig. 2 illustrates the measured small-signal parameters of the amplifier circuit as a function of frequency. As indicated from the terminal reflection coefficients S_{11} and S_{22}, the circuit has a useful band of operation between 7.5 and 10 GHz. The forward transmission coefficient, S_{21}, attains a highest value of 12 dB and gradually decreases to 9.8 dB at 10 GHz.

The MMIC amplifier circuit was tested at 8.5 GHz with a 10% duty-cycle pulse having a pulse duration of 10 μ. Because no cooling was applied to the amplifer chip, the amplifier was prone to sudden device failure at higher duty-cycle or pulse duration. The HBT's were biased in class AB mode to maximize power output while maintaining respectable power-added efficiencies. The reported results were directly measured from the MMIC chip, without additional tuning. An experimentally determined fixture loss of 0.2 dB was included in the reported output powers. The power-added efficiency accounts for the power dissipation in the base terminals of the 2-stage circuit as well as the collector terminals. Fig. 3 illustrates the output power (P_{out}) and power-added efficiency (PAE) as a function of the input power (P_{in}). The collector bias was maintained at 10 V. As shown, the linear power gain is 15 dB. When $P_{in} = 26$ dBm (0.4 W), the output power reaches a level of 9.21 W. However, P_{out} does not increase appreciably as P_{in} increases past 26 dBm. The associated power gain and PAE are 13.6 dB and 36.1%, respectively.

Fig. 4 shows the power performance of another amplifier circuit as a function of collector bias while P_{in} was maintained at 26 dBm. As the bias increases from 9 to 11 V, P_{out} increases from 8 to 9.2 W. PAE, on the other hand, decreases only slightly from 35 to 33.5%. Fig. 5 illustrates the largest output power measured from various amplifier circuits fabricated on the same wafer. While $P_{in} = 26$ dBm for all of these data points, the collector bias ranges between 9 and 10.5 V. The power-added efficiency corresponding to each P_{out} is also listed in the figure. As shown in Fig. 5, the measured P_{out}'s are fairly uniform, ranging between 8.7 and 9.9 W with an average of 9.25 W. The power-added efficiencies vary between 33.3 and 36.9%.

In summary, we reported for the first time the power performance of MMIC power amplifier based on GaInP/GaAs HBT's. A record output power of 9.9 W with an associated gain of 14 dB and a PAE of 33.3% were obtained at X-band.

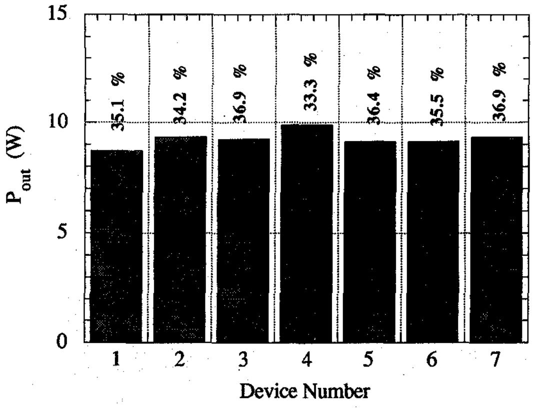

Fig. 5. Measured large-signal performance of the various amplifier circuits, showing largest P_{out} of 9.9 W is obtainable with a PAE of 33.3%.

The output power as functions of input power and collector bias for typical amplifier circuits were also presented.

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