Pulsed 1-Watt Heterojunction Bipolar Transistors at 35 GHz

M. G. Adlerstein, M. P. Zaitlin, W. Hoke, E. Tong, and G. Jackson

Abstract—**High-peak power-pulsed operation of common emitter AlGaAs–GaAs HBT's at 35 GHz is reported. A 1.0 W peak power with 2.3-dB associated gain and power-added efficiency of 28% is obtained. Small devices gave up to 43% power-added efficiency with 190 mW output at 4.8-dB gain. Pulse length was 300 nS and duty cycle was 33%. The device design, small signal characteristics, and power results obtained are described.**

I. Introduction

AlGaAs–GaAs heterojunction bipolar transistors (HBT's) have demonstrated impressive performance at 10 GHz in the CW mode and they have been used in monolithic amplifiers [1]. However, it is in pulsed operation that HBT's have the clearest power advantage over MESFET's and pseudomorphic HEMT's [2], [3]. For field effect transistors, $I_{\max}$ limits power density while for HBT's there is no equivalent to $I_{\max}$. Instead, HBT's are thermally limited and when operated in the pulsed mode with pulse lengths around 300 nS, allow application of bias current roughly in inverse proportion to the duty cycle. The result is high peak power. For example, AlGaAs–GaAs HBT's fabricated in our laboratory and operated at 33% duty cycle and 300-nS pulse length have given 1.5-W peak power at 10 GHz with 5.5-dB gain and 40% power-added efficiency. When operated in the CW mode, the devices give 0.8 W at 6.4-dB gain and 47% power-added efficiency.

To extend the pulsed advantage of HBT's to mm-wave frequencies, one must overcome frequency response limitations associated with base layer charging and collector transit time. In addition, deleterious parasitic effects of parasitic collector-base feedback capacitance and extrinsic base resistance must be minimized. Having addressed these problems, we can report pulsed AlGaAs–GaAs HBT's with 1.0-W peak power and 2.3-dB associated gain at 35 GHz. Power-added efficiency was 28%. At lower power density using the same transistor, we obtained 0.6 W with 3.2-dB gain and power-added efficiency of 35%. Pulse length was 300 nS and duty cycle was 33%.

II. Material and Device Design

The devices studied were AlGaAs–GaAs heterojunction bipolar transistors. The material was grown by molecular beam epitaxy with silicon n-type doping and beryllium p-doping of 5×10^{19} cm^{-3} in the 750-Å thick base [4]. Contacts to the 5000-Å thick collector were self-aligned to the base contact while the emitter and base contacts were separated by a thin silicon nitride sidewall. Closely spaced contacts minimize parasitic base-collector feedback capacitance. Heavy base doping and closely spaced base-emitter electrodes minimize extrinsic base resistance.

The HBT's, fabricated in our laboratory, consisted of three active cells arranged in a linear configuration. Each cell incorporated two emitter fingers ($2 \times 20\,\mu\text{m}^2$) and three base fingers ($2 \times 20\,\mu\text{m}^2$). Thus, the transistor had an active area of $240\,\mu\text{m}^2$. Common emitter connection was made with a single via hole at each end of the structure. Substrate thickness was 100 μm. Measured thermal resistance of the devices was 377 C/W [5].

Manuscript received January 20, 1993. This work was supported in part by Naval Air Warfare Center, Weapons Division under Contract N60530-90-C0352, M. Afendykiw, Technical Monitor.

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IEEE Log Number 9208973.

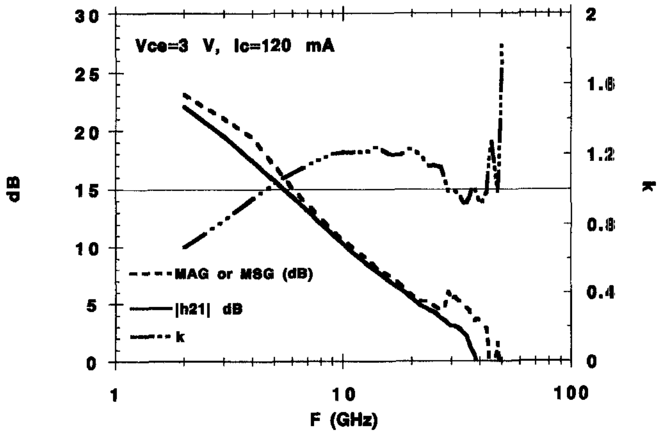

Fig. 1. Measured maximum stable and available gain, $|h_{21}|$ and k as a function of frequency.

III. Small Signal RF Measurements

The transistors were characterized for small signal RF properties at a variety of bias levels. Of most interest were higher voltages and currents close to the operating point. Bias power was limited however, by thermal considerations. In the absence of high input drive levels for small signal tests, little of the dc power is radiated from the device and most of the bias power is dissipated in the HBT as heat. Furthermore, small signal automatic network analyzer characterization of the transistors are made in the CW mode and applications of pulsed bias levels would lead to device failure in the absence of high power RF drive. Despite these limitations in choice of bias conditions, S-parameters are nevertheless useful for design.

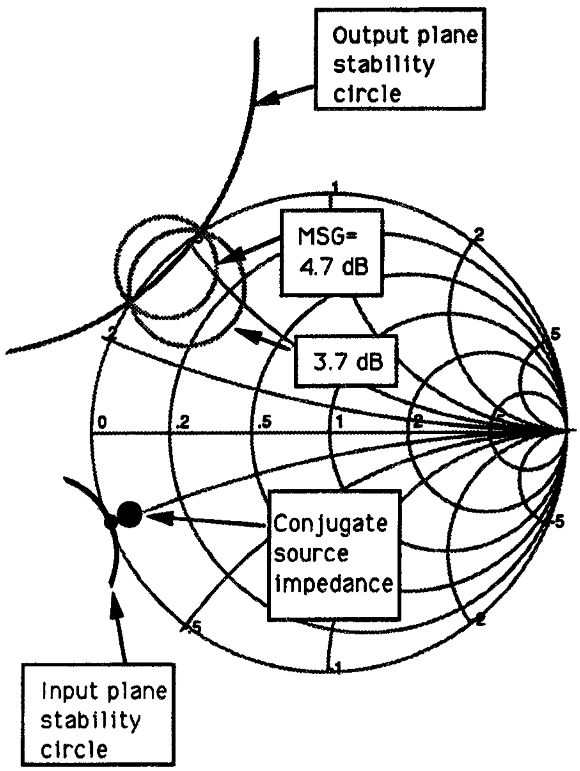

Fig. 2. Power gain circles and stability circles for a three-cell Ka-band HBT. $V_{ce} = 3$ V with $I_c = 120$ mA. Also shown is the approximate source output impedance for conjugate match to the transistor operating near its maximum stable gain.

Fig. 1 shows typical measurements up to 50 GHz of maximum stable and maximum available gains along with $|h_{21}|$. The data is referred to the transistor terminals. The k-factor, also plotted in Fig. 1, shows the transistor to be conditionally stable at 35 GHz. However, the region of potential instability is confined to very small portions of the source and load Smith Charts as shown in Fig. 2. Power gain and available gain circles are near the stability boundaries but the transistor can have regions of unconditional stability without significant sacrifice of gain.

IV. Pulsed Power Operation at 35 GHz

The transistors were tested for power performance at 35 GHz using coaxial fixtures with tuning structures on alumina substrates at the input and output of the chip. The tuning structures were characterized using an ANA and their circuit losses ($\sim$ 0.5 dB each) were accounted for in the measurement of input and output power. At each RF input power and bias point the device input and output matching were fine-tuned using small metal disks moved on the alumina tuning structures. Some small additional losses were undoubtedly introduced by these disks so that our estimates of device gain and power referred to the chip edges are slightly conservative.

The devices were tested with a pulsed waveform having a 300 nS pulse length and a duty cycle of 33%. Figure 3 shows the transistor gain versus peak output power. Bias points and power-added efficiency (PAE) are indicated in the figure. Output power of 1 W was obtained with 28% PAE at 2.3-dB

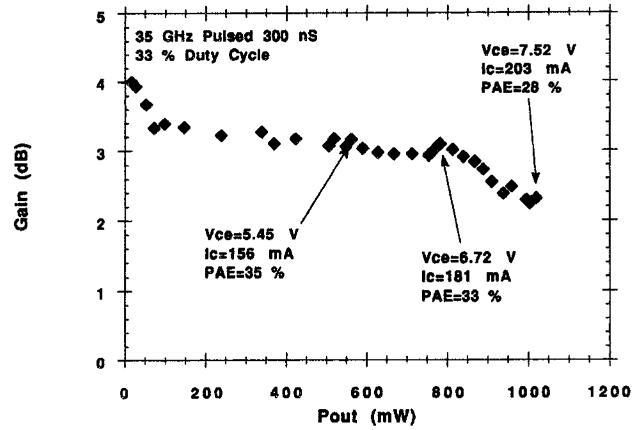

Fig. 3. Measured gain versus output power at near optimum tuning. Bias points and other parameters are indicated.

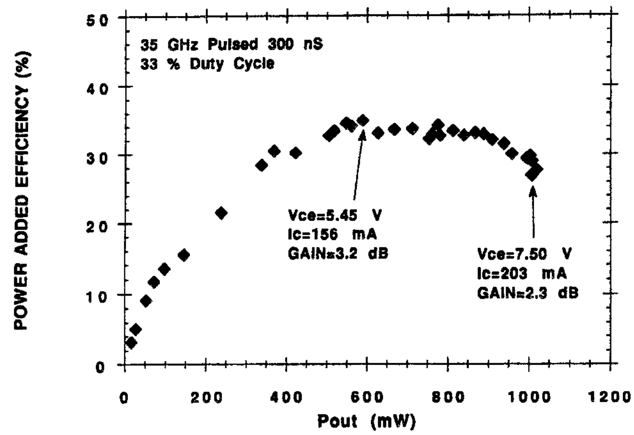

Fig. 4. Measured power-added efficiency versus output power at near optimum tuning. Bias points and other parameters are indicated.

gain. The benefit of pulsed operation is seen from the fact that had the device been operated at this power level in the CW mode, the temperature rise would result in device failure. Power-added efficiency is plotted as a function of output power in Fig. 4. Note that PAE is relatively independent of output power since the decreasing gain is partially counteracted by increasing collector efficiency that reaches 70% at the highest input drive levels. The highest values of power-added efficiency, up to 35%, were obtained in the 500 mW to 800 mW output power range where gain exceeded 3 dB. From the values of collector efficiency, it is estimated that the transistors are operating near class B.

It was found possible to obtain still higher gain and efficiency from smaller transistors. A transistor with 80 μm^2 active area gave 190 mW with 4.8-dB gain at 43% power-added efficiency. Small devices would be useful in low-power stages of multistage amplifiers.

V. Conclusion

High-power pulsed performance of AlGaAs–GaAs heterojunction bipolar transistors has been demonstrated at 35 GHz. The gain, power, efficiency, and matching requirements observed indicate that such transistors will be very useful for mm-wave solid state pulse power applications.

ACKNOWLEDGMENT

The authors thank P. Saledas for device processing and G. Flynn and D. Kelly for measurement assistance.

REFERENCES

[1] B. Bayraktaroglu, M. A. Khatibzadeh, and R. D. Hudgens "5 W monolithic HBT amplifier for broadband X-band applications," *Proc. IEEE 1990 Microwave and Millimeter-Wave Symp.*, 1990, pp. 43–46.

[2] M. G. Adlerstein, M. P. Zaitlin, G. Flynn, W. Hoke, J. Huang, G. Jackson, P. Lemonias, R. Majarone, and E. Tong, "High power density pulsed X-band heterojunction bipolar transistors," *Electron. Lett.*, vol. 27, no. 2, pp. 148–149, Jan. 1991.

[3] M. G. Adlerstein and M. P. Zaitlin, "Cutoff operation of heterojunction bipolar transistors," *Microwave J.*, vol. 34, no. 9, pp. 114–125, Sept, 1991.

[4] W. E. Hoke, P. J. Lemonias, D. G. Weir, S. K. Brierley, H. T. Hendriks, M. G. Adlerstein, and M. P. Zaitlin, "Molecular-beam epitaxial growth of heavily acceptor doped GaAs layers for GaAlAs/GaAs HBT's," *J. Vac. Sci. Technol. B*, vol. 10, no. 2, pp. 856–858, Mar/Apr 1992.

[5] M. G. Adlerstein and M. P. Zaitlin, "Thermal resistance measurements for AlGaAs/GaAs heterojunction bipolar transistors," *IEEE Trans. Electron Devices*, vol. 38 no. 6, pp. 1553–1554, June 1991.