Large-signal Modeling and Study of Power Saturation Mechanisms in Heterojunction Bipolar Transistors

Michael Y. Frankel and Dimitris Pavlidis
Solid State Electronics Laboratory
Department of Electrical Engineering and Computer Science
The University of Michigan
Ann Arbor, MI 48109

Abstract

A harmonic balance based large-signal model of the heterojunction bipolar transistor suitable for microwave circuit design and simulation has been developed. The excellent agreement between modeled and measured power characteristics, including the saturation behavior, validates its accuracy. The model has been used to investigate the device power saturation mechanisms.

Summary

1. Introduction

Heterojunction bipolar transistors (HBTs) have recently demonstrated very promising power characteristics [1] and their use has been investigated for a variety of microwave functions such as amplifiers and oscillators. These recent developments necessitated a reexamination of the issues associated with their design and implementation in microwave circuits operating under large-signal conditions. In particular, the power output limiting mechanisms have to be investigated and useful models have to be derived to facilitate circuit design. Traditionally, the power limiting effects, such as thermal effects, collector junction breakdown, as well as the effects of the distributed base-emitter junction have been considered in terms of absolute limits only. Although some output power limitation aspects for heterojunction bipolar transistors have been discussed experimentally [2], the influence of intrinsic device nonlinearities on output power is not sufficiently understood. Large-signal properties dependent on such nonlinearities are, however, required for improvement of device design and successful MMIC development for power applications.

Accurate and efficient large-signal computer models have seen extensive development for III-V semiconductor field-effect transistors [3],[4], but not for HBTs. The inherently strong nonlinearity in the base-emitter voltage to collector current transfer characteristics and the resulting device parameter nonlinearities can adversely affect the performance of the device itself or of device matching to the circuit.

This paper describes a simple and efficient method for simulating the HBT behavior under large-signal excitation. A harmonic balance analysis method is used which allows device simulation as part of a complete microwave circuit. Additionally, the influence of intrinsic device parameters on circuit operation can be investigated. The development of the large-signal model is described first, and following this it is shown that it can accurately predict experimentally measured AlGaAs/GaAs HBT power characteristics. The model is also used to analyze power saturation mechanisms.

2. Equivalent circuit model of the HBT

The harmonic balance analysis method requires the knowledge of the intrinsic device dc characteristics and the equivalent circuit (Fig. 1) conductance and susceptance values as a function of bias. These can be obtained from the theoretical considerations of the device material and fabrication parameters. Instead of deriving a physical model, we have chosen to extract the equivalent circuit from dc and multi-bias small-signal S-parameter measurements, while conforming with expected physical characteristics as imposed by a simple theoretical model derived for this purpose. This allows one to accurately simulate device large-signal performance, while preserving the physical understanding of the intrinsic behavior.

First, the bias dependence of the intrinsic device circuit elements (see Fig. 1) was investigated. This allows both to verify the equivalent circuit extraction procedure, as well as give some indication of the physical processes involved in HBT operation. The devices used in this work had a compositionally graded emitter-base heterojunction and no base grading. Hence, we may use a device model that is similar to that of Si bipolar transistors [5]. The

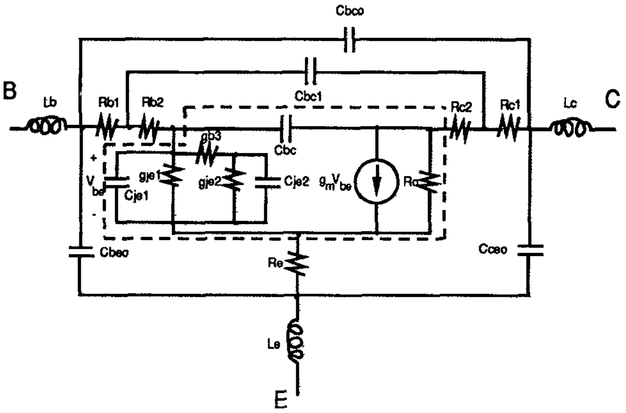


Figure 1. HBT Equivalent Circuit.

distributed nature of the base-emitter junction is taken into account by incorporating the additional junction access conductance (g_{b3}) and junction conductance (g_{je2}) and capacitance (C_{je2}) terms. Although more powerful models can be implemented for the analysis of HBTs, this approach allows model simulation as required for circuit design applications. As will be shown later, in spite of the approximations the measured and calculated results show good agreement.

In this model the transconductance can be expressed as

$$g_m = \frac{I_c}{nV_t}. \qquad (1)$$

Similarly, the input base emitter conductance component is

$$g_{je} = \frac{I_b}{nV_t}. \qquad (2)$$

The input capactance C_{je} has a contribution from the base-emitter junction depletion region, C_{te}, and a base charge storage contribution giving

$$C_{je} = C_{te} + \frac{\tau_f \beta I_b}{nV_t}. \qquad (3)$$

The feedback capacitance, C_{bc}, is primarily due to the base-collector junction depletion region and is expected to have a dependence on base-collector voltage only.

Figures 2a,b show the dependence of the input conductance g_{je} and capacitance C_{je} on the base current I_b as extracted by equivalent circuit modeling from measured S-parameters and as evaluated by fitting Eqs. (2) and (3).

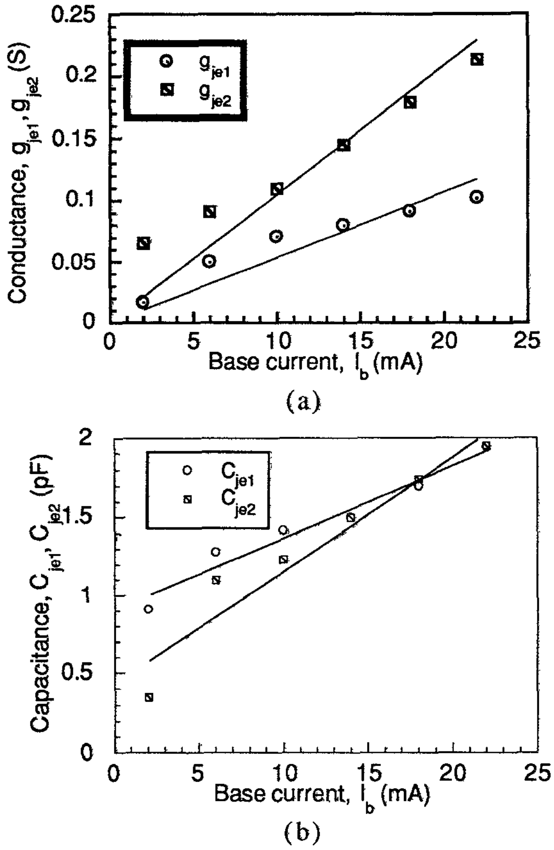


Figure 2. Extracted (symbols) and fitted (——) equivalent circuit elements.

3. Large-signal harmonic balance HBT model

The active and the cutoff regions of the device operation are of primary importance for microwave circuits. Thus, we first focused our HBT characterization and modeling work on these two regions. A simple extension of the model into the saturation region was also implemented. Four harmonics were included in the simulations since a larger number did not result in any significant improvement in accuracy. The output power was experimentally measured at 5 GHz for both Class A and Class AB device operation with the device input and output terminated into 50 Ω. Figure 3 shows the excellent agreement between the modeled and the measured power and gain characteristics for both Class A and Class AB device operation validating our modeling approach. We see that no saturation takes place for Class A operation at the investigated input power levels. The intrinsic device nonlinearities do not cause any power linearity problems as long as the device is operated in the active region. In addition, the Class A operation exhibits a higher overall power gain compared to the Class AB operation as a result of an increased dc bias current.

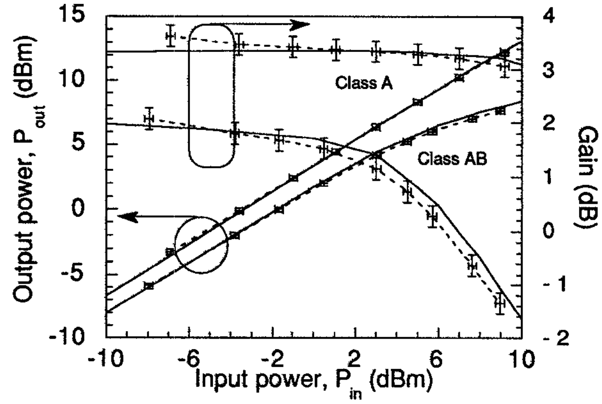
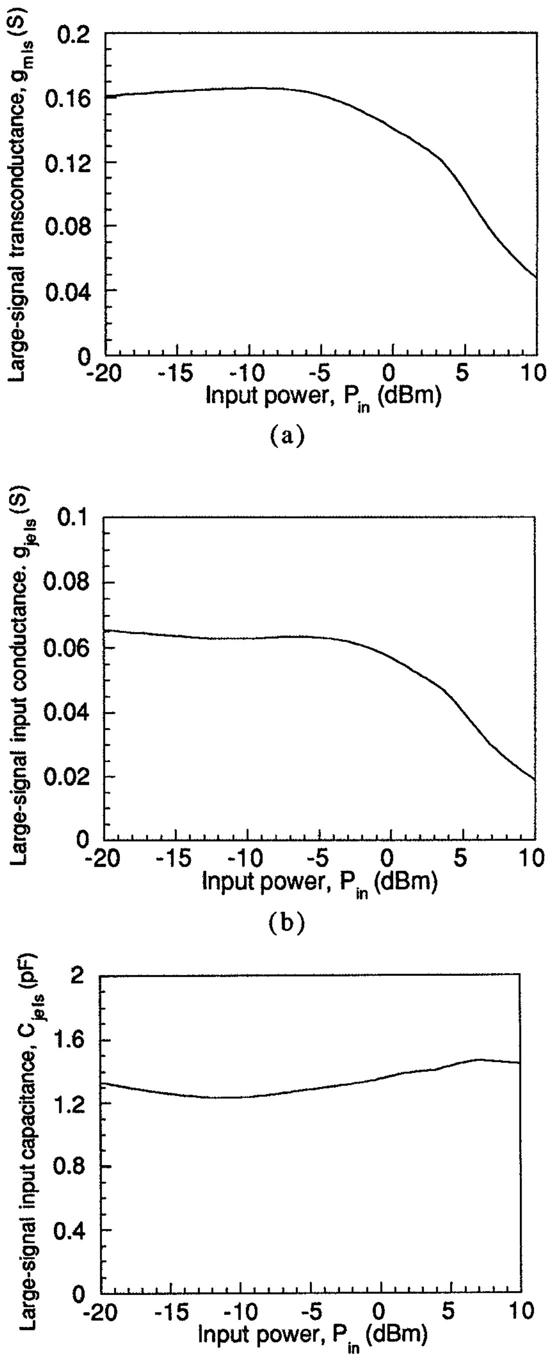


Figure 3. Modeled and measured power characteristics.

However, in Class AB operation the transistor shows strong output power saturation. From the modeled collector current waveforms we can see that the power saturation can be directly attributed to the device entering the cutoff region. As the current waveform begins to show clipping on the downswing cycle, the available power rapidly drops off. The influence of intrinsic device nonlinearities on the overall power behavior is small. Even at relatively high input powers, the higher harmonics are at least 10 dB below the fundamental. However, the nonlinearities may become important if a good input and output impedance match to the external circuits is used rather than 50 Ω terminations employed in our measurement set-up.

The large-signal HBT behavior can be further analyzed, with respect to small-signal performance, by defining equivalent large-signal circuit elements as ratios of the fundamental frequency components of large-signal currents and voltages. The observed variation with input power of such elements may influence the input and output impedance match of the device to external circuits. Typical results for the large signal elements at 5 GHz are shown in Figs 4a, b and c. The large signal transconductance ($g_{m\ ls}$) and base-emitter conductance ($g_{je\ ls}$) are initially fairly constant and then show a rapid decrease with input power when the device enters the cutoff region. The large signal input capacitance is, however, constant in the same range of input power levels. The saturation mechanisms under these bias and microwave input signal conditions can consequently be attributed in this case to $g_{m\ ls}$ and $g_{je\ ls}$ nonlinearities.



(c)

Figure 4. Large-signal characteristics of HBT equivalent circuit elements as a function of input power level.

The importance of accurate modeling of the bias-dependent equivalent circuit elements becomes apparent when the device is matched to the 50 Ω load. Load-pull measurements have been performed at 8 GHz with as close a simultaneous conjugate match to the input and the output as the equipment would allow. For this measurement, the device was biased into a Class A operation. Figure 5 shows the comparison between the modeled and the measured power and gain characteristics for one of the devices. Unlike previous results, this device biasing condition and input power levels do cause saturation. The analysis of the device nodal voltages and currents provided by the model revealed in this case that the power saturation is a direct result of the device entering the saturation region for a portion of its operating cycle. The slight discrepancy between the modeled and the measured results is attributed to the inaccuracies in modeling the bias-dependent elements.

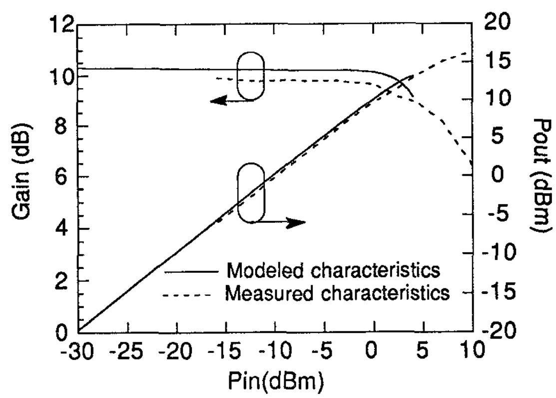


Figure 5. Modeled and measured power characteristics.

4. Conclusion

In this work, we have demonstrated the applicability of a simple and efficient small-signal bias dependent equivalent circuit model to the large-signal HBT simulation. Equivalent circuits were extracted from measured small-signal S-parameters by equivalent circuit fitting and used in a harmonic balance based simulator. Modeled power and gain results were in good agreement with directly measured characteristics. The power saturation mechanisms have been established in terms of current/voltage amplitudes and power dependent equivalent circuit elements. Saturation has been shown to be due to the signal-voltage swing entering the cutoff or saturation regions with the resulting loss of current gain. This is reflected in large nonlinearities for the large-signal transconductance and base-emitter conductance elements with input power level, but other mechanisms may be responsible depending on bias or terminating impedances.

Acknowledgement

This work was supported by Alcatel-Espace (Contr. No. 393 550 760), Army Research Office (Contr. No. DAAL-03-87-K-0007) and Air Force Office of Scientific Research, University Research Initiative (Contr. No. F49620-87-C-0016). The authors are grateful to M. Tutt, P. Marsh and A. Samelis for their help in microwave characterization.

References

1. B. Bayraktaroglu, M.A. Khatibzadeh, and R.D. Hudgens, "5 W monolithic HBT amplifier for broadband X-band applications," *Proceedings of IEEE 1990 Microwave and Millimeter-Wave Monolithic Circuits Symposium*, pp. 43-45.
2. N.H. Sheng, M.F. Chang, P.M. Asbeck, K.C. Wang, G.J. Sullivan, D.L. Miller, J.A. Higgins, E. Sovero, H. Basit, "High power GaAlAs/GaAs HBTs for microwave applications," *Proceedings of 1987 International Electron Device Meeting*, pp. 619-622.
3. R.R. Pantoja, M. J. Howes, J.R. Richardson, C.M. Snowden, "A large-signal physical MESFET model for computer-aided design and its applications," *IEEE Trans. on Microwave Theory and Techn.*, vol. MTT-37, Dec. 1989, pp. 2039-2045.
4. M.R. Weiss and D. Pavlidis, "An investigation of the power characteristics and saturation mechanisms in HEMT's and MESFET's," *IEEE Trans. Electron Devices*, vol. 35, no. 8, Aug. 1988, pp. 1197-1206.
5. R.S. Muller, T.I. Kamins, *Device Electronics for Integrated Circuits*. New York: John Wiley & Sons, 1986.