

# Large-Signal Modeling of High-Voltage GaAs Power HBTs

M. Rudolph, R. Doerner

Ferdinand-Braun-Institut für Höchstfrequenztechnik (FBH)  
Gustav-Kirchhoff-Str. 4, D-12489 Berlin, Germany, (e-mail: rudolph@fbh-berlin.de)

**Abstract**—This paper presents modeling results for newly developed InGaP/GaAs power HBTs operating at bias voltages up to  $V_{ce} = 26$  V. The devices are flip-chip mounted for heat-sinking and deliver output powers above 10 W. It is shown that the FBH HBT model is capable of describing those devices despite the fact that it was developed originally for standard ‘low-voltage’ HBTs. This result is an important statement with respect to circuit design based on this promising technology.

**Keywords**—Heterojunction bipolar transistor, semiconductor device modeling, equivalent circuit.

## I. INTRODUCTION

COMMON GaAs HBT technologies target the power amplifier market for battery-powered mobile phones. Hence, they are designed to handle supply voltages around 3 V. However, other device technologies are developed as well, which operate at ten times higher supply voltages [1], [2], [3]. These devices are promising for high-power applications, since they have proven to be able to deliver tens of Watts around 2 GHz, with a much better output impedance than competing technologies like LDMOS. Therefore, the effort to be spent on output matching is significantly reduced, enabling simplified power combining and especially broader bandwidth.

However, although these ‘high-voltage’ HBT technologies are ready for market, to the authors knowledge, no large-signal model has been published so far. Numerous work is dedicated to model the ‘traditional’ HBT, and also full-featured compact models are available and even implemented in RF simulation tools. On the other hand, modeling of ‘high-voltage’ devices usually was performed in order to support the technology development, e.g. with respect to breakdown behavior and thermal management [4], [5]. The benefit of these approaches is that they enable understanding of the transistor operation. However, they are not suitable for circuit design. For this purpose, a compact, numerically robust large-signal model is required.

In this work, it is demonstrated that a FBH high-voltage power cell with a total emitter area of  $4000 \mu\text{m}^2$  delivering more than 14 W at 2 GHz [3] can be modeled with the FBH model for GaAs HBTs. Two types of devices are considered. One is a single-finger HBT with an emitter area of  $3 \times 30 \mu\text{m}^2$ , which is measured on-wafer. The other is a power cell with 20 emitter fingers with an area of  $2 \times 100 \mu\text{m}^2$ . This one is flip-chip mounted on a submount for heat-sinking, but also measured with wafer probes prior

to bonding into a package.

## II. HBT TECHNOLOGY AND LARGE-SIGNAL MODEL

Technological details and the performance of the HBTs were already presented in [3], [6]. From the modeling point of view, there are two main differences between standard HBTs for lower voltages and the ‘high-voltage’ devices.

The first one is that thermal stability of the devices is much more critical, since the power density is about ten times higher. If the thermal management is insufficient, it is likely that the device, although electrically small, shows distributed effects, i.e. hot-spot formation and thermal crunching, which are not predicted by a compact model. In order to account for these effects, a distributed electro-thermal model has to be used as in [5], which is able to describe mutual heating and unequal temperature distribution inside the transistor. Since hot-spot formation causes performance degradations at high output levels and can significantly shorten the device’s lifetime, great efforts are spent to suppress it by proper thermal management. In case of the devices under consideration here, the emitters of the power cells are connected by a  $20 \mu\text{m}$  thick gold air bridge, and the devices are directly flip-chip mounted on a heat-sink. Thereby, thermal resistances as low as 15 K/W were achieved for the HBT under investigation, and hot-spot formation was not observed.

The other important difference of the high-voltage HBTs compared to their ‘low-voltage’ counterparts is the collector that is designed in order to allow for higher break-down voltages. Basically, the higher breakdown voltages are achieved by thick and weakly doped collectors. In our case, the collector is  $2.8 \mu\text{m}$  thick, approximately three times thicker than in conventional HBTs. Thus, high-current injection effects which result in velocity modulation and also in variation of the depletion layer width will impact the electrical behavior differently. In terms of the model, base-collector capacitance  $C_{bc}$  and collector transit-time  $\tau_c$  are affected. The description of these parameters is crucial for the model accuracy. Especially, since the bias dependence of the transit frequency  $f_t$  is dominated by  $\tau_c$ , and due to the impact of  $C_{bc}$  on the output matching.

In the FBH model which is employed in this work [7], [8] the collector transit-time is implemented together with the current-dependent base-collector capacitance by an appropriate bias dependence of the base-collector charge  $Q_c$ . In short, the formula for  $Q_c$  describes the base-collector de-

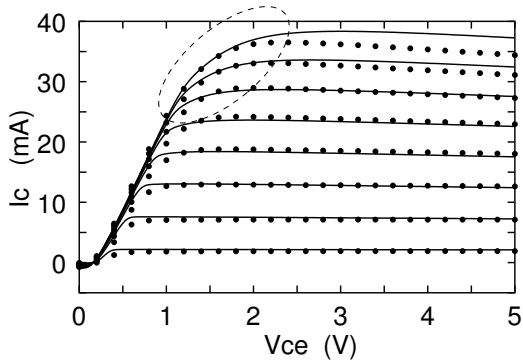


Fig. 1. Output I-V-curves of single-emitter HBT (low-voltage region), emitter area  $3 \times 30 \mu\text{m}^2$ . Symbols: measurement, lines: simulation.

pletion capacitance for low currents, but introduces a reduction of the capacitance values proportional to the collector current density. Thus, since  $Q_c$  is a function of  $V_{be}$ , a transcapacitance arises. It can be understood as the source of the collector delay [7]. Therefore, for the model to be accurate, this rather minimalistic formulation which uses only four parameters in addition to the common depletion capacitance formula, must describe the velocity modulation effects comprehensively.

These two general differences regarding thermal effects and the collector render the application of a standard HBT model questionable. While the thermal management issue is mainly a technological one, it has to be proven that the  $Q_c$  model for thin collectors is applicable to wide collectors, or if certain ‘wide-collector’ effects arise which are not observed in standard HBTs. This is of particular importance since the collector transit time generally is much higher than in case of a narrower collector.

A third concern with respect to parameter extraction is that in case of high-power devices, it is no longer possible to perform the traditional measurements at all bias points which will be reached dynamically during device operation. During parameter extraction, it has to be ensured that the heat inside the device due to power dissipation is not harmful to the device. As a result, since we did not rely on pulsed measurements, the model is expected to accurately extrapolate the device behavior for regions which were not measured.

The main purpose of this paper is to assess validity of the FBH model for ‘high-voltage’ HBTs. This will be shown in the following. One should note that, besides the specific aspects described above, the FBH model features other enhancements compared to the SPICE Gummel-Poon (SGP) model. These are a description of possible non-ideal base-emitter currents, base-emitter and base-collector breakdown, and a self-heating model, which also allows to describe dynamic mutual heating by a thermal port.

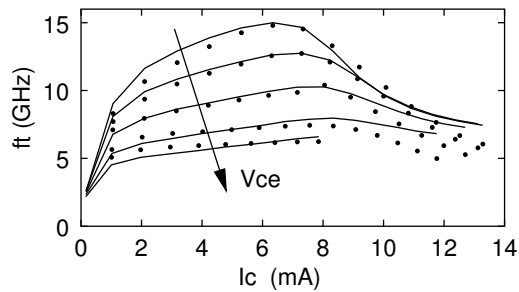


Fig. 2. Transit frequency  $f_t$  against collector current; measured (symbols) and simulated (lines) data of  $3 \times 30 \mu\text{m}^2$  HBT at  $V_{CE} = 2, 4, 8, 16, 24$  V.

### III. MODELING RESULTS

The model was derived in two steps. First, a single-finger transistor with an emitter area of  $3 \times 30 \mu\text{m}^2$  was investigated. This device was measured on-wafer. Second, the power cell with an emitter area of  $4000 \mu\text{m}^2$  was modeled.

Measured and simulated output I-V-curves are shown in Fig. 1. Besides the self-heating, which leads to the negative slope of the curves, a quasi-saturation effect is seen at high currents, indicated by the dashed line in the figure. This effect is commonly not observed in low-voltage HBTs. It can be explained by the resistance of the undepleted portion of the collector, which increases with thickness. In order to account for it properly, the formulation of the epi-layer resistance from the Mextram model [9] was implemented into the FBH model. As shown in the figure, it is well suited to describe the quasi-saturation effect also for GaAs-based HBTs. However, it turned out during the investigation that a dynamic collector resistance can harm the numerical robustness of the model in case of strong self-heating. Therefore, it was decided to neglect the effect. It is suspected that quasi-saturation will not impact the power performance significantly when the device is biased at  $V_{ce} = 26$  V. This approximation will be justified by the large-signal simulations presented at the end of the paper.

Measured and modeled  $S$ -parameters for  $V_{ce} = 8$  V up to 20 GHz are shown in Fig. 3 a and b, and Fig. 2 shows the bias-dependence of the transit frequency  $f_t$  extracted from measured and simulated  $S$  parameters. It can be seen that even the strong bias dependence of  $f_t$  is predicted well by the model. It should be noted that the corresponding extrapolated values of  $f_{max}$  range from 40...100 GHz, which leads to the high gain of 14 dB at 2 GHz measured in power amplification mode [3]. Also for the  $S$ -parameters themselves, the agreement between measurement and simulation is good.

The large-signal model was derived from the range of bias points as shown in Fig. 2, in order to keep the dissipated power, and thereby the self-heating, low. Therefore, already the bias point targeted for normal device operation at 26 V

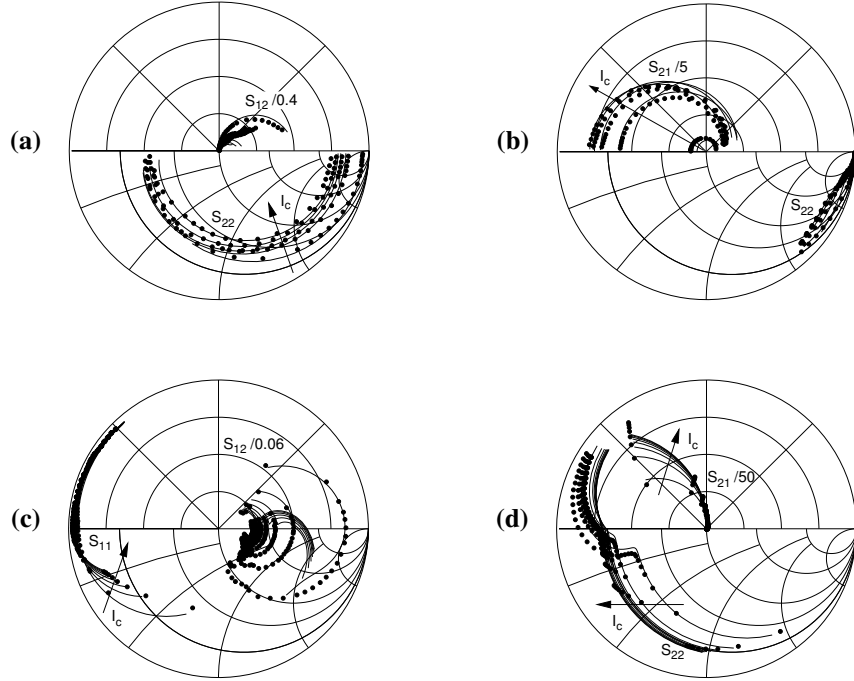


Fig. 3. Measured (symbols) and simulated (lines)  $S$ -parameters at  $V_{ce} = 8$  V,  $f = 50$  MHz...20 GHz. (a),(b): Single-emitter HBT,  $I_c = 1 \dots 12$  mA, (c),(d): HBT power cell,  $I_c = 16 \dots 190$  mA.

will be outside this region.

These results for the single-finger HBT were then used to derive the model for the power transistor. Since the layout of the individual emitter fingers of the power cell differs from that of the small transistor, and also due to the large difference in size, the parameter set for the power cell cannot be derived simply by scaling rules [8] but requires correction. It turned out that only slight adjustments to the set of parameters were necessary in order to describe the power cell. A comparison of measured and modeled  $S$ -parameters up to 20 GHz at  $V_{ce} = 8$  V is shown in Fig. 3c and d. The good agreement between measured and modeled values justifies the approach to use a compact, non-distributed model.

Finally, simulation results are compared to load-pull measurements in Fig. 4. In Figs. 4a and b, results for  $V_{ce} = 26$  V are presented, Figs. 4c and d refer to the corresponding data for  $V_{ce} = 22$  V. Both source- and load-pull was performed, with a load reflection coefficient of  $\Gamma_l = 0.5 \angle 154^\circ$ . The base bias of  $V_{be} = 1.2$  V was provided by a constant voltage source with a ballasting resistance of  $33 \Omega$ . Therefore, the collector DC current  $I_c$  is allowed to increase according to the voltage swing with increasing input power. Figs. 4b and d show that this self-biasing behavior of the device is predicted well by the model for both bias conditions. Figs. 4a and c demonstrate that also output power  $P_{out}$  and power-added efficiency  $PAE$  are described by the simulations with good accuracy.

Summarizing one can state that the model predicts the

high-power operation very well. When evaluating this result one should keep in mind that the model parameters for the high current densities were determined only by scaling from the small single-finger device, and that voltages beyond 24 V even were not measured at all during parameter extraction. This gives further evidence that the approach presented here yields reliable models for ‘high-voltage’ HBT power cells, which are suited for practical circuit design.

#### IV. CONCLUSIONS

This paper presents modeling results for ‘high-voltage’ GaAs HBTs. The devices were developed for operation at supply voltages of 20 V, and beyond, and were shown to deliver more than 14 W output power at 2 GHz. While these HBTs now are quite mature, no practical full-featured model for circuit design has been published in the literature so far. The results presented here prove that a compact lumped model is capable of simulating such power cells with good accuracy. The model employed for the task is the FBH model.

This result is significant for several reasons:

1. The model itself is capable of describing ‘high-voltage’ devices without adjustments, despite the fact that it was developed for ‘low-voltage’ HBTs with a different layer structure and technology.
2. The model is able to predict the device performance at high currents and voltages, though ‘high-voltage’ HBTs cannot be measured with fixed DC bias throughout the full range

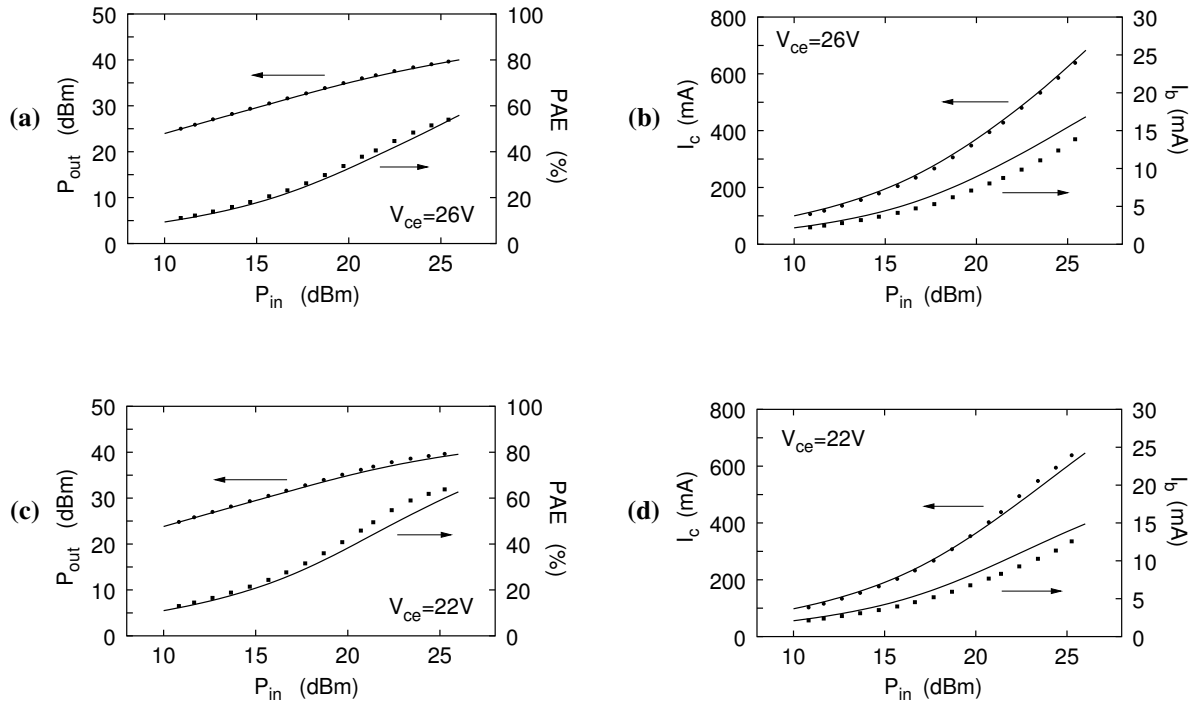


Fig. 4. Output power and DC collector current as a function of input power with bias voltage as parameter: load-pull measurements (symbols) and simulations (lines) at 2 GHz, for  $V_{CE} = 26$  V (a, b) and  $V_{CE} = 22$  V (c, d).

of currents and voltages which are reached dynamically during nonlinear operation. Therefore, scaling of the parameters from small to large transistors had to be employed. Obviously, the uncertainties caused by this procedure do not deteriorate accuracy.

3. Finally, a numerically robust and compact model can be provided for use in practical circuit design.

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#### REFERENCES

- [1] N.L. Wang, W. Ma, X. Chen, X. Sun, H.F. Chau, C. Dunnrowicz, Y. Chen, B. Lin, I.L. Lo, C.H. Huang, M.H.T. Yang, "Linearity Improvement of Multi-Watts 24-28V InGaP/GaAs HBT by Low Frequency Low Source Impedance Matching," in *IEEE MTT-S Intl. Microwave Symp. Dig.*, 2004, pp. 541 – 544.
- [2] Triquint Semiconductor, "High Voltage HBTs for 3G W-CDMA Base Station Power Amplifiers", *Microwave Journal*, Oct. 2004.
- [3] P. Kurpas, A. Maaßdorf, M. Neuner, W. Doser, P. Heymann, B. Janke, F. Schnieder, T. Bergunde, T. Graßhoff, H. Blanck, Ph. Auxemery, W. Heinrich, J. Würfl, "Flip-Chip Mounted 26 V GaInP/GaAs Power HBTs," in *IEEE IEDM Dig.*, 2004, pp. 561 – 564.

- [4] S. Heckmann, R. Sommet, J.-M. Nébus, J.-C. Jacquet, D. Floriot, Ph. Auxemery, R. Quéré, "Characterization and Modeling of Bias Dependent Breakdown and Self-Heating in GaInP/GaAs Power HBT to Improve High Power Amplifier Design," *IEEE Trans. Microwave Theory Tech.*, vol. 50, pp. 2811 – 2819, Dec. 2002.
- [5] M. Rudolph, F. Schnieder, W. Heinrich, "Modeling Emitter Breakdown in GaAs-Based HBTs" in: *IEEE MTT-S Int. Microwave Symp. Dig.*, 2003, pp. 651 – 654.
- [6] P. Kurpas, F. Brunner, W. Doser, A. Maaßdorf, R. Doerner, M. Rudolph, H. Blanck, W. Heinrich, J. Würfl, "Development and Characterization of GaInP/GaAs HBTs for High Voltage Operation", in: *International Conf. GaAs MANufacturing TEChnology, Las Vegas, USA, 21. – 24. May 2001*
- [7] M. Rudolph, R. Doerner, K. Beilenhoff, P. Heymann, "Unified Model for Collector Charge in Heterojunction Bipolar Transistors," *IEEE Trans. Microwave Theory Tech.*, vol. 50, pp. 1747 – 1751, July 2002. The FBH HBT Model is available at <http://www.fbh-berlin.de/modeling.html>
- [8] M. Rudolph, R. Doerner, K. Beilenhoff, P. Heymann, "Scalable GaInP/GaAs HBT Large-Signal Model," *IEEE Trans. Microwave Theory Tech.*, vol. 48, pp. 2370 – 2376, Dec. 2000.
- [9] J.C.J. Paasschens, W.J. Kloosterman, R. v.d. Thoor, "Model Derivation of Mextram 504 — The Physics Behind the Model", *Koninklijke Philips Electronics, Nat.Lab. Unclassified Report NL-UR 2002/806*, March 2002.