Large-Signal HBT Model Requirements to Predict Nonlinear Behaviour

M. Rudolph, R. Doerner
Ferdinand-Braun-Institut für Höchstfrequenztechnik (FBH)
Albert-Einstein-Str. 11, D-12489 Berlin, Germany, (e-mail: rudolph@fbh-berlin.de)

Abstract— **Measurements and simulations are carried out in order to determine the requirements for a HBT model to predict the generation of harmonics. Unlike investigations based on Volterra series, also the case of large excitations is investigated, where the load-line reaches through wide ranges of currents and voltages, and self-biasing effects take place. It turnes out that in class A operation, it is absolutely necessary for the model to account for the current dependence of the base-collector capacitance and collector transit time, even in a set-up where fundamental power and bias points are predicted well also without.**

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

I. Introduction

HUGE efforts were spent recently to investigate the main sources of nonlinear behaviour of GaAs-based heterojunction bipolar transistors (HBTs). Most of the investigations focused on the weakly nonlinear case and employed a Volterra series approach to determine intermodulation properties [1]–[6]. It turned out that while the nonlinearity of the base-emitter junction elements tend to cancel out [1], mainly the current dependence of the base-collector capacitance C_{bc} and of the transit time τ cause intermodulation distortion [5], [6]. Therefore, the influence of different collector designs and bias points were studied in order to find optimum linearity conditions [5], [7]. However, investigation of intermodulation intercept points and Volterra series methods are limited to excitations near to the small-signal condition. It can be a question in circuit design, to which extent the individual nonlinearities significantly contribute to the HBT behaviour, if the loadline covers wide ranges of voltages and currents.

Nowadays, several dedicated large signal models for GaAs and InP-based HBTs account for the C_{bc} and τ variation, but only a few are publicly available [8], [9], [10]. Circuit designers, therefore, often are forced to use standard models which approximate the behaviour of these devices more or less well. It is especially the question which features of a large-signal model are required at minimum to allow for realistic power simulations.

In this paper, the power performance of state-of-the-art GaInP/GaAs HBTs fabricated in the FBH process [11] is investigated. At different initial bias points, the output power at fundamental and higher harmonic frequencies are measured and simulated as function of input powers in a 50-Ω-system. The advantage of this measurement is that both weakly nonlinear and highly nonlinear cases are present. The quiescent bias points are limited to current densities around 40 kA/cm^2, as one would do in the practical case to ensure long term reliability. But dynamically, the DC currents increase with input power, since the base bias voltage is applied by a low-impedance source, so that they exceed this value by two,and the dynamic loadline peaks at even higher values.

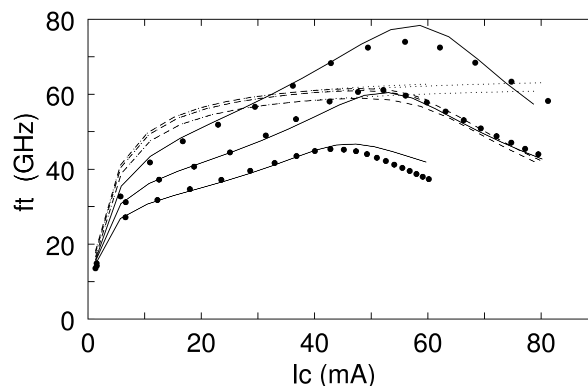

Fig. 1. Measured (symbols) and simulated (lines) f_t at V_{CE} = 1.5, 3, 5 V. Solid lines: advanced GaAs-HBT Model, dashed lines: model without velocity modulation, dotted lines: model neglecting velocity modulation and base push-out.

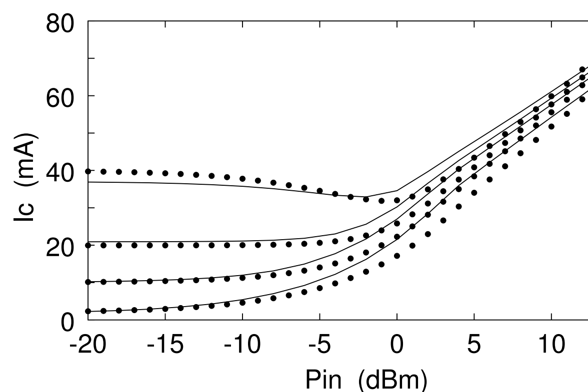

Fig. 2. Measured (symbols) and simulated (lines) DC collector currents I_C, at V_{CE} = 3V, as a function of available input power.

The measurements will be compared to harmonic balance simulations with the full featured FBH HBT model [9]. The model can be reduced step by step to the Gummel-Poon

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model in order to determine the influence of the various effects.

II. The HBT Model

The FBH HBT model is based on the Gummel-Poon description, but extended as necessary to describe GaAs-based HBTs. Self-heating is accounted for as well as parasitic base-emitter currents and partition of the base-collector diode into intrinsic and extrinsic part [12]. In the output IV curves shown in Fig. 3a, the reduction in current gain due to self-heating can be seen. The RF behaviour of the HBT is dominated by the current-dependent transit time τ and C_{bc}, which are modeled in a unified manner by a single collector charge function [9]. The shape of the f_t curves of the $3{\times}30\,\mu\text{m}^2$ HBT under test as shown in Fig. 1 are typical for GaAs-based HBTs. Between approximately 10 mA and 50 mA, f_t increases almost linearly due to velocity modulation in the collector space-charge region. At higher currents, f_t drops due to base push-out. The dashed and dotted curves in the figure show f_t values simulated without current-dependent τ and C_{bc} as in the Gummel-Poon model. Only at very low currents ($<$10 mA in the present case), the model fits the measurements. At these currents, however, the emitter charging time dominates. f_t strongly depends on the base-collector voltage, too, also due to velocity modulation in the collector space-charge region, which is not reflected in case of the Gummel-Poon description. In order to allow for a fair comparison, the parameters describing C_{bc} and τ in the simplified case are adjusted to represent an average bias point of the measurements, as seen in Fig. 1 for f_t.

III. Measurement and Simulation Results

The measurements were carried out at 6 GHz in a 50-Ω-System. Output powers up to the fourth harmonic were measured by a spectrum analyzer as a function of available input power. Since the base DC bias voltage was fixed, the collector current was allowed to increase significantly with input power, as shown in Fig. 2. The initial bias points shown here range from $I_C = 40$ mA down to $I_C = 2$ mA at $V_{CE} = 3$ V, corresponding to class A to class AB operation. Also the cases of $I_C = 2 \ldots 20$ mA at $V_{CE} = 1$ V, near to the saturation region, are investigated.

In the following, only simulation results obtained with the full-featured model are compared with a model that ignores the velocity modulation effects, but still accounts for self-heating, partition of base-collector diode and parasitic base-emitter currents. The reasons are that neglecting the partition of the diode not really is an issue at this rather low frequencies, provided that intrinsic and extrinsic part are modeled identically, as in the simplified case. Neglecting the parasitic currents also is unimportant, since they are visible only to a sharp eye for mature epitaxy and process technology. Hence, their impact on power performance or even the DC bias point is negligible, too. The opposite is true, however, in case of the thermal model. Since self-heating is only due to low-frequency signals, neglecting it will result in different bias points and self-biasing behaviour. Differences in the large-signal behaviour will therefore mostly be due to different bias conditions, which makes it difficult to draw a useful conclusion. On the other hand, also the shift in the saturation region due to different thermal coefficients of the base-emitter and base-collector junctions turned out to be of only minor importance in the present case.

The initial bias points are chosen in the region below the onset of base push-out as one would do in a realistic circuit set-up. But the trajectory can reach deep into the base push-out region (see Fig. 3a), and the bias point reaches values beyond $I_c = 60$ mA, too, due to self-biasing. The difference concerning the resulting bias points between the advanced HBT model and the simplified one is almost negligible, although the DC current increases dramatically due to self-biasing.

Regarding the measurements at $V_{CE} = 1$ V, Fig. 3b-d, it can be seen that a slight improvement in the simulation accuracy by the GaAs-HBT model is only obtained in the case of 20 mA. At lower currents, the main source of nonlinearities is clipping of the signal either at I_C=0, or in the saturation region. If the currents and voltages are too low, the output current swing enters the saturation region almost immediately from linear operation, well before the week nonlinearities can show up. This is also true in case of the initial bias point of $V_{CE} = 3$ V, $I_C = 2$ mA, see Fig. 4a. Looking at the DC current I_C in this case (Fig. 2), it turnes out that self-biasing starts almost immediately even at low input powers, and the current rapidly increases. Although the current swing widely reaches through the region where f_t significantly changes, this adds only little to the nonlinearities. In this case that corresponds to class AB, clipping of the signal is dominant until the device is driven into saturation.

This picture changes when we start in class A mode, at $I_C = 10$, 20, or 40 mA, Fig. 4b-d. At all three bias points, the simplified model significantly underestimates the generation of harmonics. When the device is driven into saturation, however, again the clipping of the signal becomes dominant, and also the simplified models yield reasonable agreement with the measurements. It is noteworthy that there is almost no additional reduction in accuracy when the base push-out effect is not accounted for. Even though the trajectory reaches the base push-out region without touching the saturation region, the region of lower currents still is dominant and velocity modulation determines the linearity. This contradicts the case of smaller input signals, where only the nonlinearities close to the bias point affect the HBT performance.

In the present case, the fundamental output power is simulated well with the simplified model, too. This is probably

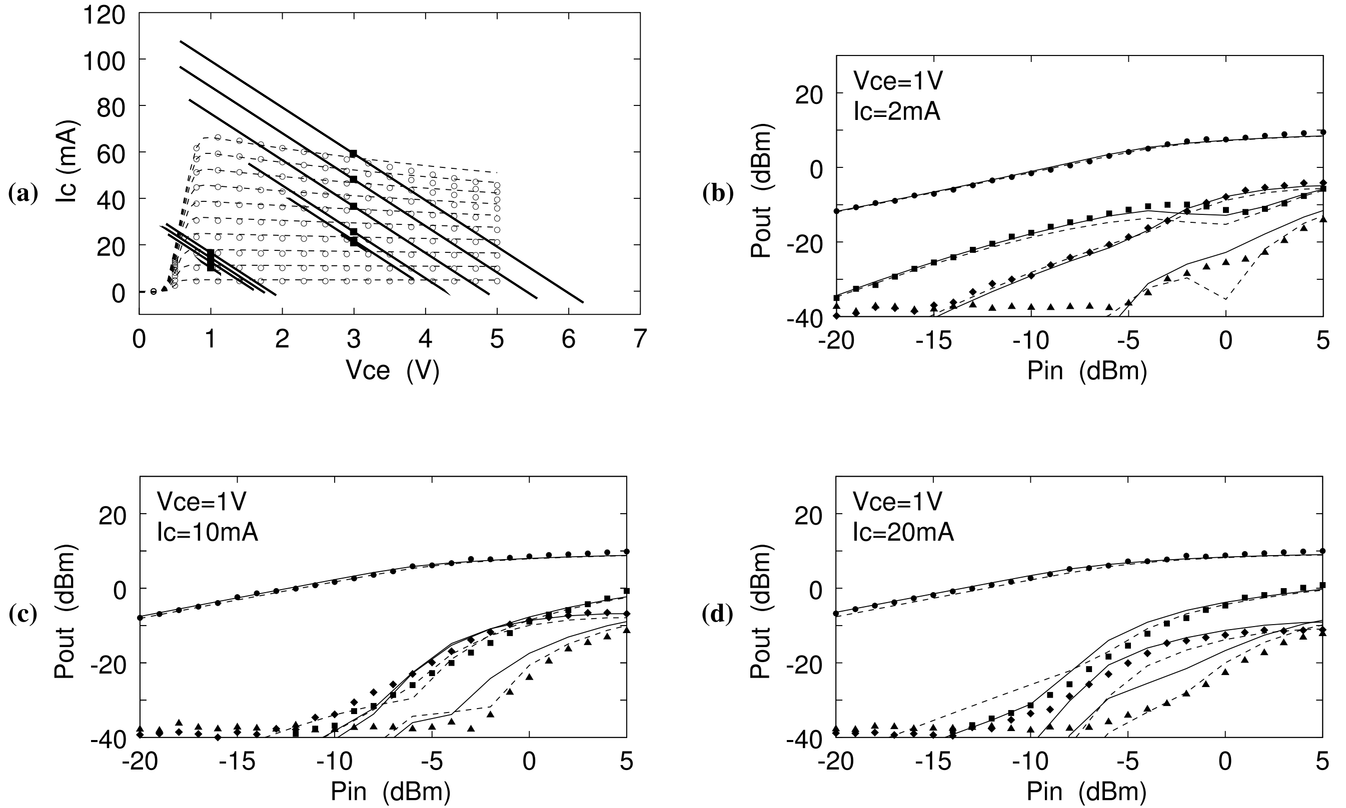

Fig. 3. **(a)** DC IV-Charactristics (measurements: symbols, simulation: broken lines), and simulated output trajectories for the initial bias points $I_C = 10$ mA, $V_{CE} = 1$ V ($P_{\rm in}$ = -20, -6, -2, 2 dBm) and $I_C = 20$ mA, $V_{CE} = 3$ V ($P_{\rm in}$ = -20, -6, -2, 2, 6, 10 dBm). Power-spectral measurement at $V_{CE} = 1$ V, $I_c = 2$ mA **(b)**, $I_C = 10$ mA **(c)**, and $I_C = 20$ mA **(d)**. Symbols: measurements, solid lines: simulated with full HBT model, broken lines: simulated neglecting velocity modulation.

the case since the HBT's output is highly mismatched to the 50-Ω load. It has been observed, that also the fundamental output power can be significantly affected by the current dependence of C_{bc} and τ in case of an optimum matched load in a load-pull measurement [9]. Even though self-biasing and fundamental output power may be predicted well using the simplified model as in this example, the generation of harmonics can be much too optimistic.

IV. Conclusions

Power measurements of GaInP/GaAs HBTs were carried out in order to asses the requirements of a large signal model to accurately describe output power and generation of harmonics at various power levels and bias points. The following conclusions can be drawn:

1. Parasitic base-emitter currents do not significantly contribute to the simulation results.
2. Clipping of the wave form, as in class AB or in saturation, is the dominating factor in the generation of harmonics.
3. In class A, the bias dependence of C_{bc} and τ has to be accounted for by the HBT model in order to predict the nonlinear behaviour accurately.
4. Although it can be possible to obtain good agreement between measurement and simulation for fundamental output power and bias point neglecting the C_{bc} and τ variations, this does not hold for the nonlinearity prediction.
5. To model linearity, the decrease of f_t in the base pushout region can be of minor relevance compared to the velocity modulation region in highly nonlinear operation, if the output load line only shortly touches or crosses this region.

In general, it can be concluded that for large-signal modeling of GaAs-based HBT's, it is crucial to account for the current dependence of C_{bc} and τ. Even in the best case, as shown in the measurements presented here, where this effect does not significantly contribute to output power and self-biasing behaviour, it proves to be a dominant factor for linearity prediction.

Acknowledgments

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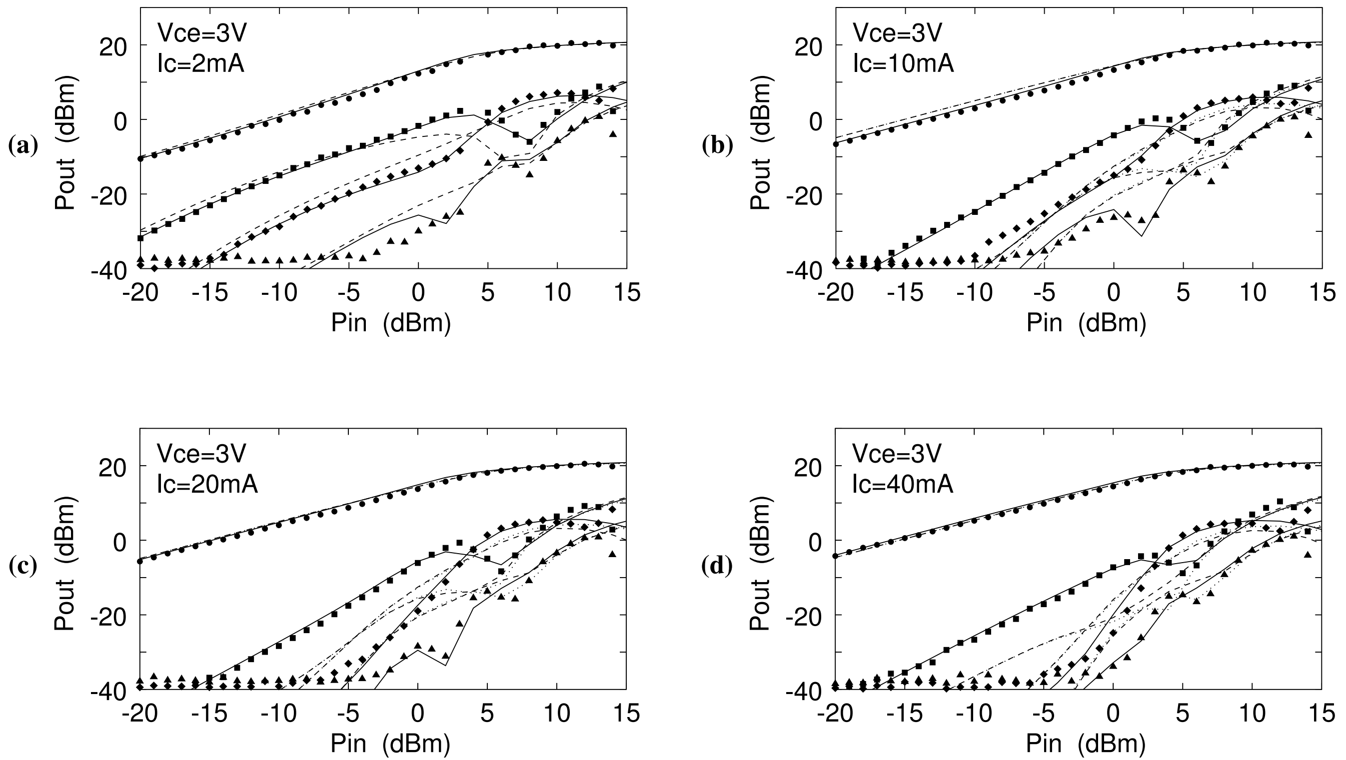

Fig. 4. Power-spectral measurement at $V_{ce} = 3$ V, $I_c = 2$ mA **(a)**, $I_c = 10$ mA **(b)**, $I_c = 20$ mA **(c)**, and $I_c = 40$ mA **(d)**. Symbols: measurements, solid lines: simulated with full HBT model, broken lines: simulated neglecting velocity modulation, dotted lines: simulated neglecting velocity modulation and base push-out.

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