6 Experimental Results

This chapter contains selected old (v2.1) examples that demonstrate HICUM's capabilities of modelling bias, frequency, geometry and temperature dependent transistor behaviour. In fact, v2.2 model provides same results as v2.1, if the additional model parameters of v2.2 are kept at their default values. Therefore, the same results can be reproduced with the v2.2 model as well. Once available, new experimental results corresponding to advanced bipolar/BiCMOS processes, verifying v2.2 model, will be provided. If not specified otherwise, all results were obtained using a *scalable single basic parameter set* (cf. chapter 3 and 4). The results cover not only a large variety of processes, ranging from low-speed (6 GHz) to high-speed (50 GHz SiGe) processes and even an example for a vertical pnp, but also various modes of operation (d.c. small-signal, large-signal). The major emphasis is on high-frequency (h.f.) characteristics and figures of merit that are related to h.f. (circuit) applications. Considering the above mentioned variables (bias, geometry, temperature, frequency), model verification is becoming a quite difficult task, the effort of which is often severely underestimated.

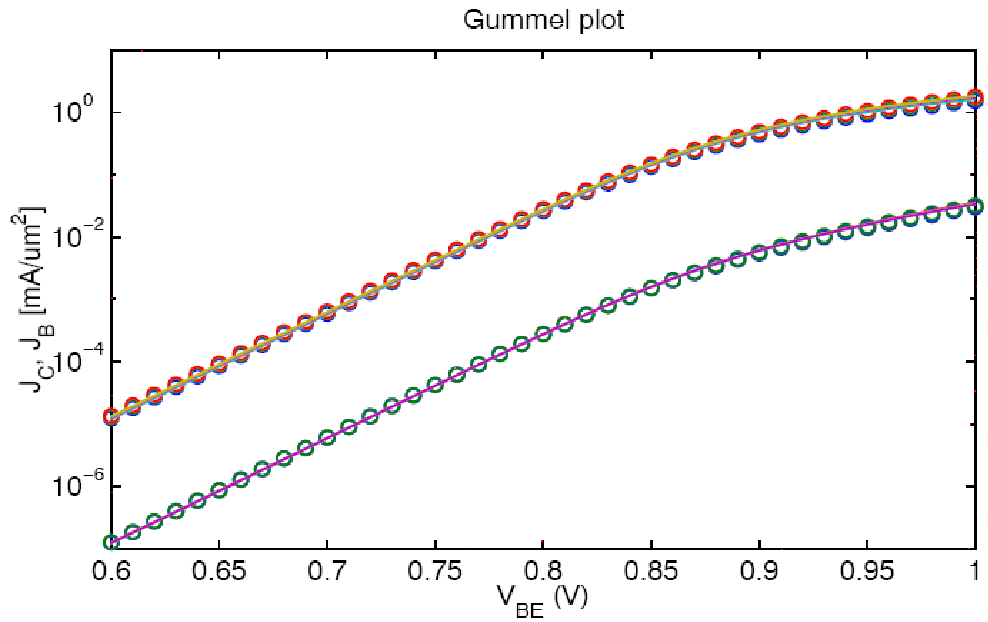
Wherever possible, the following comparisons are performed in normalized form and in variables that are related to circuit design; for instance, often the current density I_C/A_E is employed (to allow process comparisons), and the bias points are defined by $(I_C/A_E,V_{CE})$. The results do not contain examples for junction capacitance modelling, which has already been shown to be accurate. The experimental results given below cover the following areas:

- d.c. characteristics including I-V and current gain curves as well as conductances vs. bias.
- Bias dependence of transit time τ_f and transit frequency f_T. An accurate approximation of the transit time and the junction capacitances, which are a fundamental (linearly independent) variables in HICUM, guarantee an accurate modelling of composite parameters, such as f_T and *y*-parameters.
- For small-signal characteristics, *y*-parameters are preferred, since they can be easier linked directly to elements in the transistor equivalent circuit (e.g. [14,29,38]). The examples contain comparisons of all four *y*-parameters vs. frequency, bias, and geometry.
- High-speed switching is difficult to measure directly and accurately for today's fast transistors; therefore, HICUM was verified by 2D and 3D mixed-mode device/circuit simulation [39]. For older (slower) processes, however, HICUM could be verified experimentally [26,32].

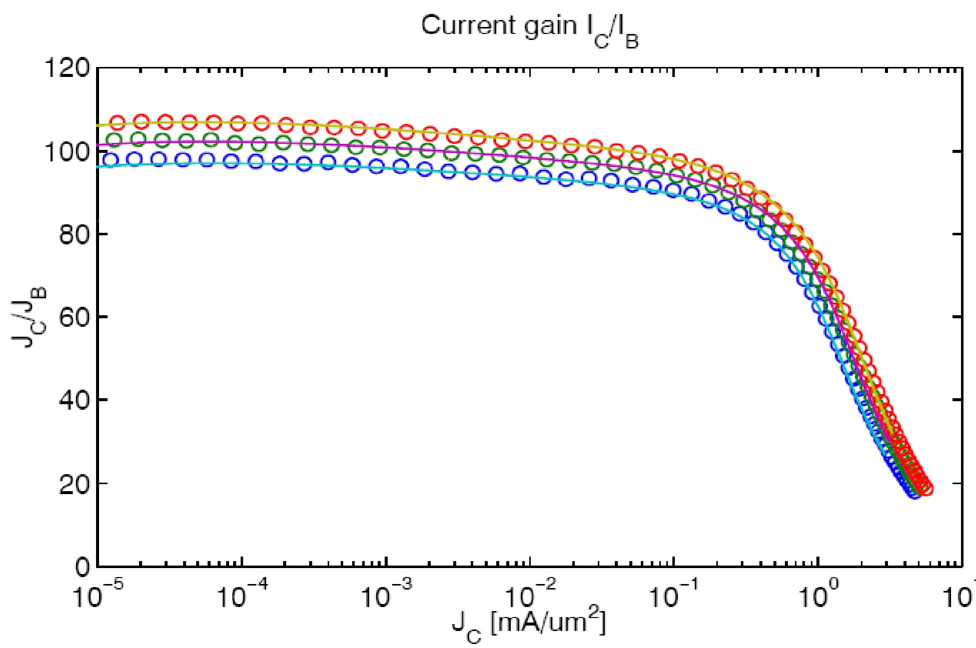
- Temperature dependent modelling has been pursued and compared to experimental data for several process generations (e.g. [32,33,43]), leading to reliable model formulations.
- Noise: both $1/f$ and high-frequency noise have been investigated as a function of bias, frequency and geometry (cf. [5,6,7,9]) and have been compared to measurements.
- Non-linear h.f. distortion can be considered as another way to verify a model's large-signal behaviour. In the presented examples, the output power P_{out} as response to a single-tone input power P_{in} is compared to measurements over frequency, bias and geometry for different types of transistors.
- Predictive and statistical modelling capability is important for reducing design cycle time, but have not been included for bipolar applications in commercial simulators and design tools in a physics-based and generic way. The given examples show f_T as one of several useful figures of merit (FoM) for high frequency applications; compared to other h.f. FoMs, f_T is clearly defined and can most easily be measured, although its measurement time is still not suitable for statistical data acquisition.
- Circuit results have been included for a CML ring-oscillator as standard benchmark circuit for digital applications. Sufficiently simple benchmark circuits for wireless applications are more difficult to obtain.

6.1 DC characteristics

(a)

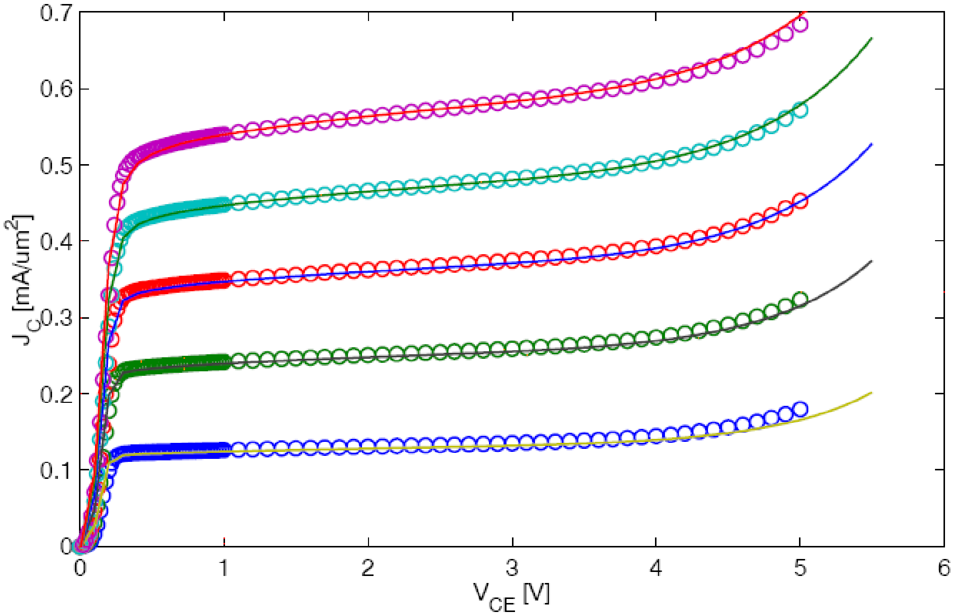


(b)

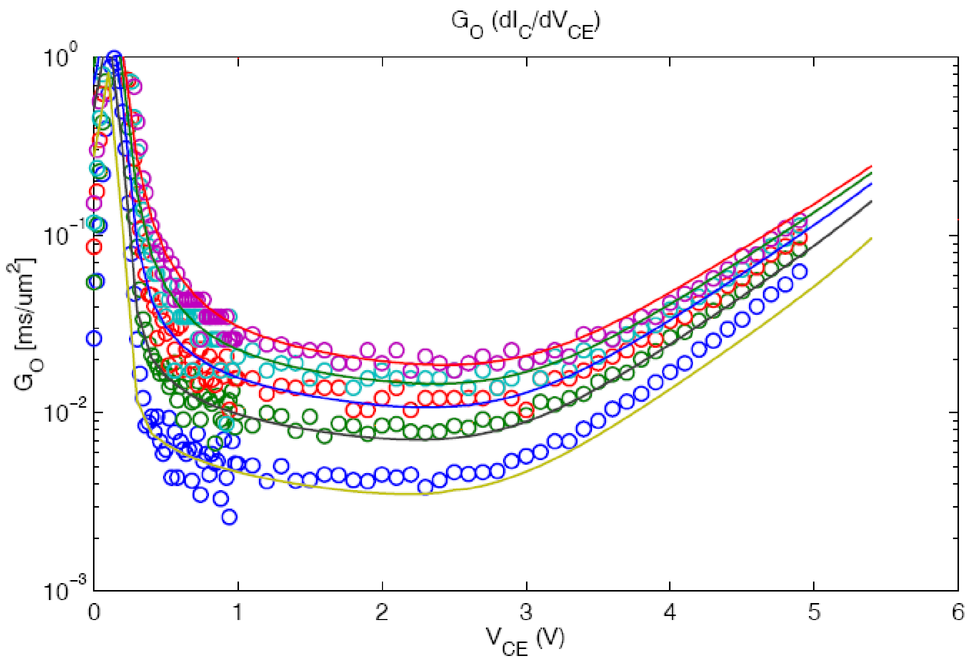


Comparison between measurement (symbols) and HICUM (solid lines) from a single transistor parameter extraction for a 12 GHz bipolar transistor [4]: (a) Gummel plot; (b) current gain. V_{BC}/V = 0,-2,-4; emitter size: 0.6*4.8μm^2

(a)

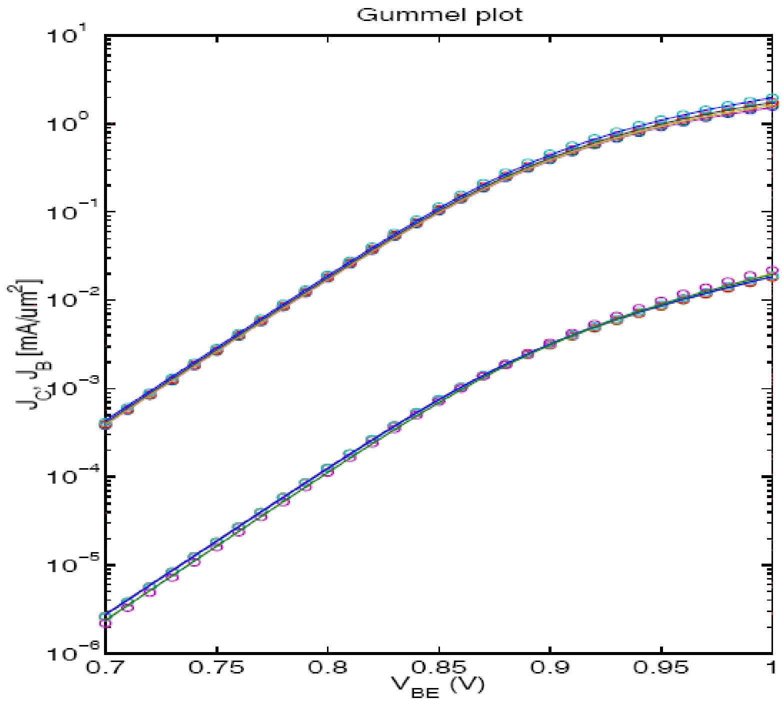


(b)

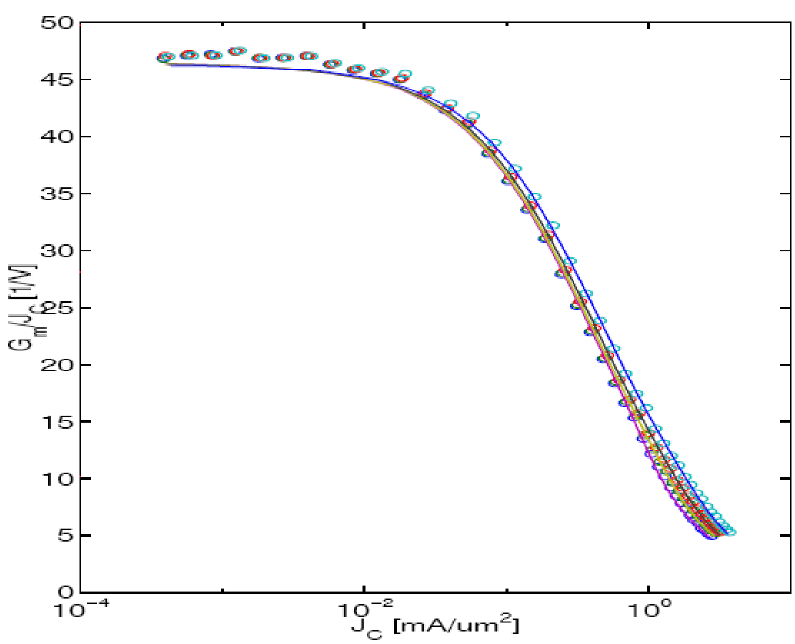


Comparison between measurement (symbols) and HICUM (solid lines) from a single transistor parameter extraction for a 12 GHz bipolar transistor [4]: (a) output characteristics for I_B=const; (b) output conductance dI_C/dV_{CE}; emitter size: 0.6*4.8μm^2

(a)



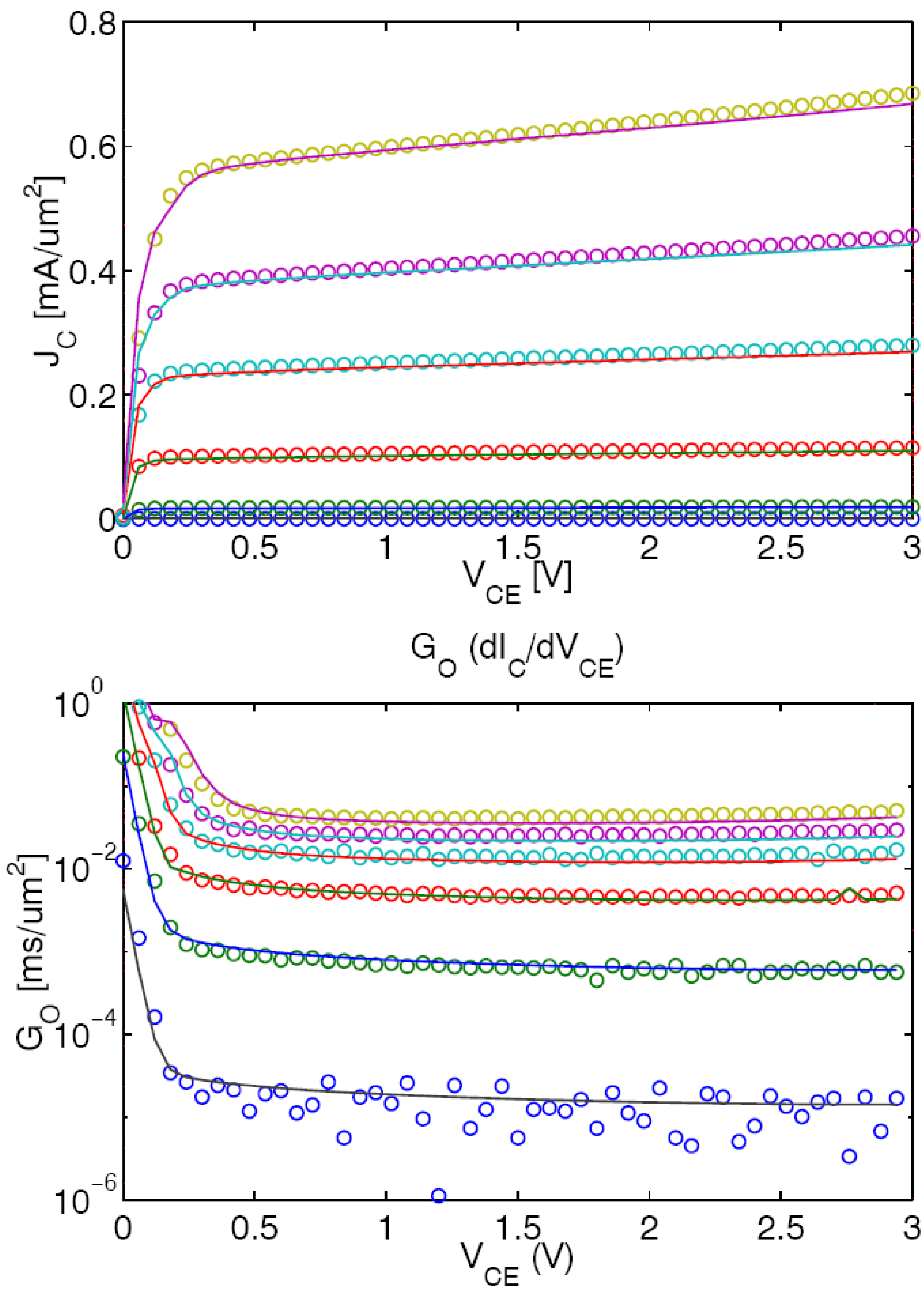
(b)



Comparison between measurement (symbols) and HICUM (solid lines) for a 25 GHz bipolar transistor: (a) Gummel plot; (b) normalized transconductance. V_{CE}/V=0.5,0.8,1.5,3; emitter size: 0.4*14μm^2

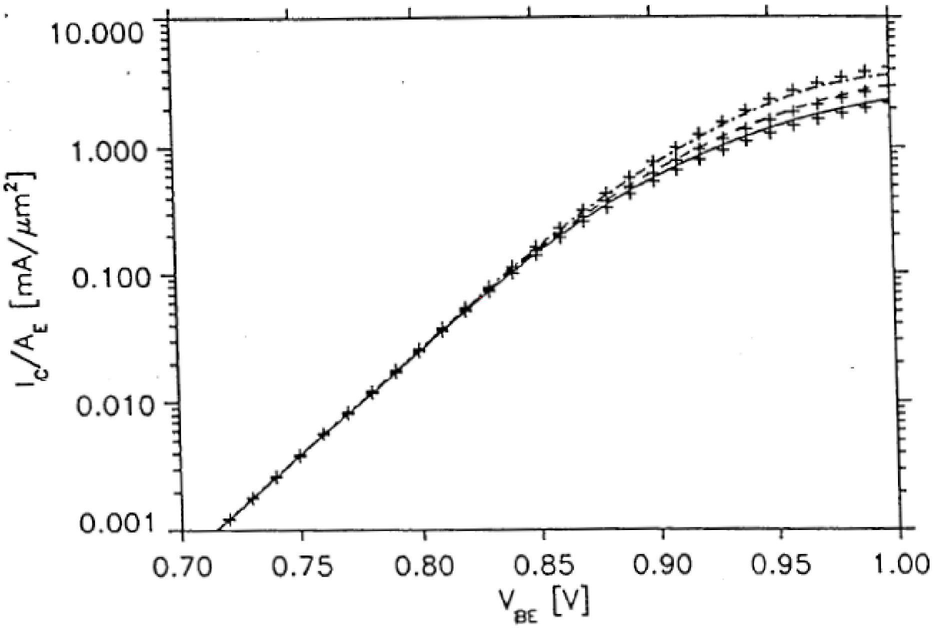
(a)

(b)

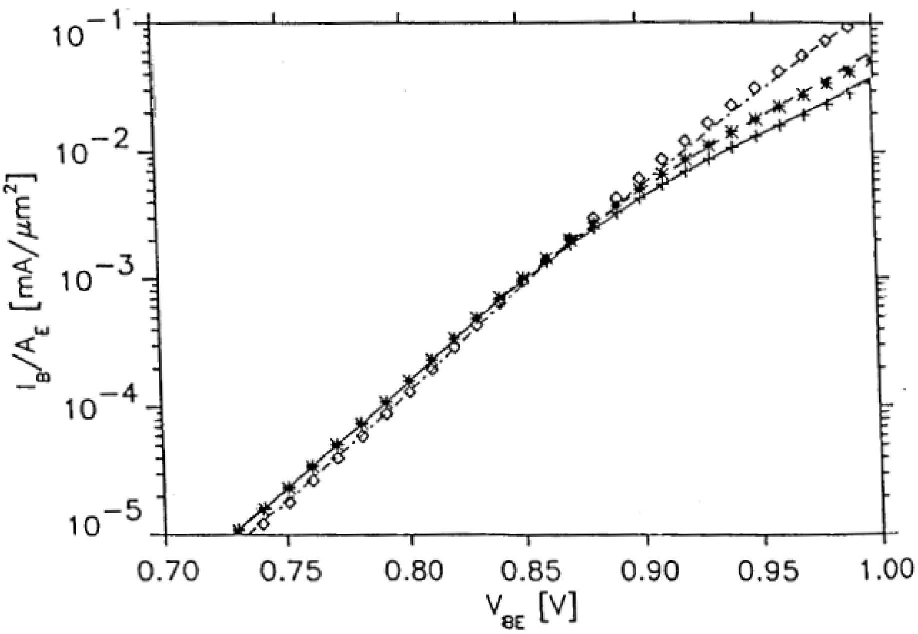


Comparison between measurement (symbols) and HICUM (solid lines) for a 25 GHz bipolar transistor: (a) output characteristics for V_{BE}=const; (b) output conductance dI_C/dV_{CE}; emitter size: $0.4*14\mu m^2$.

(a)



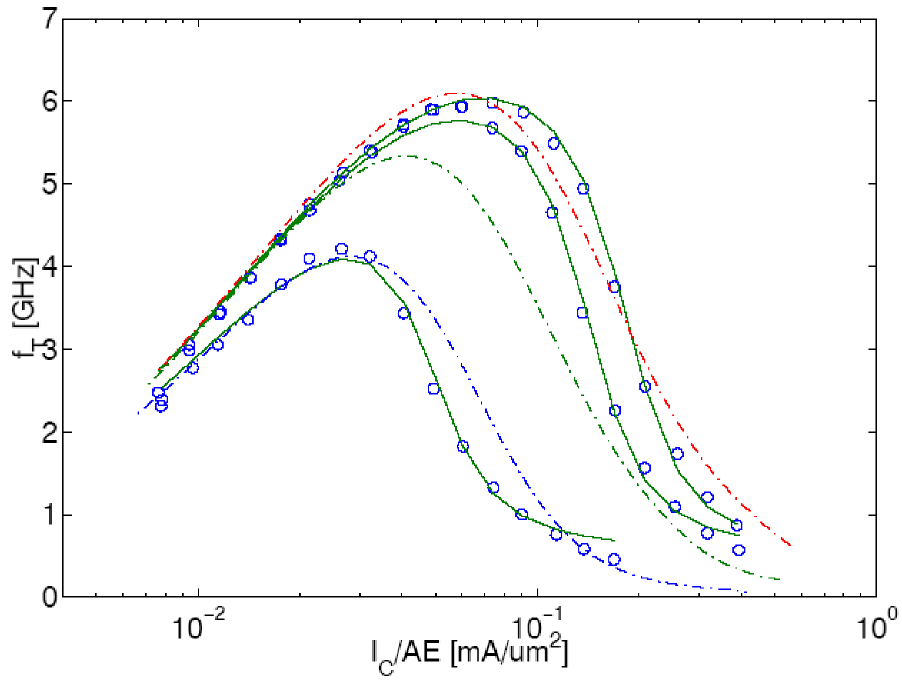
(b)



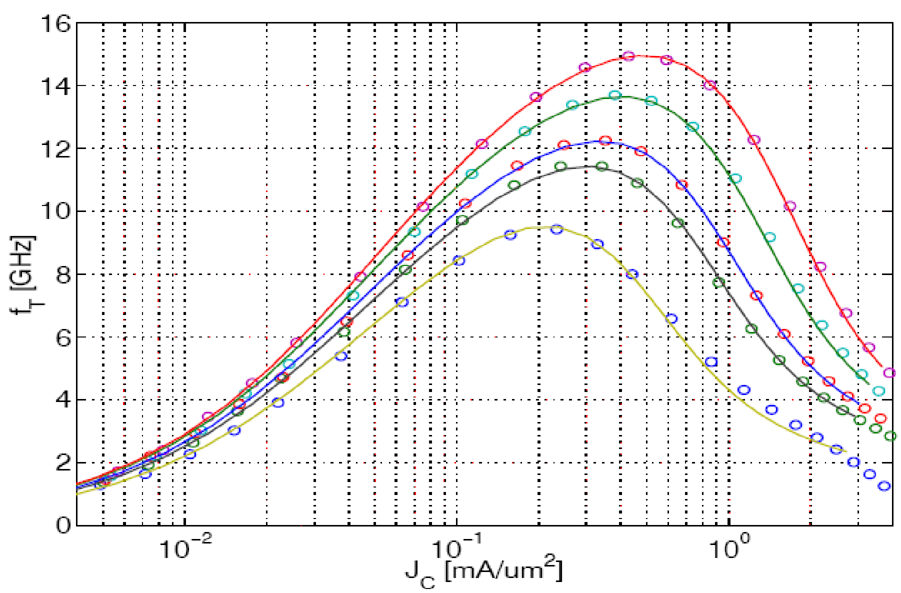
Comparison between measurement (symbols) and HICUM (solid lines) for a 45 GHz IBM SiGe bipolar transistor [49,50]: (a) collector current density; (b) base current density. V_{CE}/V=0.8,1.6,2.4; emitter size: 0.5*10μm^2. Self-heating and avalanche breakdown are quite pronounced for this transistor.

6.2 Transit frequency and transit time

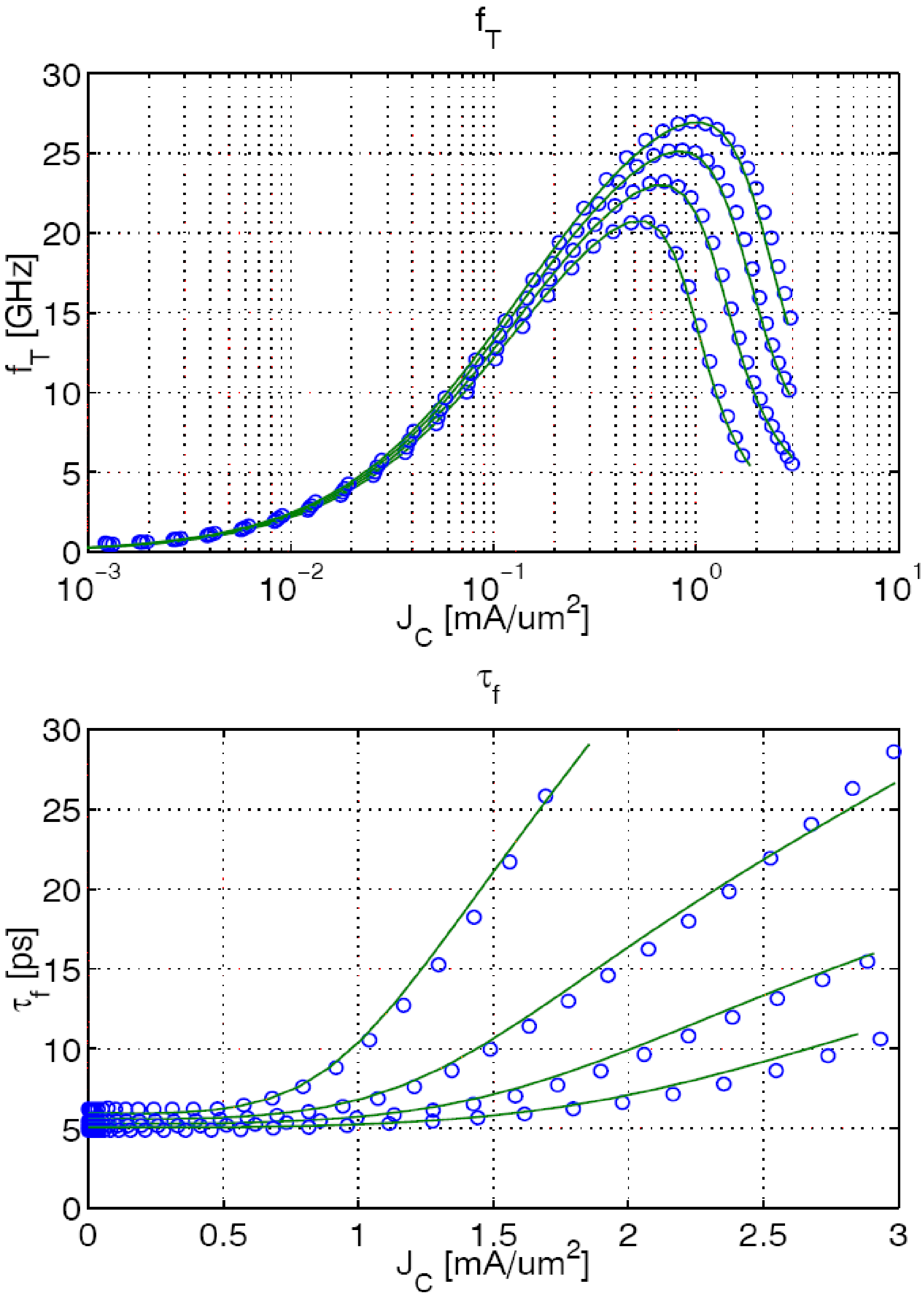
(a)



(b)

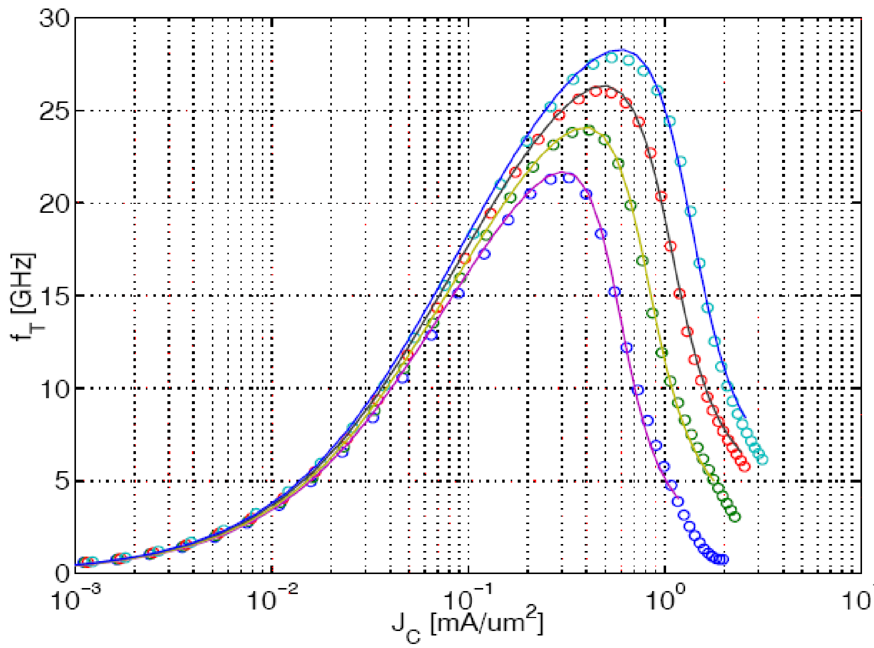


Transit frequency vs. collector current density (V_{BC}=const) for different bipolar processes. Comparison between measurement (symbols) and HICUM (solid lines) from single transistor parameter extraction: (a) emitter size 0.5*10µm^2, V_{BC}/V=0,-5,-10 (the dashed lines are the results of the SPGM) [18,43]; (b) emitter size 0.6*4.8µm^2; V_{BC}/V = 0.5, 0, -0.5, -2,-4 [4,18].

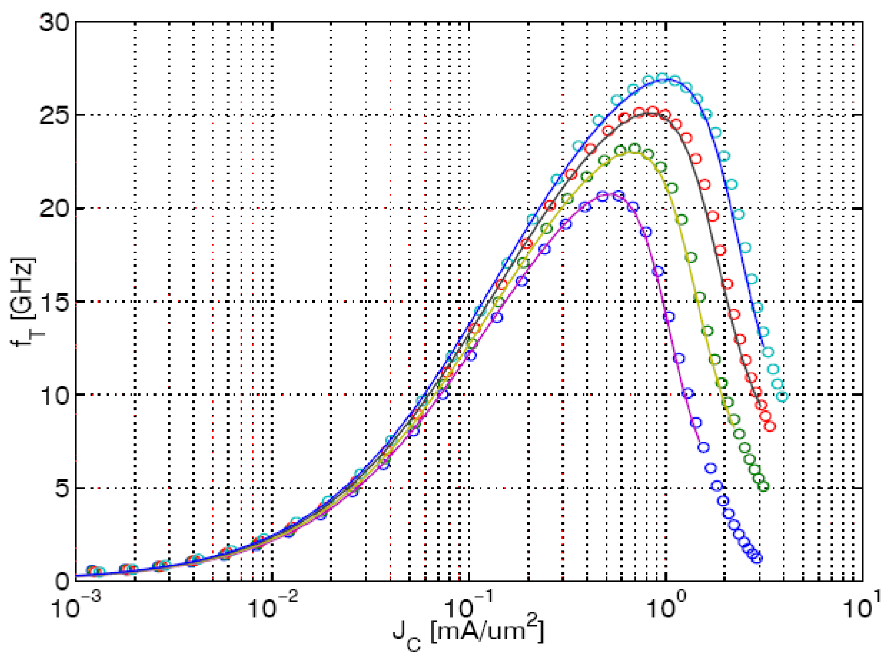


Comparison between measurement (symbols) and HICUM (solid lines) for a 25GHz bipolar process [43]: (a) transit frequency; (b) transit time. Emitter size 0.4*14µm^2, V_{CE}/V=0.5,0.8,1.5,3.

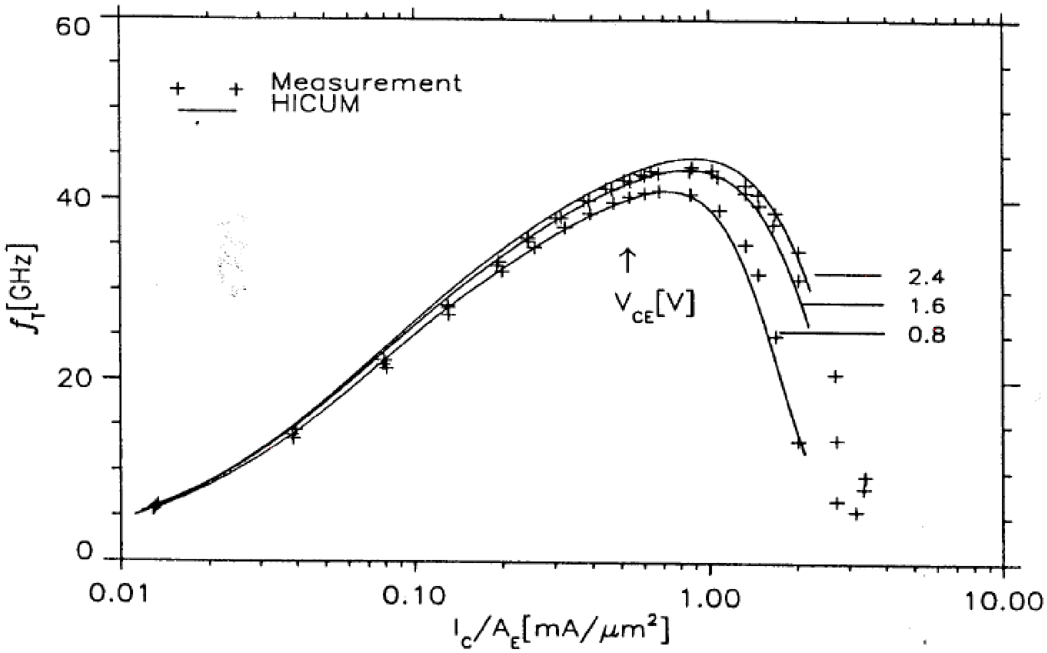
(a)



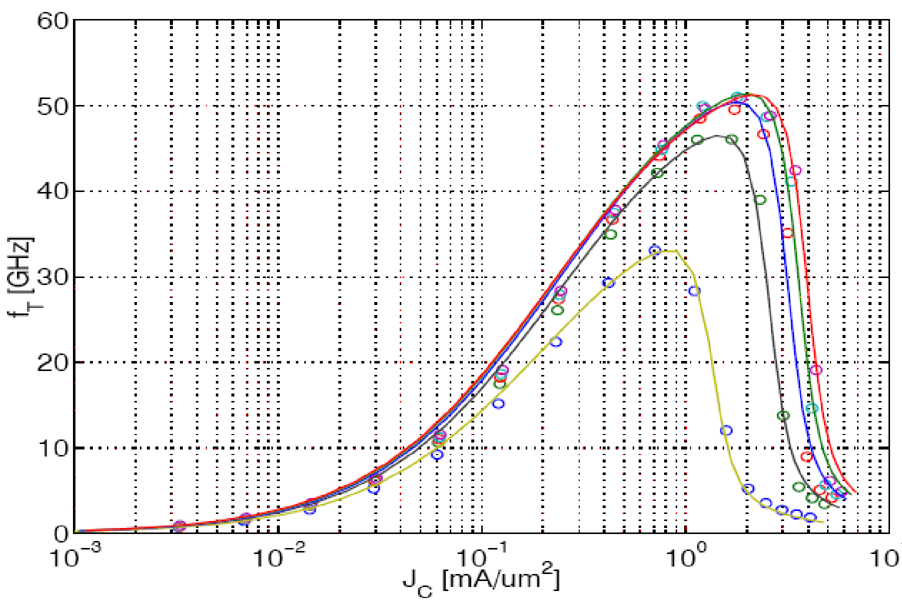
(b)



Comparison for the bias dependent transit frequency between measurement (symbols) and HICUM (solid lines) for a 25GHz bipolar process. Transistor size: (a) $1.2*14\mu m^2$; (b) $0.4*1.4\mu m^2$. V_{CE}/V=0.5, 0.8, 1.5, 3.



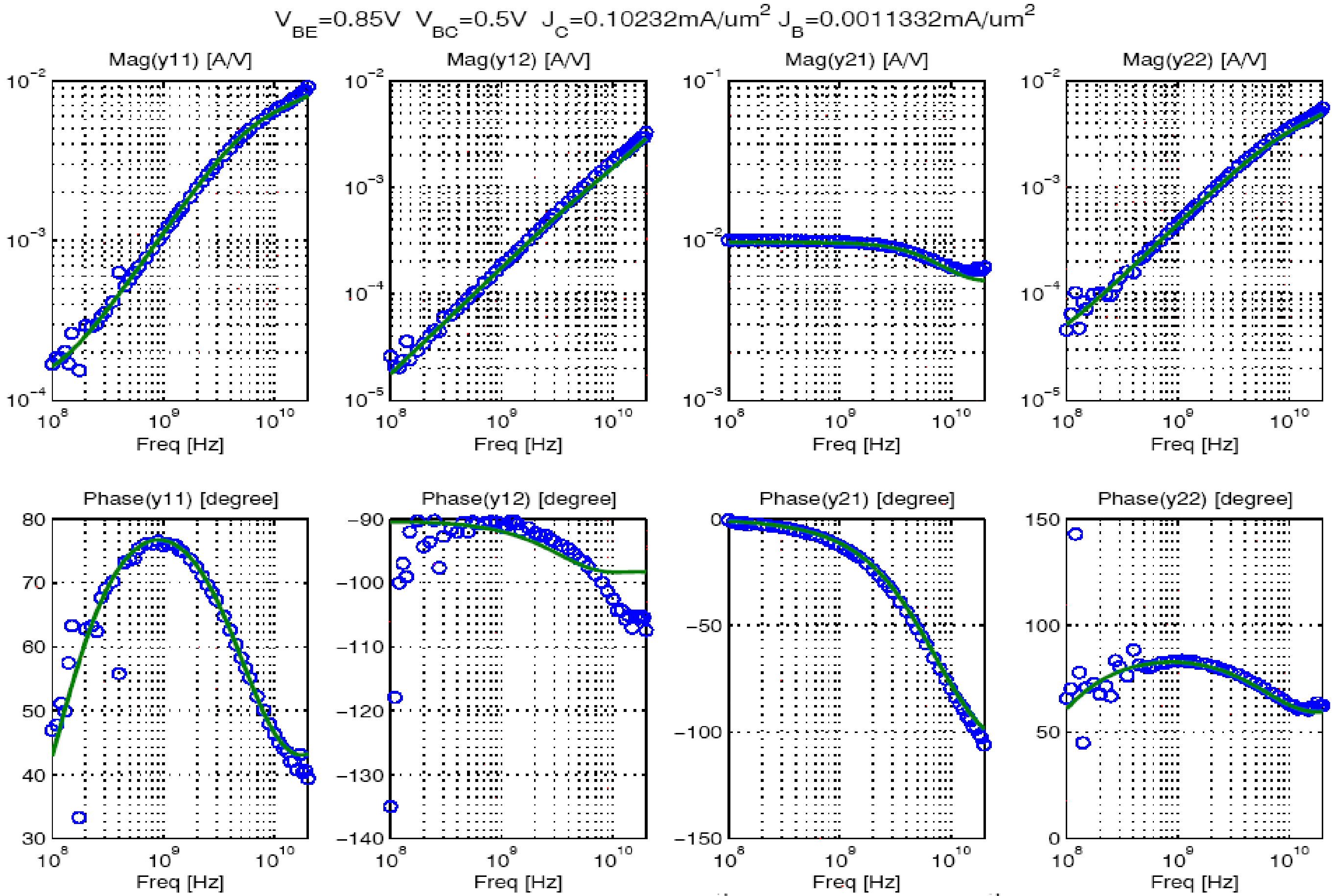
Bias dependent transit frequency of an IBM SiGe bipolar transistor. Comparison between measurement (symbols) and HICUM (solid lines) [50]; emitter size 0.5*10μm^2; V_{CE}/V=0.8,1.6,2.4.



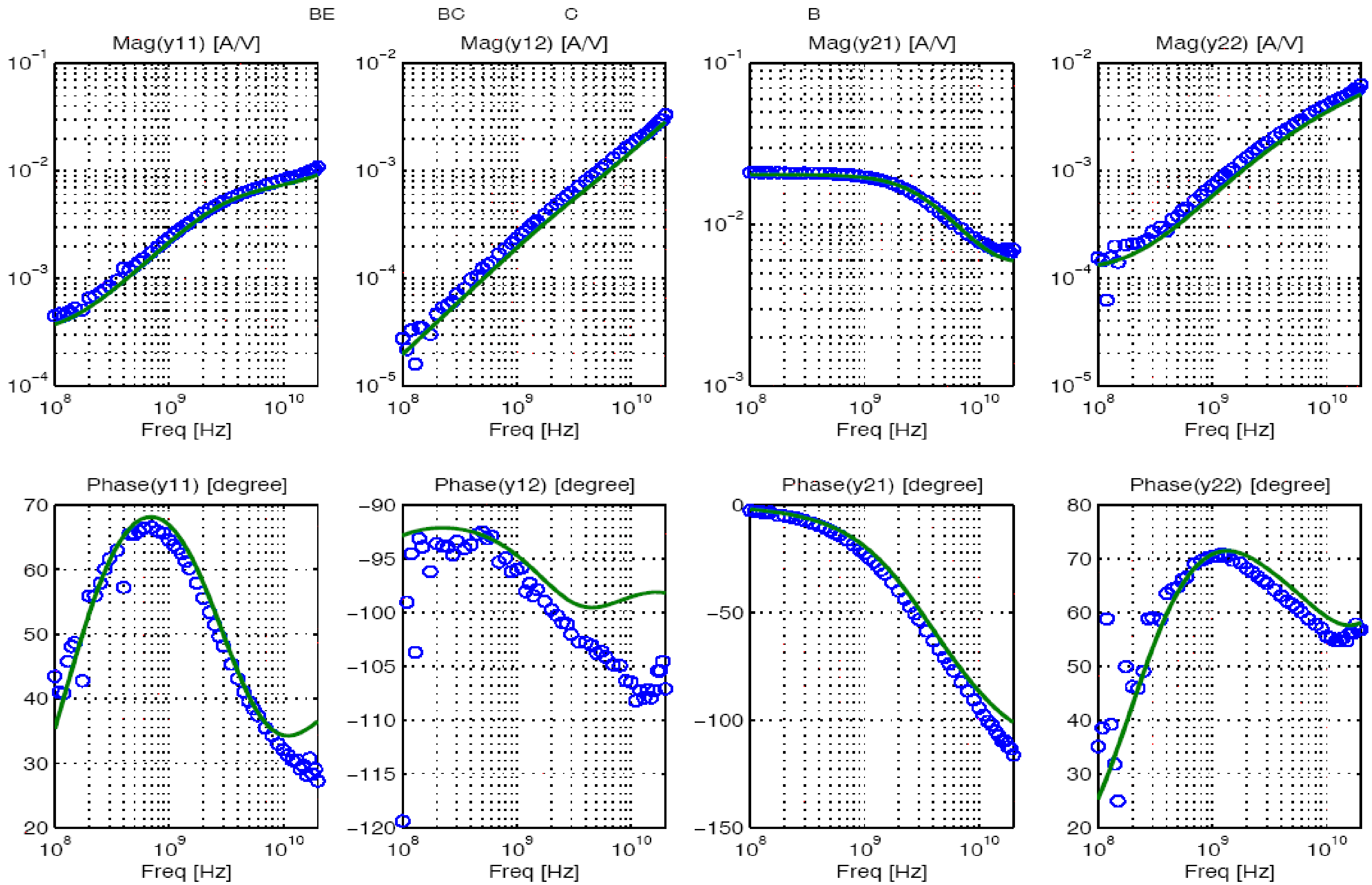
Bias dependent transit frequency of a SiGe bipolar process [4]. Comparison between measurement (symbols) and HICUM (solid lines); emitter size 0.4*2μm^2; V_{BC}/V = 0.5, 0, -0.5, -1, -1.5.

6.3 High-frequency small-signal characteristics

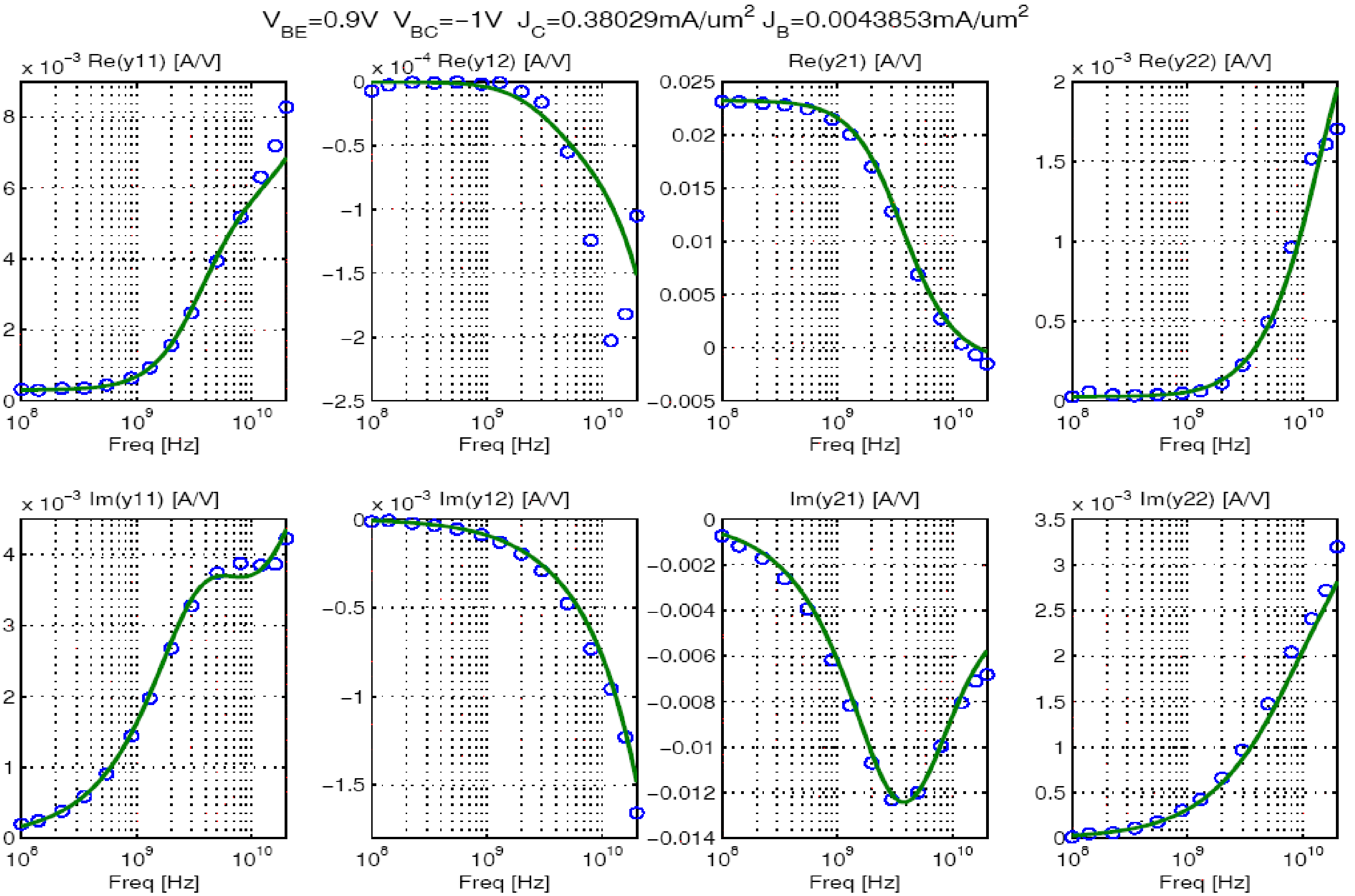
Note: real$\{y_{12}\}$ is very small and usually of little practical interest, but can cause the modelled phase of y_{12} to deviate from measurements.



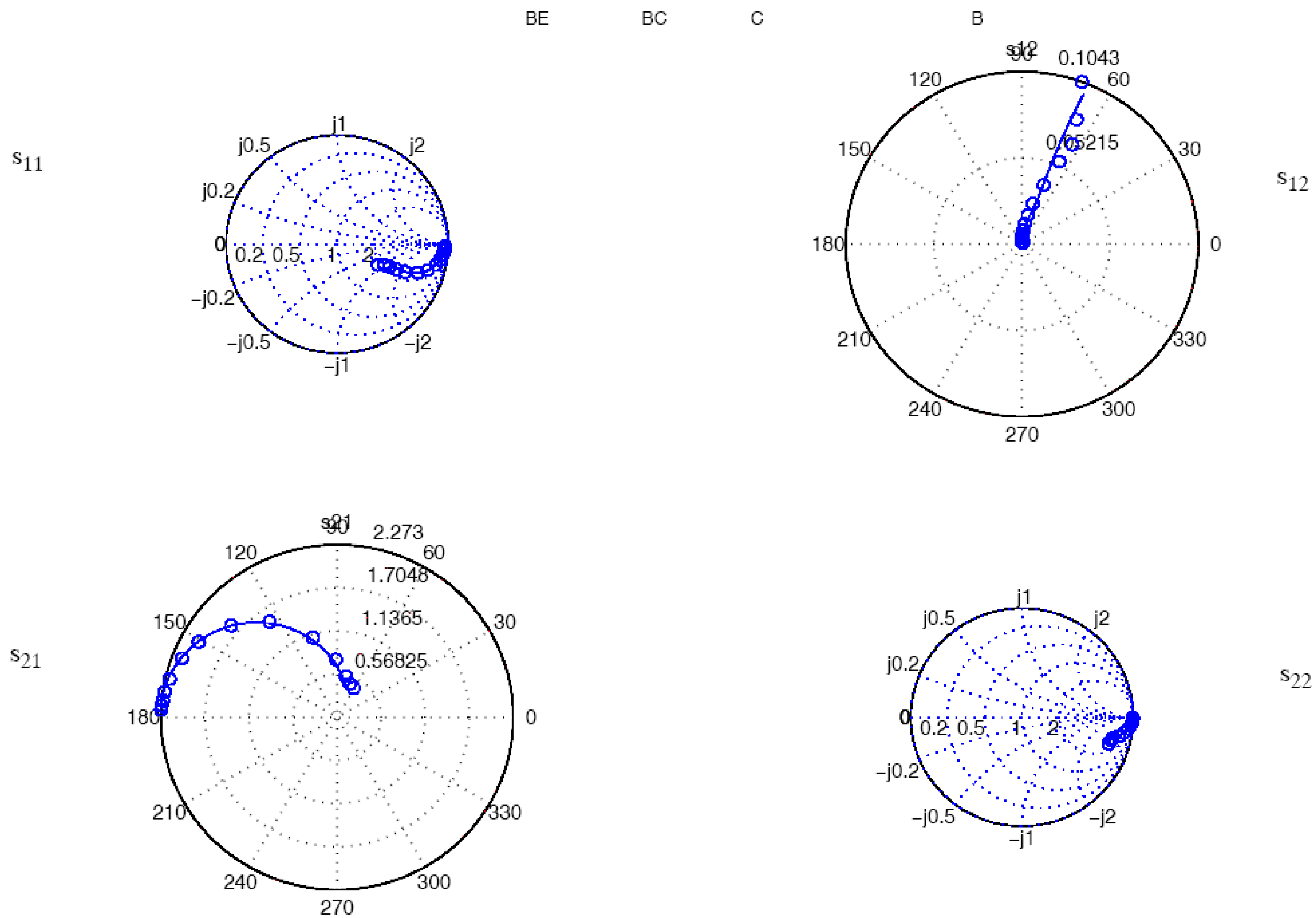
Frequency dependence of Y-parameters for a 12 GHz transistor (0.6*4.8µm^2) at I_C/A_E = 0.1mA/µm^2, V_{BC} = 0.5 V (cf. f_T curves): comparison between measurement (symbols) [4] and HICUM (lines). Single transistor parameter extraction.



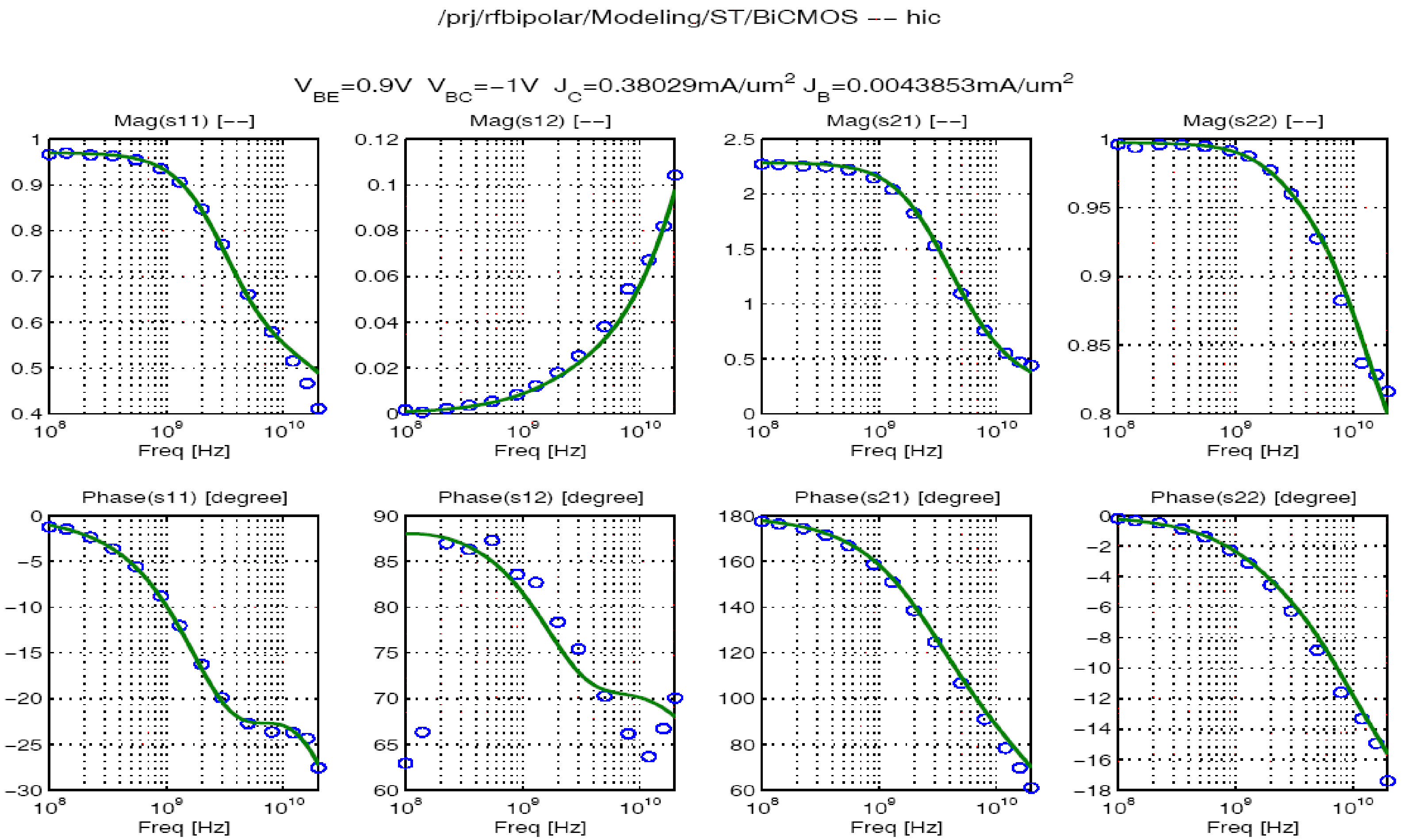
Frequency dependence of Y-parameters for a 12 GHz transistor (0.6*4.8µm^2) at I_C/A_E = 0.34 mA/µm^2, V_{BC} = 0.5 V (cf. f_T curves): comparison between measurement (symbols) [4] and HICUM (lines). Single transistor parameter extraction.



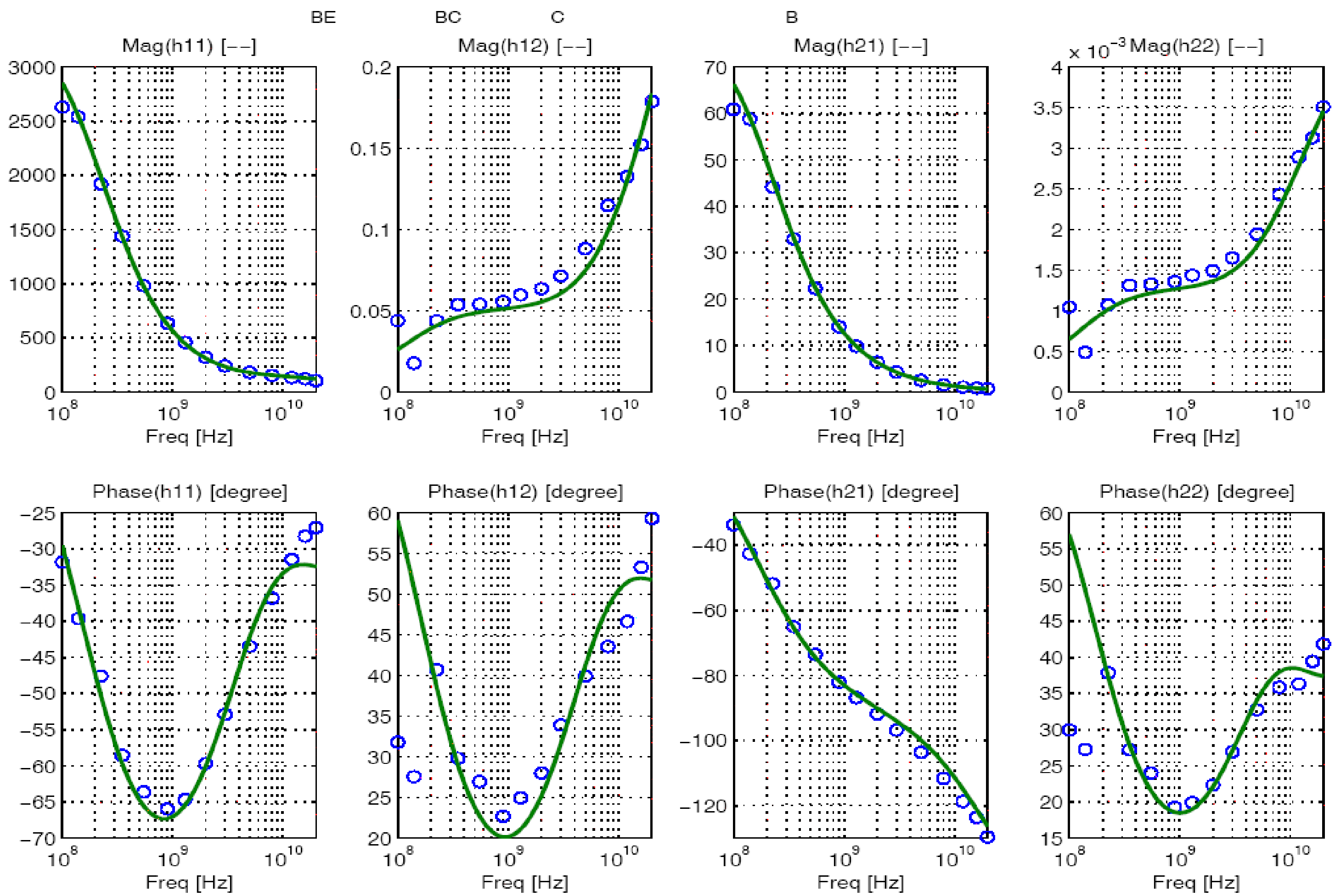
Frequency dependence of Y-parameters for a 12 GHz transistor (0.6*4.8µm^2) at I_C/A_E = 0.38 mA/µm^2, V_{BC} = -1 V (cf. f_T curves): comparison between measurement (symbols) [4] and HICUM (lines). Single transistor parameter extraction.



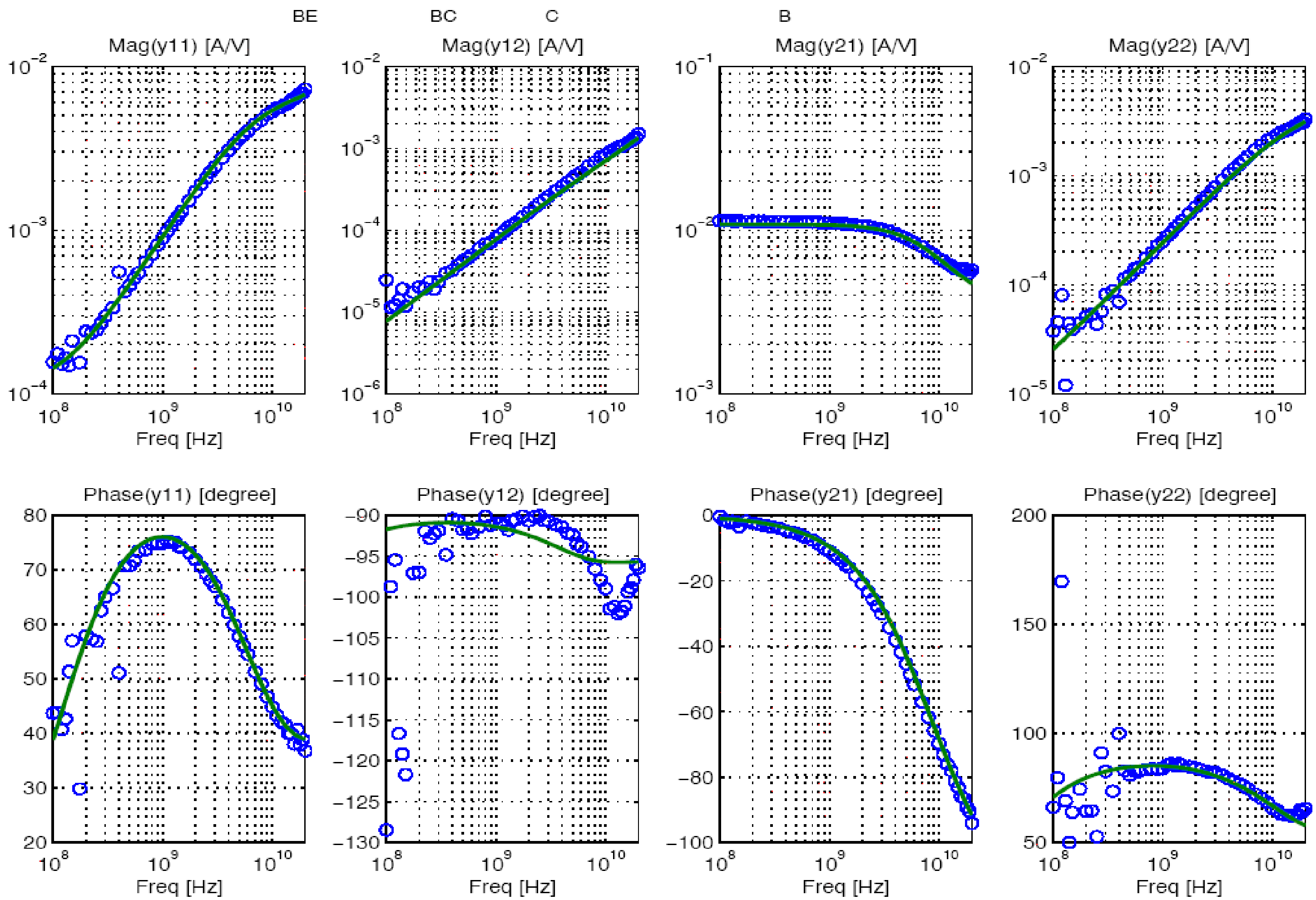
Frequency dependence of S-parameters (in Smith and polar chart) for a 12 GHz transistor (0.6*4.8µm^2) at I_C/A_E = 0.38 mA/µm^2, V_{BC} = -1 V (cf. f_T curves): comparison between measurement (symbols) [4] and HICUM (lines). Single transistor parameter extraction.



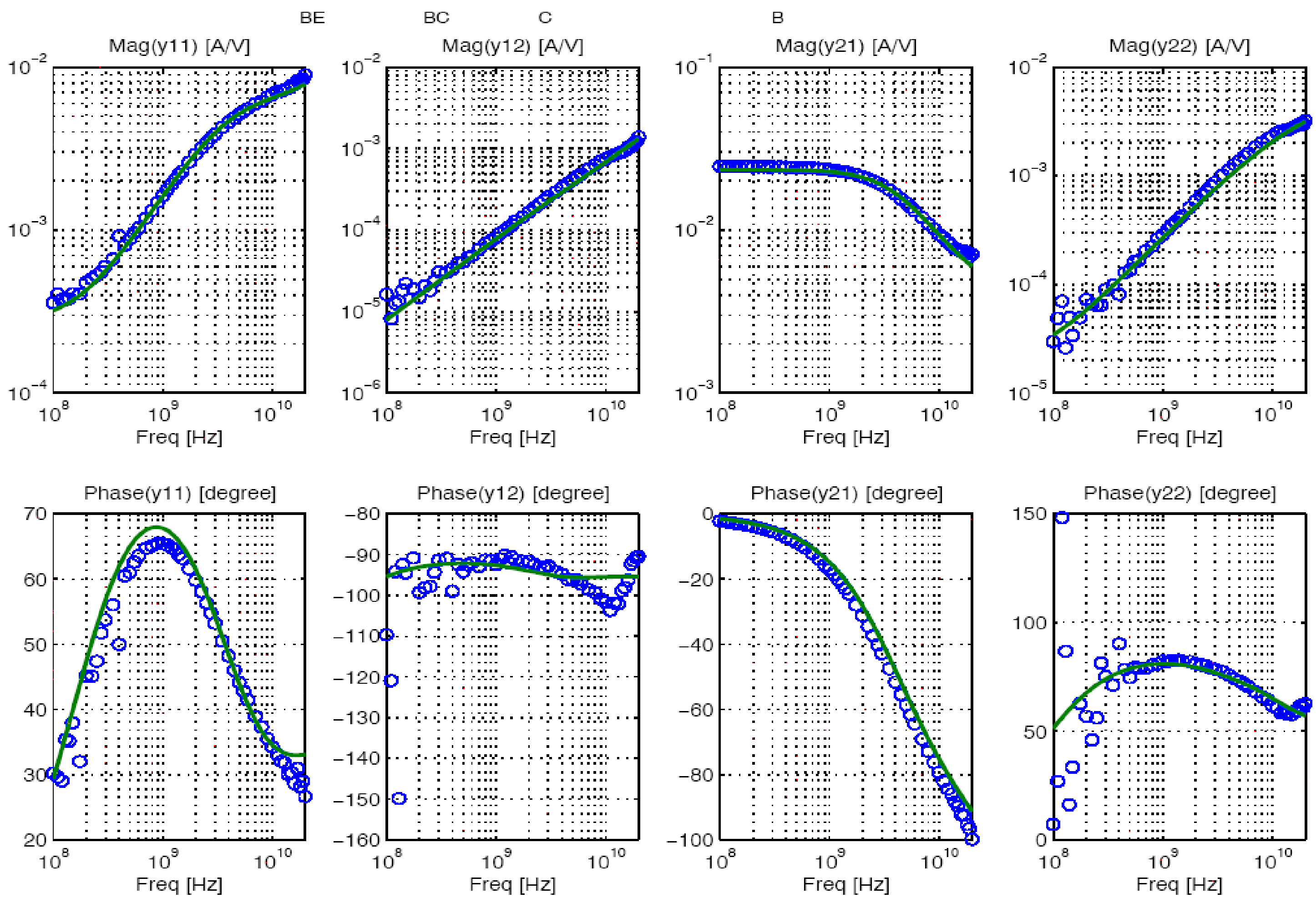
Frequency dependence of S-parameters (in magnitude and phase) for a 12 GHz transistor (0.6*4.8μm^2) at I_C/A_E = 0.38 mA/μm^2, V_{BC} = -1 V (cf. f_T curves): comparison between measurement (symbols) [4] and HICUM (lines). Single transistor parameter extraction.



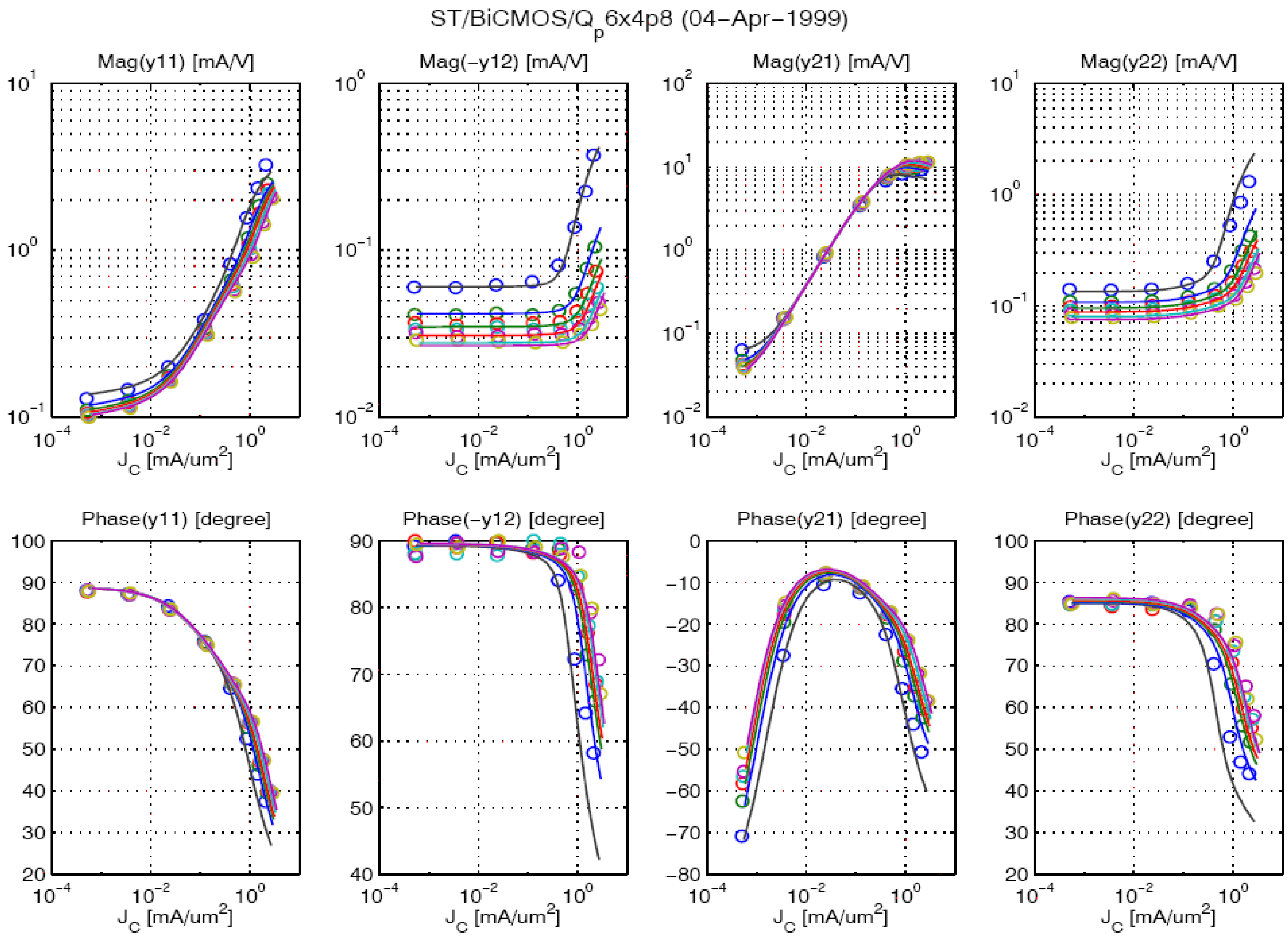
Frequency dependence of H-parameters for a 12 GHz transistor (0.6*4.8µm^2) at I_C/A_E = 0.38 mA/µm^2, V_{BC} = -1 V (cf. f_T curves): comparison between measurement (symbols) [4] and HICUM (lines). Single transistor parameter extraction.



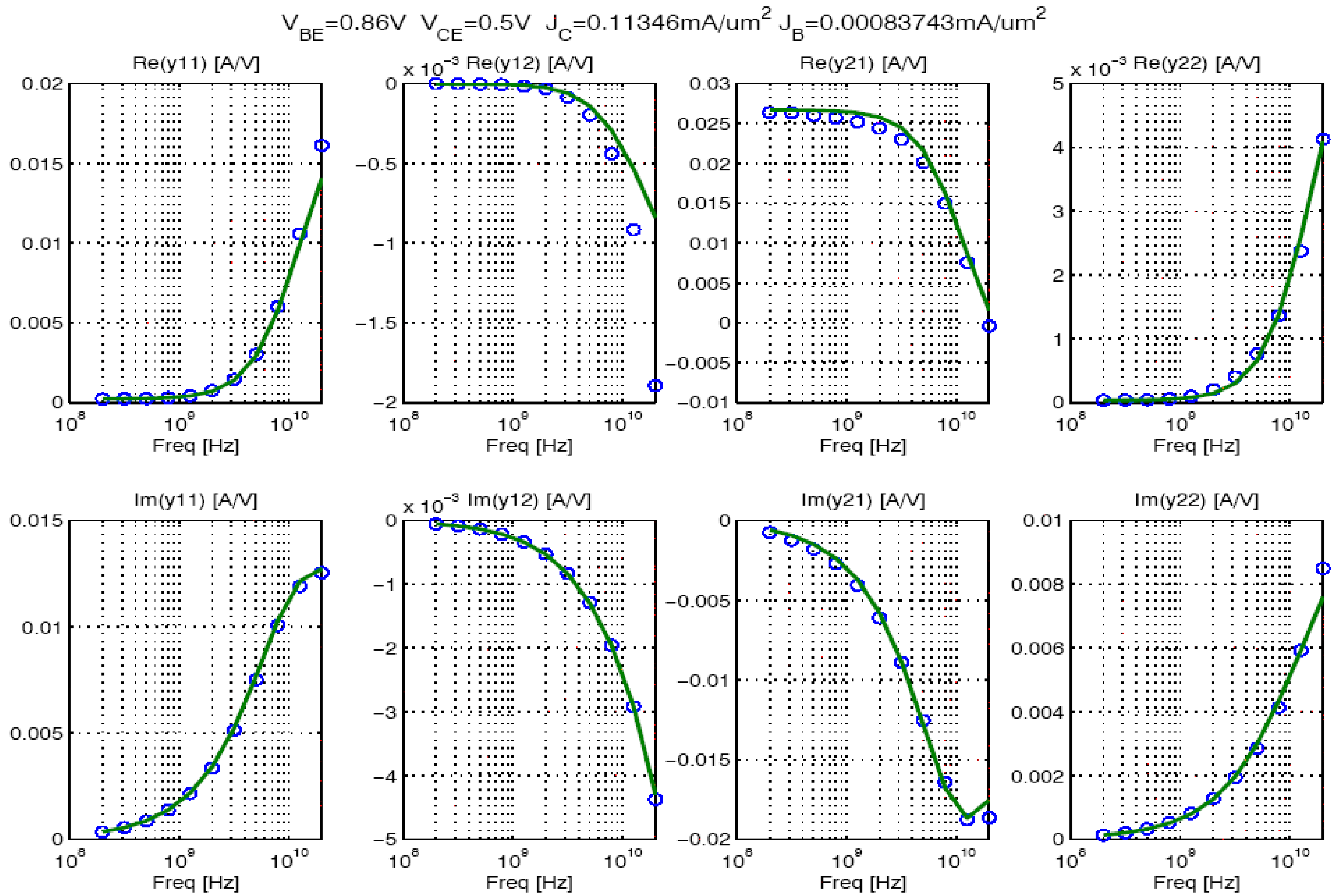
Frequency dependence of Y-parameters for a 12 GHz transistor (0.6*4.8µm^2) at I_C/A_E = 0.12 mA/µm^2, V_{BC} = -3 V (cf. f_T curves): comparison between measurement (symbols) [4] and HICUM (lines). Single transistor parameter extraction.



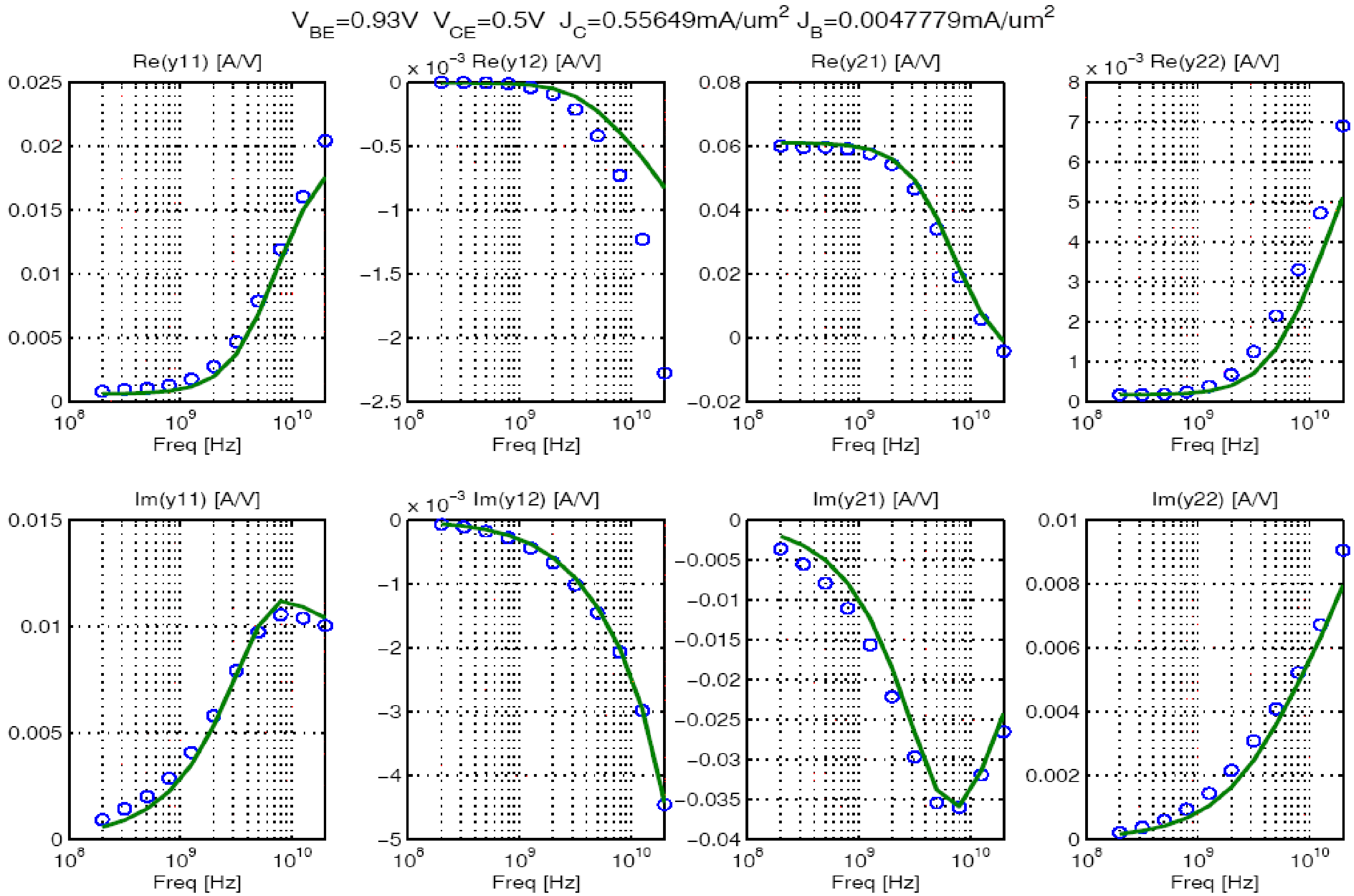
Frequency dependence of Y-parameters for a 12 GHz transistor (0.6*4.8µm^2) at I_C/A_E = 0.425 mA/µm^2, V_{BC} = -3 V (cf. f_T curves): comparison between measurement (symbols) [4] and HICUM (lines). Single transistor parameter extraction.



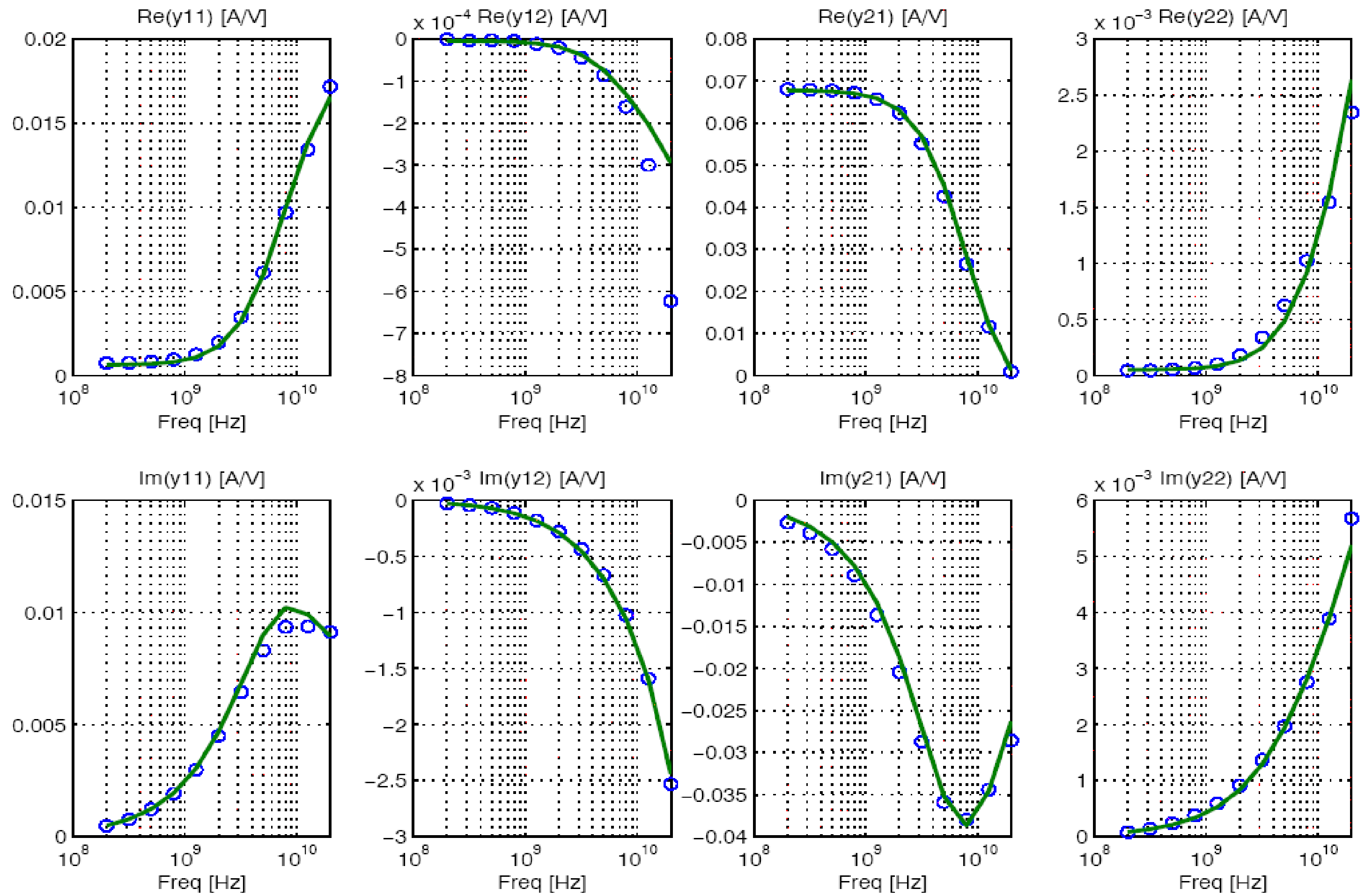
Y-parameters as a function of collector current density for a 12 GHz transistor ($0.6*4.8\mu m^2$) at f = 1GHz: comparison between measurement (symbols) and HICUM (lines). V_{CB}/V= -0.5, 0, 0.5, 2, 4.



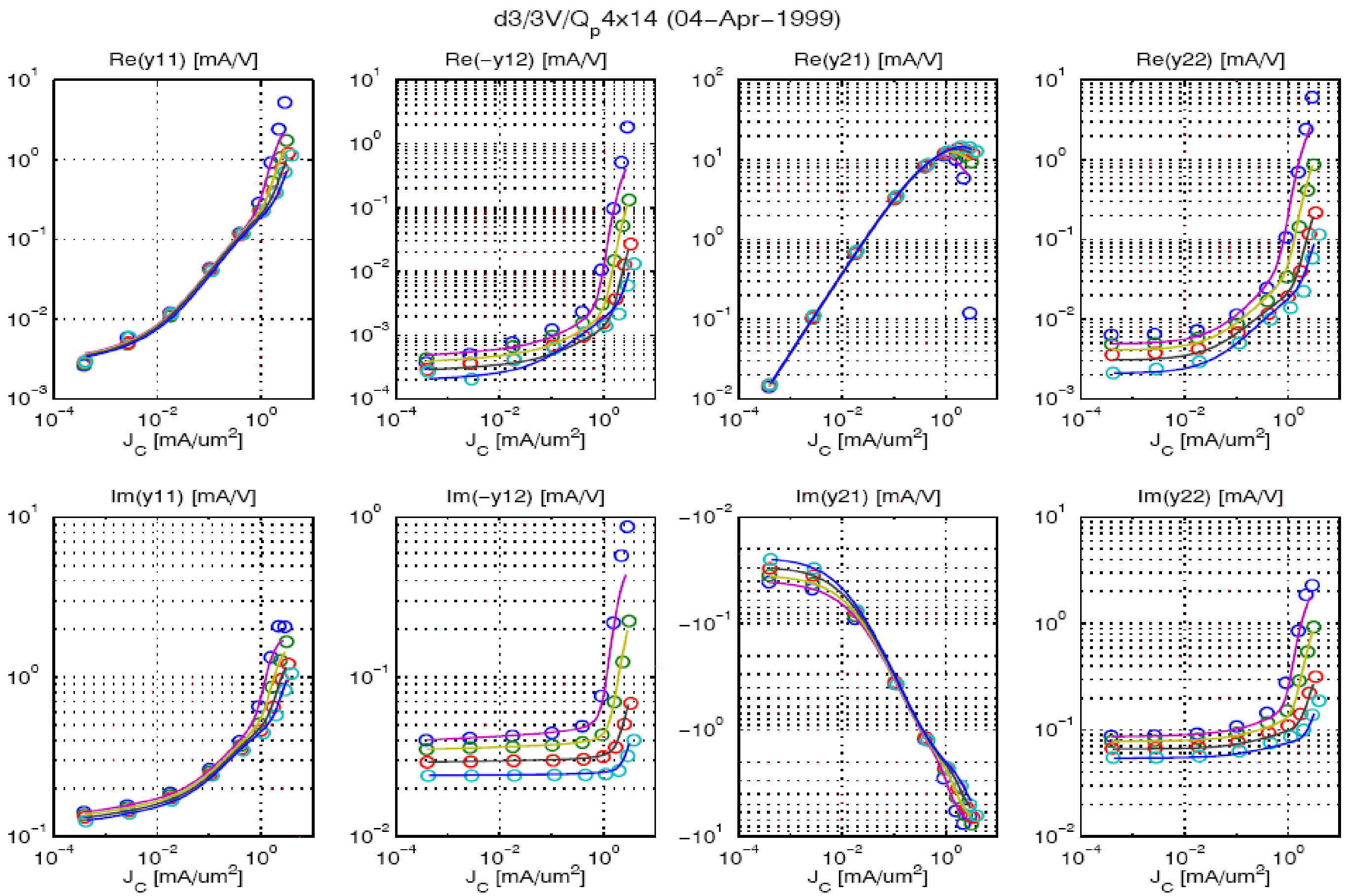
Frequency dependence of Y-parameters for a 25 GHz transistor (0.4*14μm^2) at I_C/A_E = 0.1 mA/μm^2, V_{CE} = 0.5 V (cf. f_T curves): comparison between measurement (symbols) and HICUM (lines).



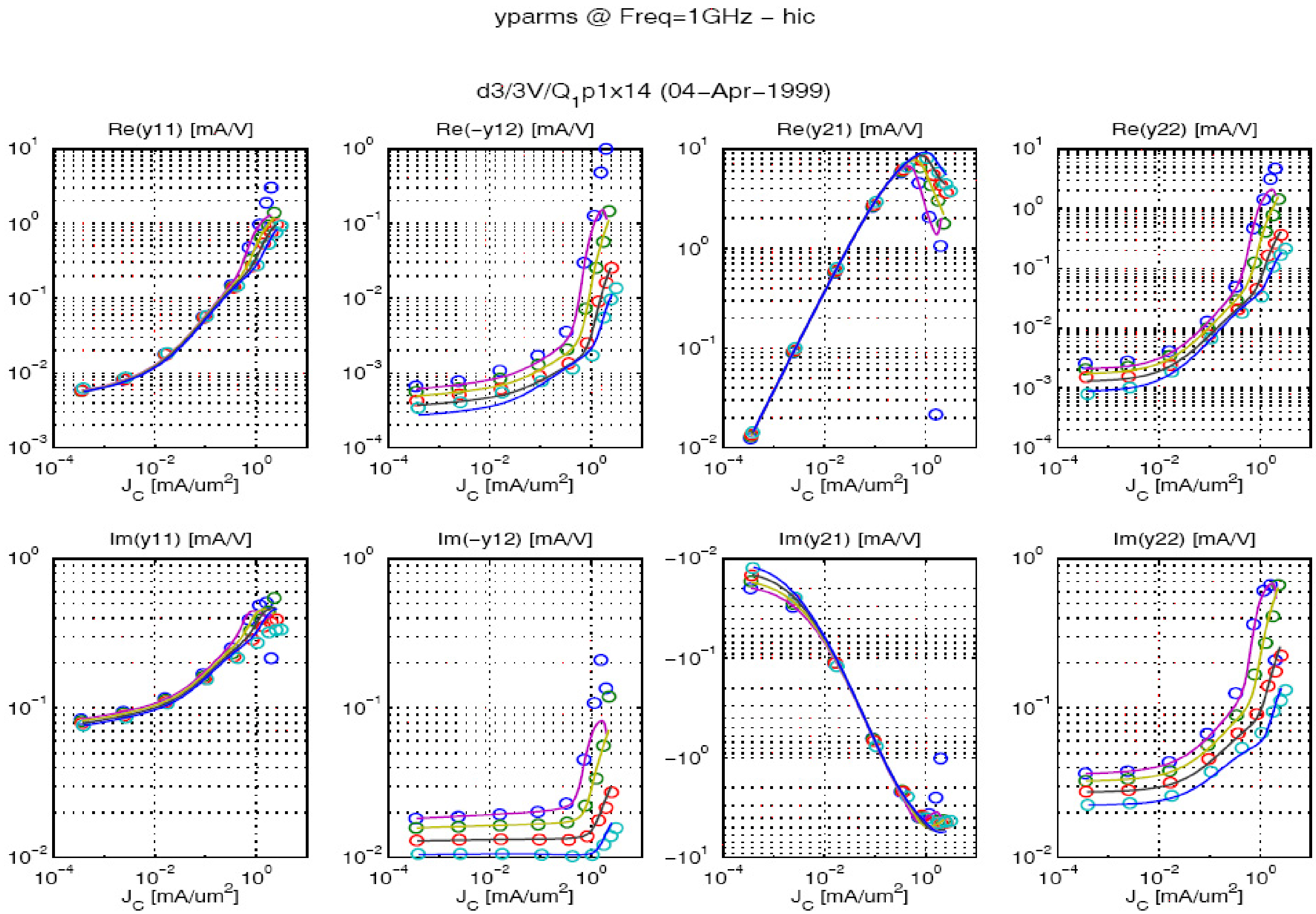
Frequency dependence of Y-parameters for a 25 GHz transistor (0.4*14µm^2) at I_C/A_E = 0.56 mA/µm^2, V_{CE} = 0.5 V (cf. f_T curves): comparison between measurement (symbols) and HICUM (lines).



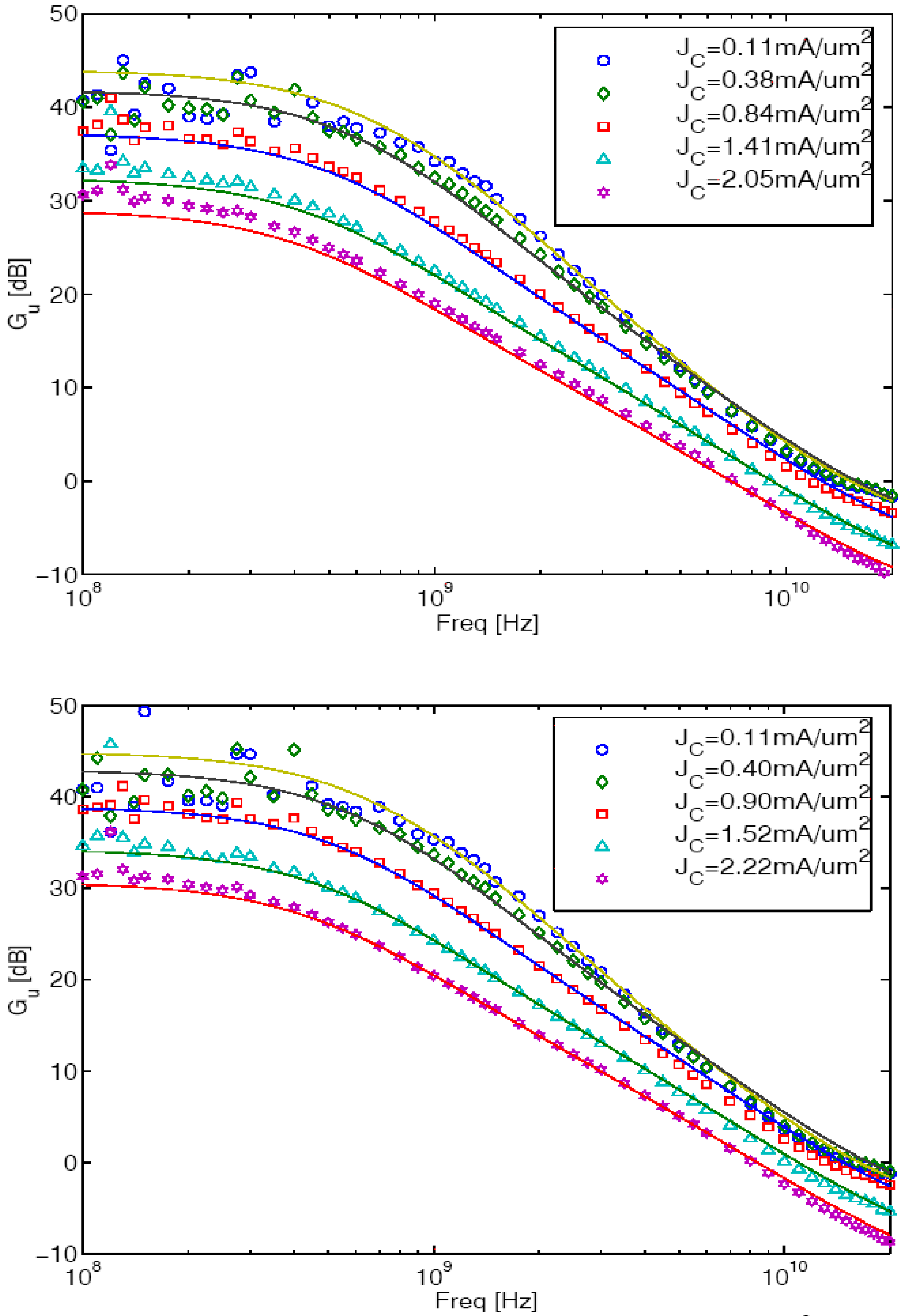
Frequency dependence of Y-parameters for a 25 GHz transistor (0.4*14μm^2) at I_C/A_E = 0.67 mA/μm^2, V_{CE} = 3 V (cf. f_T curves): comparison between measurement (symbols) and HICUM (lines).



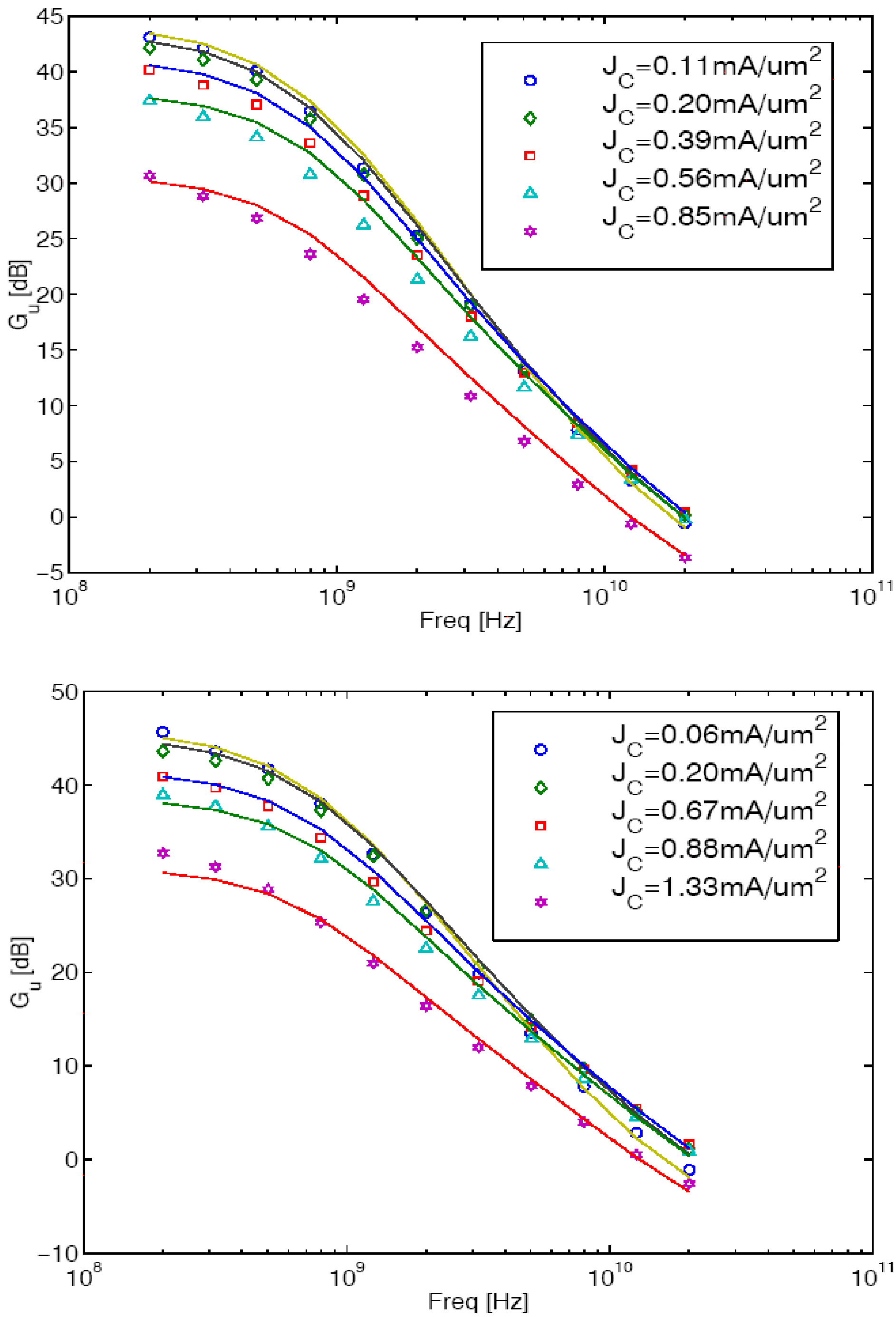
Y-parameters as a function of collector current density (V_{CE} = const.) for a 25 GHz transistor (0.4*14μm^2) at f = 1 GHz: comparison between measurement (symbols) and HICUM (lines). V_{CE}/V= 0.5, 0.8, 1.5, 3.



Y-parameters as a function of collector current density (V_{CE} = const.) for a 25 GHz transistor (1.2*14µm^2) at f = 1 GHz: comparison between measurement (symbols) and HICUM (lines). V_{CE}/V= 0.5, 0.8, 1.5, 3.



Unilateral gain G_U as a function of frequency for a 12 GHz transistor (0.6*4.8μm^2) at various bias points. Comparison between measurement (symbols) and HICUM (lines): (a) V_{BC} = -1 V; (b) V_{BC} = -2 V. Note the high accuracy even at current densities far beyond I_C/A_E(@peak f_T).

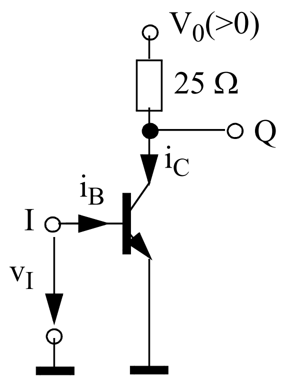


Unilateral gain G_U as a function of frequency for a 25 GHz transistor ($0.4*14\mu m^2$) at various bias points. Comparison between measurement (symbols) and HICUM (lines): (a) V_{CE} = 0.5 V; (b) V_{CE} = 0.8 V. Note the high accuracy even at current densities far beyond I_C/A_E(@peak f_T).

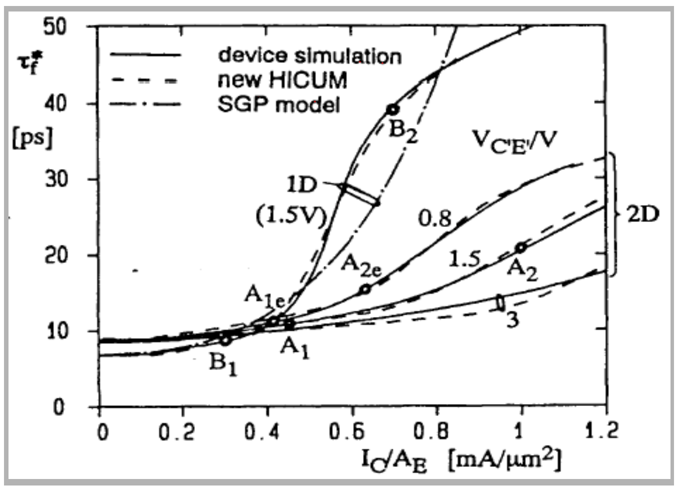
6.4 High-speed transient (switching) operation

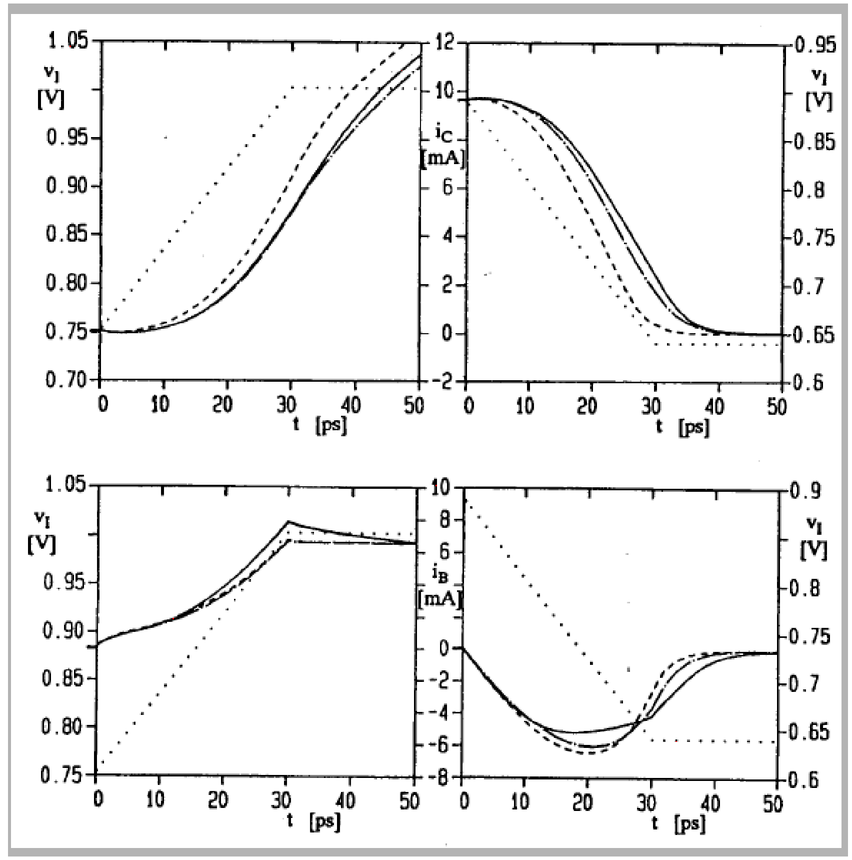
(2D mixed-mode device/circuit simulation [39]; for experimental results of an older process see [26])

(a)



(b)



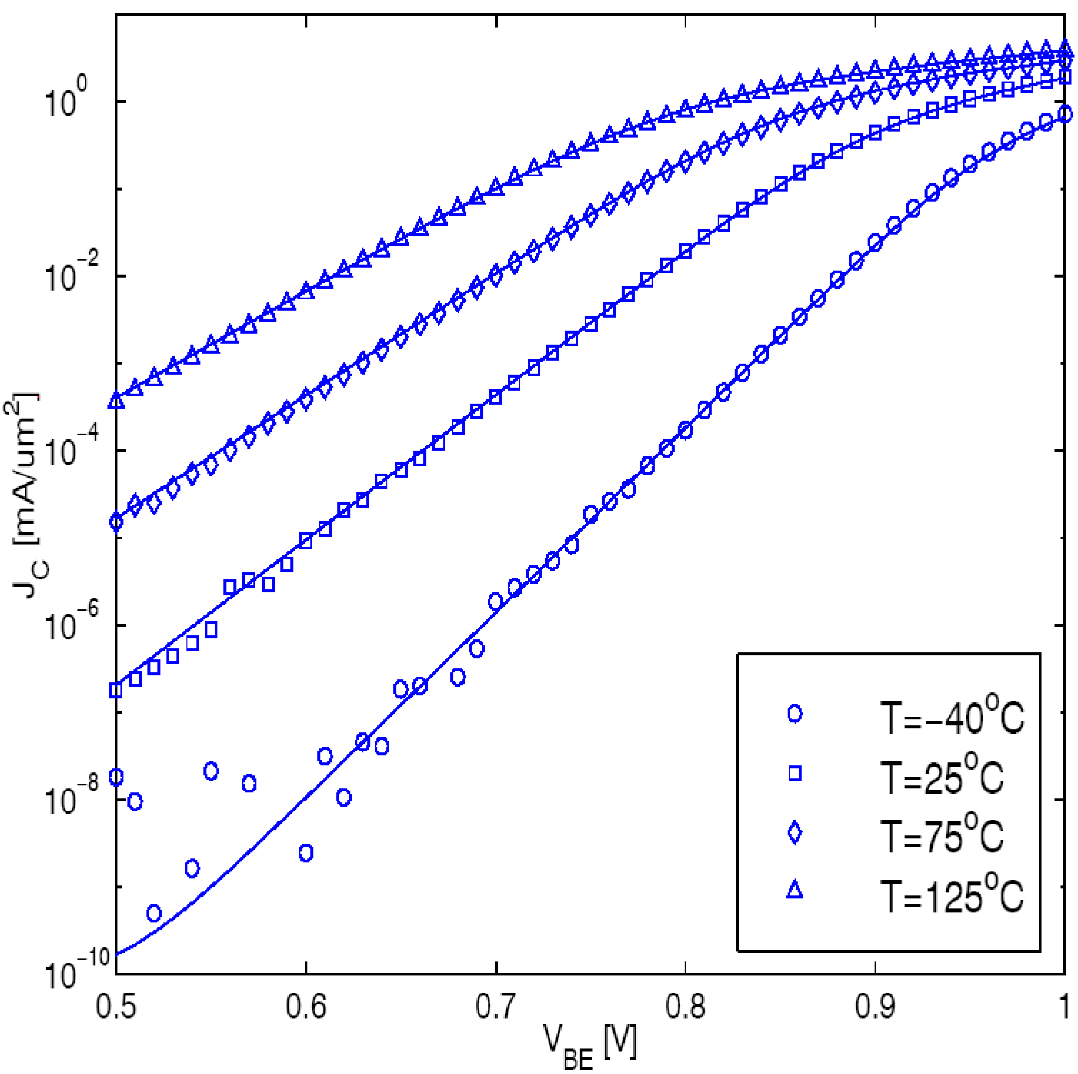


(c)

(a) Transistor inverter (worst-case for switching behaviour comparison). (b) Transit time vs. collector current density of a 14 GHz bipolar transistor. (c) Switching-on and -off behavior for i_C (top) and i_B (bottom) into and out of, respectively, the bias point A_2 in Fig. (b). Comparison between device simulation (solid lines), HICUM with NQS effects (dash-dotted lines), and HICUM without NQS effects (dashed lines) [39].

6.5 Temperature dependence

6.5.1 DC characteristics

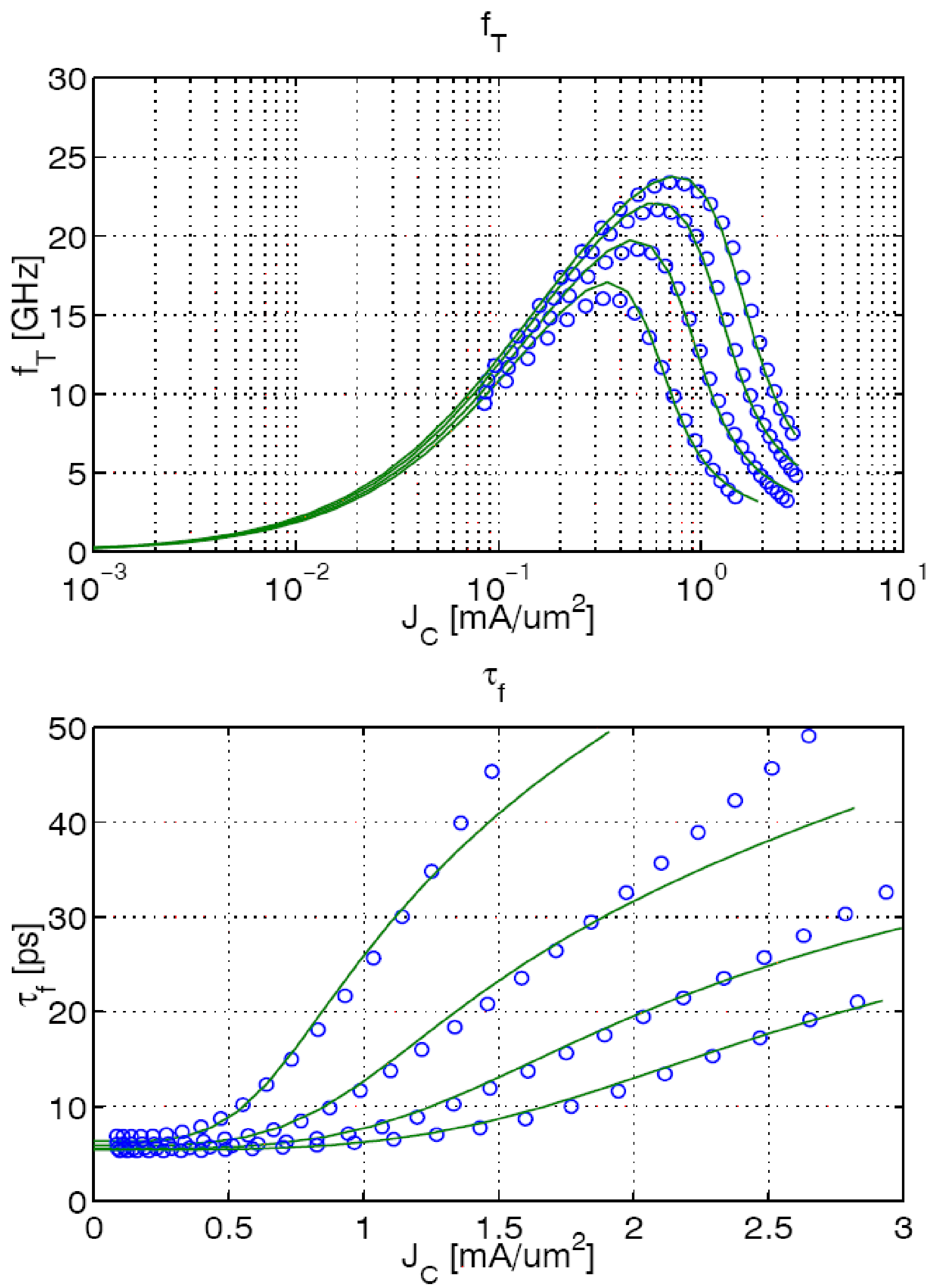


Comparison between measurement (symbols) and HICUM (solid lines) for a 25 GHz bipolar transistor: collector current density I_C/A_E vs. V_{BE} for different temperatures. Emitter size: 0.4*14 µm^2; V_{BC} = 0 V.

6.5.2 AC characteristics

(a)

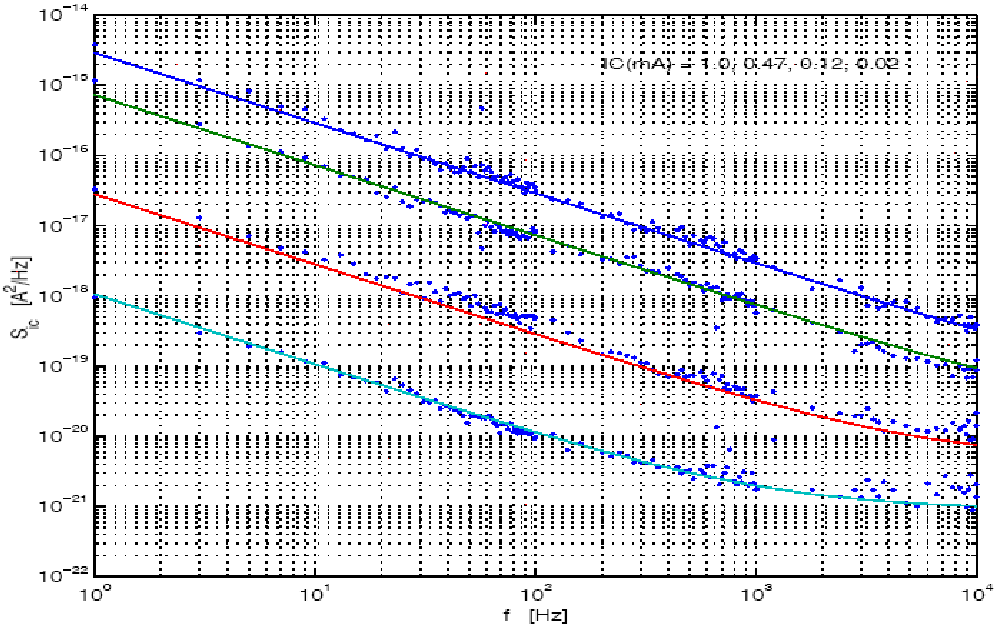
(b)



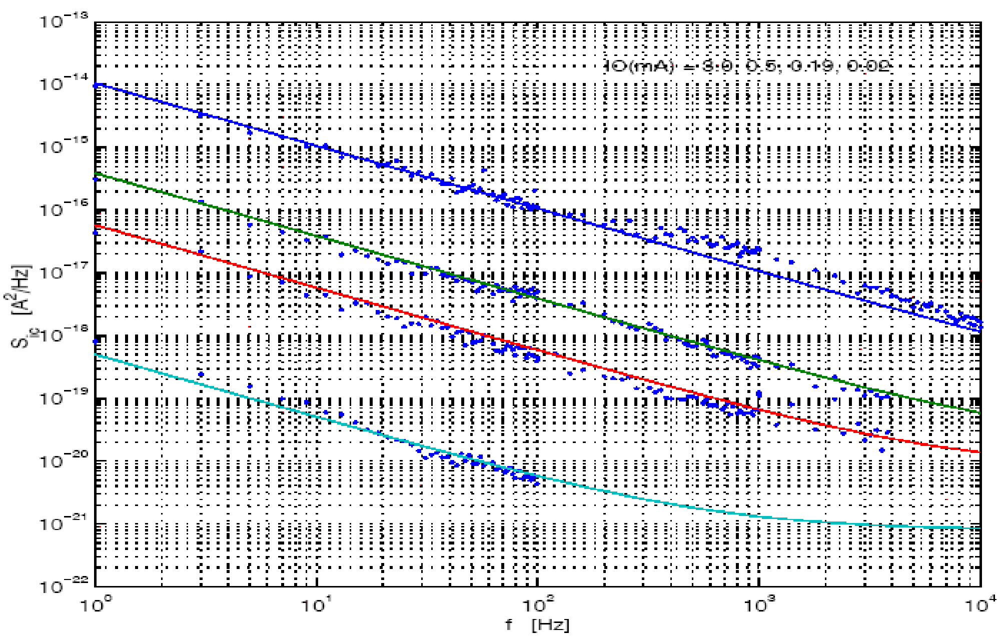
(a) Transit time and (b) transit frequency vs. I_C/A_E for T = 125 C: comparison between measurement (symbols) and HICUM (solid lines) [43]. Emitter size: 0.4*14 μm^2; V_{CE}/V = 0.5,0.8,1.5,3. Note, that the results were generated with a single model parameter set, except for the temperature coefficients of τ_0.

6.6 Low-frequency noise

(a)

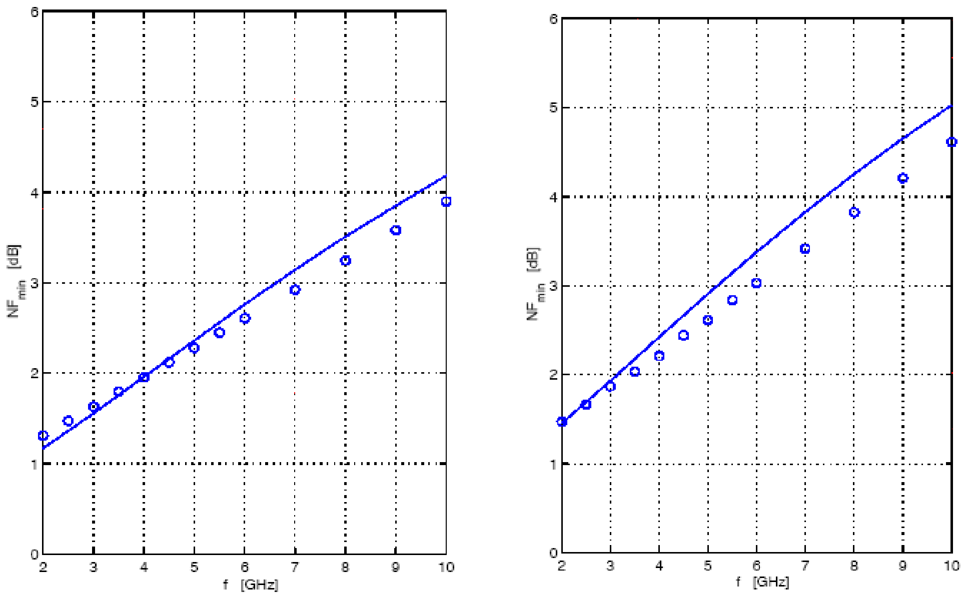


b)

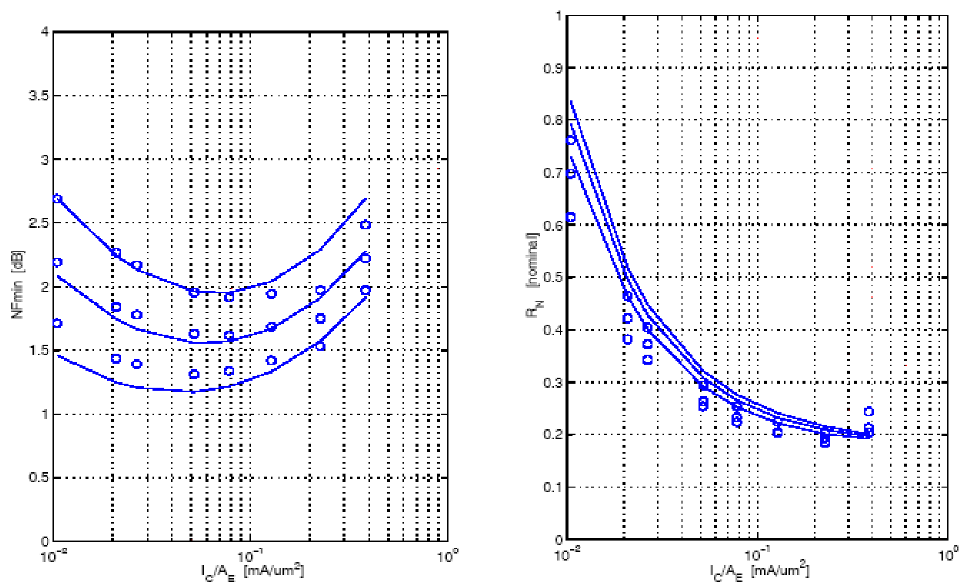


Collector current noise spectral density S_{iC} vs. frequency f for 25 GHz transistors at T = 25 C and various bias points I_C (cf. insert) and V_{CE} = 1 V. Comparison between measurement (symbols) and HICUM (lines): (a) $A_{E0} = 0.4*14\mu m^2$, (b) $A_{E0} = 0.8*14\mu m^2$.

6.7 High-frequency noise

(a)  (b)

Minimum noise figure F_{min} vs. frequency f for a 25 GHz transistor. Comparison between measurement (symbols) and HICUM (lines): (a) emitter size is 4*0.4*21μm^2, I_C/A_E = 0.405mA/μm^2, V_{CE} = 1V; (b) emitter size is 0.8*14μm^2, I_C/A_E = 0.03mA/μm^2, V_{CE} = 1V.

(a)  (b)

Comparison between measurement (symbols) and HICUM (lines) for a 25 GHz transistor (4*0.4*21μm^2): (a) Minimum noise figure F_{min} vs. collector current density I_C/A_E; (b) equivalent noise resistance R_n vs. collector current density. *f*/GHz = 1, 2, 3; V_{CE} = 1V.

6.8 High-frequency distortion

Some general remarks are required for explaining and understanding the distortion results.

The transistors were measured on-wafer in a 50Ω system using the same h.f. pad configuration that is employed for small-signal S-parameter measurements. An automated measurement system was set-up which facilitates bias point sweeps [20,45,46]. The system was carefully calibrated in order to take into account all losses up to the device and to accurately obtain both output power P_{in} and input power P_{out} at the transistor terminals for all relevant frequencies. Single-tone measurements were performed at four different fundamental frequencies f_1/GHz = (0.05, 0.1, 0.9, 1.8). The two low frequencies at 50 and 100 MHz were chosen to be able to separate later the cause of non-linearities during model comparison. The following table shows the relation between P_{in} specified in dBm by the power sweeper (defined for a 50Ω load) and the respective voltage amplitude.

P [dBm]	-40	-30	-20	-10
$\hat{v}$ [V]	6.4	20	64	200

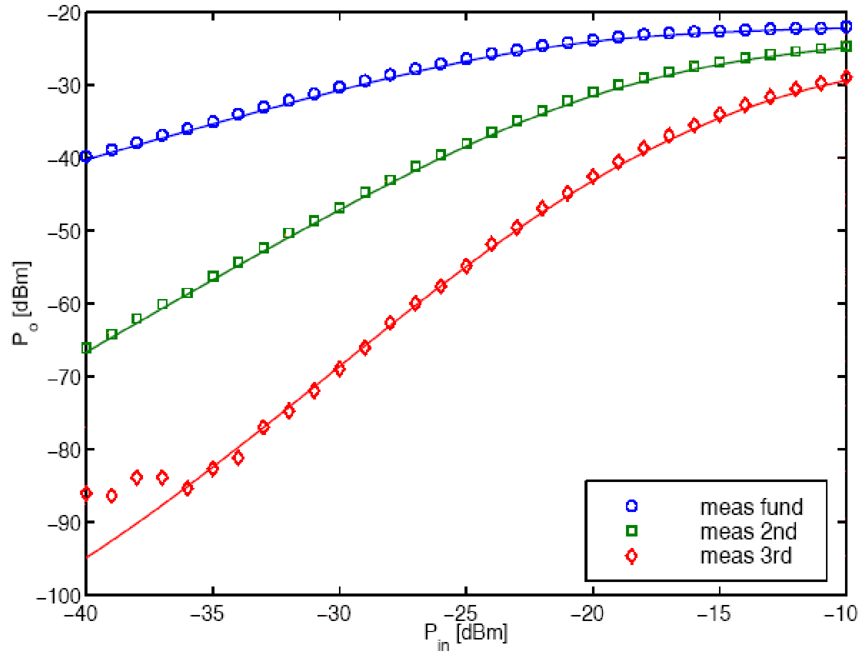
As response at the output, the signals at the respective fundamental frequency as well as the second and third harmonic frequency (f_2 and f_3) were measured with a spectrum analyser for different transistor types. The table below lists the frequencies that belong together. The resulting P_{out} at the various frequencies can then be compared to model characteristics as a function of d.c. bias and geometry. Figures of merit, such as the 1dB compression point and harmonic distortion, can also be calculated.

f_1/GHz	0.05	0.1	0.9	1.8
f_2/GHz	0.1	0.2	1.9	3.6
f_3/GHz	0.15	0.3	2.7	5.4

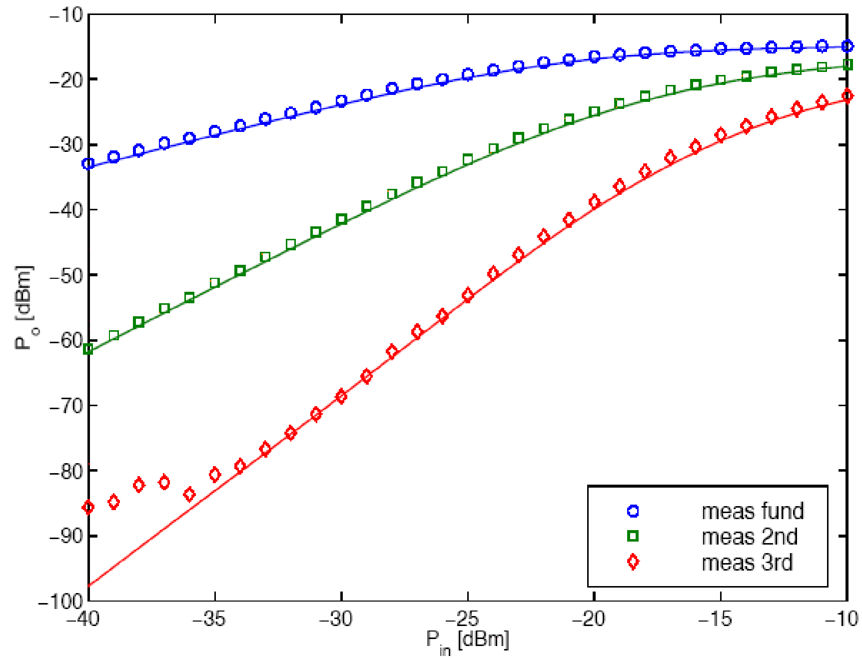
For circuit simulation, the periodic steady-state method available in SPECTRE-RF was used. However, time-domain based simulators seem to generate an incorrect d.c. component (probably converted from the second harmonic) at the transistor input, which causes the d.c. bias point to run away at high input power. This (probably) numerical effect, which should not occur according to the measurement set-up, was not observed during harmonic balance simulations (using HP-MDS) with the same circuit and parameters. A corresponding correction algorithm was developed and implemented in MATLAB, the results of which were verified by HP-MDS.

For logistical reasons the measurements were carried out on a different die of the same wafer the parameter extraction was performed on. Process variations across the wafer might cause slightly increased deviations between model and measurements. Nevertheless, the model still turned out to be quite accurate.

(a)

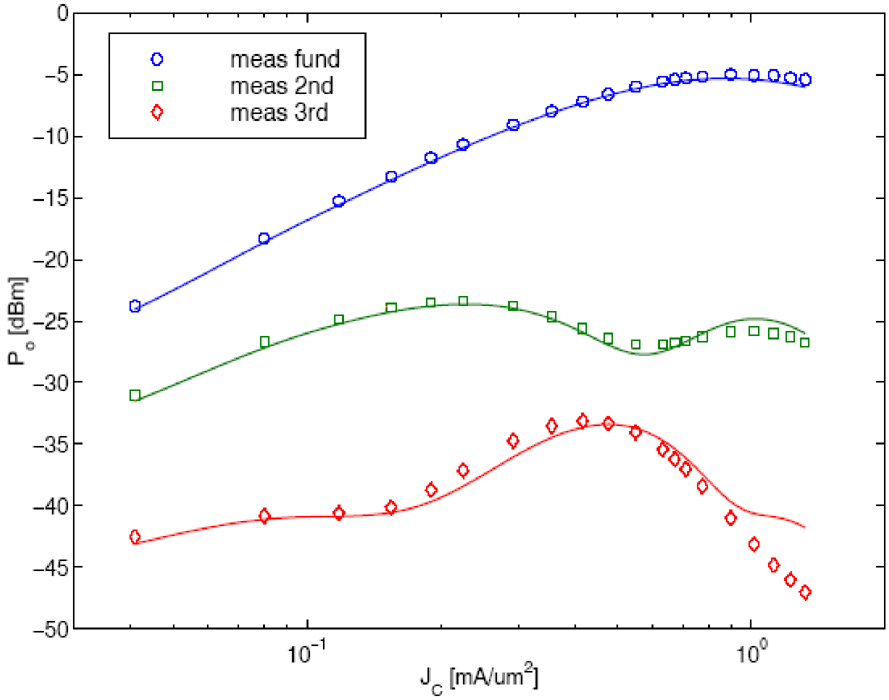


(b)

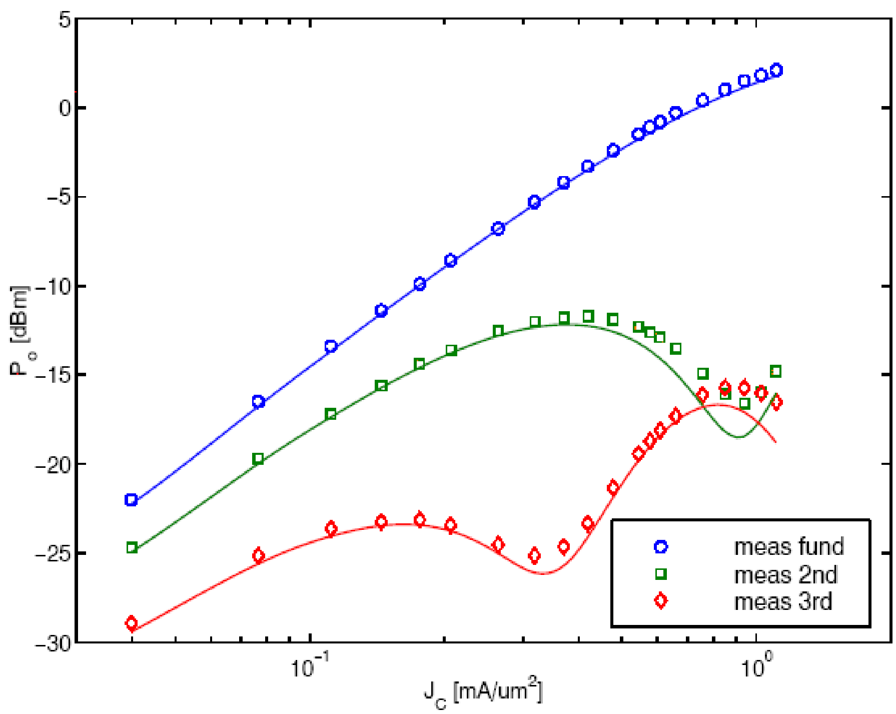


P_{out} vs. P_{in} for f_0 = 0.9 GHz; comparison between measurement (symbols) and HICUM (lines):
(a) 10 GHz (power) transistor (0.4*14µm^2) at I_C/A_E = 0.05 mA/µm^2, V_{CE} = 0.8 V;
(b) 25 GHz transistor (0.4*14µm^2) at I_C/A_E = 0.13 mA/µm^2, V_{CE} = 3 V.

(a)

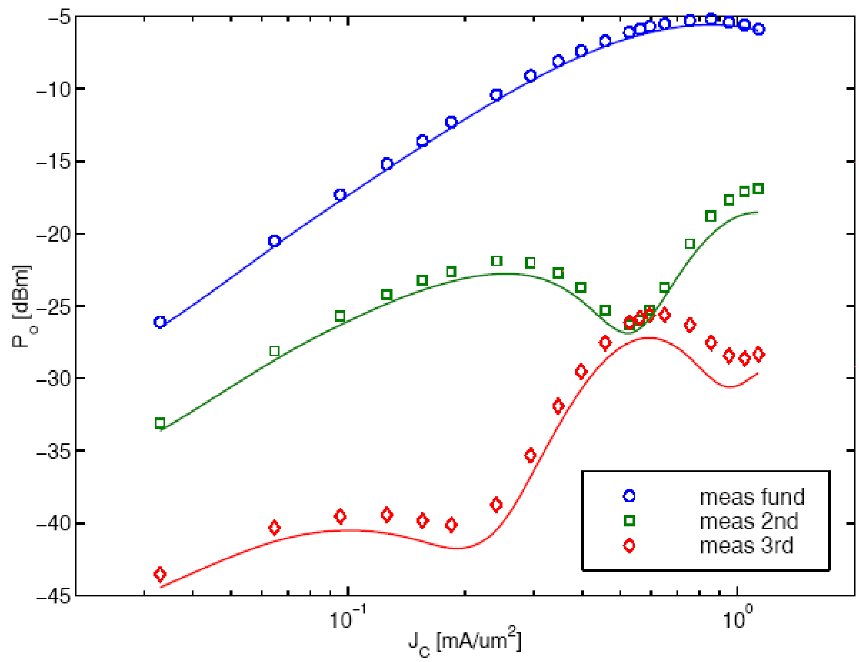


(b)

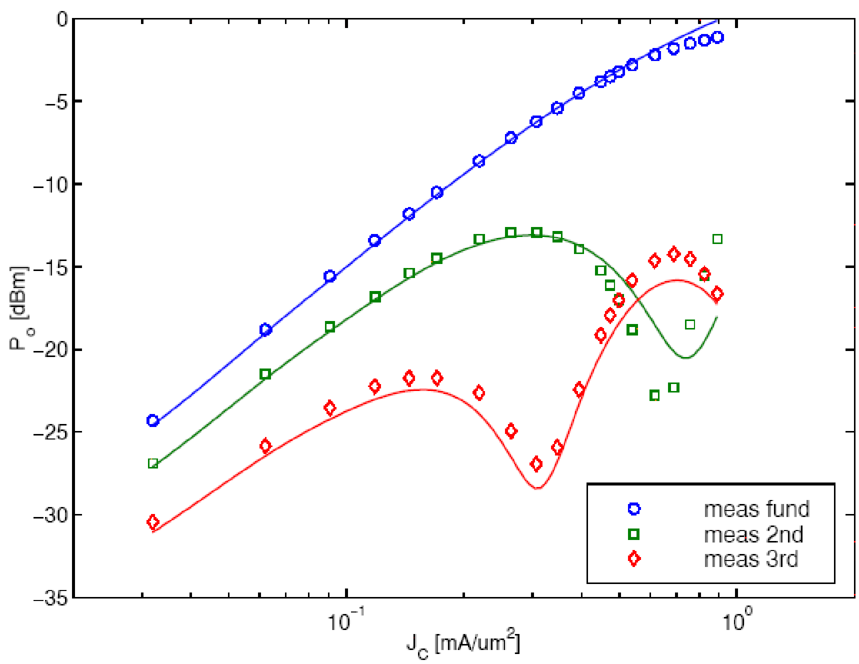


P_{out} vs. collector current density I_C/A_E at f_0 = 0.9 GHz for a 10 GHz (power) transistor (0.4*14μm^2); comparison between measurement (symbols) and HICUM (lines):
(a) P_{in} = -20 dBm; (b) P_{in} = -10 dBm. V_{CE} = 0.8 V.

(a)

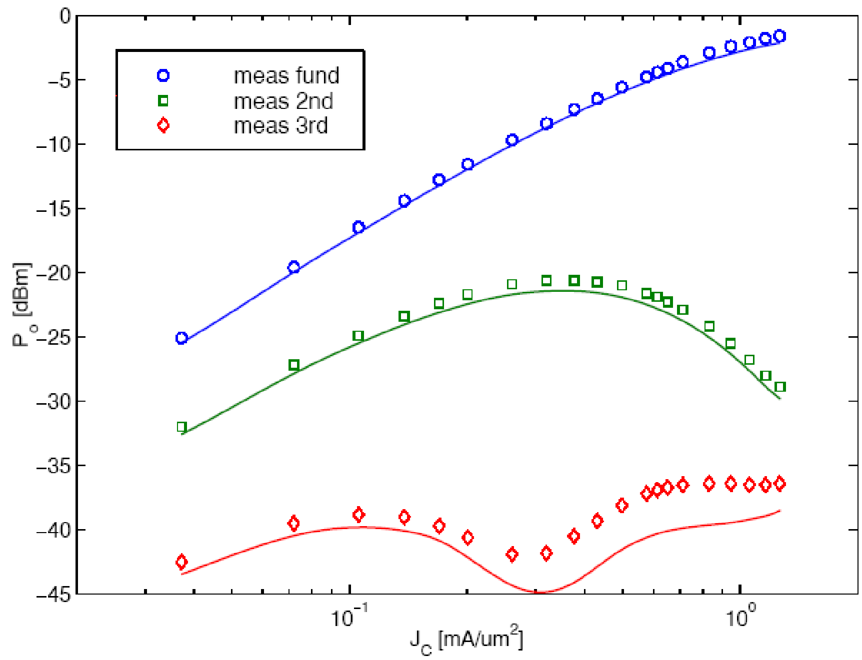


(b)

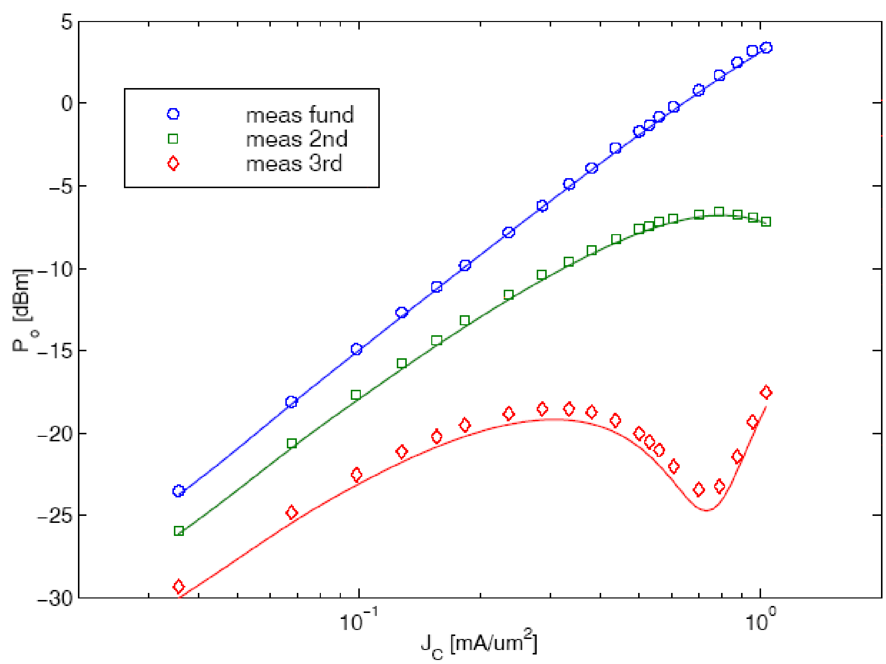


P_{out} vs. collector current density I_C/A_E at f_0 = 0.9 GHz for a 25 GHz transistor (0.4*14μm^2); comparison between measurement (symbols) and HICUM (lines):
(a) P_{in} = -20 dBm; (b) P_{in} = -10 dBm. V_{CE} = 0.5 V.

(a)

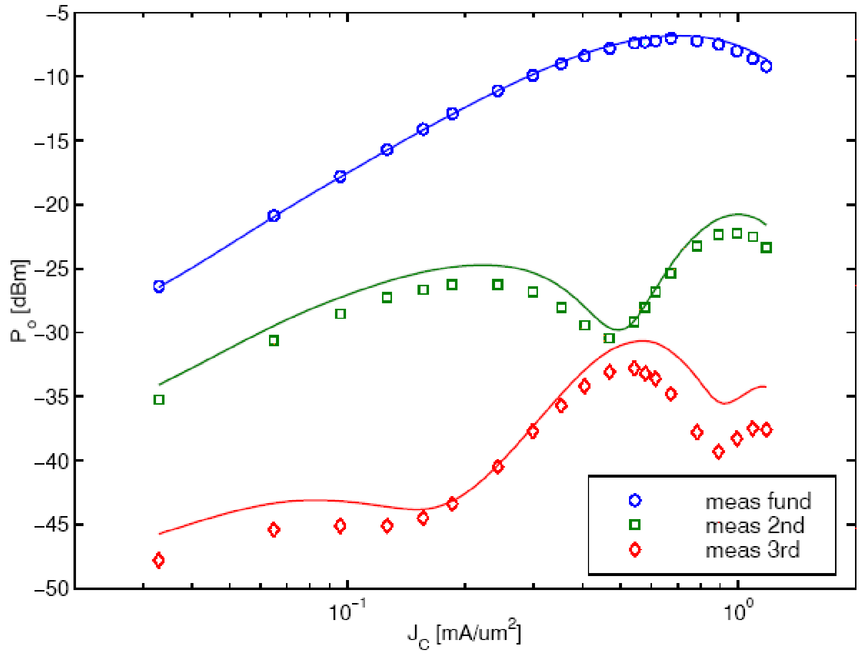


(b)

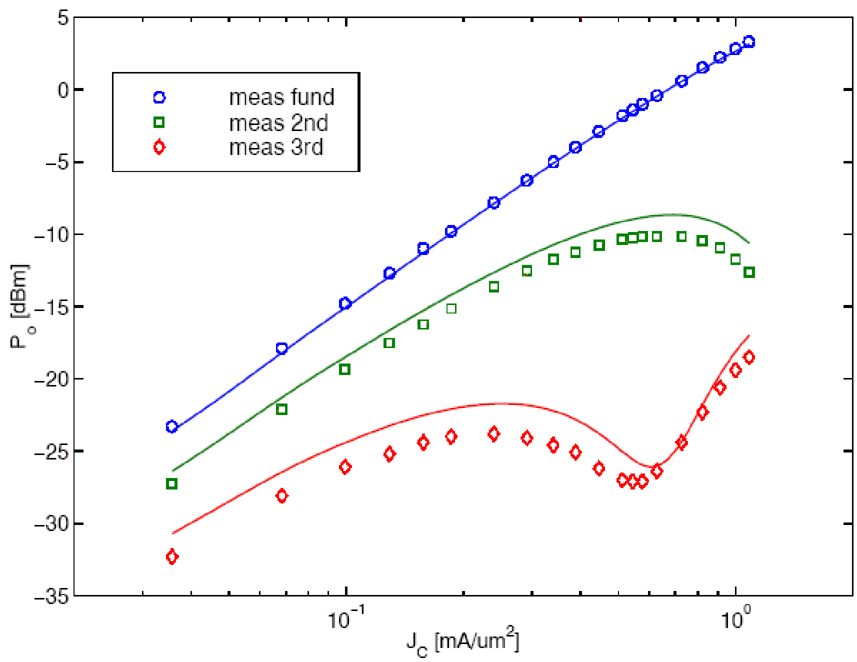


P_{out} vs. collector current density I_C/A_E at f_0 = 0.9 GHz for a 25 GHz transistor (0.4*14μm^2); comparison between measurement (symbols) and HICUM (lines):
(a) P_{in} = -20 dBm; (b) P_{in} = -10 dBm. V_{CE} = 3 V.

(a)

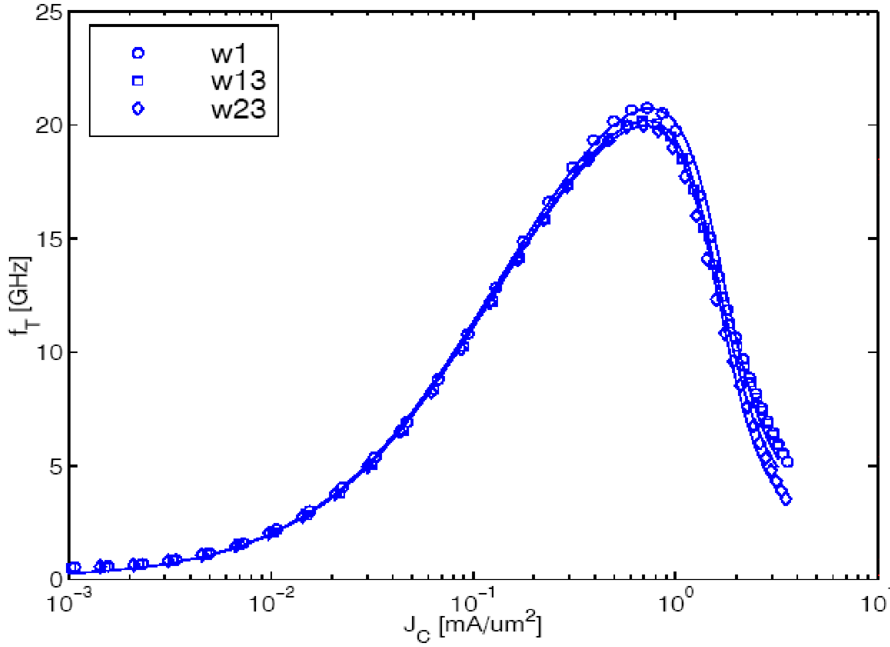


(b)

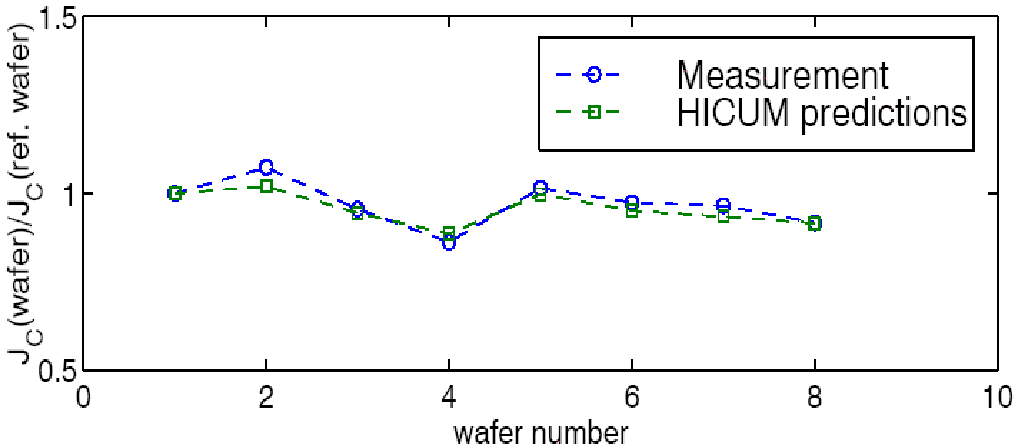


P_{out} vs. collector current density I_C/A_E at f_0 = 1.8 GHz for a 25 GHz transistor (0.4*14μm^2); comparison between measurement (symbols) and HICUM (lines):
(a) P_{in} = -20 dBm, V_{CE} = 0.5 V; (b) P_{in} = -10 dBm, V_{CE} = 3 V.

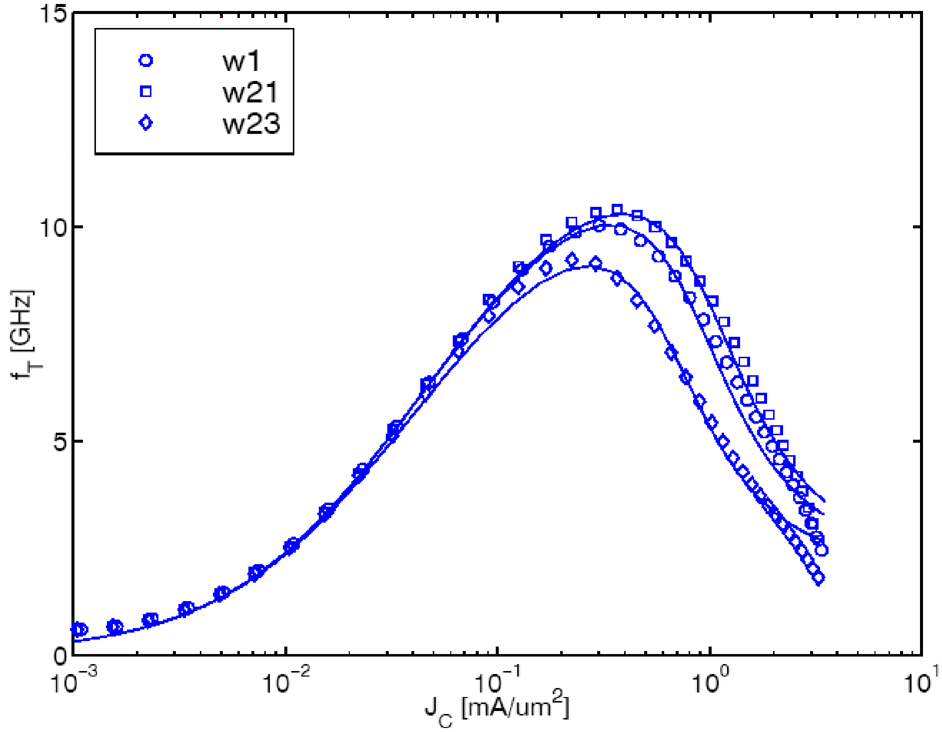
6.9 Predictive modelling



Transit frequency vs. collector current density for several process variations: base line (circles), 10% decrease of selectively implanted collector dose (squares), 25% increase of epi width w_C (diamonds). Comparison between measurement (symbols) and HICUM predictions (solid lines). V_{CE} = 0.8 V; emitter size: 0.4*14 µm^2.

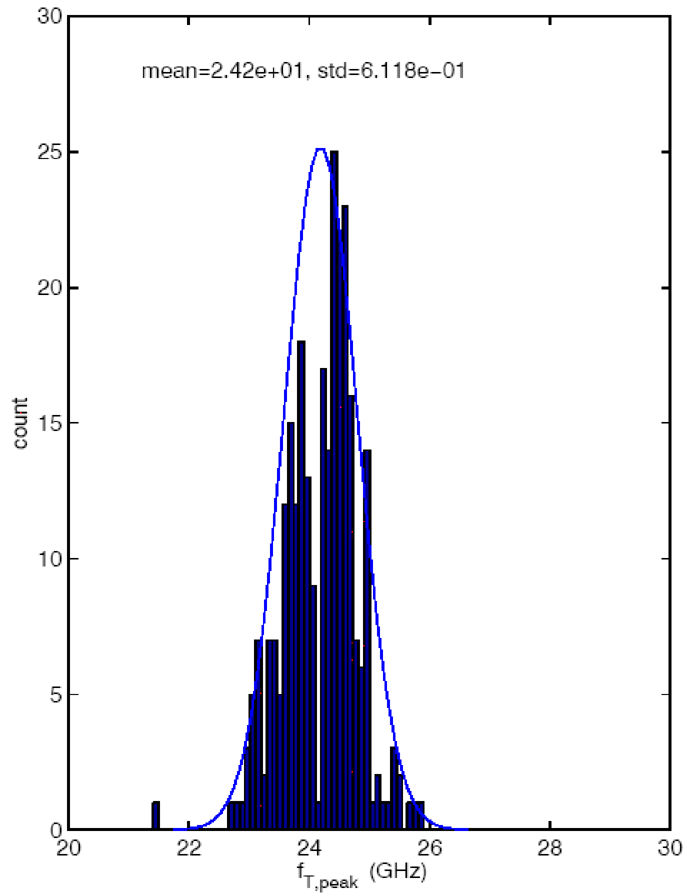


Collector current density at fixed V_{BE} = 0.8V for the same process variants as above; comparison between measurement (o) and HICUM predictions (-). V_{CE} = 0.8V; Emitter size: 0.4*14µm^2

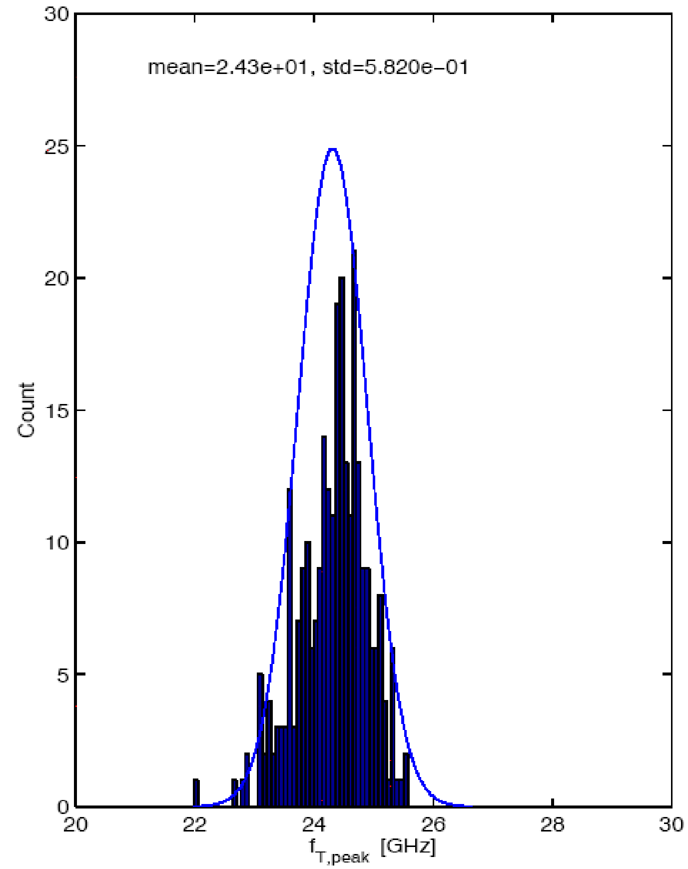


Transit frequency vs. collector current density for several variations of a “high-voltage” process: base line (circles), ≈5% increase of epi collector doping (squares), 25% increase of epi width w_C (diamonds). Comparison between measurement (symbols) and HICUM predictions (solid lines). V_{CE} = 0.8 V; emitter size: 0.4*14 μm^2.

6.10 Statistical modelling

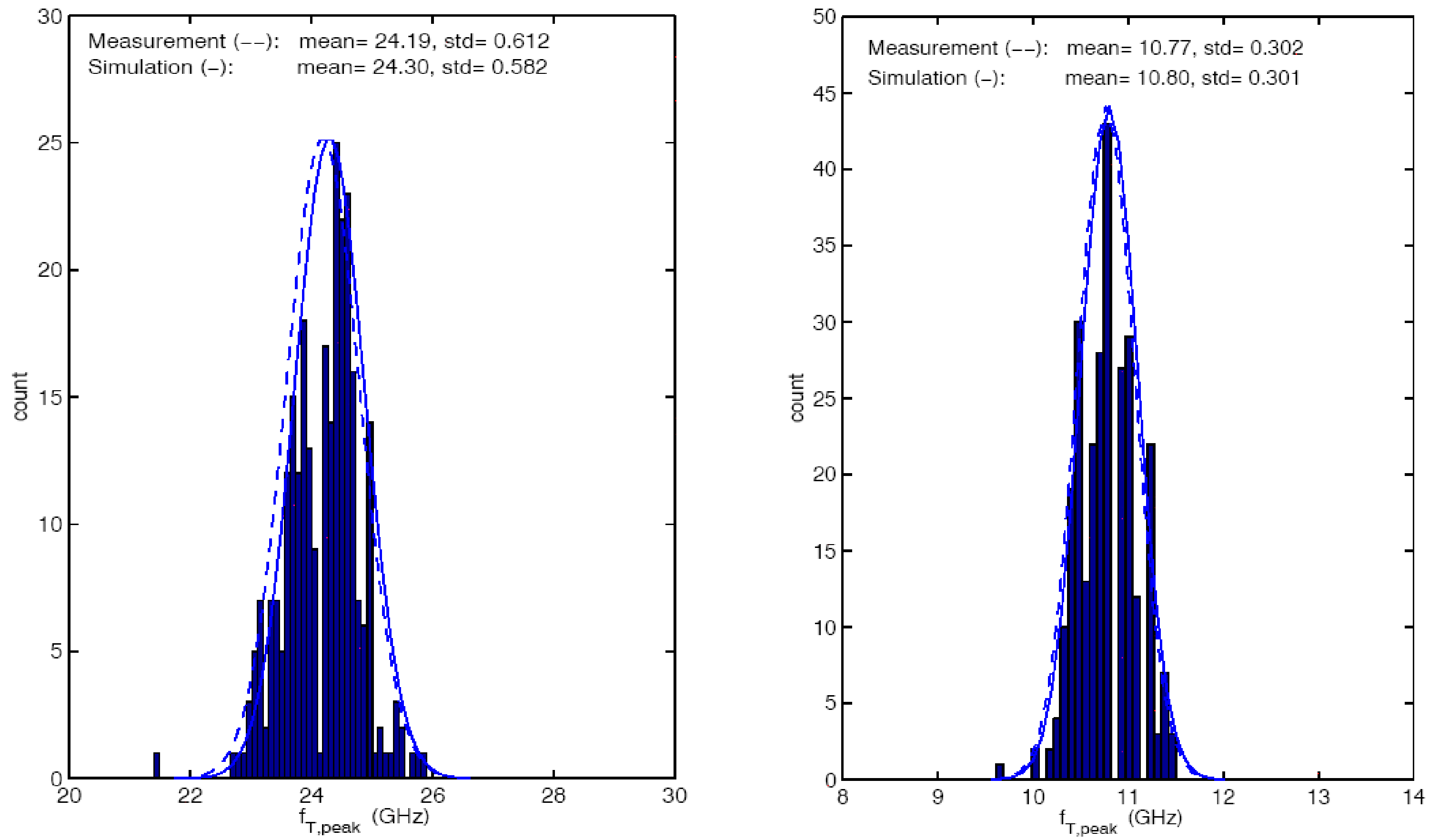


(a)



(b)

Statistical distribution curves of peak f_T for a "high-speed" process. Comparison between (a) measurements and (b) HICUM predictions from process monitors. V_{CE} = 2 V; emitter size: 0.4*14 µm^2. The results were obtained from 5 different lots.

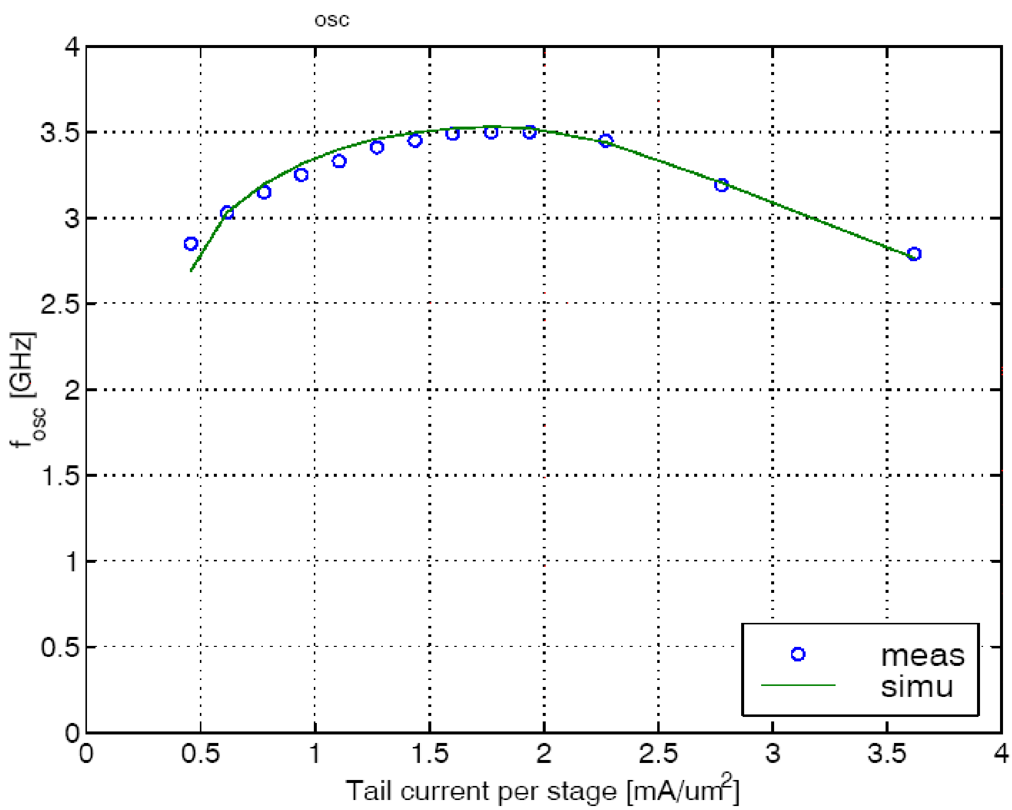


(a) (b)

Statistical distribution curves of peak f_T for transistors with 0.4*14µm^2 emitter size. Comparison between measurements (histogram and solid lines) and HICUM predictions from process monitors (dashed lines): (a) “high-speed” process; (b) “high-voltage” process. The results were obtained from 5 different lots.

6.11 Circuit results

A few remarks are required here. In principle, there is agreement between design and modelling engineers that model validation on benchmark circuits is beneficial for both sides (cf chapter 4). However, this validation loop is rarely closed in an industrial environment for various reasons, such as simply the large schedule and product pressure on one hand and the very limited resources on the other hand. In addition, it is difficult to obtain agreement on which benchmark circuits satisfy at least the majority of design applications. For digital applications, often frequency dividers and ringoscillators consisting of CML or ECL gates are employed; experimental results for the latter will be shown below. For h.f. analog (e.g.. wireless) applications, not only the selection but also the design and testing itself is much more difficult. A larger variety of designs that are suited for on-wafer testing are required. As of now, results of only few production circuits are available that agree well with model "predictions", but which have not been included here due to proprietary reasons.



Oscillation frequency f_{osc} vs. current density (I_{tail}/A_E) per stage for a CML ring-oscillator fabricated in a 25 GHz process; comparison between measurement (symbols) and HICUM (lines).
Due to power considerations, the smallest manufacturable emitter size ($0.4*0.7\mu m^2$) has been used; no specific or other model parameters were adjusted for this example.