Small-Signal Analysis and Direct S-Parameter Extraction

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Abstract. We present a comparison of several device parameters obtained by fully two-dimensional physical device simulation of several device parameters and measurements. Several features for direct extraction of either extrinsic or intrinsic (de-embedded) parameters sets from AC-simulation were implemented in the three-dimensional device simulator Minimos-NT [1]. The scattering parameters (S-parameters) and other figures of merit of a complex heterostructure device have been obtained directly by using small-signal simulation. Thus, we use a combination of rigorous III-V group and IV group semiconductor materials modeling and the ability to simulate in the frequency domain. The results were verified both by analytical methods and by comparison with measurement data.

Introduction

Two-dimensional device simulation has proven to be valueable for understanding the underlying device physics and for improving the device reliability [2, 3, 4] of advanced heterostructure device, such as Heterojunction Bipolar Transistors (HBTs). The highly sophisticated physical models can also be used for high-frequency simulations, the results of which are required and commonly used for future device and circuit designs. For example, S-parameters are an extremely useful design aid provided by manufactures for high-frequency transistors. Normalized incident and reflected waves are used to characterize the operation of a two-port network. Thus, in contrary to the Y-parameters, no short circuit is required which often causes unstable devices and prevents measurements.

Small-signal parameters are often taken to extract other figures of merit, such as the cut-off frequency for current gain f_t or the maximum oscillation frequency f_{max}, which characterize a device and technology or emphasize their superiority, respectively.

The simulation of these parameters can be based on several approaches, e.g. Fourier decomposition, applying quasi-static or equivalent-circuit parameter models [5, 6]. These approaches use a transient simulation mode and are both more CPU-time consuming and more inaccurate. Furthermore, they can perform only a limited number of time steps in reasonable CPU-time (basically, many time steps are necessary to obtain sufficient time-domain accuracy to generate sufficient frequency-domain accuracy). Usually, the transient effort must be reduced by extracting an equivalent circuit using the results of only one frequency. Our direct small-signal simulation mode is based on the S^3A (sinusoidal steady-state analysis) approach presented in [7], which is rigorously correct, regarded to be computationally inexpensive and very accurate. The high accuracy is due to the formal linearization of the device and because of doing the calculations directly in the frequency domain. Fig.1 sketches comparison of the different approaches. Since the simulator offers both simulation modes, we were able to directly compare the computational effort.

The paper includes a description of the implemented small-signal simulation mode and a short overview about the physical modeling used in the simulator. We present the current state of development by showing six simulation examples followed by an analysis of the computational effort.

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Finally, a conclusion is given to summarize the improvements of the simulator and the advantages of our approach.

The Small-Signal Simulation Mode

After a conventional DC-step for the calculation of an operating point the simulator is switched to the complex-valued small-signal simulation mode, the implementation of which is based on the S^3A approach [7]. A complex sinusoidal perturbation of infinitesimal amplitude is used to excite the device directly in the frequency domain. The device is linearized at the DC operating point, which avoids harmonic generation within the device.

A crucial aspect for the implementation of this approach is the requirement of solving complex-valued equation systems. For that reason our simulator was equipped with a linear equation assembly and solving module being able to handle both real-valued and complex-valued entries or systems, respectively. Thus, it is not necessary to split the equation system into a real and imaginary part causing double dimension or fourfold size of the system matrix. The real-valued mode used for DC and transient simulations was kept due to performance considerations.

This already established method to perform small-signal simulation was extended by several additional functionalities. A dedicated feature allows to efficiently simulate the intrinsic admittance parameter set (Y-parameters) or admittance matrix (Y-matrix), which is used to retrieve several other sets. The quality of the admittance matrix can be explicitly proven by calculating the row and column sums, which have to be zero according to Kirchhoff's laws. We observed an error of 10^{-16} having typical entries of about 10^{-3}. Using a general transformation formula (including the characteristic impedance which can be independently defined for each contact) allows to calculate intrinsic S-parameters for the complete device, that means for all ports.

A two-port representation (common emitter) is often used to get four parameters such as the scattering parameters S_{11}, S_{12}, S_{21} or S_{22}. Thus, parasitics caused by measurement equipment can be accounted for. Minimos-NT provides one standard (common-emitter) equivalent circuit to calculate extrinsic device parameters. For each contact a resistance, an inductance and a capacitance (to another contact) can be defined. The extrinsic admittance parameters can be straightforwardly converted to Z-, Y-, or H-parameters.

Physical models

An important prerequisite of our approach is a correct modeling both in the steady-state condition and of all frequency-dependencies. Thus, much effort has been invested to develop and implement the simulator models. Minimos-NT deals with different complex structures and materials, such as Si, Ge, GaAs, AlAs, InAs, GaP, InP, their alloys and non-ideal dielectrics. All important physical effects implicitly necessary for the simulation of advanced structures, such as bandgap narrowing, surface recombination, transient trap recombination, self-heating, and hot electron effects, are taken into account. Experimental data and Monte Carlo simulations were used during the development and implementation of these models covering the complete material composition range.

The simulator parameters are checked against several independent HEMT and HBT technologies to obtain one concise set used in all simulations. Efficiency and quality are also proven by hydrodynamic DC-simulations with self-heating enabled, e.g. see Fig. 2 for a comparison of the simulated and measured DC-output characteristics.

Simulations

By means of the presented simulation mode, we extracted various high-frequency data for a one-finger InGaP/GaAs HBT with an emitter area of 3 μm × 30 μm. This high-power device is used for power amplifier circuits for mobile communication. Fig. 3 shows the simulated device structure and the pad parasitics (capacitances and inductances) of the measurement environment used for the S-parameter measurement in the two-port pad parasitic equivalent circuit. Table 1 summarizes the values used for the circuit elements. The resistive parasitics are neglected, since we consider a rather small device and, therefore, only low currents. The combined smith charts in Fig. 4, 5, and 6 show a comparison of simulated and measured S-parameters at V_{CE} = 3 V, with current densities $J_C = 2\times10^3$ A/cm^2, $J_C = 8\times10^3$ A/cm^2, and $J_C = 15\times10^3$ A/cm^2, respectively, for the frequency range between 50 MHz and 10 GHz.

For the same device we extracted the high-frequency figures of merits current gain g_m and the squared absolute value of current ratio parameter h_{21}. The cut-off frequency f_t and maximum oscillating frequency f_{max} are found at the intersection of these curves at 1. Fig. 7 gives a comparison of simulated and measured g_m and H-parameter h_{21}. The measurement data ends with 10 GHz, whereas the simulation was continued to 20 GHz – showing another important advantage of simulators to measurement equipments.

In addition, we set up a mixed-mode circuit to compare large signal measurement data in the small-signal range. Fig. 8 shows a comparison between measured and simulated collector currents i_C, Fig. 9 shows an almost perfect match of the curves in the small-signal area of the figure. A further increase of the input power causes harmonics in the device, which can not be obtained by the linear small-signal mode as presented in this work.

Computational effort of S-parameter measurement

The AC-simulation takes about 200 s CPU-time on a 2.4 GHz Linux Pentium machine for S-parameters computation with 20 frequency steps. A number of 20 steps is more than sufficient to produce the graphs. For comparison, the conventional small-signal equivalent-circuit approach [3] takes about 590 s CPU-time at the same machine for 200 time steps at only one given frequency.

As stated in the introduction, many time steps have to be performed to ensure appropriate accuracy in the time-domain to obtain sufficient accuracy for one frequency. To avoid this number of time steps for all frequencies required, only one frequency is used to extract an equivalent circuit valid in a specific frequency range. The time for such a post-processing of the transient simulation results to obtain the S-parameters at all frequencies is not included. Thus, the more accurate approach can speed up the frequency-domain simulation by about 98% (taking one frequency into account).

Conclusion

The good agreement with measured data and the speed-up achieved demonstrate the quality and the efficiency of our approach. A tuning or a linear optimization of the parasitics can yield an excellent match for all figures, as it has already been demonstrated [8]. Modern measurement equipments often account for parasitics or provide originary deembedding features, for that reason the intrinsic parameters provided by Minimos-NT can be used for comparisons. The simulator can transform the calculated admittance parameters to several other parameter sets and to additional figures of merit. In addition, the two-dimensional physical simulation allows obtaining a direct relation between the material properties and the high-frequency device behavior.

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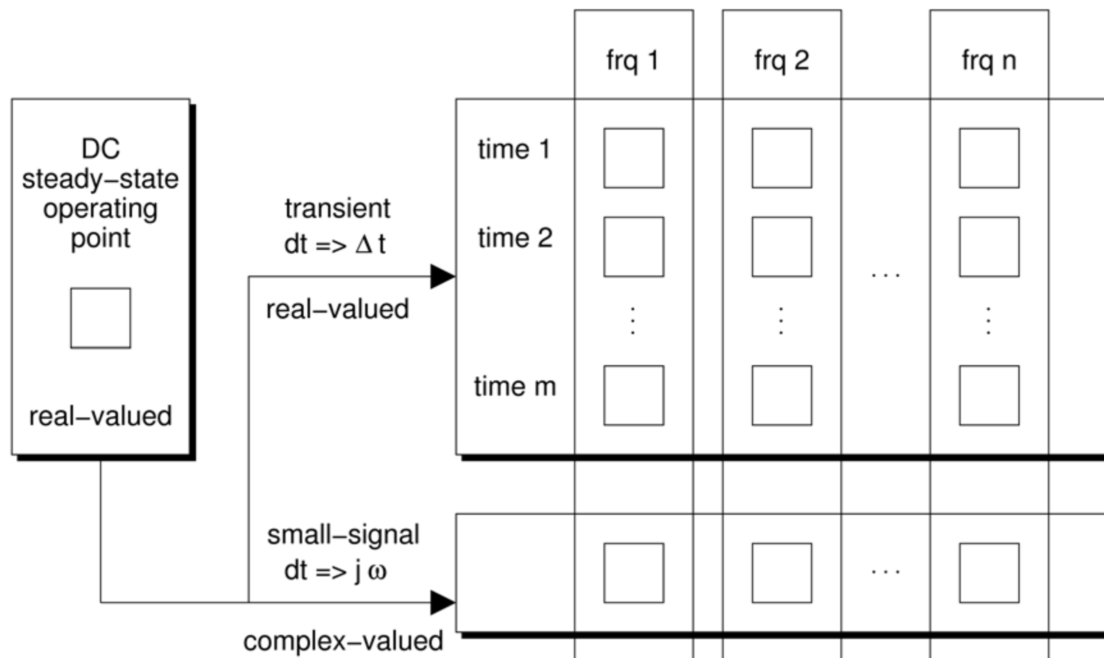

Figure 1. Comparison of small-signal and transient approaches: for one frequency step the transient mode has to perform many time steps to achieve sufficient accuracy. The small-signal mode is simulating directly in the frequency domain and, thus, no approximations are necessary. For that reason the small-signal approach is both more accurate and faster.

Parasitic element	Value
C_{pBE}	150 fF
C_{pCE}	75 fF
C_{pBC}	24 fF
L_E	1 pH
L_B	75 pH
L_C	50 pH
R_E	0 Ω
R_B	0 Ω
R_C	0 Ω

Table 1. Values of capacitive and inductive elements in the equivalent circuit used for accounting in parasitics caused by the measurement equipment.

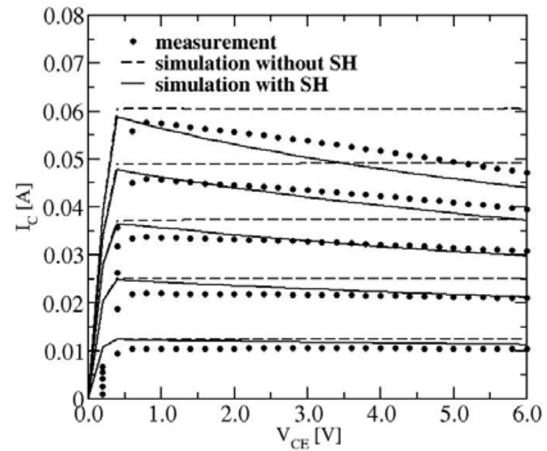

Figure 2. Output characteristics: Simulation with and without self-heating (SH) compared to measurement data at constant IB stepped from 0.1 to 0.5 mA.

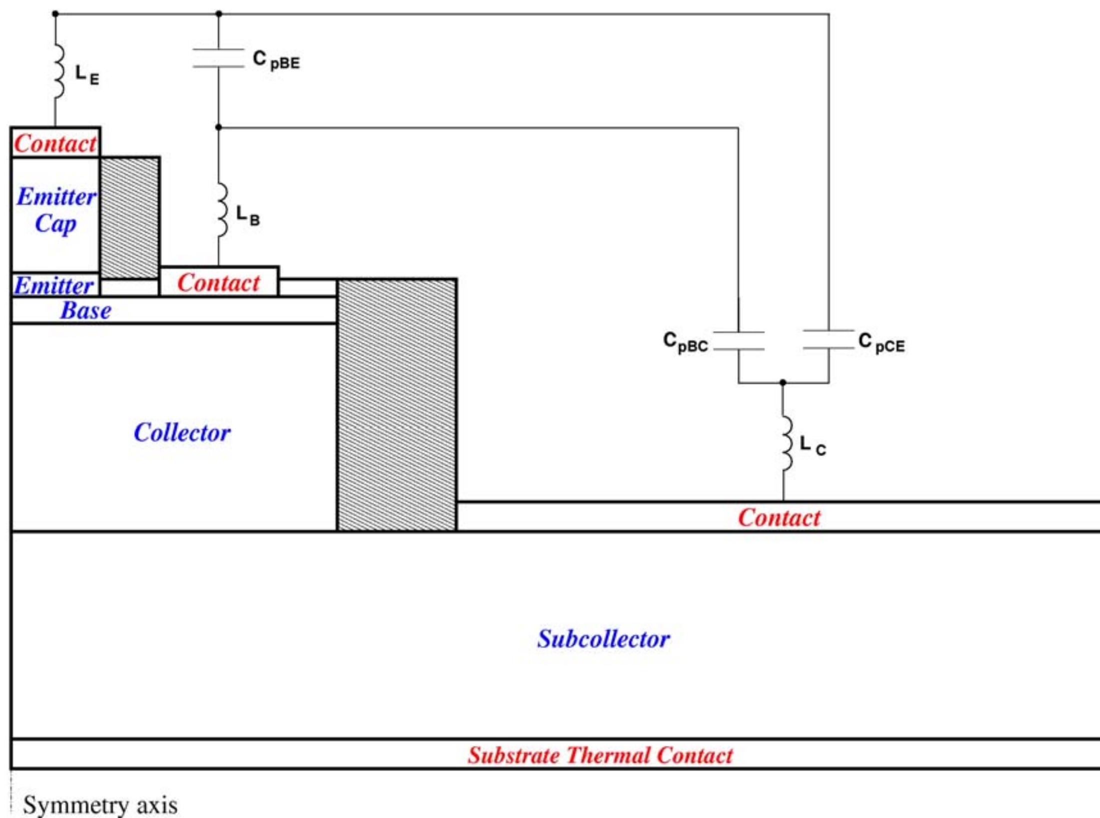

Figure 3. Simulated device structure together with pad parasitics used for S-parameter calculation. See Table 1 for the respective values of the parasitic elements.

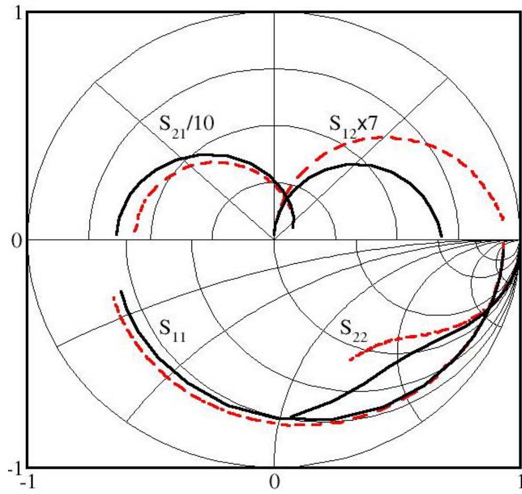

Figure 4. S-parameters (measurements dashed) in a combined Smith chart at $J_C = 2\times10^3$ A/cm^2.

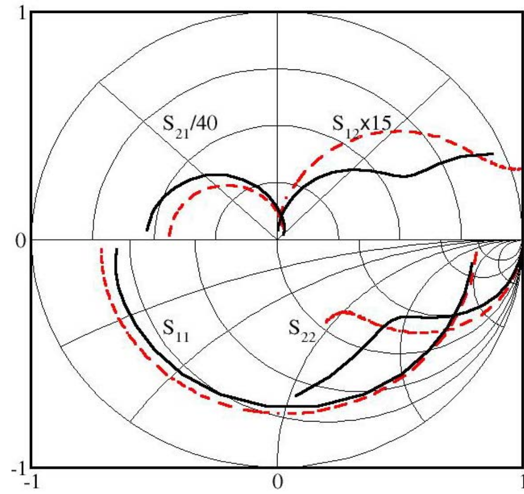

Figure 5. S-parameters (measurements dashed) in a combined Smith chart at $J_C = 8\times10^3$ A/cm^2.

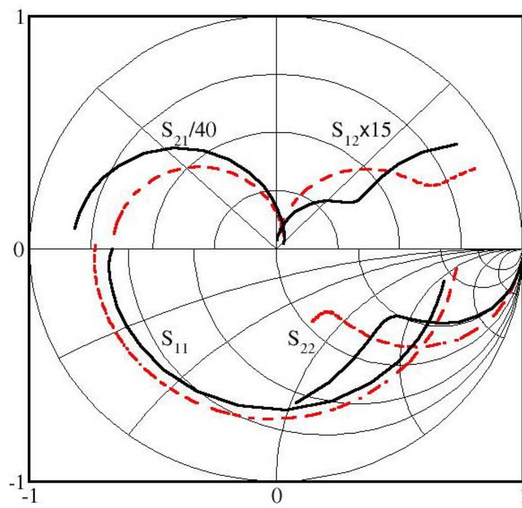

Figure 6. S-parameters (measurements dashed) in a combined Smith chart at $J_C = 15\times10^3$ A/cm^2.

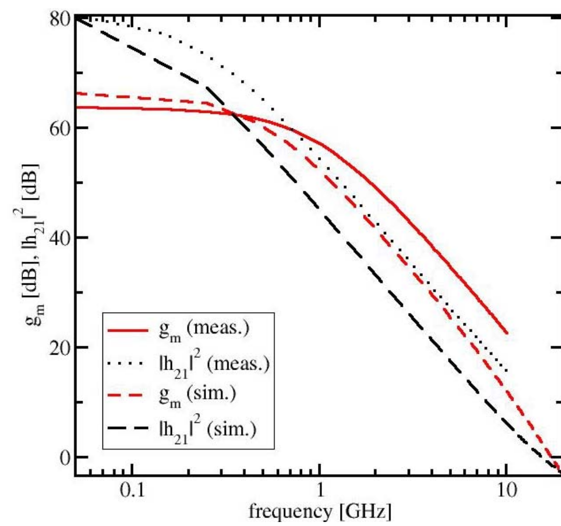

Figure 7. Simulated vs. measured current gain g_m and parameter $|h_{21}|^2$ at $J_C = 15\times10^3$ A/cm^2.

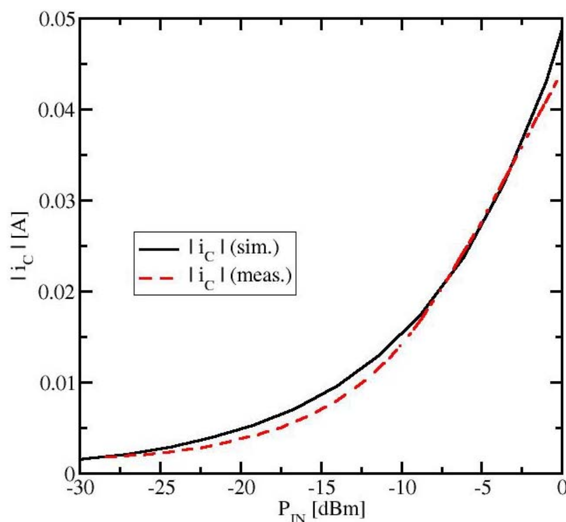

Figure 8. Simulated vs. measured AC collector current i_C over AC input power P_{IN}.

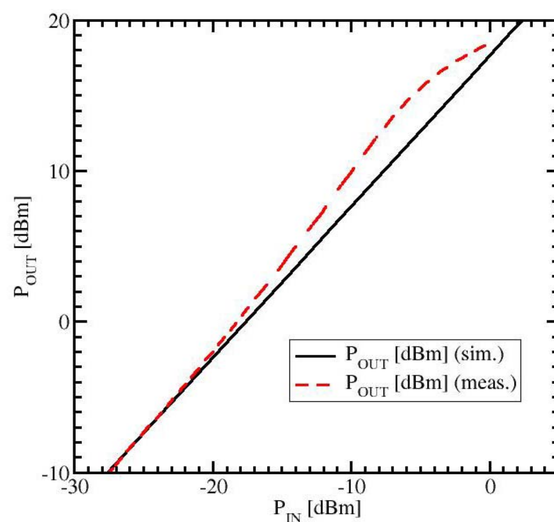

Figure 9. Simulated vs. measured AC output power P_{OUT} over AC input power P_{IN}.