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Direct extraction feature for scattering parameters of SiGe-HBTs

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Abstract

We present a direct approach to obtain scattering parameters (*S*-parameters) and other derived figures of merit of SiGe-HBTs by means of small-signal (ac) analysis. Therefore, an additional simulation mode has been implemented in the three-dimensional device simulator MINIMOS-NT. Several additional features are provided for efficiently obtaining various small-signal parameters. The accuracy of the results is proven by analytical methods and by comparison with measurements.

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1. Introduction

Since advanced SiGe techniques allow competitive performance of high frequency devices in markets that were prior the object of other materials, small-signal analysis by means of simulation of these devices becomes more important. The idea of small-signal ac device characterization is to analyze the relationship between small (in terms of the limit of the amplitude to avoid harmonic generation) sinusoidal contact currents and voltages superimposed upon a dc device operating point obtained by a steady-state simulation mode. *S*-parameter sets which are widely used for rf circuit design, are one particular result of a small-signal analysis. The advantage over *Y*-parameters is that normalized incident and reflected waves are used to characterize the operation of the two-port network. Thus, no short circuit is required, which often cannot be achieved because the parasitics cause unstable devices and thus prevent measurements.

The current version of the device simulator MINIMOS-NT [1] has been equipped with an efficient feature for obtaining intrinsic admittance and scattering parameters, which can then easily be converted to other parameter sets, such as *Z*- or *H*-parameters. For example, it is common practice to use the parameter h_{21} to extract the cut-off frequency f_T. Hence, a direct small-signal analysis of complex structures can crucially ease device design and circuit development.

2. Physical modeling

The physical models implemented in MINIMOS-NT allow advanced simulation of heterostructure devices [2], since all important physical effects such as bandgap narrowing, surface recombination, transient trap recombination, impact ionization, self-heating, and hot electron effects are taken into account. In addition, we use an anisotropic electron mobility model. The

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simulator deals with different complex structures and materials, such as Si, Ge, SiGe, GaAs, AlAs, InAs, GaP, InP, their alloys and non-ideal dielectrics.

The models are based on experimental or Monte Carlo simulation data and cover the whole material composition range. The carrier transport, generation-recombination, and the self-heating models take also the transient contributions into account, and therefore, the same models are used for the small-signal simulation mode in our approach.

3. The small-signal simulation mode

A small-signal simulation mode can be based on several approaches, e.g. Fourier decomposition and applying quasi-static or equivalent-circuit parameter models. These approaches commonly use a transient simulation mode as shown in Fig. 1. The time derivatives are usually discretized by a backward Euler discretization, and thus a high number of steps has to be performed to achieve sufficient accuracy. For that reason, the time consumption is usually reduced by extracting an equivalent circuit using the information of only one frequency.

Our small-signal analysis mode is based on the S^3A approach presented in [3]. After a conventional dc step at a given operating point, the simulator is switched to the simulation mode in the frequency domain, where the device is excited by a complex sinusoidal perturbation of infinitesimal amplitude. For example, the electron current continuity equation can be symbolically given as $F(V, n, p) = \mathrm{d}G(n(t))/\mathrm{d}t$, with non-linear functions F and G. The time-dependent vector function of electron concentration $n(t)$ is then substituted by $n(t) = n_0 + n\,\mathrm{e}^{\mathrm{j}\omega t}$. The system is thus Fourier transformed ($\mathrm{d}t \rightarrow \mathrm{j}\omega$) and the final small-signal approximation is obtained by terminating the Taylor series expansion after the linear part. In comparison to transient methods [4,5] performance is better (only one equation system per frequency step has to be solved) and the results are more accurate, since approximations are not required. As was shown in [6] the speed-up can be up to 98%.

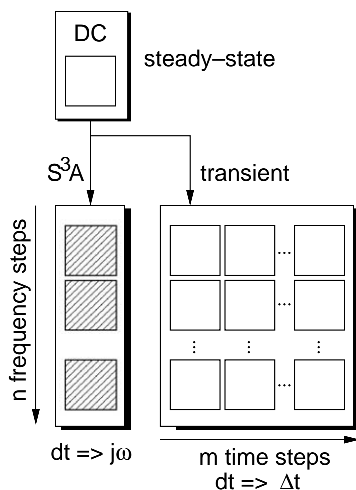

Fig. 1. Comparison of small-signal and transient approaches. The dashed rectangles of the S^3A approach symbolize complex-valued equation systems, the other real-valued ones.

This approach requires the ability for solving complex-valued linear equation systems, for which several methods can be applied. One possibility is to reuse a real-valued assembly and solver system, split the real and imaginary part and solve both systems separately. In terms of memory consumption, this approach has, especially for three-dimensional simulations, severe disadvantages, since the dimension doubles causing a four-fold-sized system matrix. Thus, the computational effort for factorization can be excessive. Iterative methods like block-Gauss–Seidel or block-SOR are suggested in [3] for reducing this effort. Another approach implemented in MINIMOS-NT is to provide a template-based assembly and solver system (BiCGStab and GMRES(m) iterative solvers) capable to handle both real- and complex-valued systems. The real-valued variant was kept due to performance considerations.

In addition to this already established small-signal analysis method, we have implemented a feature for direct extraction of intrinsic (de-embedded) *Y*- and *S*-parameters. As an optional feature these parameters can be transformed into extrinsic parameters in order to take parasitics introduced by the measurement setup into account.

4. The simulation device and results

The investigated $0.4\,\mu\mathrm{m} \times 12\,\mu\mathrm{m}$ SiGe-HBT device structure is obtained by process simulation [7]. For dc simulations usually only the active part

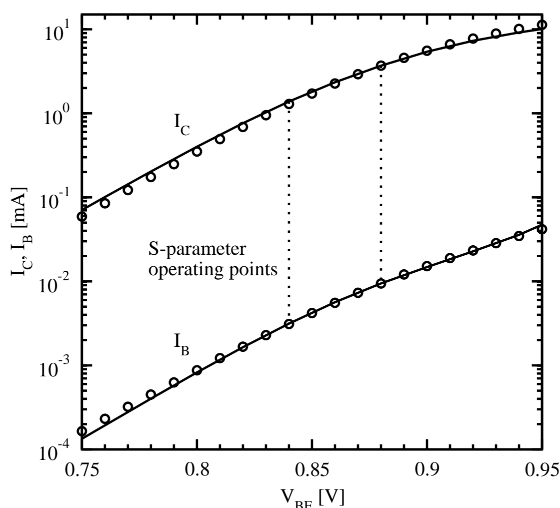

Fig. 2. Comparison of simulated and measured forward Gummel plots at $V_{CE} = 1$ V.

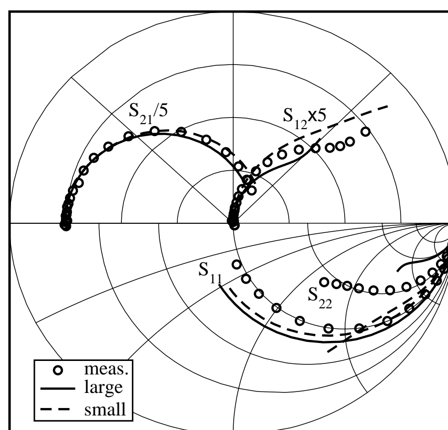

Fig. 3. *S*-parameters in a combined Smith-polar chart (radius 1) from 50 MHz to 31 GHz at $V_{CE} = 1$ V and current density $J_C = 28$ kA/cm^2. For simulations either a larger device structure or a small one embedded in a circuit is used.

(base and emitter area, collector contact was moved to the bottom) of the device is required. For that reason the collector area was cut to speed-up simulations due to the reduced grid size. Only half of the real structure was simulated because of symmetry. Fig. 2 shows a comparison of simulated and measured forward Gummel plots at $V_{CE} = 1$ V.

Note that it is absolutely necessary for ac simulations to take the complete device structure into account. Thus, for the reduced device structure the important capacitances between collector and substrate C_{CS} as well as between base and collector C_{BC} could not be reproduced. In addition, the correct base and collector resistances are missing. There are two possibilities to overcome this problem. Either the missing parts are approximated by introducing linear elements in a postprocessing step or a larger or even complete structure is used for ac simulations. The first option allows faster simulations but gives approximated results. The second one produces more accurate results and does not require a postprocessing step, but takes much more time: in the example the computational effort of device simulation is 2.5 times higher.

In Figs. 3 and 4 both options are compared: in the frequency range between 50 MHz and 31 GHz measured and simulated *S*-parameters at $V_{CE} = 1$ V and current densities $J_C = 28$ and 76 kA/cm^2 are shown. For the first option we embedded the device structure in a circuit containing the following elements: $C_{CS} = 50$ fF, $C_{BC} = 20$ fF, $R_B = 15\ \Omega$ and $R_C = 27\ \Omega$. Their values were experimentally estimated. The results of the second option are the intrinsic parameters only.

The quality of the simulated (intrinsic) *Y*-parameters is proven by calculating the row and column sums of the admittance matrix, which have to be zero according to Kirchhoff's laws. The simulation yields errors of about 10^{-16} A/V for typical matrix

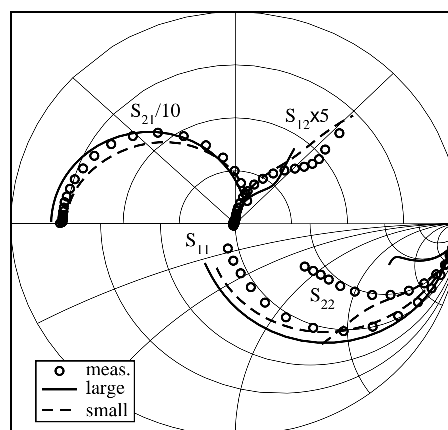

Fig. 4. *S*-parameters in a combined Smith-polar chart (radius 1) from 50 MHz to 31 GHz at $V_{CE} = 1$ V and current density $J_C = 76$ kA/cm^2.

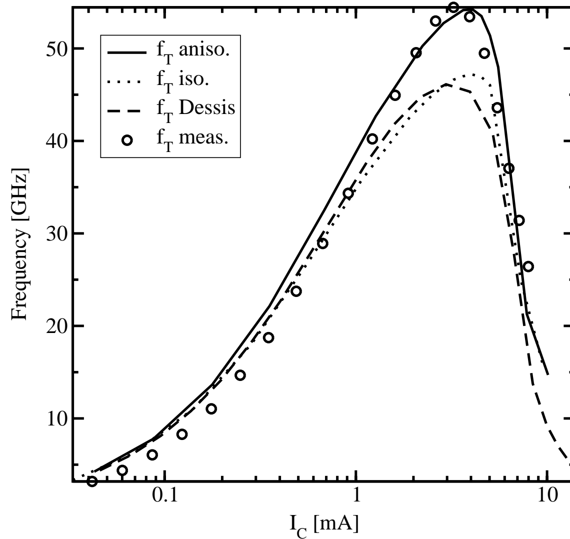

Fig. 5. Cut-off frequency f_T vs. collector current I_C at $V_{CE} = 1$ V.

entries of 10^{-3} A/V. The transformation to intrinsic *S*-parameters is completely analytical (also the accounting for the capacitances) and, thus, the results can be directly compared to the measurement data. Since the measurement environment accounts for the parasitics, no transformation to extrinsic parameters is necessary.

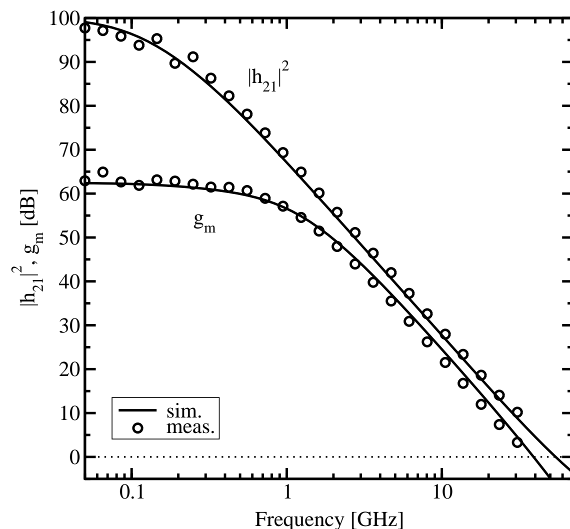

Fig. 6. Short-circuit current gain h_{21} and matched gain g_m vs. frequency at $V_{CE} = 1$ V and current density $J_C = 76$ kA/cm^2.

For the same device we calculated the matched gain g_m and the short-circuit current gain h_{21} in order to extract the figures of merit f_T (short-circuit cut-off frequency) and f_{max} (maximum oscillation frequency) found at the intersection with 0 dB (unity gain point). Figs. 5 and 6 show the comparison of our results and the corresponding measurement data. While the measurement data ends at 31 GHz the simulation could be extended to frequencies beyond this intersection. The peak of the f_T-curve in Fig. 5 corresponds exactly to the frequency at the respective intersection in Fig. 6.

Fig. 5 shows also the effect of the introduction of anisotropic electron mobility. In addition, results obtained by a commercial device simulator (DESSIS [8]) using default models and parameters are included for comparison.

5. Conclusion

The agreement in order of the typical curve characteristics with measured and transformed data proves the efficiency of our approach. In addition, the performance speed-up in comparison to alternatives is an important advantage. However, a general approach to match simulated results and measured data perfectly has to comprise a proper physical modeling of the complete device since there are no extrinsic fitting parameters available. We are able to extract various sets of small-signal parameters as well as related figures of merit by means of simulation with MINIMOS-NT.

Acknowledgements

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