S-Parameter Simulation of RF-HEMTs

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Abstract

This paper describes the results of a physically based time efficient method of simulating S-parameters of RF-High Electron Mobility Transistors (HEMTs). In a frequency range from 2 GHz up to 120 GHz the simulated S-parameters show good agreement with the measurements obtained in the same frequency range. Using the two-dimensional device simulator MINIMOS-NT and a time domain method critical HEMT structures can be characterized in the RF-domain. Equivalent to the S-parameters also the full set of the eight-element small signal equivalent circuit elements is obtained. The dependence of small signal circuit elements on changes in the bias can be reproduced realistically.

Introduction

GaAs based High Electron Mobility Transistors (HEMTs) are established devices for MMICs operating at frequencies up to 100 GHz being used in a growing field of applications [1,2,3]. The fast, reliable simulation of HEMT devices is an important issue due to the increasing complexity of such devices with respect to specific applications. In addition, cost effective volume production demands the forecast of the behavior of devices with critical dimensions before starting actual production. In this work the results of DC- and RF-simulations of AlGaAs/InGaAs/GaAs pseudomorphic HEMTs are presented. In particular, aspects of their high frequency behavior are investigated. The simulations are carried out with the two-dimensional device simulator MINIMOS-NT, the capabilities of which in respect to HEMTs have been described in [4]. Complementing investigations with examples characterized by DC and by small signal equivalent circuit elements were presented in [5,6].

Aim of this work

Being used up to 100 GHz, next to their DC-behavior, the HEMT devices need RF-characterization, which is commonly performed by model extraction of small signal equivalent circuits from measured S-parameters and modeling of the S-parameters measured from the small signal equivalent circuit model [7]. Yet, in volume production the processes may vary slightly causing variations of the physical properties of the devices. For this reason it is desirable to investigate and forecast the dependence of the RF-behavior from process controlled properties of the fabricated HEMTs. Hereby crucial parameters such as e.g. the gate-source capacitance and the gate-drain capacitance can be stabilized with respect to possible process variations already during the design period.

Physically based S-parameter simulations for HEMTs have been reported e.g. in [8]. The results published there were based on a quasi two-dimensional simulation which was used due to an existing trade-off between the necessary simulation time and the complexity of the models. Yet, in order to describe the bias dependence of the equivalent circuit elements over a wide bias range the appropriate analytical modeling of III-V structures is absolutely necessary for devices with critical dimensions [9]. Therefore a fully two-dimensional simulator such as MINIMOS-NT is used in our work.

By means of a small signal approach Y-parameters are extracted in the time domain at a frequency of choice. Based on the analytical eight-element small signal model extracted from the Y-parameters, the

S-parameters of the HEMTs can be simulated for a wide frequency range, in this case between 2 and 120 GHz. This approach requires modest simulation time for a given bias point relative to the possible alternative, the fast Fourier approach in the frequency domain.

Results

Fig.1 schematically shows the vertical geometry of the simulated HEMTs. A double recess, pseudomorphic AlGaAs/InGaAs/GaAs HEMT with a backside doping and a T-shaped gate of 120 nm gate-length is used. A critical parameter of such a RF-device is the gate-to-channel distance d_{gc}. In Fig.2 a comparison of the transfer characteristics of the HEMT simulated for V_{DS}=2.0 V for three gate-to-channel distances d_{gc} and measured data is shown, which reveals a good agreement between measurement and simulation. The values of the gate-to-channel distance d_{gc} given are obtained by the calibration of the simulation to technology variations.

In the case of a pure DC-simulation the simulator can reveal extrinsic characteristics, since ohmic contact resistances can be implemented into the simulation. Therefore, a direct comparison to measured data is possible as shown in Fig. 2. For both RF-measurements and simulations in the GHz range the HEMTs have to be placed into the circuit environment due to the parasitic capacitances and inductances not included in the simulation. Fig. 3 shows the related equivalent circuit illustrating the deembedding approach: The most inner shell shown in the Fig. 3 represents the intrinsic device behavior. The next outer shell includes the ohmic contact resistances and to a good degree of approximation represents the RF-results obtained by the simulator. The most outer shell represents the transistor as being implemented into the measurement and also circuit environment: The parasitic values of L and C in this shell are found to be characteristic for the layout of the device used and are thus taken as constants from typical extractions.

The S-parameters were simulated by applying small signal AC-voltages to the terminals of the device at a particular bias point. Y-Parameters were obtained at a simulation frequency of 5 GHz. By using the eight-element small signal equivalent model given in Fig. 3 the results were expanded up to 120 GHz and compared to measurements taken at the same bias and frequency range. Fig. 4 shows this comparison for a HEMT with 2x40 μm gate-width. The measurements are represented by the crosses whereas the simulation results are represented by the lines. The physical simulation results agree quite well with the measurements for S_{22} and S_{21}. The deviations for S_{11} for high frequencies and S_{12} can be explained by the overestimation of the ohmic resistances in the eight-element model. This can be understood since these elements include parts of the resistances from the contact models and the resistances in the semiconductor regions and the comparison to real devices bear a lot of sources for errors. Varying the ohmic resistances slightly from the values simulated an even better agreement could be found. Hence, up to 120 GHz the eight-element circuit model can describe the transistor based on the physical simulation results obtained at one simulation frequency.

Fig. 5 shows the bias dependence of the small signal equivalent circuit elements C_{gs} and C_{gd} for a constant source-to-drain voltage. It is found that the gate-to-drain capacitance C_{gd} is almost independent of V_{GS}, whereas C_{gs} rises with increasing V_{GS}. Above a voltage of V_{GS} = 0.7 V the carrier generation due to the opening gate-to-source diode has to be included into the simulation. Fig. 6 shows the bias dependence of the RF-output conductance. Again a quite a good agreement can be found with the values extracted from S-parameter measurements.

Discussion

The results shown in Fig. 4-6 support the idea that it is possible to combine the modeling features of a fully two-dimensional device simulator with a simulation time efficient approach of obtaining a broad variety of RF-information for different bias points. The S-parameters characterize the RF-performance of the device much more accurately than the few small signal equivalent circuit elements that can be derived from pure DC-simulations. Fig. 4 shows the complete set of S-parameters. The agreement of physically based S-parameter simulations with measurements to our knowledge has never been demonstrated over such a wide frequency range. The deviations found can be explained and are subject to ongoing research.

Fig. 5 shows the bias dependence of two of the eight available small signal equivalent circuit elements obtained by the simulation and they show relatively good agreement to the extracted data from S-parameter measurements taking into consideration that the external capacities were set constant and electrically are in line with the internally determined values. Fig. 6 shows the RF-output conductance as a function of the bias. These values actually represent additional RF-information, since the DC-values obtained from the output characteristics normally differ from the actual RF-values. The RF-values can now be obtained directly by simulation using the AC-simulation.

Conclusion

In our TCAD (Technology Computer Aided Design) environment a fully two-dimensional device simulator was combined with an RF-simulation approach for efficiently obtaining S-parameters at arbitrary frequencies up to 120 GHz. The simulation results obtained reveal good agreement with the measurements obtained for comparable devices with critical dimensions. They can be used for forward engineering to evaluate possible effects of the optimization of structures with respect to production technology.

Acknowledgments

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Figures

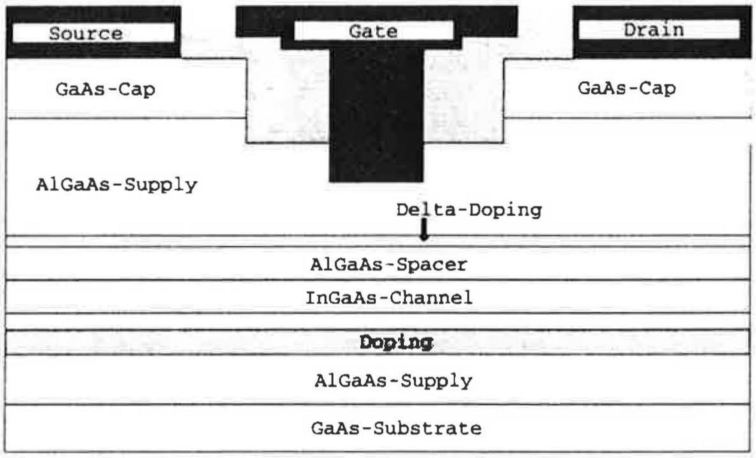

Fig. 1: Schematic cross-section of the simulated HEMTs.

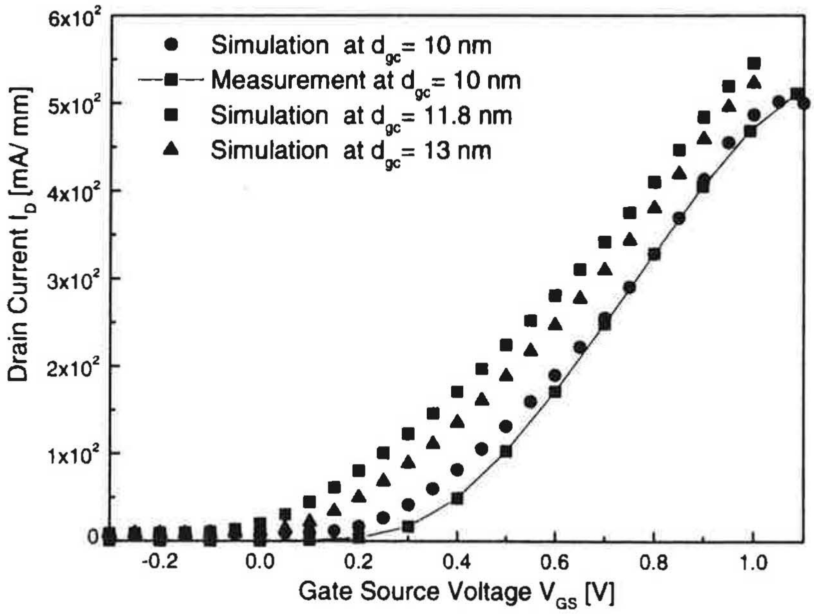

Fig. 2: Transfer characteristics of the simulated HEMTs at V_{DS} = 2.0 V at different gate-to-channel distances d_{gc}.

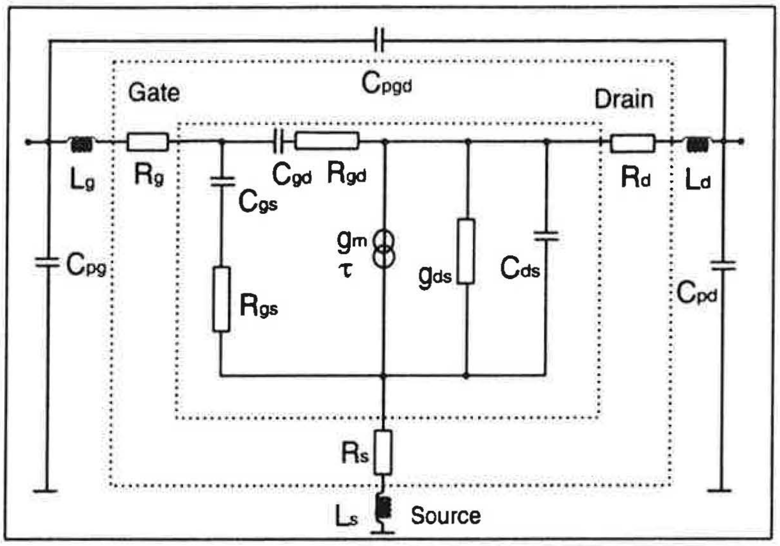

Fig. 3: Small signal HEMT equivalent circuit.

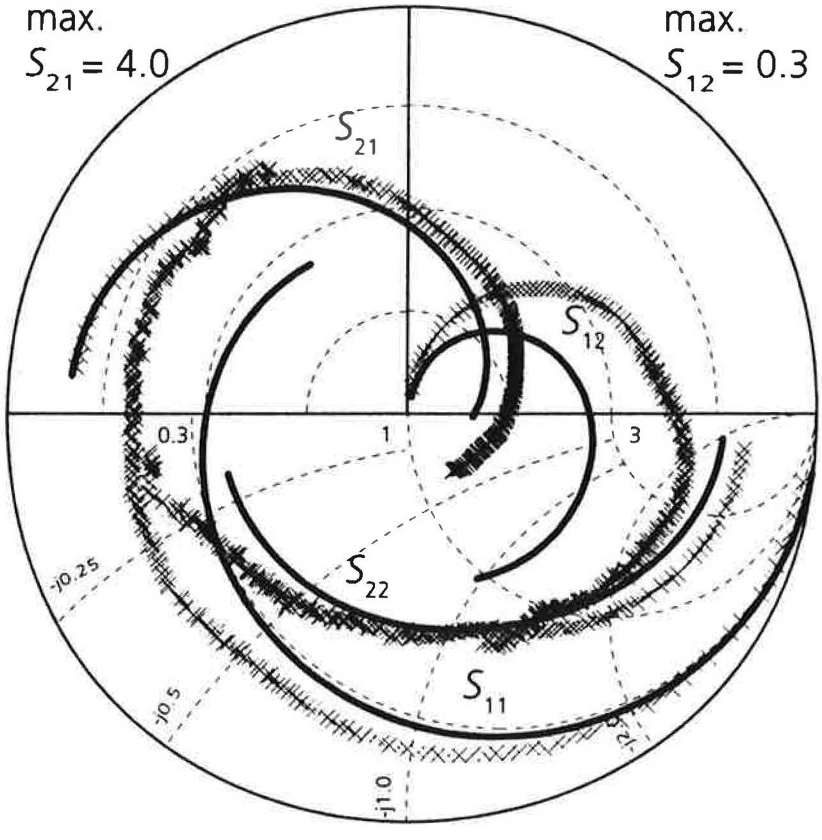

Fig. 4: Comparison of measured (×) and modeled (-) S-parameters for the frequency range f= 2 to 120 GHz, V_{GS}= 0.4 V, V_{DS}= 2.0 V.

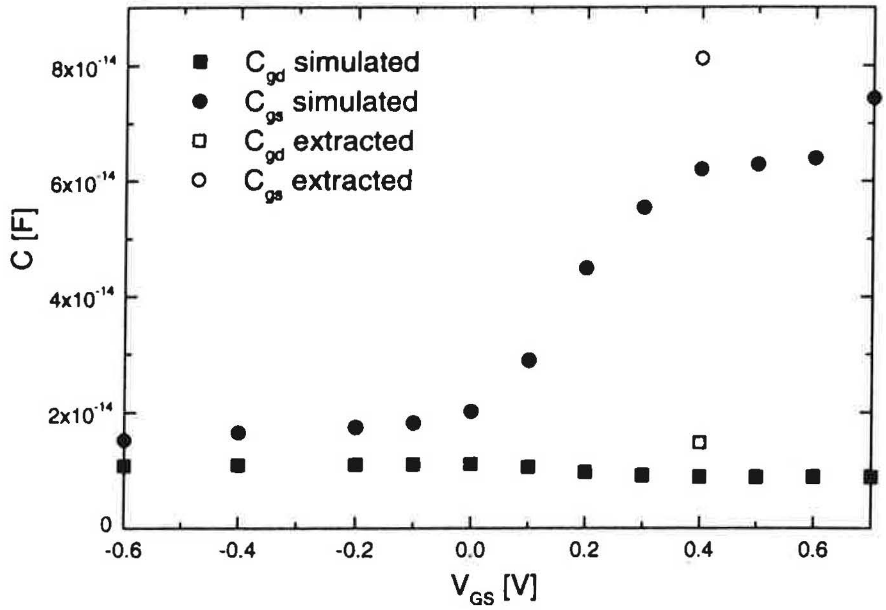

Fig. 5: Simulated bias dependence of C_{gs} and C_{gd} compared to values extracted from S-parameter measurements.

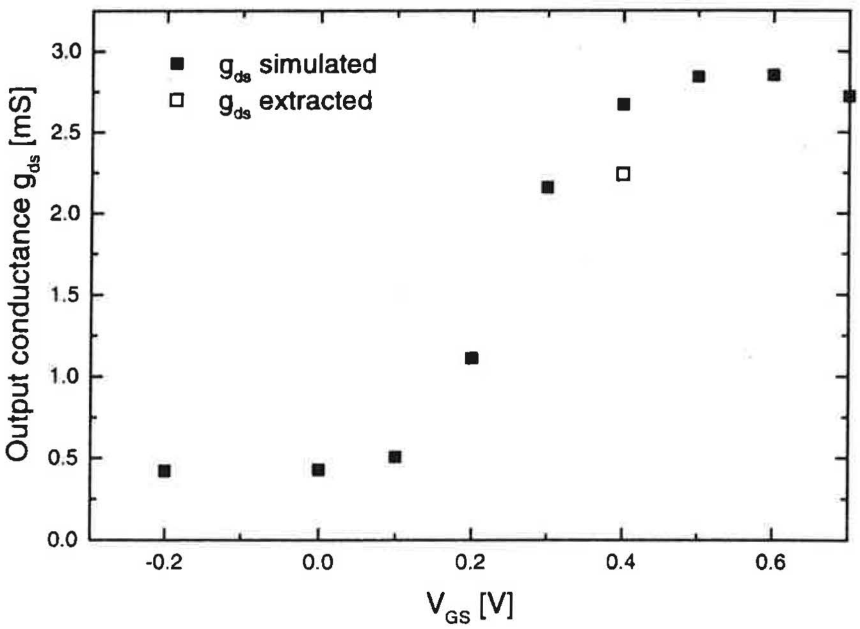

Fig. 6: Simulated bias dependence of the RF-output conductance for a HEMT with 2×40 μm gate-width compared to an extracted value, V_{DS} = 2.0 V.