A Review of Modeling Issues for RF Heterostructure Device Simulation

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Abstract

We give a summary of the state-of-the-art of heterostructure RF-device simulators for industrial application based on III-V compound semiconductors and compare critical modeling issues. Results from two-dimensional hydrodynamic simulations of High Electron Mobility Transistors (HEMTs) and Heterojunction Bipolar Transistors (HBTs) with MINIMOS-NT are presented. Simulation examples are chosen to demonstrate technologically important issues which can be addressed and solved by III-V device simulation. A summary of remaining modeling issues is provided.

1 Introduction

Heterojunction Bipolar Transistors (HBTs) and High Electron Mobility Transistors (HEMTs) are among the most advanced semiconductor devices. They match well today's requirements for high-speed operation, low power consumption, medium- integration, low cost in large quantities, and operation capabilities in the frequency range from 0.9 to 215 GHz. HBT ICs are used for microwave power and low power wireless communications applications, hand held communication, and high-speed digital data transmission. HEMT ICs are used for low power wireless communication applications, local multi-point distribution services for broadband Internet access (LMDS), for automotive cruise control (ACC) radar, and high-speed digital transmission (40 Gbit/s and beyond). The paper summarizes the state-of-the-art of device simulators, including the two-dimensional device simulator MINIMOS-NT, and discusses particular simulation results of such devices obtained with the same simulation tool, model set, and set of model parameters. It concludes with critical modeling issues remaining to develop for the simulation of advanced III-V semiconductor devices.

2 RF-Simulators

Commercial tools, e.g. [1, 2, 3, 4], and University-developed simulators, e.g. [5, 6, 7], are available for device engineering applications. However, for the fast development of the RF industry a stronger feedback from technological state-of-the-art process development to simulator development is needed. Table 1 summarizes features of III-V device simulators to the best of the authors knowledge.

Gateway Modeling offers a one-dimensional Schrödinger-Poisson solver POSES [3] for charge analysis in HEMT devices for process control. Several quasi-two-dimensional approaches are demonstrated, e.g. [7]. This approach, based on a one-dimensional current equation, stresses the interface to the microwave simulator as MDS/ADS. The emphasis is put on the extraction of compact large-signal models. This tool combines the advantages of a hydrodynamic (HD) transport model coupled with Schrödinger's equation, but has the drawback of the simplified one-dimensional current equation. The

Simulator	Dimension	Model	Features	Remarks
POSES	1D		Schrödinger-Poisson solver	
Leeds	quasi 2D	HD	Schrödinger equation Electrothermal model	1D current equations interfaces
Fast Blaze	quasi 2D	HD		1D current equations interfaces
ATLAS	2D	DD,ET	TE heterojunction model	no tunelling modeling
PISCES	2D	DD,ET	III-V models	
G-PISCES	2D	DD	full set III-V models	no HD
MEDICI	2D	DD,HD	anisotropic properties	mixed-mode interfaces
MINIMOS-NT	2D	DD,HD	full set III-V models TE/TFE model	
DESSIS	2D,3D	DD,HD	trap modeling, TFE model	III-V modeling

Table 1: Comparison of different device simulators. (TE): thermionic emission, (TFE): thermionic field emission.

two-dimensional device simulator PISCES has modeling capabilities for GaAs and InP based devices. The variant called G-PISCES from Gateway Modeling [3] has been extended by a more complete set of III-V models. Examples of MESFETs, HEMTs, and HBTs for InAlAs/InGaAs, AlGaAs/InGaAs, AlGaAs/GaAs, and InGaP/GaAs HBTs are demonstrated. A disadvantage is the lack of an energy transport model (ET) or HD transport model. The device simulator MEDICI from Avant!, also based on PISCES, offers simulation capabilities for SiGe/Si HBTs and AlGaAs/InGaAs/GaAs HEMTs. Advantages of this simulator are HD simulation capabilities and the rigorous approach to generation/recombination processes. An option treating anisotropic properties was announced. Weaknesses are found for the III-V materials modeling, for the heterostructure interface modeling and for mixed-mode device-circuit simulation. A quasi-two-dimensional tool is Fast Blaze from Silvaco, based on code from the University of Leeds, which together with the two-dimensional ATLAS [4] has addressed the simulation of AlGaAs/GaAs and pseudomorphic AlGaAs/ InGaAs/GaAs HEMTs. DESSIS from ISE [2] has demonstrated a rigorous approach to semiconductor physics modeling. Critical issues, as the above stated extensive trap modeling, are solved. A heterojunction framework has been included. In the following section simulation results with MINIMOS-NT are presented.

3 Selected Results for Industrially Relevant Devices

Self-heating simulations, especially of high-power multi-finger devices, require realistic boundary conditions taken from a three-dimensional circuit environment. For high-power HBTs self-heating is a major source of limitation. The simulated output device characteristics of an InGaP/GaAs HBT compared to measurements are shown in Fig. 1 with constant boundary conditions for the base current (I_B=0.1-0.5 mA). Note that agreement of simulation and measurement can be achieved introducing self-heating (SH) into the two-dimensional simulation with appropriate boundary conditions, while the isothermal simulation completely disagrees with the measurement. Fig. 2 shows a comparison between the simulated and measured Gummel plots for 400×400 μm^2 $Si_{1-x}Ge_x$ HBTs fabricated with the same geometry and layer specification and with x = 16%, 22%, and 28% Ge content in the base. All simulations were carried out with the same set of models, and no adjustment of model parameters was performed.

For the next generation of data transmission at 80 Gbit/s or high gain analogue applications InAlAs/InGaAs HEMTs high-speed transistors are used. Fig. 3 shows simulation and measurements for a gate length l_g = 150 nm $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ HEMT on a metamorphic buffer. High field effects such as impact ionization are considered [8]. The precise simulation for various low V_{DS} is useful to account for the low power RF capabilities. Fig. 4 shows an evaluation of the possible use of low-k dielectrics to reduce critical capacitances (e.g. C_{gd}) for highest frequency operation.

4 Critical Issues of Modeling Heterostructure Devices

A number of critical modeling issues for III-V devices can be solved with a precise physics-based small-signal parameter extraction [9]. An interface to a microwave simulator such as MDS/ADS from Agilent Technologies, e.g. in [7], allows the analysis of statistical variations of the large-signal models used for circuit design. A statistical sensitivity analysis is especially important for applications beyond 50 GHz, where speed, gain, and output power are very sensitive to the parasitic environment and the large signal properties are very sensitive to the statistical changes of mass production. The simulators have successfully demonstrated good agreement with measurements. Further, improved understanding of the processed semiconductors with respect to the large signal properties is needed. This includes the understanding of changes of transport and interface parameters due to the process. In particular: More attention is required for the process dependence of the insulator semiconductor surface quality and the development of models for non-ideal dielectrics. The impact of the ledge thickness and the surface charge density was studied for a one-finger InGaP/GaAs HBT with respect to reliability [10]. The contact modeling needs further attention since contact degeneration is a major source of device degradation. Non-local approaches for Ohmic and Schottky contacts have been demonstrated, such as [11], however due to the meshing required for application, they are not suitable for general purpose simulators. For the analysis of dynamic breakdown during large-signal operation, e.g., in pseudomorphic GaAs HEMTs, a study requires a combination of impact ionization, traps, and thermionic field emission effects. The treatment of anisotropic properties is needed for SiGe HBTs for the inclusion into a conventional simulator concepts. In contrast to Monte Carlo approaches, this offers the possibility to extract RF information. Quaternary material models are required for a number of III-V devices, i.e. for InGaAsP, AlGaAsSb, and InAlGaAs [12].

5 Conclusion

A review of critical modeling issues for simulation tools of heterostructure RF-devices is presented, specifically addressing remaining modeling issues. New simulation results for industrially relevant devices in good agreement with measured data are demonstrated. With an increasing number of stable, reliable heterostructure technologies available, a meaningful comparison between simulation results and statistically analyzed small and large signal data is possible and delivers model verification and valuable process information.

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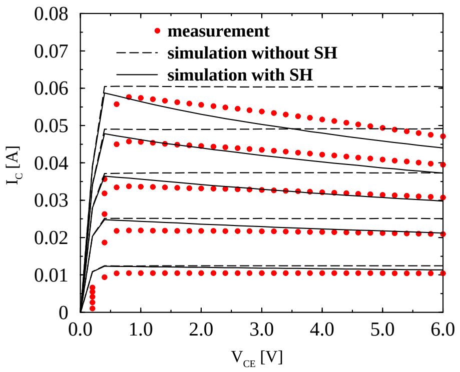

Fig. 1: GaAs HBT output characteristics. Simulation with and without self-heating (SH) compared to measurement data at constant I_B stepped from 0.1 mA to 0.5 mA.

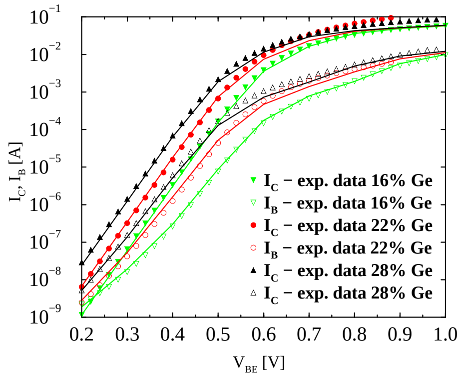

Fig. 2: Forward Gummel plots at V_{BC} = 0 V for SiGe HBTs. Comparison between simulation and measurement for different Ge contents.

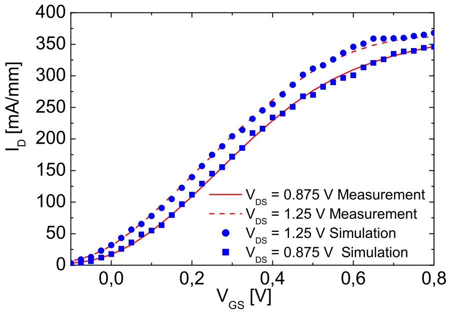

Fig. 3: Transfer characteristics of a metamorphic InAlAs/ InGaAs HEMT with l_g = 150 nm for two different biases.

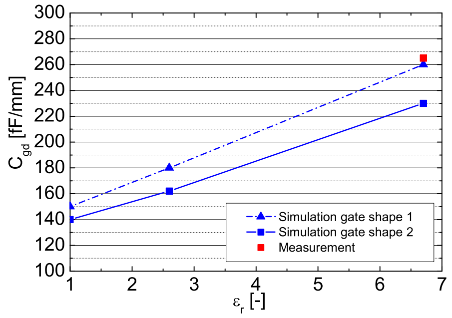

Fig. 4: Reduction of the gate-drain capacitance C_{gd} of an l_g = 100 nm InAlAs/InGaAs HEMT using different dielectrics.

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