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Challenges in Modeling of High-Speed Electron Devices

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The paper discusses the status of research regarding the most important high-speed electron devices, Heterojunction Bipolar Transistors (HBTs) and High Electron Mobility Transistors (HEMTs). This includes a review of materials, devices, driver applications, and device simulators. Proper simulation examples of HBTs and HEMTs are chosen to demonstrate technologically important issues which can be addressed and solved by device simulation.

I. Introduction

Heterojunction Bipolar Transistors (HBTs) and High Electron Mobility Transistors (HEMTs) are among the fastest and most advanced high-frequency devices. SiGe HBTs progressively replace III-V devices for their typical applications, such as low-noise amplifiers and frequency dividers, and are considered essential for 40 Gb/s optical communication systems. The devices are fully compatible with existing state-of-the-art 0.13 μm CMOS technology [1]. GaAs HBTs are typically used in the cellular phone handsets. They have also been applied for 40 Gbit/s data transmission [2]. Their major advantages are the very low off-state power consumption and the high current amplification for low battery-driven circuits. InP HBTs are used for oscillator applications because of the low phase noise properties. Due to a combination of high speed and high breakdown voltages they are suitable for high-speed digital applications up to at least 100 Gbit/s for long distance communication. InP HEMTs also deliver high speed but exhibit gate current issues. Fig. 1 shows the progress of peak-f_T of SiGe and InP HBTs over the last couple of years.

Optimization of geometry, doping, materials, and material composition profiles targets at high power, high breakdown voltage, high speed (high f_T, f_max), low leakage, low noise, and low power consumption. This is a challenging task that can be significantly supported by device simulation.

II. Device Simulators

The continuously increasing power of computer systems allows the use of TCAD tools on a very large scale. Several commercial device simulators (such as [3]-[8]) company-developed simulators (such as [9]-[10]), and university-developed simulators (like [11]-[15]) have been successfully employed for device engineering applications. These simulators differ considerably in dimensionality (one, quasi-two, two, quasi-three, or three), in choice of carrier transport model (drift-diffusion, energy-transport, or Monte Carlo statistical solution of the Boltzmann transport equation), and in the capability of including electrothermal effects. The drift-diffusion transport model [16] is by now the most popular model used for device simulation. With down-scaling of the feature sizes, non-local effects become more pronounced and must be accounted for by

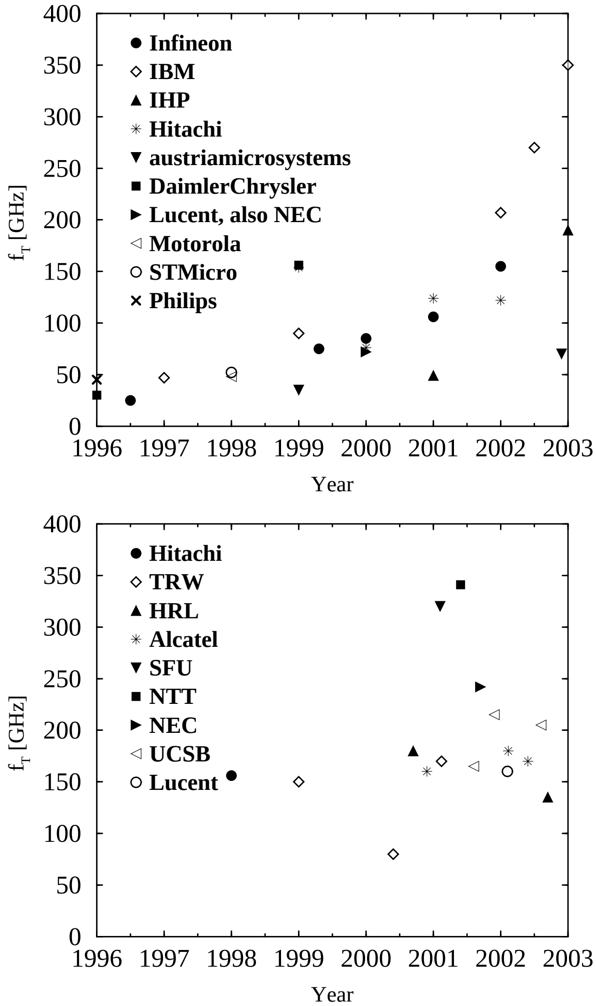

Fig. 1: Current gain cutoff frequency f_{T} of SiGe HBTs (above) and InP HBTs (below) over time.

applying an energy-transport model or a hydrodynamic transport model [17]. During the last two decades, Monte Carlo methods for solving the Boltzmann transport equation have been developed [18] and applied for device simulation [19, 20]. However, reduction of computational resources is still an issue, and therefore Monte Carlo device simulation is still not feasible for industrial application on daily basis. An approach to preserve accuracy at lower computational cost is to calibrate lower order transport parameters to Monte Carlo simulation data.

III. Critical Issues of Modeling Heterostructure Devices

There are several challenges which are specific for modeling and simulation of heterostructure devices. A generic device simulator must be capable not only to account for various semiconductor materials (such as III-V binary, ternary, and quaternary compounds, and Si, SiGe, and SiGe:C) but also for different complex geometrical structures and material sequences in multiple dimensions. The physical properties of SiGe and III-V compounds must be modeled for wide ranges of material compositions, temperatures, doping concentrations, etc. The model parameters have to be verified against several independent HEMT and HBT technologies to obtain one concise set used for all simulations. Reviewing simulation of HBTs and submicron HFETs with gate lengths down to 100 nm used for millimeter-wave devices, solutions of energy transport equations are necessary to account for non-local effects, such as velocity overshoot.

Heterointerface modeling is a key issue for devices which include abrupt junctions. Thermionic emission and field emission effects critically determine the current transport parallel and perpendicular to the heterointerfaces. Another critical issue for recessed HFETs and for III-V HBTs is the description of the semiconductor/insulator interfaces, especially with respect to the treatment of the interfaces during the manufacturing process. Fermi-level pinning prevails for typical barrier materials such as AlGaAs or InAlAs and for ledge materials such as InGaP [21].

Modeling of strained SiGe is not a trivial task, since special attention has to be paid on the stress-induced change of the bandgap as a function of Germanium content [22]. This effect must be separated from doping induced bandgap narrowing which in turn depends on the semiconductor material composition, the doping concentration, and the lattice temperature [21]. As the minority carrier mobility is of considerable importance for bipolar transistors, a distinction between majority and minority electron mobilities is required [21]. The

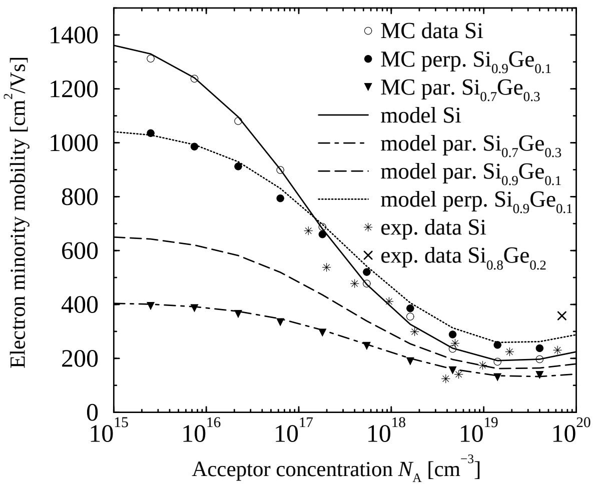

Fig. 2: Minority electron mobility in $\mathrm{Si}_{1-x}\mathrm{Ge}_x$ as a function of N_A and x: The model agrees well with measurements and Monte Carlo simulation data both for in-plane and perpendicular to the surface directions.

good agreement of the model with the measured and the Monte Carlo simulation data, both for in-plane and perpendicular to the surface directions, is illustrated in Fig. 2.

All the important physical effects, such as bandgap narrowing, anisotropic electron minority mobility in strained SiGe, Shockley-Read-Hall recombination, surface and Auger recombination, and impact ionization are taken into account. III-V materials and SiGe are known to have a reduced heat conductivity in comparison to Silicon [21]. Self-heating effects are accounted for by solving the lattice heat flow equation self-consistently with the energy transport equations. Examples are given in the next section for both HEMT and HBT devices.

Advanced device simulation allows a precise physics-based extraction of small-signal parameters [21, 23]. Measured bias dependent S-parameters serve as a valuable source of information when compared at different bias points to simulated S-parameters from a device simulator, such as Minimos-NT. This procedure reflects the full RF-information contained in the S-parameters and allows process control beyond the comparison of DC-quantities.

IV. Selected Results of Industrially Relevant Devices

It is well known that GaAs-HBTs with an InGaP ledge have an improved reliability [24]. Power amplifiers with InGaP/GaAs HBTs are part of many cellular phones today. Two-dimensional device simulation allows the analysis of experimental data in cases which cannot be explained by simple analytical assumptions. This proved to be especially useful for explaining and avoiding device degradation which occurs as a result of electrothermal stress aging. The impact of the ledge thickness and the negative surface charges existing at the ledge/nitride interface, was studied for a one-finger 3×30 $\mu\mathrm{m}^2$ InGaP/GaAs HBT with respect to reliability [21, 25]. We found a surface charge density of ρ_surf = 10^{12} cm^{-2} to be sufficient to get good agreement with the measured Gummel plots at V_CB = 0 V. Simulation results for the electron current density at V_BE = 1.2 V without and with a surface charge density of 10^{12} cm^{-2}, respectively, are shown in Fig. 3. Based on these investigations it is possible to explain the base current degradation (see Fig. 4) of a strongly stressed device by a decrease in the effective negative surface charge density along the interface from 10^{12} cm^{-2} to 4×10^{11} cm^{-2} due to compensation mechanisms.

For HFET performance the very critical issues are process control and inverse modeling of geometrical structures. Various examples for high-power AlGaAs/InGaAs/GaAs and high-speed InAlAs/InGaAs/InP HEMTs are demonstrated in [26]. Two factors contributing to the gate currents in pseudomorphic GaAs HEMTs: thermionic field emission (TFE) effects and impact ionization are analyzed in detail in [21, 27]. The comparison of several lattice matched and metamorphic technologies gave consistent simulation parameters also for this material system [28]. Fig. 5 shows simulations and measurements for two different substrate temperatures for a composite channel $\mathrm{In}_{0.52}\mathrm{Al}_{0.48}\mathrm{As}/\mathrm{In}_{0.66}\mathrm{Ga}_{0.34}\mathrm{As}/\mathrm{In}_{0.53}\mathrm{Ga}_{0.47}\mathrm{As}/\mathrm{InP}$ HEMT with a gate-length l_g = 150 nm [21]. High-field effects such as impact ionization are

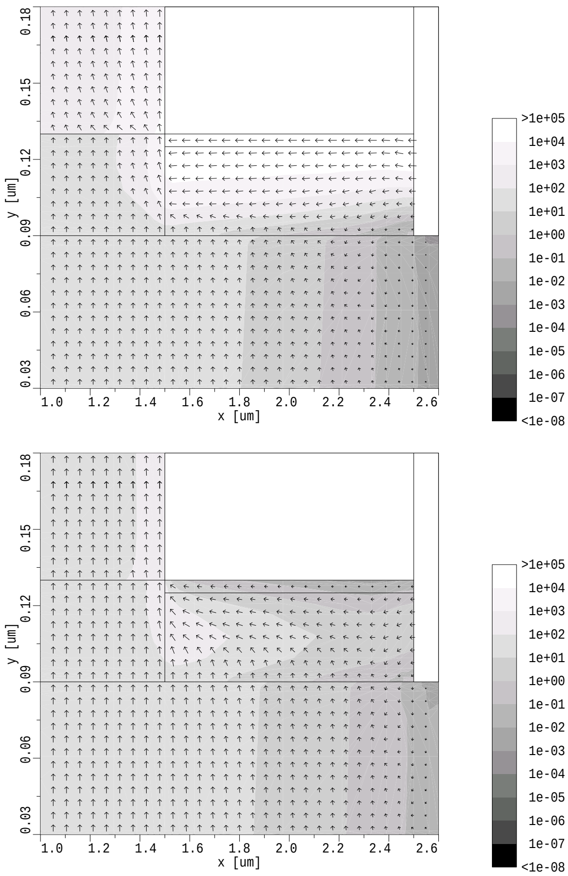

Fig. 3: Electron current density [A/cm^2] at V_{BE} = 1.2 V: Simulations without surface charges (above) and with a surface charge density of 10^{12} cm^{-2} (below).

considered. This allows the analysis of both, optimized speed and limited gate current, when scaling δ-doping and gate-to-channel separation for the requirements of 80 Gbit/s operation.

The investigated 12×0.4 μm^2 SiGe HBT device structure is obtained by process simulation with DIOS [6] which reflects real device fabrication as accurately as possible. The implant profiles as well as the annealing steps are calibrated to one-dimensional SIMS profiles. To save computational resources the simulation domain covers only one half of the real device which is symmetric and the collector-sinker is not included in the structure (see Fig. 6).

Important physical effects, such as surface re-

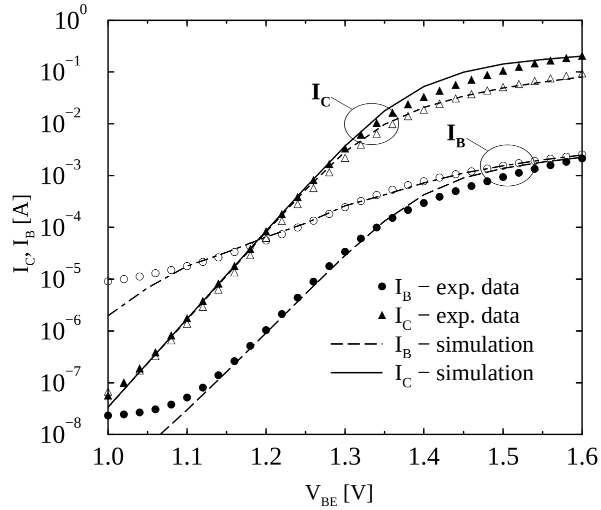

Fig. 4: Comparison of measurements (symbols) and simulations (lines) before (filled) and after (open) electrothermal aging of InGaP/GaAs HBT.

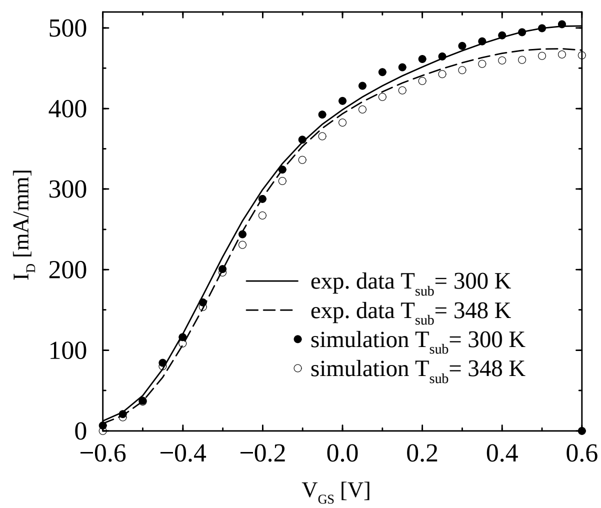

Fig. 5: Transfer characteristics of a composite channel InAlAs/InGaAs/InP HEMT with l_g = 150 nm for two different temperatures at V_{DS} = 0.75 V.

combination, generation due to impact ionization, and self-heating, must be properly modeled and accounted for in the simulation in order to get good agreement with measured forward and output characteristics (Fig. 7). However, simulation without including self-heating effects cannot reproduce the experimental data, especially at high power levels. A closer look at the increasing collector cur-

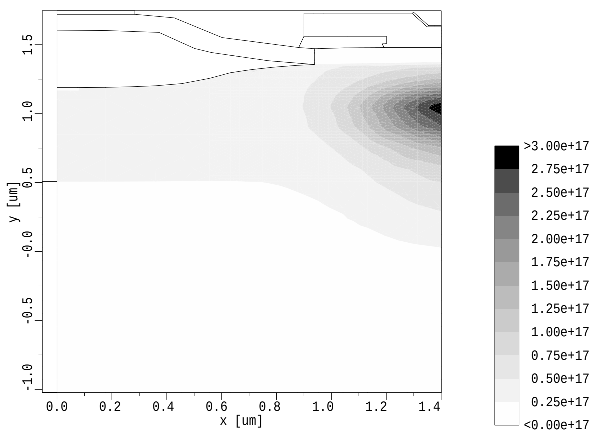

Fig. 6: Simulated device structure and phosphorus collector implant [cm^{-3}] in the SiGe HBT.

rent I_C at high collector-to-emitter voltages V_{CE} and constant base current I_B stepped by 0.4 μA from 0.1 μA to 1.7 μA reveals the interplay between self-heating and impact ionization. While impact ionization leads to a strong increase of I_C, self-heating decreases it. In fact, both I_C and I_B increase due to self-heating at a given bias condition. As the change is relatively higher for I_B, in order to maintain it at the same level, V_{BE} and, therefore, I_C decrease.

Since advanced SiGe techniques exhibit competitive performance of high frequency devices in markets that were prior the domain of other materials, small-signal analysis by means of simulation of these devices becomes more important. Fig. 8 compares simulated and measured cut-off frequency f_T as a function of I_C. Fig. 8 shows also the effect of an anisotropic electron mobility. In addition, results obtained by a commercial device simulator (DESSIS [6]) using default models and parameters are included for comparison.

V. Conclusion

A brief overview of simulation tools for heterostructure RF-devices has been given. We have presented experiments and simulations of SiGe and GaAs HBTs. Good agreement was achieved both with experimental DC-results and with high-frequency data. With an increasing number of stable and reliable heterostructure technologies avail-

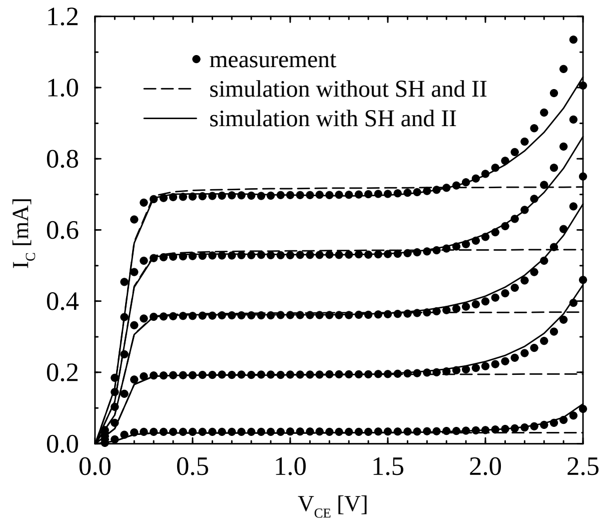

Fig. 7: Output characteristics: Simulation with and without self-heating (SH) and impact ionization (II) compared to measurement data. I_B is stepped by 0.4 μA from 0.1 μA to 1.7 μA.

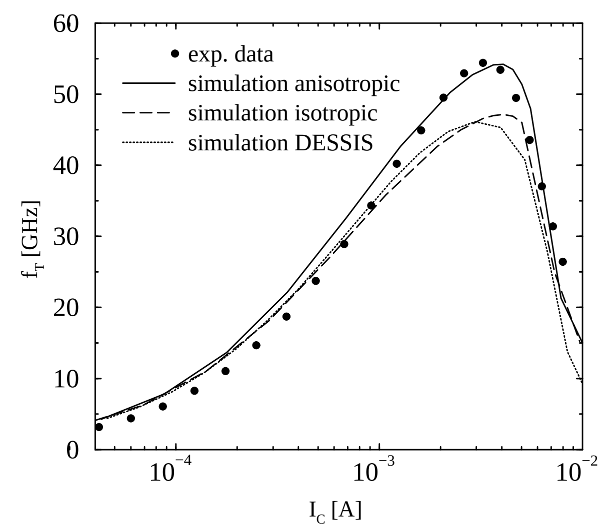

Fig. 8: Cut-off frequency f_T versus collector current I_C at V_{CE} = 1 V (anisotropic line, isotropic dotted, DESSIS dashed, measurements with circles).

able, a meaningful comparison between simulation results and statistically analyzed data is possible and delivers on the one hand side model verification, and on the other hand side valuable process information.

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