Rigorous Modeling Approach to Numerical Simulation of SiGe-HBTs

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We present results of fully two-dimensional numerical simulation of Silicon-Germanium (SiGe) Heterojunction Bipolar Transistors (HBTs). An overview of the physical models used and comparisons with experimental results is given.

Our SiGe HBT-CMOS integrated process is based on a 0.35 μm mixed-signal CMOS process and includes an additional high-performance analog-oriented HBT module. The applications reach from circuits for mobile communication to high-speed networks. Using simulation in a predictive manner has been recognized as an integral part of any advanced technology development. In order to satisfy predictive capabilities the simulation tools must capture the process as well as the device physics.

The double-base SiGe HBT structures are CVD-grown with emitter areas of 12×0.4 μm^2. The base-emitter (BE) junction is formed by Rapid Thermal Processing which causes outdiffusion of Aresenic from the poly-Silicon layer into the crystalline Silicon. The process simulation with DIOS [1] 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.

Beside mainstream Silicon, the two-dimensional device simulator MINIMOS-NT [2] can deal with different complex materials and structures. Previous experience gained in the area of III-V HBT modeling and simulation which lead to successful results [3] was a prerequisite to use MINIMOS-NT also for simulation of SiGe HBTs. However, the modeling of strained SiGe is not a trivial task, since special attention has to be paid on stress-dependent change of the bandgap due to Ge content [4]. This effect must be split from the dopant-dependent bandgap narrowing, which depends itself on the semiconductor material composition, the doping concentration, and the lattice temperature [5]. As the minority carrier mobility is of considerable importance for bipolar transistors, an analytical low field mobility model which distinguishes between majority and minority electron mobilities [5] has been developed using Monte-Carlo (MC) simulation data for electrons in Si and implemented in MINIMOS-NT. MC simulation, which accounts for alloy scattering and the splitting of the anisotropic conduction band valleys due to strain in combination with an accurate ionized impurity scattering model, allowed us now to obtain results for SiGe for the complete range of acceptor concentrations and Ge contents x. We use the same functional form [5] to fit the doping dependence of the in-plane mobility component for two mole fractions (e.g. Si and $Si_{0.7}Ge_{0.3}$ in Fig. 1) and model by a new function the dependence on x. The perpendicular component is then obtained by a multiplication factor which holds the ratio of the two mobility components. The good agreement of the model with the measured and the MC simulation data, both for in-plane and parallel direction, is illustrated in Fig. 1.

All important physical effects, such as surface recombination, impact ionization (II) generation, and self-heating (SH), are properly modeled and accounted for in the simulation in order to get good agreement with measured forward (Fig. 2) and output characteristics (Fig. 3) using a concise set of models and parameters. A closer look at the increasing collector current 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 SH and II (see Fig. 4). While II leads to a strong increase of I_C, SH decreases it. In fact, both I_C and I_B increase due to SH at a given bias condition. As the change is relatively higher for I_B, in order to keep it at the same level, V_{BE} and, therefrom, I_C decrease.

References

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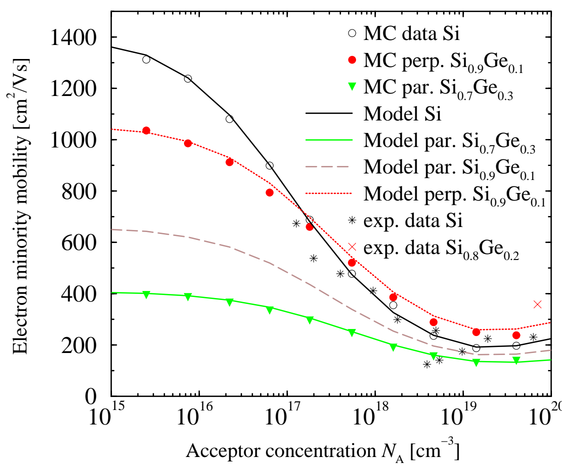

Fig. 1: Minority electron mobility in $Si_{1-x}Ge_x$ as a function of N_A and x: The model agrees well with measurements and MC simulation data both for in-plane and parallel direction.

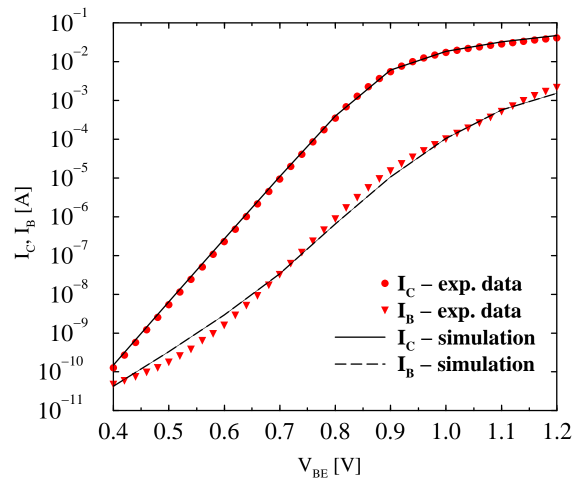

Fig. 2: Forward Gummel plots at V_{CB} = 0 V: Comparison between measurement data and simulation at room temperature. Bandgap is one of the crucial modeling parameters.

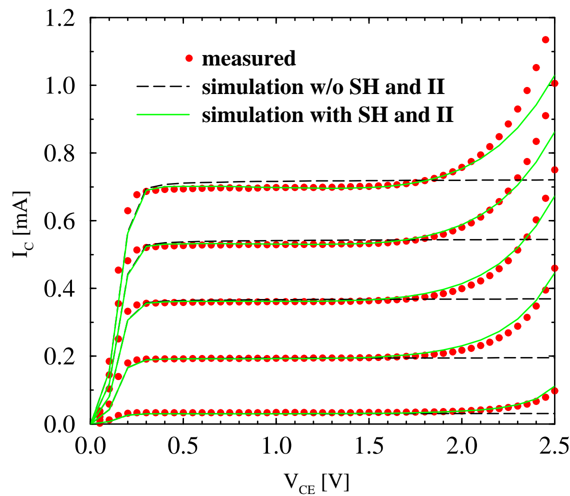

Fig. 3: Output characteristics: Simulation with and without self-heating (SH) and impact ionization (II) compared to measurement data. I_B is stepped by 0.4 μA from 0.1 μA to 1.7 μA.

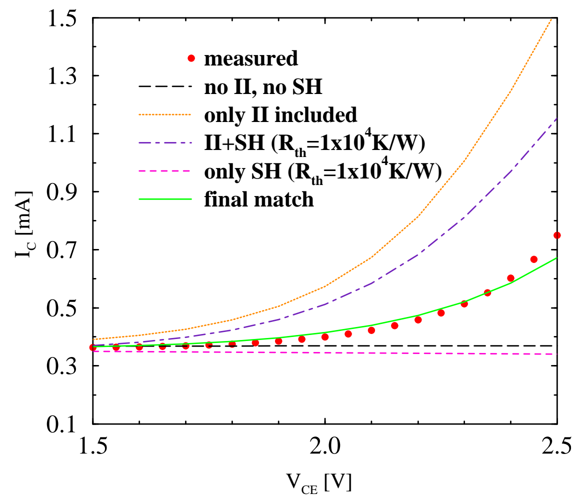

Fig. 4: Output characteristics for I_B = 0.9 μA: A closer look at the increasing I_C at high V_{CE} reveals the interplay between self-heating (SH) effect and impact ionization (II) generation.