Hydrodynamic Mixed-Mode Simulation

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Abstract

Recent advances in development of semiconductor devices lead to more and more complex device structures. This concerns device geometry as well as the combination of different materials. Due to the rapid reduction of device geometries, the models describing the device physics increase in complexity. To gain additional insight into the performance of devices under realistic dynamic boundary conditions imposed by a circuit, mixed-mode simulation has proven to be invaluable. We present our approach of handling the complex situations arising from these problems. Since advanced SiGe Heterojunction Bipolar Transistors (SiGe HBTs) are currently amongst the fastest semiconductor devices, we demonstrate the capabilities of our simulator by simulating a 5-stage Current Mode Logic (CML) ring oscillator. Accurate simulation of HBT circuits must account for non-local effects such as velocity overshoot which calls for hydrodynamic (HD) mixed-mode simulation.

1. Introduction

Our device simulator MINIMOS-NT is equipped with an extensive mixed-mode capability including HD modeling on distributed devices. In general the convergence of HD simulations is known to be poor. Therefore we enhanced MINIMOS-NT with an interface where different iteration schemes such as the full Newton scheme and various block iteration schemes based upon the Gummel scheme can be easily defined and augmented with special damping algorithms.

2. Segments

To allow for a flexible handling of distributed devices in a mixed-mode circuit simulation, their geometry is partitioned into independent regions, so-called segments. For these segments different sets of parameters, models and algorithms can be defined independently. As an example it is possible to solve only Poisson's equation on one segment, or the transport equation for only one carrier type in addition to Poisson's equation on another segment.

The segments are linked together by interface models which account for the interface conditions. This results in high flexibility which allows, for example, to use a HD model on one segment and a drift diffusion (DD) model on another segment. Furthermore, the explicit treatment of volume and interface models leads to a better condition of the linearized system compared to a method which simply reduces grid spacing in the vicinity of heterojunctions[1].

3. Model Assembly

During simulator development we frequently encountered the problem, that several different formulations for, e.g., the HD model are available (either in the model itself or in its discretization). To compare these formulations easily in a general manner, without adding a lot of keywords or recompiling the code, we developed a particular strategy. First, each partial differential equation (PDE) is split into its constituent terms. Second, these terms are combined to so-called groups, which then form the basic unit of model control. It is important to note that these groups can contain terms from more than one PDE, since the groups serve as an abstraction of the desired effect to model.

Finally, these groups are combined to build the complete equation set. For instance, in an oxide segment it is sufficient to use only the Poisson-group which contains the basic terms of the Poisson equation (discrete differential operator, contributions to the space charge density). In a channel of a HEMT it might be sufficient to use only the Poisson and the electron group (contains the static DD continuity equation and the electron charge term of the Poisson equation). In the base of a HBT one should use the Poisson, electron and hole group. Furthermore, the Shockley-Read-Hall (SRH) group should be added to account for the recombination rates in the continuity equation and the trap charge in the Poisson equation. When considering transient analysis, the transient-groups add the time dependent terms to each equation. With this modular scheme it is easy to replace the DD electron group by the HD electron group or the static SRH group by the dynamic SRH without affecting the other groups. To guaranty model consistency a proper design of these groups is of course crucial.

4. Quantity Classes

Each equation term requires on its respective segment so-called quantity classes, such as potential, carrier concentrations and carrier temperatures. These quantity classes are automatically generated and initialized and can be independently marked for solving. An example might be a segment where a HD model should be solved. The HD model is selected by its appropriate group, but in many cases the influence of one carrier type turns out to be negligible. Now it can be decided to either completely ignore this carrier type by not selecting its model group, or to ignore only its temperature quantity by unmarking the latter for the solution process.

Despite of the quantity classes generated by the model groups, three classes are automatically generated when using the mixed-mode feature: the node voltage (NV), branch current (BC), and the fixed node voltage quantity class (FNV). The NV and the BC classes result from the modified node voltage analysis formulation, whereas the FNV class is actually part of the NV class and allows the user to, e.g., set an initial condition or to fix some of the node voltages to their respective old values at distinct timepoints.

5. Programmable Iteration Scheme

The features outlined above can be utilized when defining the iteration sequence. Each iteration block can contain other arbitrarily nested sub-blocks. First, for each block the groups to use are defined. Second, it must be specified which quantities are to be solved for and which are to be left to their respective old or initial value. The simulator will iterate until a block-specific termination criterion is satisfied. These criteria can

be arbitrary expressions containing norms, iteration counters, time step information and much more. After each iteration the sub-blocks are entered recursively. Blocks can be empty to form a linear sequence of sub-blocks only.

6. Matrix Assembly

For each iteration all marked quantity-related equations are assembled into the system matrix. By unmarking for instance the node voltage quantity class, the single devices become decoupled. However, they are all stored in the same matrix which increases the time needed to find the solution, compared to several small matrices. To overcome this drawback, a two-level Newton algorithm can be specified by using a separate iteration block for each device. In contrast, by marking all quantities, a full Newton algorithm is achieved. Furthermore, it is easy to identify devices causing convergence problems. For these devices a separate sub-block employing a decoupled iterative scheme might be used.

7. Example

As a particular example, a 5-stage CML ring oscillator containing 10 SiGe HBTs (Fig. 1) was simulated. The two-dimensional HBT structure was taken from [2] and is shown in Fig. 2.

The physical models for the SiGe alloy are temperature and mole-fraction-dependent, the low field mobility model distinguishes between majority and minority electron mobilities on one hand, and between different dopant species on the other hand, both as a function of temperature and dopant concentration.

Fig. 3 shows a comparison of the DD and HD results of the ring oscillator given in Fig. 1. A full Newton scheme has been employed to both the DD and the HD model. Since the hole density in the collector and emitter is very low and the doping in the base is very high, the holes were modeled by a DD model only. The rank of the matrix was 29169 for DD and 36389 for HD. The circuit simulation was carried out for 50 timesteps and took 1h 56min for DD and 3h 26min for HD on a Pentium II 266 MHz LINUX workstation. The DD simulation shows a much lower inverter delay time compared to the HD simulation. This is due to the velocity overshoot in the base-collector space charge region which can not be modeled using a DD simulation as pointed out by [2]. Furthermore, since the current is higher in the case of HD simulation, the overall speed of the circuit increases. The error of the DD simulation in the inverter delay is in the range of 60% compared to the HD simulation, which proves the necessity for a HD model.

8. Conclusion

Due to the large number of possible formulations for the semiconductor transport properties, a flexible handling of model compilation is mandatory. We presented our new approach whose strength lies in its simple extend- and maintainability. Using these features it is possible to build arbitrary sequences of iteration blocks which is of fundamental importance for state-of-the-art simulations. We demonstrated the capabilities of our simulator by the simulation of a complex circuit, showing the importance of the hydrodynamic transport model in the case of HBT circuits.

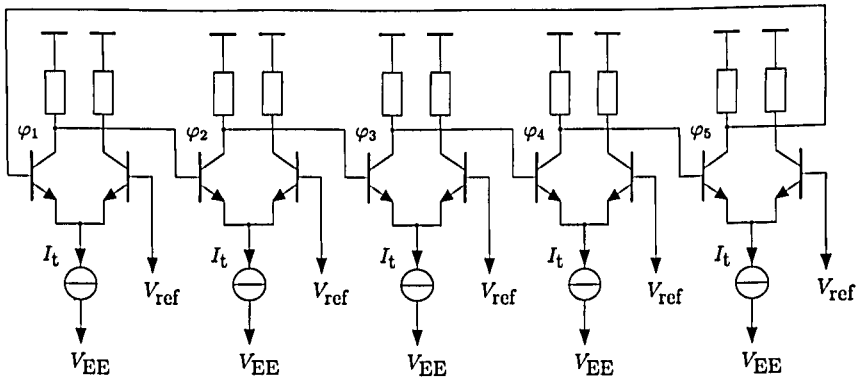

Figure 1: CML ring oscillator circuit.

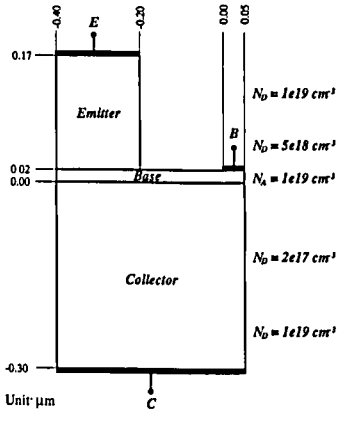

Figure 2: The HBT structure.

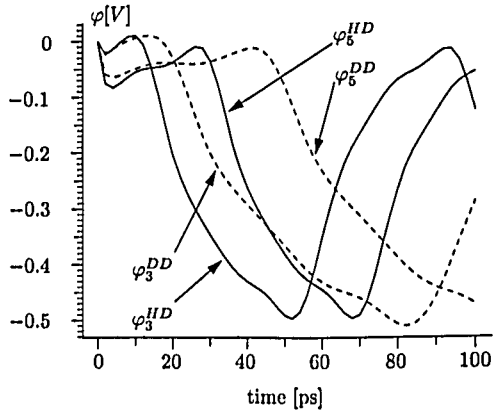

Figure 3: Comparison of the DD vs. HD transient response.

References

[1] T. Simlinger, R. Deutschmann, C. Fischer, H. Kosina, and S. Selberherr, "Two-Dimensional Hydrodynamic Simulation of High Electron Mobility Transistors Using a Block Iterative Scheme in Combination with Full Newton Method," in *Fourth Int. Conf. on Solid-State and Integrated-Circuit Technology* (G. Baldwin, Z. Li, C. Tsai, and J. Zhang, eds.), (Beijing, China), pp. 589–591, 1995.

[2] B. Neinhüs, P. Graf, S. Decker, and B. Meinerzhagen, "Examination of Transient Drift-Diffusion and Hydrodynamic Modeling Accuracy for SiGe HBTs by 2D Monte-Carlo Device Simulation," in *27th European Solid-State Device Research Conference* (H. Grünbacher, ed.), (Stuttgart, Germany), pp. 188–191, Editions Frontieres, 1997.