A Global Self-Heating Model for Device Simulation

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Abstract

For the design and simulation of many state-of-the-art devices self-heating effects must be considered. This is a very difficult task as thermal effects are basically three-dimensional effects which can not as easily be reduced to two-dimensions as it is possible for many purely electrical problems. Furthermore, the thermal active volume is much larger than the electrical area and the thermal boundary conditions are difficult to measure. We propose a global self-heating model which is capable of accurate consideration of thermal effects and is because of its computational efficiency and robustness sometimes even better suited for some problems than the solution of the standard lattice heat flow equation.

1. Introduction

Due to the ever increasing packaging density of integrated circuits, self-heating and thermal coupling effects become more and more important. To account for self-heating effects, normally the lattice heat flow equation is solved. This alters the device performance by inclusion of thermal diffusion currents and by the temperature dependence of the physical parameters, e.g., for the band edge energies, recombination rates, and mobilities. However, this approach is problematic for several reasons. First, the heat spreading volume is normally much larger than the electrically active area and extends to several $100\ \mu\mathrm{m}^3$. Secondly, thermal effects are real three-dimensional effects which can not easily be approximated by two-dimensional cross-sections as is the case for purely electrical problems. The two-dimensional thermal boundary conditions are difficult to formulate basically for two reasons: the Neumann boundary condition in the third dimension for the heat flux equation causes an overestimation of the temperature which can exceed $100\ \%$ and thus renders the results unusable except for first principle estimations [1]. This can also lead to severe numerical problems since the overestimation leads to local lattice temperatures during solver iteration, that exceed the validity of the lattice temperature dependent material models. Secondly, the thermal boundary conditions are determined by the thermal resistors at material transitions as much as by the bulk properties. As these unknown thermal resistivities of industrially relevant materials, such as e.g. glue or thermal bumps, have to be verified by experiments, a self consistent fitting procedure and various assumptions will always be part of application oriented simulations. Thus the

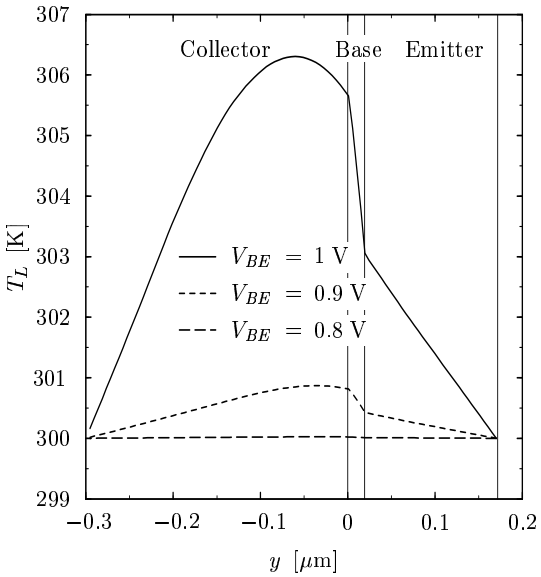

Figure 1. Lattice temperature distribution of an BJT with the isothermal contact model for different bias voltages.

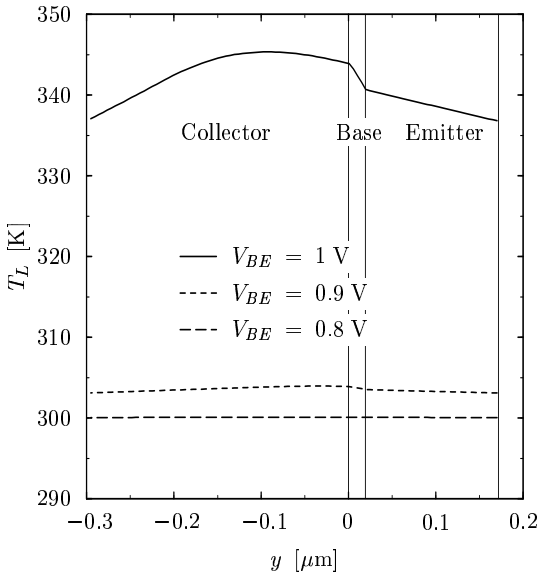

Figure 2. Lattice temperature distribution of an BJT with the contact resistance model for different bias voltages.

thermal boundary conditions have to be determined with respect to aspects normally not included in device simulation such as neighboring devices or chip mounting.

For RF devices, even more aspects have to be considered, since for large signal use, part of the DC power is converted into microwave power, so not all DC power leaves the devices through the thermal contacts as assumed by the DC self-heating model.

2. Global Self-Heating Model

To overcome these problems we make use of the observation that the temperature distribution inside the devices is mainly controlled by the thermal contact models. This is due to the fact that the thermally active region is truncated to the electrically active region and that the outside region has to be approximated by e.g. thermal contact resistances. If the thermal boundaries are modeled by an isothermal contact model without knowledge of the exact contact temperature, the resulting temperature distribution will be completely unrealistic (Fig. 1). With appropriate thermal resistances at the thermal contacts realistic temperature distributions are obtained (Fig. 2)

Given the strong dependence on the boundary conditions, we approximate the distributed device temperature at a first order by a spatially constant value. Focusing on the terminal quantities, we now use a global self-heating model (GSH) instead of the standard lattice heat flow equation (SH) to calculate the dissipated power as

$$P = \sum_C I_C \cdot V_C \tag{1}$$

with I_C and V_C being the contact currents and voltages. The spatially constant lattice temperature is modeled as

$$T_L = T_\mathrm{C} + P \cdot R_g \tag{2}$$

with R_g being the global thermal resistance.

The GSH model gives only two additional unknowns (T_L and P) to the purely electrical system as opposed to the 33 % increase in system size for a drift-diffusion SH

model. R_g should be equal to the effective thermal contact resistance plus an equivalent resistance of the device which can be approximated as

$$R_g = R_{th}^{eff} + \frac{w}{A \cdot \kappa} \qquad (3)$$

with w being the average distance of the thermal contact to the region where the heat is generated and A being the average area of the section connecting the junction with the thermal contact. κ is the thermal conductivity of the underlying material which shows a strong temperature dependence [2] and must therefore be evaluated at an average temperature value. Of course, this formula is far too simple to give exact results and it is better to consider R_g a mere fitting parameter only roughly approximated by (3).

Two models are mainly used to analyze the electrical properties of semiconductor devices, both of which can be derived from Boltzmann's transport equation: the drift-diffusion and the more complex hydrodynamic transport model. Both models give an additional diffusion current caused by carrier temperature gradients. For the drift-diffusion model the carrier subsystems are assumed to be in thermal equilibrium with the lattice temperature, whereas in the hydro-dynamic model carrier temperature relaxation to the lattice temperature is modeled by an energy relaxation time. Both transport models normally assume a constant lattice temperature but can be consistently extended to non-constant lattice temperatures [3]. As the transport model is not relevant in the following context, the simpler drift-diffusion model has been used for the example.

3. Example

The GSH model has been implemented in the device simulator MINIMOS-NT [4] and

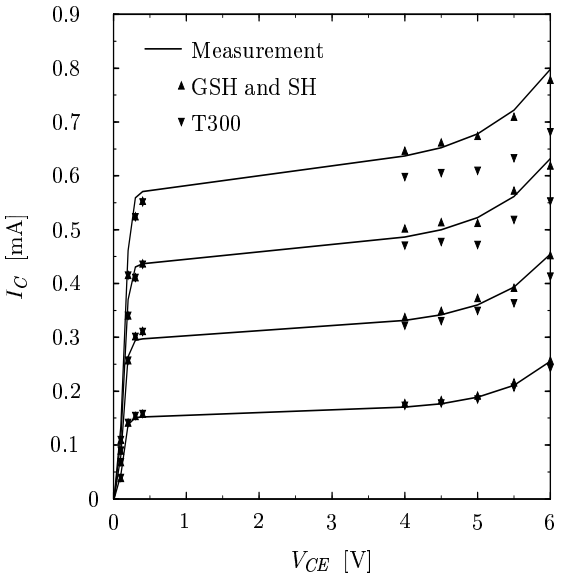

Figure 3. Output characteristic of the BJT for $I_B = 2 - 8\mu A$.

verified against measurements and the SH model. Furthermore, simulation times and convergence properties have been compared to the purely electrical system which has been solved at $T_L = 300$ K (T300 model).

The example device is a state-of-the-art Double Base Bipolar Junction Transistor (BJT). Despite of proper temperature dependencies for the physical parameters [5] a proper model for the polysilicon Emitter contact is of fundamental importance to achieve good accuracy. We implemented the model given in [6]. The output characteristic is shown in Fig. 3 where the GSH model with $R_g = 800$ K/W and the SH model delivered the same results (within 2 %). Furthermore it can be seen that without consideration of self-heating effects, the simulation deviates significantly from the measurement. For an average operating point the convergence properties of the GSH model are similar to that of the T300 model whereas the SH model takes 20 % more iterations and twice as long in terms of CPU time (see Table 1). This advantage of the

Table 1. Computational details for the example BJT ($V_{CE} = 5$ V, $I_B = 8$ μA).

Method	System-Size	CPU	It
T300	4956	33 s	26
GSH	4958	37 s	27
SH	6738	62 s	31

GSH model becomes even more significant for higher biases. In addition, the GSH model is approximately as robust as the T300 model and we were able to find a solution even for very high device temperatures were the SH model already failed.

On the other hand, one should be aware of the simplifications introduced by the GSH model. As the device temperature is the same for the whole device, the additional component in the diffusion current caused by temperature gradients is neglected. Furthermore, it is obvious that no information about hot-spots inside the device can be extracted from these simulations.

However, strong justification for the GSH model is the finding, that different devices, including complex devices like SiGe and InGaP/GaAs HBTs and InGaAs HEMTs, have been accurately simulated using different transport models.

4. Conclusions

We have investigated the impact of a computation time efficient approach to cover self-heating effects on device and circuit performance. It was shown in a realistic example that self-heating is dominated by the resistive thermal boundary conditions. Thus, the lattice heat flow equation can be substituted by a global self-heating model with nearly no loss of accuracy in the electrical terminal characteristic. This observation is of fundamental importance in the case of mixed-mode device simulations where thermal-coupling effects dramatically increase the complexity of the problem. Using this approximation the problem can be solved in considerably less time with reasonably accurate inclusion of thermal effects. The benefits provided by this approach can be even better exploited in three-dimensional device simulations as there the reduction in the number of unknowns is obviously even more significant.

5. Acknowledgments

This work is supported by Infineon Technologies, Munich, Germany.

[1] W. Marsetz, *Thermische und elektrische Konzeption von GaAs-HEMTs für Leistungsverstärker bis 80 GHz*, Dissertation, Technische Universität Karlsruhe, 1999, VDI Verlag Düsseldorf.

[2] S. Selberherr, *Analysis and Simulation of Semiconductor Devices*, Springer, Wien–New York, 1984.

[3] G.K. Wachutka, "Rigorous thermodynamic treatment of heat generation and conduction in semiconductor device modeling," *IEEE Trans.Computer-Aided Design*, vol. 9, no. 11, pp. 1141–1149, Nov. 1990.

[4] T. Grasser, V. Palankovski, G. Schrom, and S. Selberherr, "Hydrodynamic Mixed-Mode Simulation," in *Simulation of Semiconductor Processes and Devices*, K. De Meyer and S. Biesemans, Eds., pp. 247–250. Springer, Wien–New York, 1998.

[5] V. Palankovski and S. Selberherr, "Thermal Models for Semiconductor Device Simulation," in *IEEE Proc. European Conference on High Temperature Electronics HITEN'99*, Berlin, pp. 25–28, 1999.

[6] Z. Yu, B. Ricco, and R.W. Dutton, "A Comprehensive Analyical and Numerical Model of Polysilicon Emitter Contacts in Bipolar Transistors," *IEEE Transactions on Computer-Aided Design of Integrated Circuits*, vol. ED-31, no. 6, pp. 773–784, 1984.