SELF - CONSISTENT SIMULATION OF HEAT GENERATION AND CONDUCTION IN SEMICONDUCTOR DEVICES

P. Dickinger, G. Nanz, S. Selberherr
Institute for Microelectronics
Technical University Vienna
Gußhausstraße 27–29, A–1040 Vienna, AUSTRIA

Tel. +43/222/58801–3713

Abstract — Heat generation is of special interest in power semiconductor devices. We have implemented a rigorous treatment of heat generation in semiconductor devices in our two-dimensional device simulator BAMBI in a fully self - consistent way to verify the applicability of this new approach.

Classic Semiconductor Equations

Heat generation in semiconductor devices is caused by power dissipation and is of major importance especially in bipolar power devices. The rigorous treatment by Wachutka [1] provides a new approach which is applicable in a general device simulation program without further restrictions and assumptions. The classic semiconductor equations do not include terms that account for generation of heat inside the semiconductor.

$$\begin{aligned}
\operatorname{div}\operatorname{grad}\psi &= \frac{q}{\varepsilon}(n-p-C)\\
\operatorname{div}\vec{J}_n - q\cdot\frac{\partial n}{\partial t} &= q\cdot(G-R)\\
\operatorname{div}\vec{J}_p + q\cdot\frac{\partial p}{\partial t} &= -q\cdot(G-R)\\
\vec{J}_n &= -q\cdot(\mu_n\cdot n\cdot\operatorname{grad}\psi - D_n\cdot\operatorname{grad} n)\\
\vec{J}_p &= -q\cdot\left(\mu_p\cdot n\cdot\operatorname{grad}\psi - D_p\cdot\operatorname{grad} p\right)
\end{aligned}$$

In most simulation programs the temperature T is assumed to be constant, only temperature dependent physical models for the generation G, recombination R and the mobilities μ_n and μ_p can be supplied. $\vec{J}_{n,p}$ denote the current densities of electrons and holes, respectively.

Extended Semiconductor Equations

The following formulation makes no assumptions concerning the form of the solution of any operating point.

$$\begin{aligned}
\operatorname{div}\operatorname{grad}\psi &= \frac{q}{\varepsilon}(n-p-C)\\
\operatorname{div}\vec{J}_n - q\cdot\frac{\partial n}{\partial t} &= q\cdot(G-R)\\
\operatorname{div}\vec{J}_p + q\cdot\frac{\partial p}{\partial t} &= -q\cdot(G-R)\\
\vec{J}_n &= -q\cdot(\mu_n\cdot n\cdot\operatorname{grad}\psi - D_n\cdot\operatorname{grad} n + P_n\cdot\operatorname{grad} T)\\
\vec{J}_p &= -q\cdot\left(\mu_p\cdot n\cdot\operatorname{grad}\psi - D_p\cdot\operatorname{grad} p + P_p\cdot\operatorname{grad} T\right)
\end{aligned}$$

The coefficients P_n and P_p are the thermoelectric powers associated with the electron - hole system and present new model parameters. The heat flow equation

$$c\left(\frac{\partial T}{\partial t}\right) = \operatorname{div}(\kappa \operatorname{grad} T) + H \tag{1}$$

(c: heat capacity, κ: thermal conductivity, H: heat generation) must be added to the semiconductor equations where the left term is zero at steady state conditions. For heat generation H different heuristic models have been published [2], [3], [4], [5], but some of them violate the underlying postulates. In the stationary case the heat source H is written in [1] as

$$H = \frac{q\,\vec{J}_n^2}{\mu_n n} + \frac{q\,\vec{J}_p^2}{\mu_p p} + q\,(R-G)\left[\phi_p - \phi_n + T\left(P_n + P_p\right)\right] - qT\left[\vec{J}_n \mathrm{grad} P_n + \vec{J}_p \mathrm{grad} P_p\right] \tag{2}$$

where ϕ_n and ϕ_p denote the Quasi-Fermi levels.
The first two terms are the Joule heat of electrons and holes, the third describes the recombination and the fourth the Thompson heat.

Boundary conditions
For a consistent implementation taking into account the heat fluxes across contacts and other boundaries mixed boundary conditions would be necessary. This problem is similar to current controlled contacts and will provide convergence problems in some cases. The interface conditions for simulating MOS devices are a complex task and will not be discussed in this work.

First Realization
We implemented the heat flow equation (1) as a fourth equation in the Gummel algorithm for the stationary case. Now we have the unknowns ψ, n, p, T. We assumed Dirichlet assboundary conditions at the contacts and used physical models which include temperature dependence [6]. Our goal was to show the applicability of the new approach [1] in device simulation under arbitrary operating conditions. The effort of solving the system with the additional equation is 16/9 in comparison to the solution of the classical system (if a Newton algorithm is used).

Example
The cross section of the diode which we used as an example is shown in Fig. 1. In Fig. 2 the temperature distribution of the backward biased diode at 177.5V near breakdown is shown. Neglections of the temperature effects will result in a significantly higher breakdown voltage (> 190V). Avalanche generation is taken into account by van Overstraeten's model [7]. It is evident that the generation/recombination term in equation (2) is dominant for this operating point. In Fig. 3, Fig. 4 and Fig. 5 the temperature distributions at forward biases of 0.7V, 0.75 and 0.8V are shown. The significant rise of temperature at higher currents is due to the Joule heat generation terms in equation (2). In Fig. 6 the I - V curves of a bipolar transistor are shown, the dotted line accounts for temperature effects, the solid one neglects temperature dependence.

Conclusion
The new model of Wachutka is the first one for general use. It gives plausible results for

different operating conditions in semiconductor devices. On the other hand, additional effort in CPU time and storage is required to solve the heat conduction equation. Dealing with a particular simulation problem one should consider very well whether to take the heat generation into account or not. Also some related problems in numerical mathematics, like convergence control, are not solved yet. The fully self-consistent implementation in the Newton and Gummel algorithm of BAMBI with mixed boundary conditions is under investigation.

Acknowledgement
This work has been supported by SIEMENS Bauelemente Ges.m.b.H., Villach, Austria, by the SIEMENS Research Laboratories at Munich, Germany, and by DIGITAL EQUIPMENT CORP. at Hudson, U.S.A.. The authors are indebted to Prof. H. Pötzl for many helpful discussions.

References

[1] Wachutka, G.; Rigorous thermodynamic of heat generaton and conduction in semiconductor device modeling. Simulation of semiconductor devices and processes Vol. 3, edited by G. Baccarani, M. Rudan - Bologna (Italy) September 26-28, 1988 - Tecnoprint

[2] Adler, M.S. et al.; Accurate calculations of the forward drop and power dissipation in thyristors. IEEE Transactions on Electron Devices, Vol. ED-25, pp. 16-22 (1978)

[3] Chryssafis, A.; Love, W.; A computer-aided analysis of one-dimensional thermal transients in p-n-p power transistors. Solid State Electronics, Vol. 22, pp. 249-266 (1979)

[4] Gaur, S; Navon, D.H.; Two - dimensional carrier flow in a transistor structure under nonisothermal conditions. IEEE Transactions on Electron Devices, Vol. ED-23, pp. 50-57 (1976)

[5] Nakagawa, A.; Ohashi, H.; A study on GTO turn - off failure mechanism - a time and temperature - dependent 1-D model analysis. IEEE Transactions on Electron Devices, Vol. ED-31, pp. 273-279 (1984)

[6] Selberherr, S.; Analysis and simulation of semiconductor devices. Springer Verlag Wien, New York (1984)

[7] Overstraeten, R.V.; DeMan, H.; Measurement of the ionization rates in diffused silicon p-n junctions. Solid-State Electronics, Vol. 13, p. 583-608 (1970)

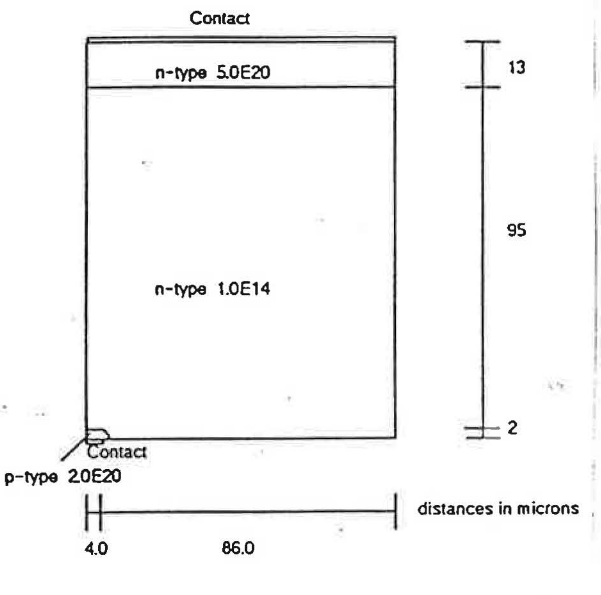

Fig.1 Cross section of diode

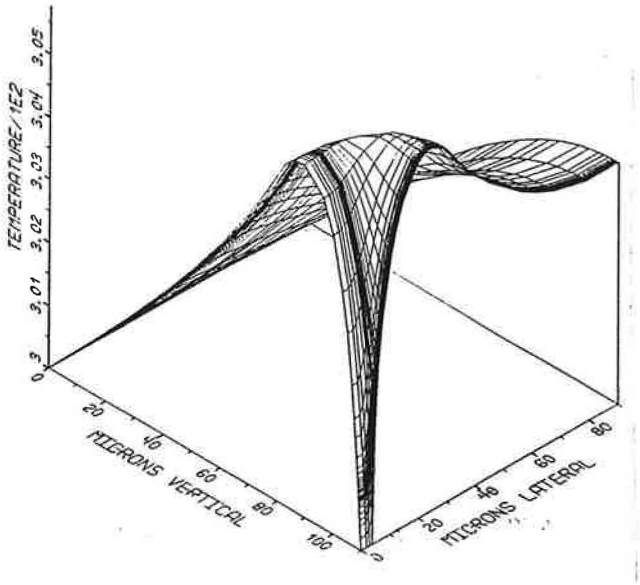

Fig.2 Temperature distribution of diode near breakdown

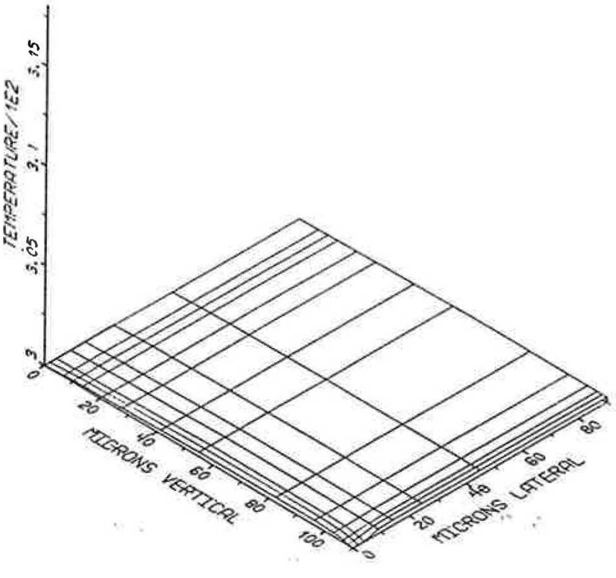

Fig.3 Temperature distribution of diode at 0.7V forward bias

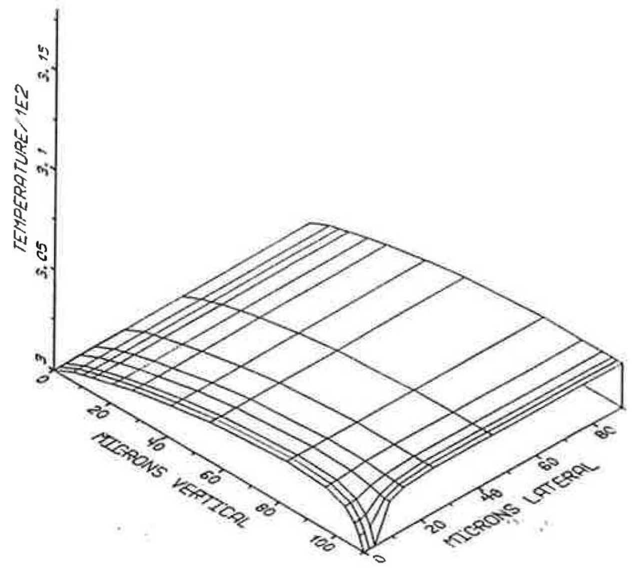

Fig.4 Temperature distribution of diode at 0.75V forward bias

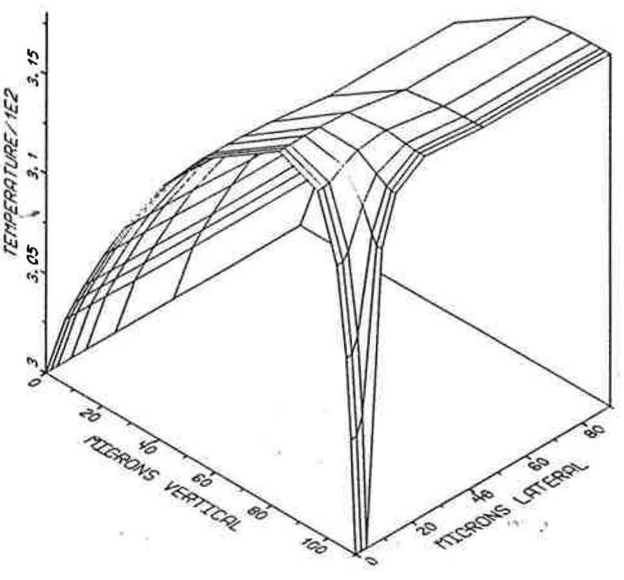

Fig.5 Temperature distribution of diode at 0.8V forward bias

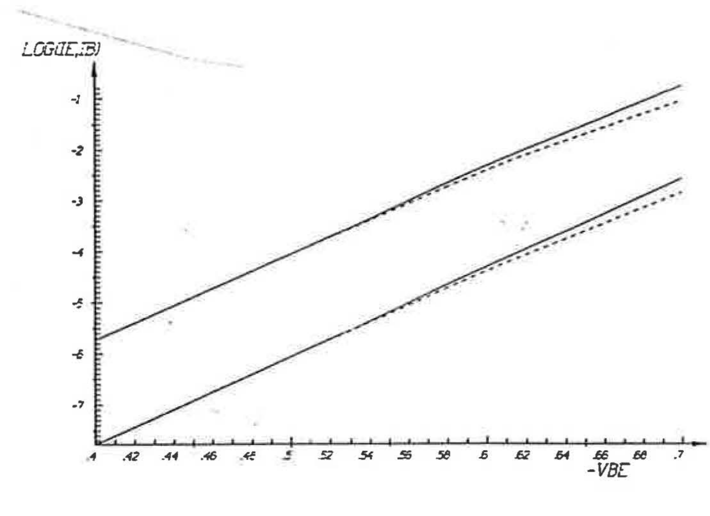

Fig.6 $I - V$ curve of bipolar transistor, dotted lines account for temperature dependence