An Improved Energy Transport Model Suitable for Simulation of Partially Depleted SOI MOSFETs

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An anomalous output characteristics is observed in energy transport simulations of partially depleted SOI MOSFETs. The effect that the drain current reaches a maximum and then decreases is peculiar to the hydrodynamic transport model. It is not present in drift-diffusion simulations and its occurance in measurements is questionable. An explanation of the cause of this effect is given, and a solution is proposed by modifying the energy transport model.

INTRODUCTION

The small minimum feature size of todays devices makes it more and more difficult to get proper simulation results using the widely accepted drift-diffusion (DD) transport model. In particular the lack of accounting for nonlocal effects such as carrier heating and velocity overshoot makes it desirable to use more sophisticated transport-models. These are obtained by considering the first three or four moments of the BOLTZMANN equation. However, these so called energy transport models (ET) which are nowadays available in most of the device simulation programs, lead to interesting problems when applied to SOI MOSFETs.

Device Used

The simulations discussed in this paper were performed on a device with an assumed effective gate-length of 130 nm, a gate-oxide thickness of 3 nm, and a silicon-film thickness of 200 nm. With a p-doping of $N_A = 7.5 \cdot 10^{17}\,\mathrm{cm}^{-3}$ the device is partially depleted. The Gaussian-shaped n-doping under the electrodes has a maximum of $N_D = 6 \cdot 10^{20}\,\mathrm{cm}^{-3}$.

Observed Behavior

By using the energy transport model for simulation of the output characteristics of partially depleted SOI MOSFETs, an anomalous decrease of the drain current with increasing drain-source voltage can be observed [1] [2] (Fig. 1). The anomalous effect has been reproduced using two different device simulators, namely MINIMOS-NT [3] and DESSIS [4]. It is believed that this decrease is a spurious effect because to our knowledge it is neither present in experiments nor can it be observed when using the drift-diffusion (DD) transport model. One exception is given in [5], where a weak decrease of the drain-current is reported.

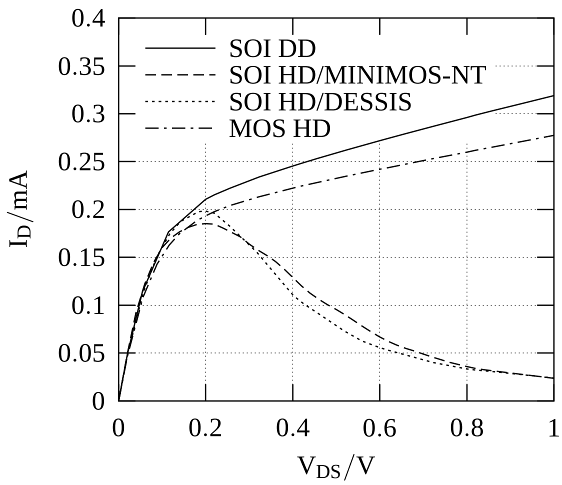

Fig. 1: Output characteristics of the SOI obtained by DD an ET simulations using two different device simulators.

Cause of the Effect

The main difference between the ET and the DD transport model is given by the energy balance equation. The benefit of the increased computational effort is that the carrier temperature can differ from the lattice temperature. Since the diffusion of the carriers is proportional to their temperature, the diffusion can be significantly higher with the ET model. Fig. 2 clearly shows the enhanced vertical diffusion of electrons as compared with the DD result in Fig. 3.

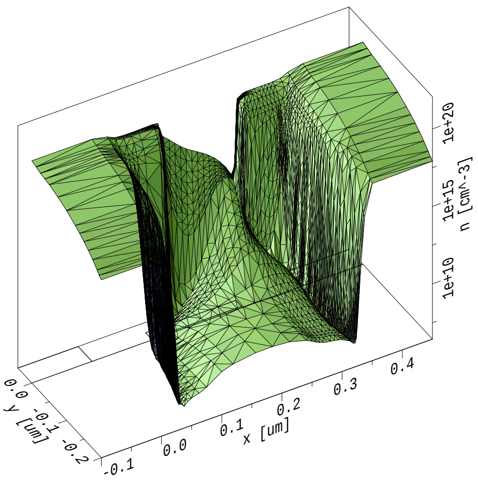

Fig. 2: Electron concentration in an SOI MOSFET obtained by a ET simulation.

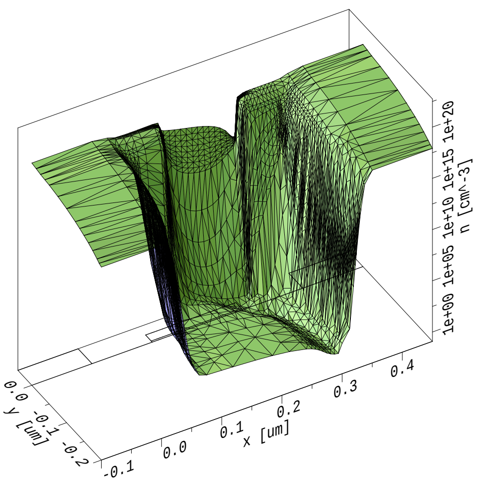

Fig. 3: Electron concentration in an SOI MOSFET obtained by a DD simulation.

When simulating SOI MOSFETs this increased diffusion has a strong impact on the body potential, because the hot electrons of the pinch-off region have enough energy to overcome the energy barrier towards the floating body region and thus enter into the sea of holes. Some of these electrons in the floating body are sucked-off from the drain-body and source-body junctions, but most recombine. The holes removed by recombination cause the body potential to drop. A steady state is obtained when the body potential reaches a value which biases the junctions enough in reverse direction so that thermal generation of holes in the junctions can compensate this recombination process. The decrease in the output characteristics is directly connected to the drop of the body potential via the body-effect.

Weight Factors

Our first attempt to avoid the anomalous current decrease was to tune the empirical weight factors of thermal diffusion and heat flow, as provided by the ET model of DESSIS. Within this parameter-space only minor improvements in the IV characteristics were possible. Therefore, our investigations continued with more physically motivated modifications, using MINIMOS-NT.

Modifications

In Monte-Carlo (MC) simulations the spreading of hot carriers away from the interface is much less pronounced than in ET simulations. If we assume that the Boltzmann equation does not predict the hot carrier spreading, and if the ET equations derived from the Boltzmann equation do so, the problem must be introduced by the assumptions made in the derivation of the ET model. Relevant in this regard is the approximation of tensor quantities by scalars and the closure of the hierarchy of moment equations.

In order to capture more realistically the phenomenon of hot carrier diffusion we derived a ET equation set from the Boltzmann equation permitting an anisotropic temperature and a non-Maxwellian distribution function. The current density $J_{n,l}$ and the energy density $S_{n,l}$ are given by

$$J_{n,l} = \mu_n \left(k_B \nabla_l (n T_{ll}) + q E_l n\right) ,$$
$$S_{n,l} = -\frac{5}{2} \frac{k_B}{q} \mu_S \left(k_B \nabla_l (n \beta_n T_{ll} \Theta) + q E_l n \Theta\right) ,$$
$$\text{with} \quad \nabla_l = \frac{\partial}{\partial l} \quad \text{and} \quad \Theta = \frac{3 T_n + 2 T_{ll}}{5} .$$

T_{ll} denotes the diagonal component of the temperature tensor for direction $\vec{e}_l$. Off-diagonal components are neglected. β_n is the normalized moment of fourth order. By setting $T_{ll} = T_n$ and $\beta_n = 1$ the conventional ET model is obtained. The solution variable is still the carrier temperature T_n, whereas the tensor components and the fourth moment are modeled empirically as functions of the carrier temperature. First empirical modeling of T_{ll} was performed by distinguishing between directions parallel and normal to the current density:

$$T_{ll} = T_{xx} \cos^2 \varphi + T_{yy} \sin^2 \varphi , \quad T_{xx} = \gamma_x T_n , \quad T_{yy} = \gamma_y T_n ,$$

$$\gamma_\nu(T_n) = \gamma_{0\nu} + (1 - \gamma_{0\nu}) \exp\left(-\left(\frac{T_n - T_L}{T_{\mathrm{ref},\gamma}}\right)^2\right) , \quad \nu = x, y .$$

The anisotropy functions $\gamma_\nu(T_n)$ assume 1 for $T_n = T_L$ and an asymptotic value $\gamma_{0\nu}$ for large T_n, ensuring that only for sufficiently hot carriers the distribution becomes anisotropic, whereas the equilibrium distribution stays isotropic. With respect to numerical stability the transition should not be too steep. $T_{\mathrm{ref},\gamma} = 600\,\mathrm{K}$ appeared to be appropriate.

Another effect observed in MC simulations is that in most parts of the channel the high energy tail is less populated than that of a MAXWELLian distribution, which gives $\beta_n < 1$ (Fig. 6). A simple model for β_n was used.

$$\beta_n(T_n) = \beta_0 + (1 - \beta_0) \exp\left(-\left(\frac{T_n - T_L}{T_{\mathrm{ref},\beta}}\right)^2\right)$$

Again, this expression ensures that only for sufficiently large T_n the distribution deviates from the MAXWELLian shape.

RESULTS

The modified flux equations have been implemented in MINIMOS-NT using a straight forward extension of the Scharfetter-Gummel discretization scheme. Numerical stability does not degrade as compared to standard ET simulations. Parameter values were estimated from MC results for one-dimensional test structures. Fig. 4 indicates that $\gamma_{0y} = 0.75$ is a realistic value for the anisotropy parameter. Fig. 5 shows the influence of γ_{0y} on the output characteristics. By accounting for a reduced vertical temperature it is possible to reduce the spurious current decrease, but only to a certain degree and by assuming a fairly large anisotropy. MC sim-

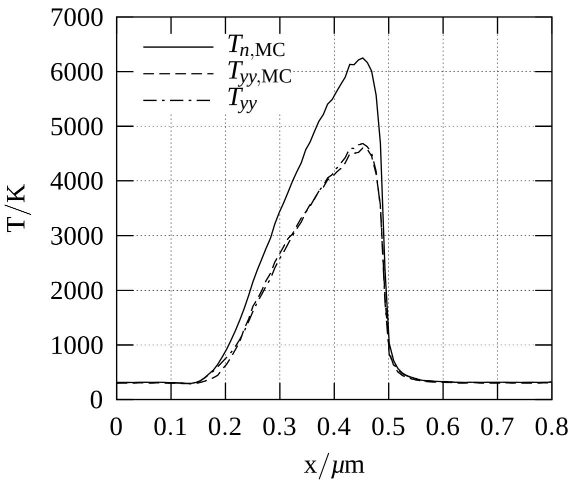

Fig. 4: MC simulation of an *nin*-structure showing the x-component of the temperature compared to the mean temperature $T_{n,\mathrm{MC}}$. The analytical T_{yy} uses $\gamma_{0\nu} = 0.75$.

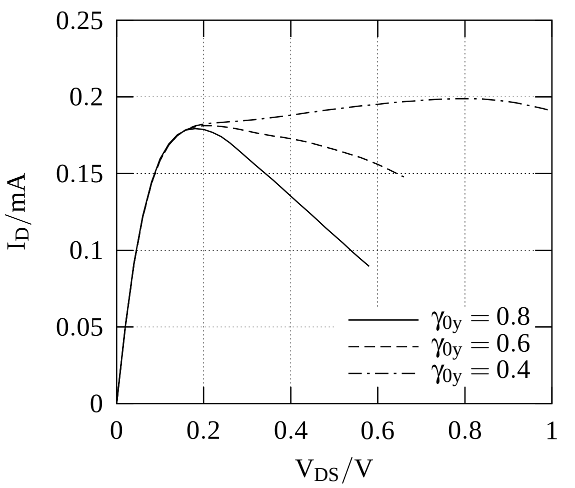

Fig. 5: Output characteristics of the SOI obtained by anisotropic ET simulations.

ulations yield values close to $\beta_0 = 0.75$ for the non-MAXWELLian parameter in the channel region (Fig. 6). This parameter shows only a weak dependence on doping and applied voltage.

By combining the modifications for an anisotropic temperature and a non-MAXWELLian closure relation the artificial current decrease gets eliminated (Fig. 7). Parameter values roughly estimated from MC simulations can be used, e.g. $\gamma_{0y} = 0.75$ and $\beta_0 = 0.75$. In the parameter range where the current drop is eliminated the output characteristics are found to be rather insensitive to the exact parameter values.

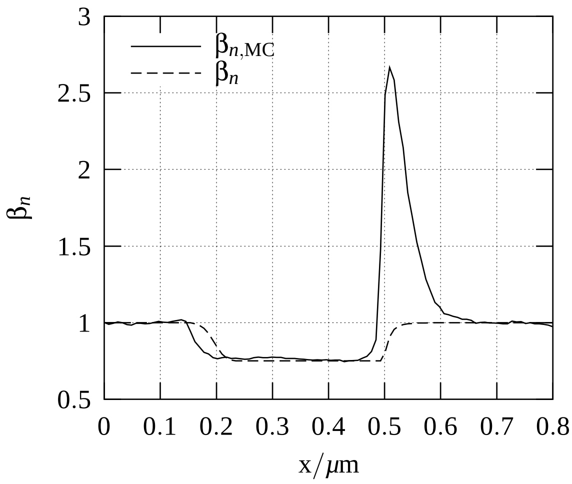

Fig. 6: MC simulation of a *nin*-structure showing the normalized moment of fourth order $\beta_{n,\mathrm{MC}}$ compared to the analytical β_n with $\beta_0 = 0.75$.

CONCLUSION

Standard ET simulations of SOI MOSFET give anomalous output characteristics. To solve this problem, an improved ET model has beed developed. By including two distinct modifications, namely an anisotropic carrier temperature and a modified closure relation, the spurious diffusion of hot electrons in the vertical direction has been sufficiently reduced. Further careful modeling of these two effects on the basis of MC data may be required.

ACKNOWLEDGEMENTS

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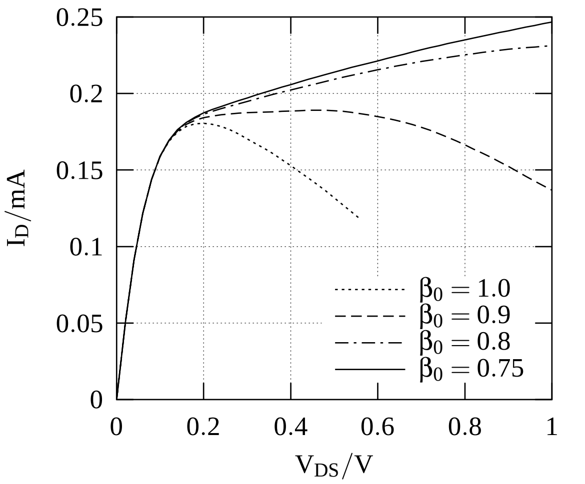

Fig. 7: Output characteristics of the SOI assuming an anisotropic temperature ($\gamma_{0y} = 0.75$) and a modified closure relation.

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