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

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Abstract

When applied to partially depleted SOI MOSFETs, the energy transport model predicts anomalous output characteristics. The effect that the drain current reaches a maximum and then decreases is peculiar to the energy transport model. It is not present in drift-diffusion simulations and its occurrence in measurements is questionable. The effect is due to an overestimation of the diffusion of channel hot carriers into the floating body. A modified energy transport model is proposed which describes hot carrier diffusion more realisticly and allows for proper simulation of SOI MOSFETs.

Keywords: energy transport, moment equations, Boltzmann equation, device simulation, silicon on insulator.

INTRODUCTION

With the ongoing down-scaling of modern semiconductor devices simulation results obtained by the widely accepted drift-diffusion (DD) transport model become more and more questionable. 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 typically by considering the first four moments of the BOLTZMANN equation. However, the resulting energy transport (ET) models, which are nowadays available in most of the device simulation programs, lead to interesting problems when applied to SOI MOSFETs.

Using the ET model for the simulation 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 DD transport model. One exception is given in [5], where a weak decrease of the drain-current is reported.

CAUSE OF THE EFFECT

A major difference between the ET and the DD transport model is the treatment of the carrier temperature. While in the ET model the carrier temperature can differ from the lattice temperature, in the DD model carriers are assumed to stay at lattice temperature. Since the diffusion of carriers is proportional to their temperature, the diffusion can be significantly higher when predicted by the ET model. Fig. 2 clearly shows the enhanced vertical diffusion of electrons near the pinch-off region of a bulk MOSFET, as compared with the DD result in Fig. 3.

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 collected by the drain-body and source-body junctions, but many 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.

THE ENERGY TRANSPORT MODEL

A 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. However, within this parameter-space only minor improvements in the output characteristics were possible.

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. Assumptions considered important in this regard are 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 an ET equation set has been derived from the BOLTZMANN equation, permitting an anisotropic temperature and a non-MAXWELLian distribution function. The current density $J_{n,l}$ and the energy flux density $S_{n,l}$ are given by

$$J_{n,l} = \mu_n \left(\mathrm{k_B}\, \nabla_l \big(n\, T_{ll}\big) + \mathrm{q}\, E_l\, n\right) , \tag{1}$$

$$S_{n,l} = -\frac{5}{2}\,\frac{\mathrm{k_B}}{\mathrm{q}}\, \mu_S \left(\mathrm{k_B}\, \nabla_l \big(n\, \beta_n\, T_{ll}\, \Theta_l\big) + \mathrm{q}\, E_l\, n\, \Theta_l\right) , \tag{2}$$

$$\Theta_l = \frac{3\,T_n + 2\,T_{ll}}{5} . \tag{3}$$

The carrier temperature is defined by the average energy, $1.5\mathrm{k_B}T_n = <\epsilon>$. The diagonal component of the temperature tensor for direction $\vec{e}_l$, T_{ll}, is given by $\mathrm{k_B}T_{ll} = < v_l p_l >$. Off-diagonal components are neglected. β_n is the normalized moment of fourth order, which evaluates to $\beta_n = 1$ for a MAXWELLian distribution. 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.

The empirical model for the temperature tensor distinguishes between directions parallel (x) and normal (y) to the current density.

$$T_{xx} = \gamma_x(T_n)\, T_n\ , \quad T_{yy} = \gamma_y(T_n)\, T_n \tag{4}$$

$$\gamma_\nu(T_n) = \gamma_{0\nu} + \big(1 - \gamma_{0\nu}\big)\, \exp\Big(-\Big(\frac{T_n - T_L}{\mathrm{T_{ref,\gamma}}}\Big)^2\Big)\ , \quad \nu = x, y \tag{5}$$

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. $\mathrm{T_{ref,\gamma}} = 600\,\mathrm{K}$ appeared to be appropriate. The diagonal temperature for a generic direction

$\vec{e}_l = (\cos\varphi, \sin\varphi)$ is obtained from the average $<\vec{v}\cdot\vec{e}_l\vec{p}\cdot\vec{e}_l>$ after neglecting the off-diagonal terms as

$$T_{ll} = T_{xx}\,\cos^2\varphi + T_{yy}\,\sin^2\varphi\,. \tag{6}$$

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. Quantitatively, such a situation is characterized by the fourth order moment as $\beta_n < 1$. Aiming only at a model for the $\beta_n < 1$ region in Fig. 5, a simple expression for β_n has been assumed.

$$\beta_n(T_n) = \beta_0 + \big(1 - \beta_0\big)\,\exp\Big(-\Big(\frac{T_n - T_L}{\mathrm{T}_{\mathrm{ref},\beta}}\Big)^2\Big) \tag{7}$$

This expression ensures that only for sufficiently large T_n the distribution deviates from the MAXWELLian shape.

RESULTS

The simulations discussed in the following were performed on a device with an assumed effective gate-length of $130\,\mathrm{nm}$, a gate-oxide thickness of $3\,\mathrm{nm}$, and a silicon-film thickness of $200\,\mathrm{nm}$. With a p-doping of $\mathrm{N_A} = 7.5\cdot10^{17}\,\mathrm{cm}^{-3}$ the device is partially depleted. The Gaussian-shaped n-doping under the electrodes has a maximum of $\mathrm{N_D} = 6\cdot10^{20}\,\mathrm{cm}^{-3}$.

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 vertical anisotropy parameter. Simulations show that 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. On the other hand, the lateral anisotropy parameter has little influence on the output characteristics and has been set to $\gamma_{0x} = 1.0$.

MC simulations yield values close to $\beta_0 = 0.75$ for the non-MAXWELLian parameter in the channel region (Fig. 5). 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. 6). 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.

CONCLUSION

Standard ET simulations of SOI MOSFET give anomalous output characteristics. To solve this problem, an improved ET model has been developed. By including empirical models for an anisotropic carrier temperature and the closure relation, the spurious diffusion of hot electrons in vertical direction has been sufficiently reduced.

ACKNOWLEDGMENT

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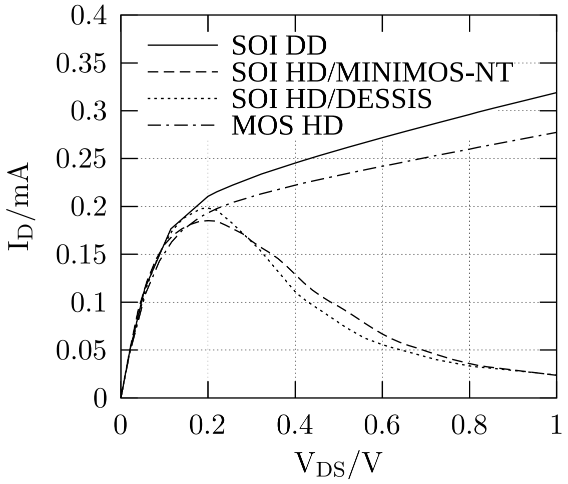

Fig. 1: Output characteristics of an SOI MOSFET obtained by DD an ET simulations using two different device simulators.

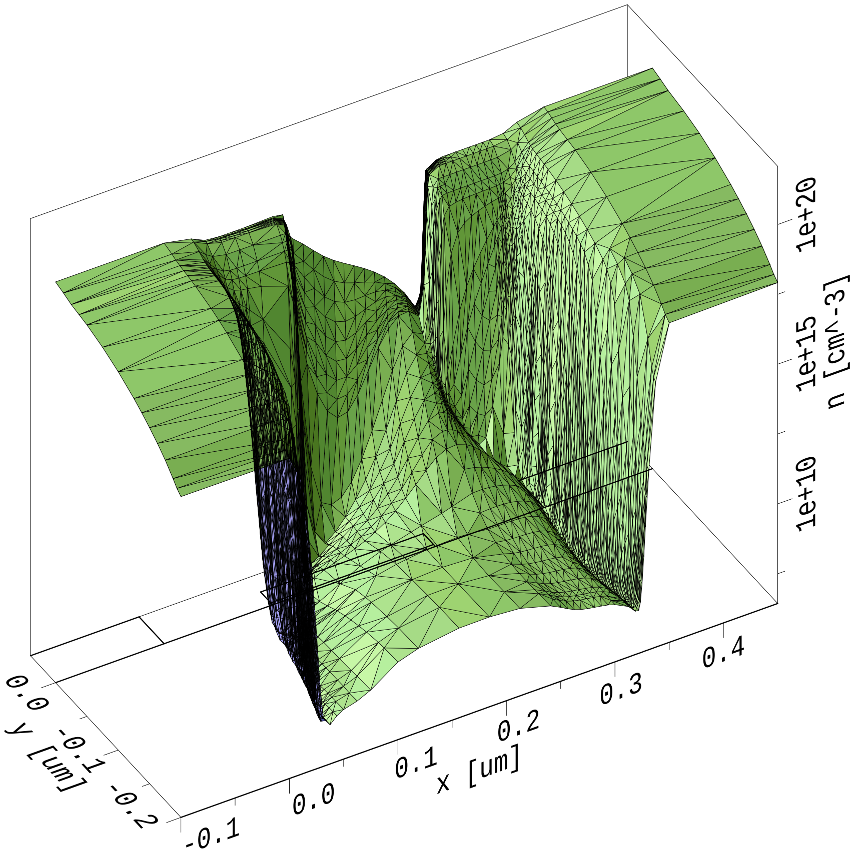

Fig. 2: Electron concentration in a MOSFET obtained by a ET simulation.

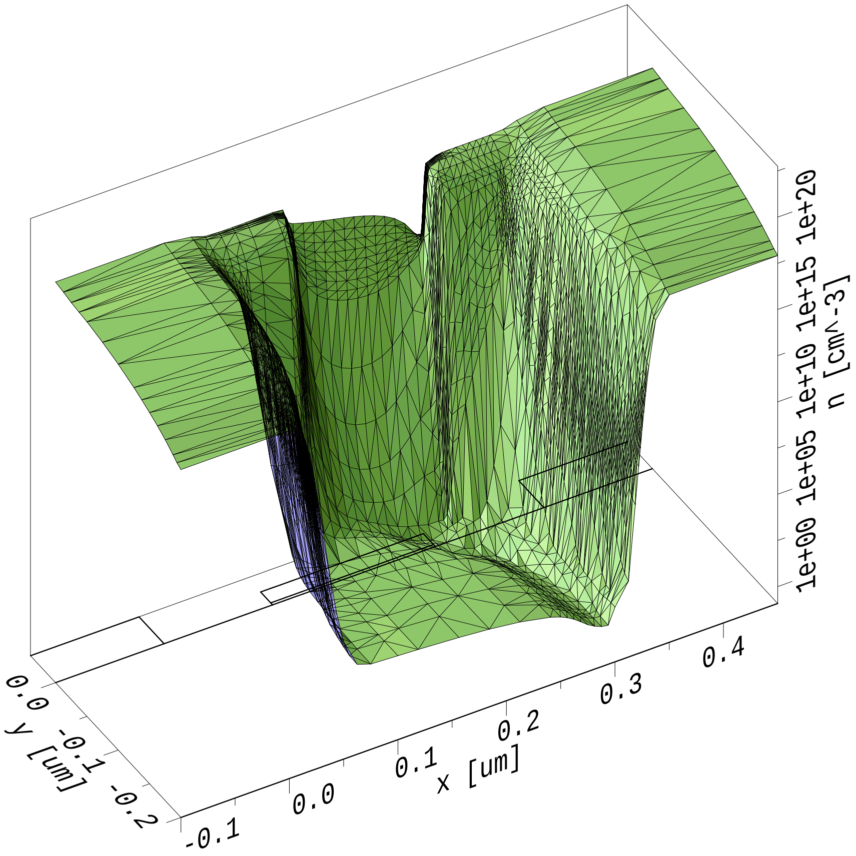

Fig. 3: Electron concentration in a MOSFET obtained by a DD simulation.

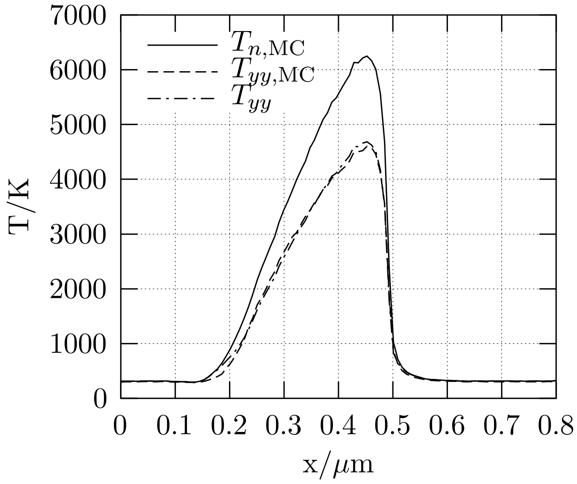

Fig. 4: MC simulation of an nin-structure showing the y-component of the temperature tensor and the temperature $T_{n,\mathrm{MC}}$ obtained from the mean energy. Also shown is the analytical model (4) and (5) with $\gamma_{0\nu} = 0.75$.

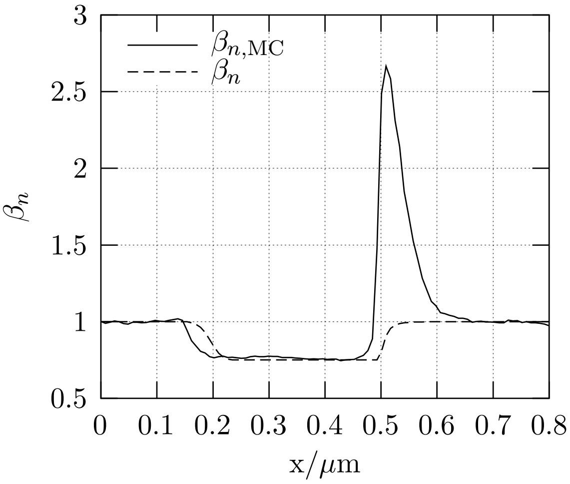

Fig. 5: MC simulation of a nin-structure showing the normalized moment of fourth order $\beta_{n,\mathrm{MC}}$ compared to the analytical model (7) with $\beta_0 = 0.75$.

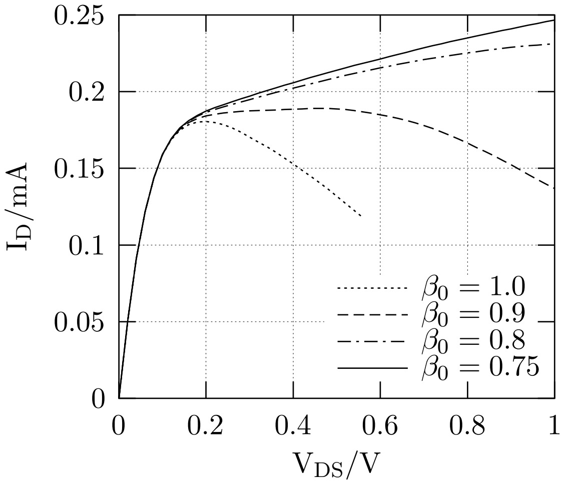

Fig. 6: Output characteristics of the SOI MOSFET assuming an anisotropic temperature ($\gamma_{0y} = 0.75$) and a modified closure relation.