The Failure of the Hydrodynamic Transport Model for Simulation of Partially Depleted SOI MOSFETs and its Revision

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ABSTRACT

An anomalous output characteristics is observed in hydrodynamic 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 hydrodynamic transport model.

Keywords: silicon on insulator, body effect, hydrodynamic transport model, BOLTZMANN equation, device simulation.

1 INTRODUCTION

Using the standard hydrodynamic (HD) transport model for simulation of partially depleted SOI MOSFETs, an anomalous decrease of the drain current with increasing drain-source voltage has been observed (Fig. 1). The anomalous effect has been reproduced using the two different device simulators MINIMOS-NT [1] and DESSIS [2], and can be explained by an enhanced diffusion of channel hot carriers into the floating body [3] [4]. It is believed that this decrease in drain current is an artifact because experimental data do not show this effect, 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 measured drain current of a p-MOS SOI is reported.

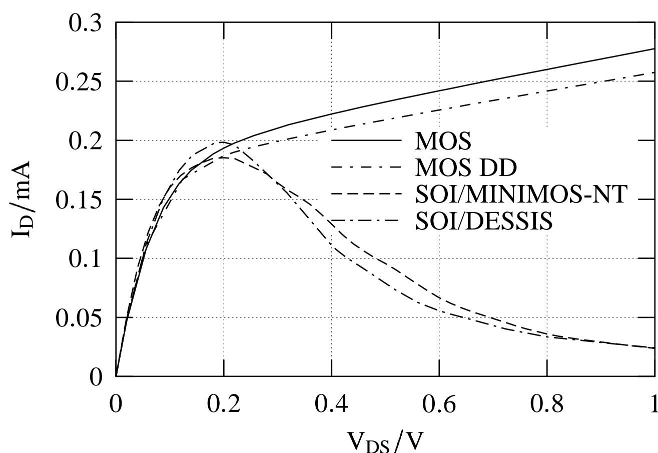

Figure 1: Output characteristics obtained by standard HD simulations; verified by using two different device simulators.

However, applicability of the HD model to the ever downscaled devices is desirable, because in contrast to the DD model it takes non-local effects into account. Empirical measures provided by DESSIS, such as weighting heat flow and thermal diffusion, have only little influence on the current drop. This paper presents a revision of the HD model which enables proper simulation of SOI MOSFETs.

2 CAUSE OF THE EFFECT

The main difference between the HD and the DD transport model is given by the energy balance equation. The benefit of the increased computational effort of solving an additional equation 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 HD transport model. Fig. 2 clearly shows the enhanced vertical diffusion of electrons 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 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.

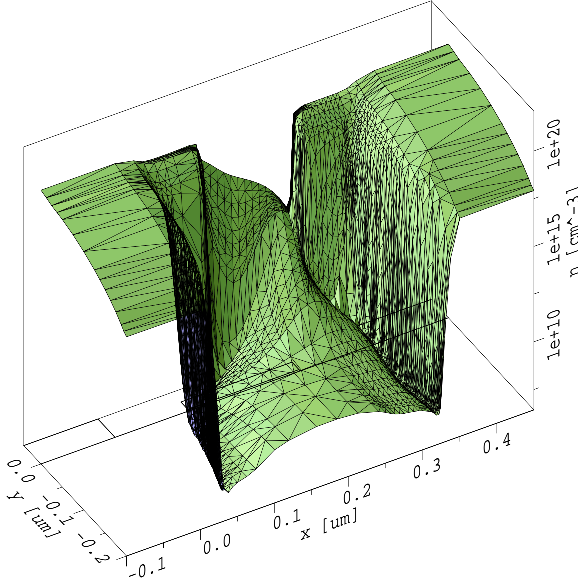

Figure 2: Electron concentration in an SOI MOSFET obtained by a HD simulation.

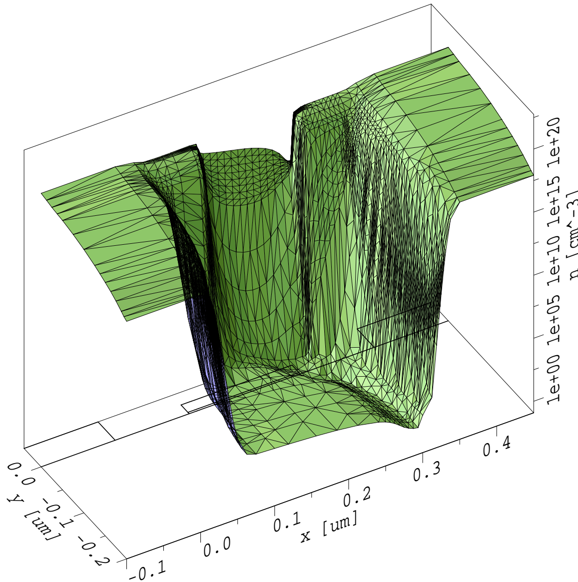

Figure 3: Electron concentration in an SOI MOSFET obtained by a DD simulation.

3 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 HD 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.

4 MODIFICATIONS

In Monte-Carlo (MC) simulations the spreading of hot carriers away from the interface is much less pronounced than in HD simulations. If we assume that the BOLTZMANN equation does not predict the hot carrier spreading, and if the HD equations derived from the BOLTZMANN equation do so, the problem must be introduced by the assumptions made in the derivation of the HD 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 HD equation set from the BOLTZMANN equation permitting an anisotropic temperature and a non-MAXWELLian distribution function:

$$J_{n,\xi} = \mu_n \left(\mathrm{k_B}\, \nabla_\xi \left(n\, T_{\xi\xi}\right) + \mathrm{q}\, E_\xi\, n\right) \tag{1}$$

$$S_{n,\xi} = -\frac{5}{2}\frac{\mathrm{k_B}}{\mathrm{q}}\mu_S \left(\mathrm{k_B}\, \nabla_\xi \left(n\, \beta_n\, T_{\xi\xi}\, \Theta\right) + \mathrm{q}\, E_\xi\, n\, \Theta\right) \tag{2}$$

$$\text{with} \quad \nabla_\xi = \frac{\partial}{\partial \xi} \quad \text{and} \quad \Theta = \frac{3\,T_n + 2\,T_{\xi\xi}}{5} \tag{3}$$

$T_{\xi\xi}$ denotes the diagonal component of the temperature tensor for direction $\vec{e}_\xi$. Off-diagonal components are neglected. β_n is the normalized moment of fourth order.

By setting $T_{\xi\xi} = T_n$ and $\beta_n = 1$ the conventional HD model is obtained. The solution variable is still the carrier temperature T_n, whereas the tensor components and β_n are modeled empirically as functions of T_n. First empirical modeling of $T_{\xi\xi}$ was performed by distinguishing between directions parallel and normal to the current density:

$$T_{\xi\xi} = T_{xx} \cos^2\varphi + T_{yy} \sin^2\varphi\ , \ T_{xx} = \gamma_x\, T_n\ , \ T_{yy} = \gamma_y\, T_n \tag{4}$$

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

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 (Fig. 4), ensuring that only for sufficiently hot carriers the distribution becomes anisotropic, whereas the equilibrium distribution stays isotropic (Fig. 5). With respect to numerical stability the transition should not be too steep. $\mathrm{T_{ref,\gamma}} = 600\,\mathrm{K}$ 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).

$$\beta_n(T_n) = \beta_0 + \left(1 - \beta_0\right) \exp\left(-\left(\frac{T_n - T_L}{\mathrm{T_{ref,\beta}}}\right)^2\right) \tag{6}$$

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

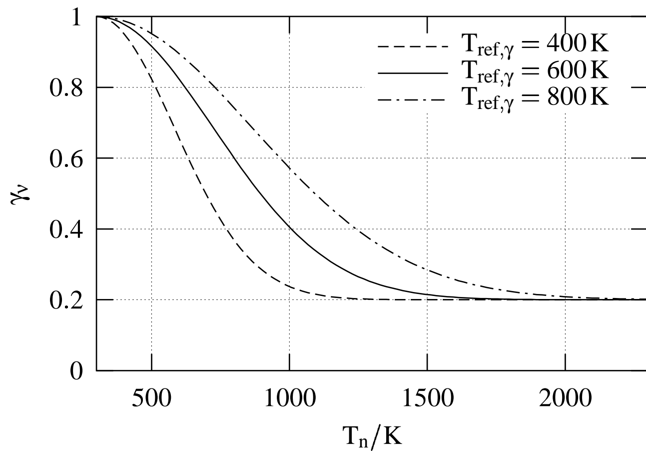

Figure 4: Shape of the function used to model γ and β.

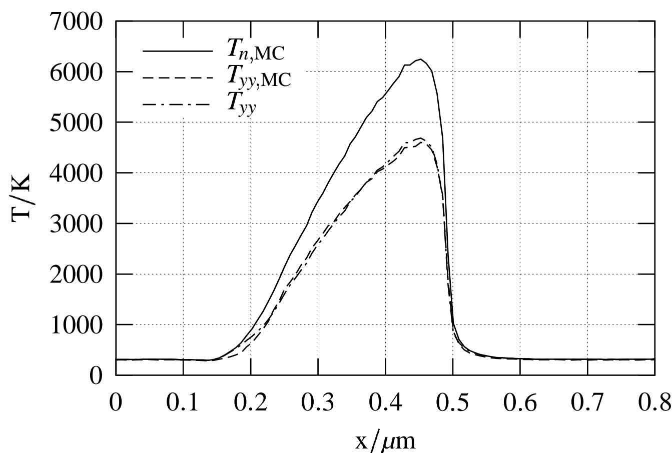

Figure 5: MC simulation of an *nin*-structure showing the x-component of the temperature compared to the mean temperature $T_{n,\mathrm{MC}}$. The analytical T_{yy} uses $\gamma_{0\nu} = 0.75$.

5 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 HD simulations. Parameter values were estimated from MC results for one-dimensional test structures.

As a first example simulations 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 $N_D = 6 \cdot 10^{20}\,\mathrm{cm}^{-3}$.

Fig. 5 indicates that $\gamma_{0y} = 0.75$ is a realistic value for the anisotropy parameter. Fig. 7 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 simulations 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.

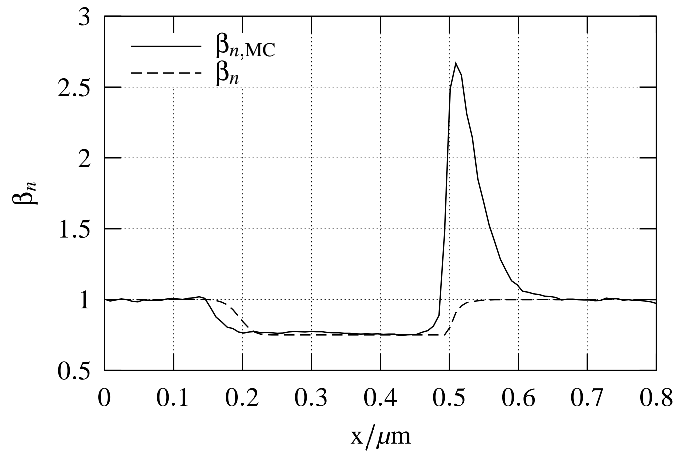

Figure 6: MC simulation of a *nin*-structure showing the normalized moment of fourth order $\beta_{n,\mathrm{MC}}$ compared to the analytical β_n with $\beta_0 = 0.75$.

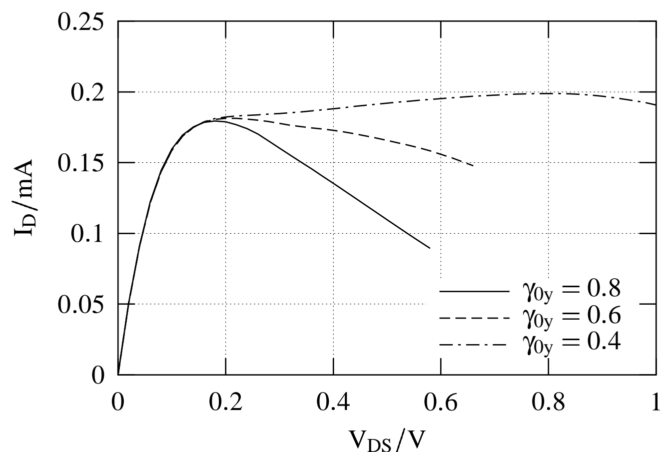

Figure 7: Output characteristics of the SOI obtained by anisotropic HD simulations without closure modification ($\beta_0 = 1$).

By combining the modifications for an anisotropic temperature and a non-MAXWELLian closure relation the artificial current decrease gets eliminated (Fig. 8). 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.

To verify the modified hydrodynamic transport model, a second device has been investigated. Basically this SOI

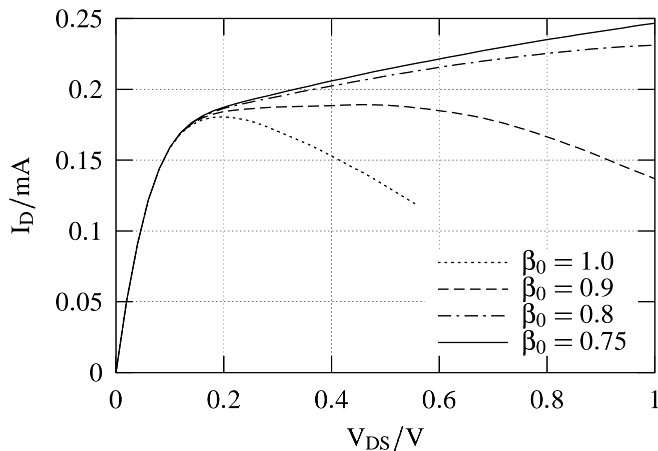

Figure 8: Output characteristics of an SOI-MOSFET with analytical doping profile assuming an anisotropic temperature ($\gamma_{0y} = 0.75$) and a modified closure relation. $V_{GS} = 1\,V$.

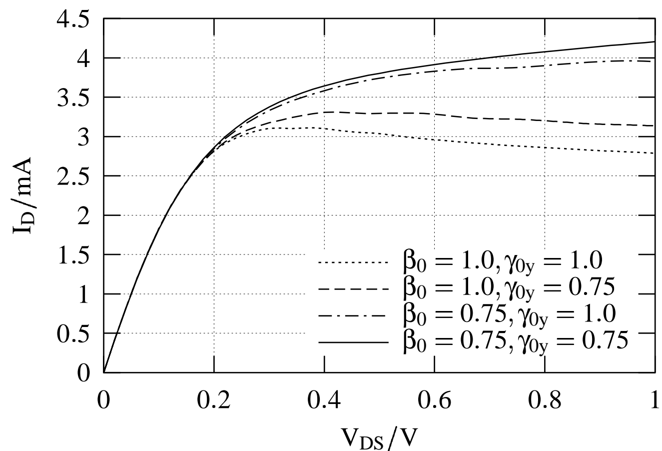

Figure 9: Output characteristics of the "Well-Tempered" SOI. $V_{GS} = 1\,V$.

has been modeled after the 90 nm "Well-Tempered" MOSFET [6] using the doping profiles available online, including the SSR channel doping and source/drain halo. To achieve a partically depleted device a substrate doping of $N_A = 7.5 \cdot 10^{17}\,\mathrm{cm}^{-3}$ has been assumed and the substrate thickness has been limited to 200 nm.

By using the standard HD transport model the drop in the drain current is also present in this device ($\beta_0 = 1.0, \gamma_{0y} = 1.0$ in Fig. 9). Applying the modified model using the same parameters as before the output characteristics obtains its normal shape.

The different order of magnitude of the drain currents seen with Device 1 and Device 2 mainly stems from the rather high threshold voltage of Device 1.

6 Conclusion

Standard HD simulations of SOI MOSFET give anomalous output characteristics. To solve this problem, an improved HD transport 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. The improved hydrodynamic transport model has successfully been used to simulate different SOI devices.

ACKNOWLEDGEMENTS

This work has been supported by the *Christian Doppler Gesellschaft*, Vienna, Austria.

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