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

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Introduction

Using the standard energy transport (ET) 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). This effect has been reproduced using two different device simulators MINIMOS-NT and DESSIS, and can be explained by an enhanced diffusion of channel hot carriers into the floating body. It is believed that this decrease in drain current is an artifact because experimental data does not show this effect, nor can it be observed when using the drift-diffusion (DD) transport model. Empirical measures provided by DESSIS, such as weighting heat flow and thermal diffusion, have only little influence on the current drop.

Modifications

In Monte Carlo (MC) simulations the spreading of hot carriers away from the surface of a MOSFET is much less pronounced than in ET simulations. Therefore, the assumptions underlying the ET model should be carefully reconsidered. While in the standard ET model an isotropic Maxwellian distribution is assumed to close the hierarchy of moments, in this work an equation set is derived from the Boltzmann equation permitting an anisotropic temperature and a non-Maxwellian distribution:

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

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

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

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 β_n are modeled empirically as functions of T_n. A first empirical model of T_{ll} distinguishes between directions parallel and normal to the current density:

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

$$T_{xx} = \gamma_x\, T_n \ , \ T_{yy} = \gamma_y\, T_n ,$$

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

Off-diagonal components of the temperature are neglected. 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. 2), 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. $\mathrm{T}_{\mathrm{ref},\gamma} = 600\,\mathrm{K}$ appeared to be appropriate.

Another effect observed in MC simulations is that in most of the channel the high energy tail is less populated than that of a Maxwellian distribution, which gives $\beta_n < 1$ (Fig. 5). A simple model for β_n was used.

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

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. Parameter values were estimated from MC results for one-dimensional test structures. Fig. 3 indicates that $\gamma_{0y} = 0.75$ is a realistic value for the anisotropy parameter. Fig. 4 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. 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.

Acknowledgement

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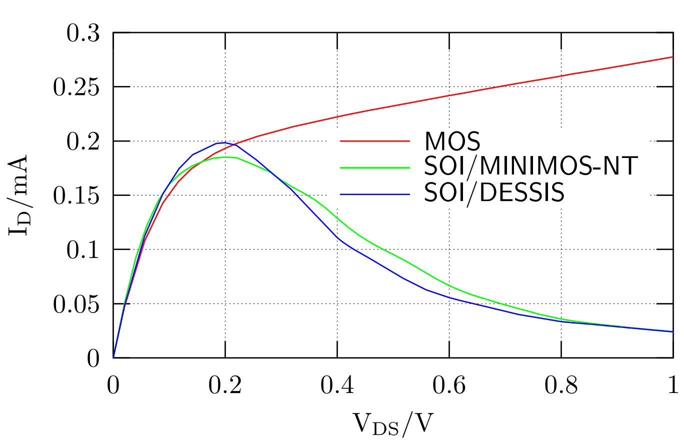

Fig. 1: Output characteristics obtained by standard ET simulations; verified by using two different device simulators.

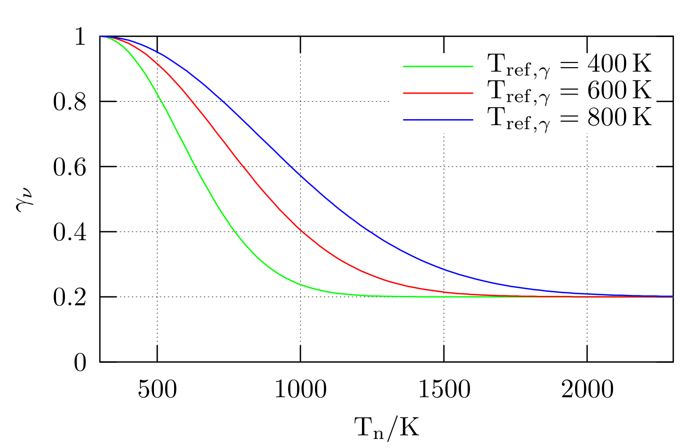

Fig. 2: Shape of the function used to model γ and β.

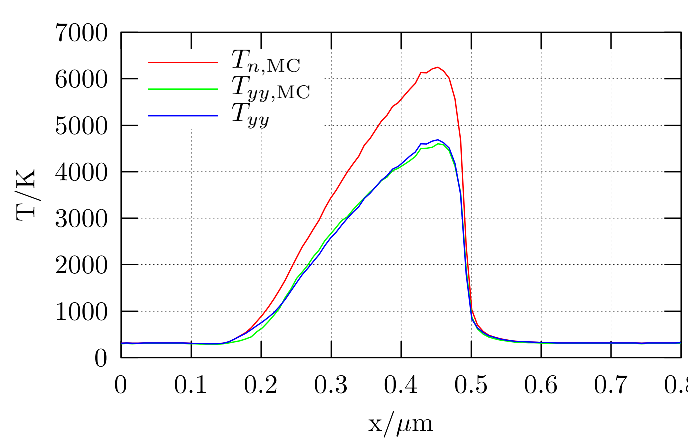

Fig. 3: MC simulation of an nin-structure showing the x-component of the temperature compared to the carrier temperature $T_{n,\mathrm{MC}}$. The analytical T_{yy} uses $\gamma_{0\nu} = 0.75$.

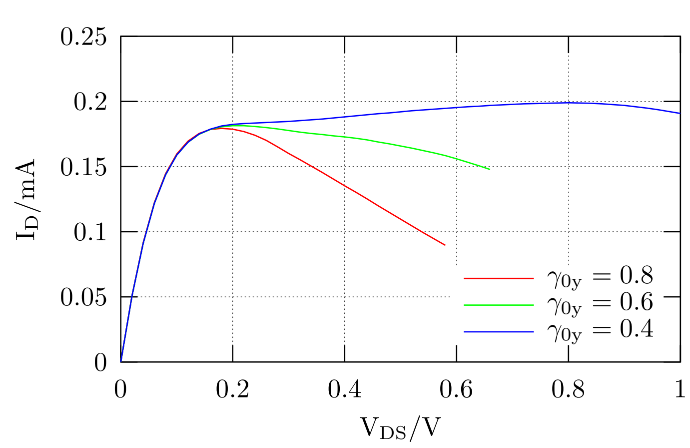

Fig. 4: Output characteristics of the SOI obtained by anisotropic ET simulations. No closure modification ($\beta_0 = 1$).

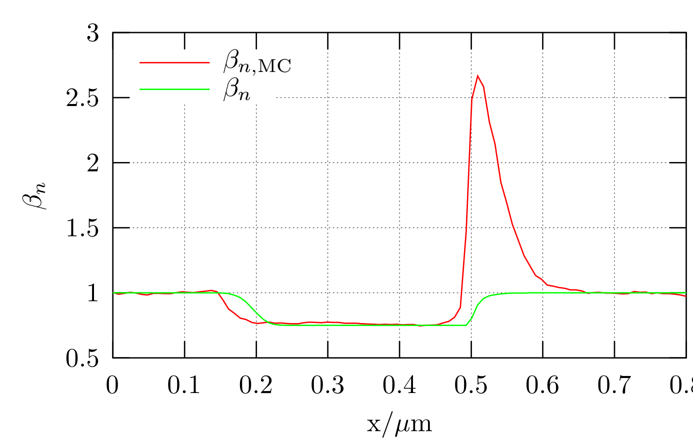

Fig. 5: MC simulation of a nin-structure showing the normalized moment of fourth order $\beta_{n,\mathrm{MC}}$ compared to the analytical β_n with $\beta_0 = 0.75$.

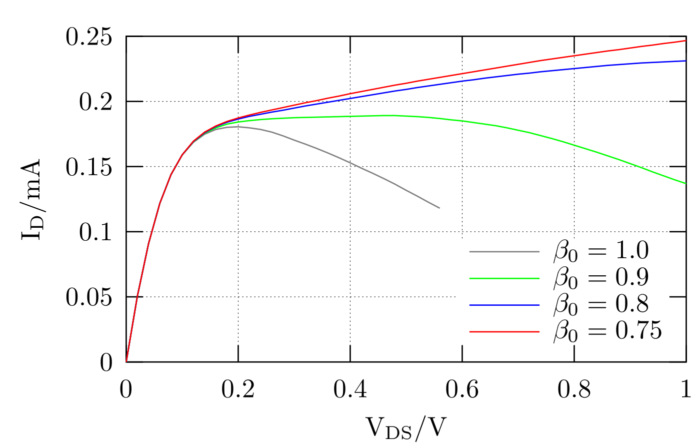

Fig. 6: Output characteristics of the SOI assuming an anisotropic temperature ($\gamma_{0y} = 0.75$) and a modified closure relation.