Influence of Generation/Recombination Effects in Simulations of Partially Depleted SOI MOSFETs

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Abstract—This paper reports on two anomalous effects observed in simulations of partially depleted SOI MOSFETs. The first is an unrealisticly high I_D increase due to impact-ionization for both drift-diffusion and hydro-dynamic transport models. Second, for hydro-dynamic simulations an anomalous output characteristic is observed. The effect that the drain current reaches a maximum and then decreases is peculiar to the hydro-dynamic transport model. It is neither present in measurements nor in drift-diffusion simulations. The problem is investigated under various generation/recombination conditions and an explanation of the cause of this effect is given.

1 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 like carrier heating and velocity overshoot makes it desirable to use more sophisticated transport-models which are obtained by considering the first three or four moments of the Boltzmann transport equation. However these so called hydro-dynamic transport models, which are nowadays also quite common in simulations of bulk MOSFETs, lead to interesting problems when used in conjunction with SOI MOSFETs.

2 Used Device

The simulated SOI device is depicted in Fig. 1. It has an 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 $N_A = 7.5 \times 10^{17}\,\mathrm{cm}^{-3}$ the device is partially depleted. The Gaussian n-doping under the electrodes has a maximum of $N_D = 6 \times 10^{20}\,\mathrm{cm}^{-3}$.

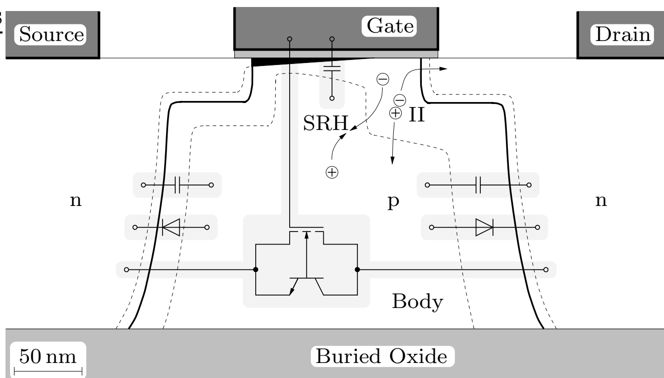

Figure 1: The geometry of the simulated SOI including the symbolic compact devices.

3 Simulation Results

3.1 Drift-Diffusion

Carrying out DD simulations shows a remarkable difference depending on whether impact-ionization (II) is turned on or off (Fig. 2). The increase of the drain current can

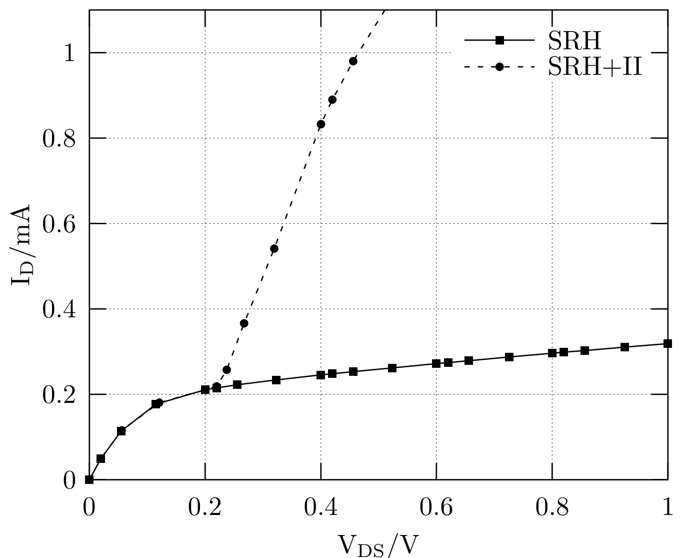

Figure 2: Output characteristics of the SOI obtained by DD simulations.

be partially explained by the kink-effect [1]: Due to II in the pinch-off region, the holes are drawn into the floating body where they raise the potential (Fig. 3). This increased body potential leads via the body effect to an increased drain current. Simulating the device without II leads to a much smaller shift in the body potential (Fig. 4).

The kink effect alone cannot be responsible for such a big increase of the drain current. Another effect happening here is the bipolar effect, which means that the increased

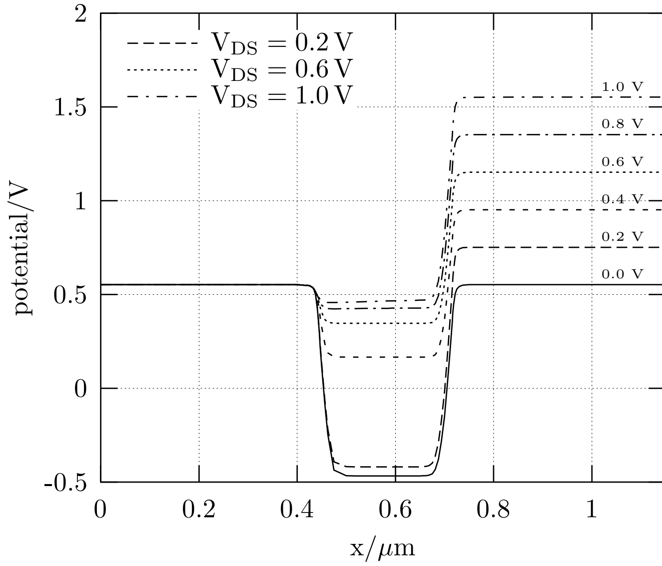

Figure 3: Distributed potential of the SOI obtained by DD simulations with II.

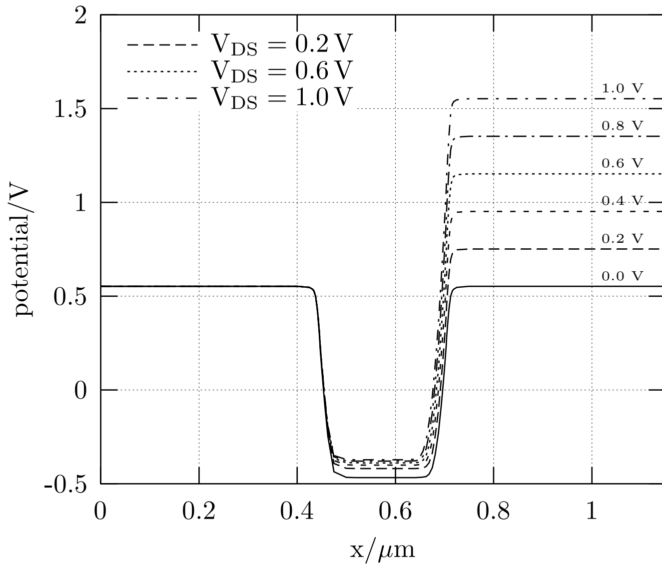

Figure 4: Distributed potential of the SOI obtained by DD simulations without II.

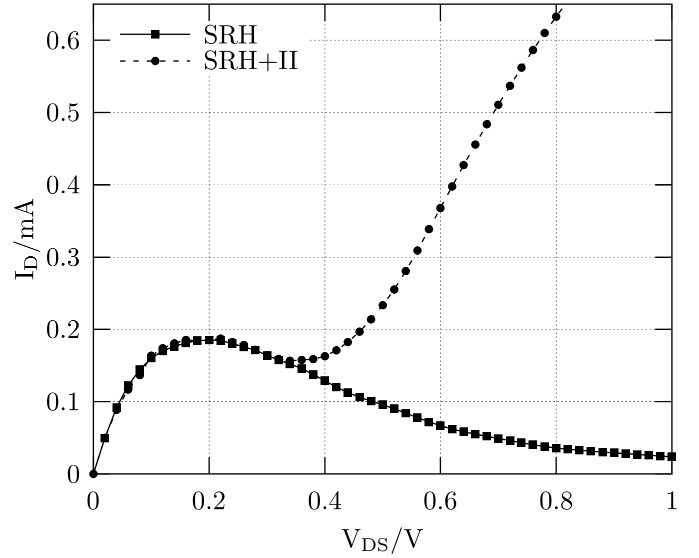

Figure 5: Output characteristics of the SOI obtained by HD simulations using MINIMOS-NT.

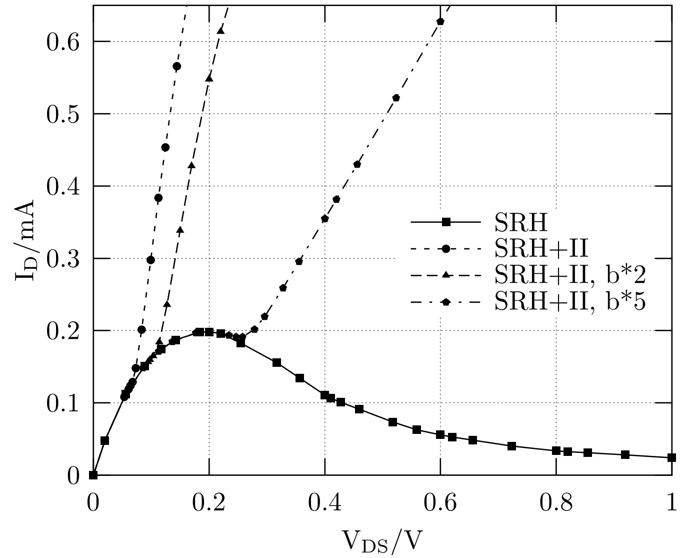

Figure 6: Output characteristics of the SOI obtained by HD simulations using DESSIS.

body potential causes the source-body diode being biased slightly forward, and thus makes it possible that more electrons can cross the lowered barrier coming from the source (emitter). Because of the small body (base) width, they are able to diffuse towards the drain (collector), where they are sucked off.

3.2 Hydro-Dynamic

Carrying out HD simulations complicates the subject further. As can be seen in Fig. 5 and Fig. 6, the output characteristics behave quite differently from those obtained by DD. Without II the drain current shows a negative differential output characteristic after the maximum at about $V_{DS} = 0.2\,\mathrm{V}$. This can be explained by the difference in Shockley-Read-Hall generation/recombination (SRH): Using the DD transport model it makes virtually no difference whether SRH is turned on or not, but with the HD transport model the diffusion of the heated electrons near the pinch-off region is so significant, that they are transferred in the floating body where they recombine. This leads to an experimentally not observed decrease in the body potential which decreases via the body effect the drain current at a given drain-source voltage. The interesting point is that this behavior is observed with two different device simulators. Fig. 5 shows the results obtained from MINIMOS-NT [2], while Fig. 5 was produced using DESSIS [3]. In the DESSIS simulation the kink is located even before $V_{DS} = 0.1\,\mathrm{V}$, a difference to DD which is not yet understood and needs further analysis. The II model used in MINIMOS-NT is described in [4]. Further analysis of the problem will be given in Section 4.

3.3 Body Contact

The order of magnitude of the involved currents can be estimated by looking at simulations of a device with a body contact attached. Fig. 7 shows the output characteristics of this device and it is clear, that because of the fixed (pinned) body potential the drain current is not much affected by II. The big difference can be seen in the corresponding bulk (body) currents (Fig. 8): If SRH and II are used, one obtains the expected result that there is a body current which flows out of the transistor and has therefore a negative sign. But if in contrast only SRH without II is used, there is a body current of positive sign, which is several orders of magnitude smaller.

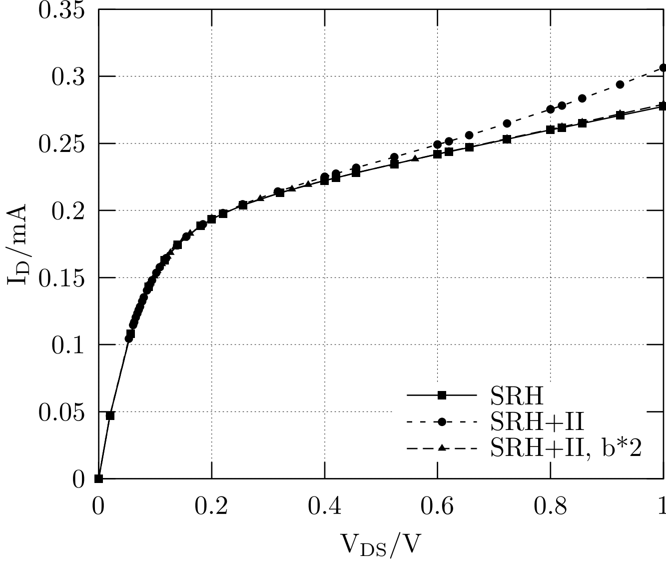

Figure 7: Output characteristics of the SOI with a body contact obtained by HD simulations.

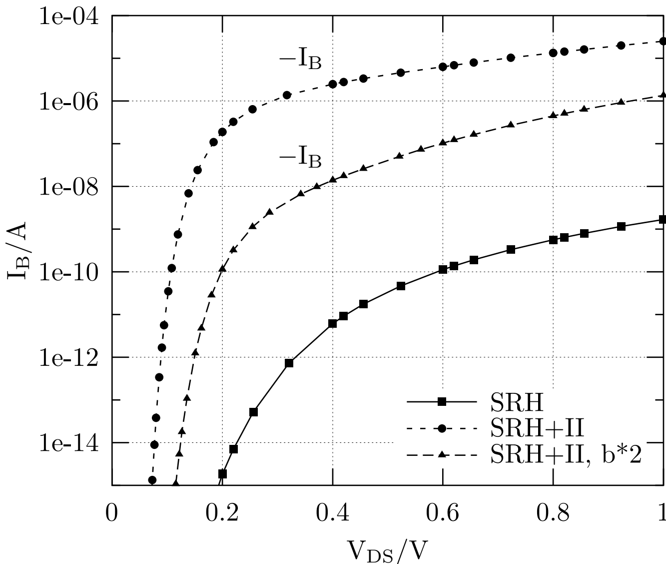

Figure 8: Bulk currents of the SOI with body contact obtained by HD simulations.

To estimate if the resulting current obtained by simulations with II is really caused by the increased body potential the simulations shown in Fig. 9 and Fig. 10 were made. In this case the source-body diode (and at small V_{DS} even the drain-body diode) is biased in forward direction using a body potential of $V_{BS} = 0.93\,\mathrm{V}$. (This voltage is taken from Fig. 3, where the body potential is raised by this value.) Accounting for the negative current offset at $V_{DS} = 0\,\mathrm{V}$ total agreement with the SRH+II curve taken from Fig. 2 is obtained at $V_{DS} = 1\,\mathrm{V}$.

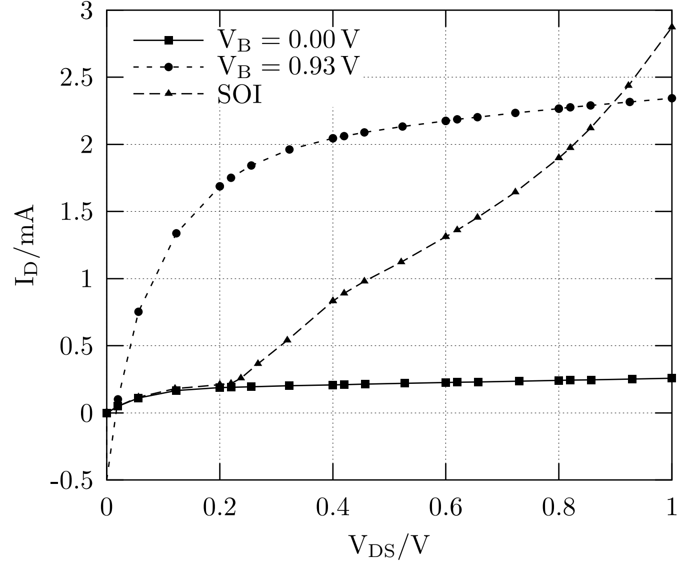

Figure 9: Comparison of the drain currents of the SOI and the device with body contact obtained by DD simulations.

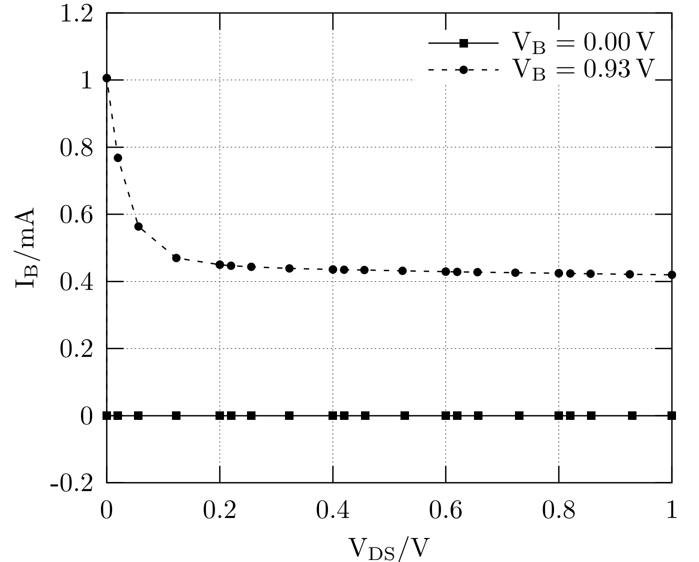

Figure 10: Comparison of the bulk currents at different body potentials obtained by DD simulations.

The mentioned b-parameter depicted in several figures can be found in the formula of the II-coefficient which is known as the Chynoweth law, $\alpha(F) = \gamma\, a\, e^{-\frac{\gamma\, b}{F}}$. The default coefficients are taken from [5]. The factor γ expresses the dependance with respect to the lattice temperature. A variation of b can be interpreted as a scaling of the effective electric field F.

4 Cause of the Effect

It is believed that the main difference between the DD and the HD transport model responsible for the negative output conductance is the difference in the balance of the drift and diffusion currents:

$$\frac{|\mathbf{J}_{\mathrm{diff}}|}{|\mathbf{J}_{\mathrm{drift}}|} = \frac{k_B\,T_L}{q}\,\frac{|\boldsymbol{\nabla}\,n|}{n\,|\mathbf{E}|}\cdot\begin{cases} 1 & \ldots\ \ \mathrm{DD} \\ T_n/T_L & \ldots\ \ \mathrm{HD}\end{cases} \tag{1}$$

Apparently, in the HD model carrier diffusion is by a factor T_n/T_L higher than in the DD model.

Due to the high temperature in the pinch-off region, the electrons spread away from the interface and diffuse into the body, where they recombine (Fig. 1). Removing holes there causes the body potential to drop which decreases the drain current via the body effect.

The difference in the carrier concentration between DD and HD can be seen clearly in Fig. 11 and Fig. 12.

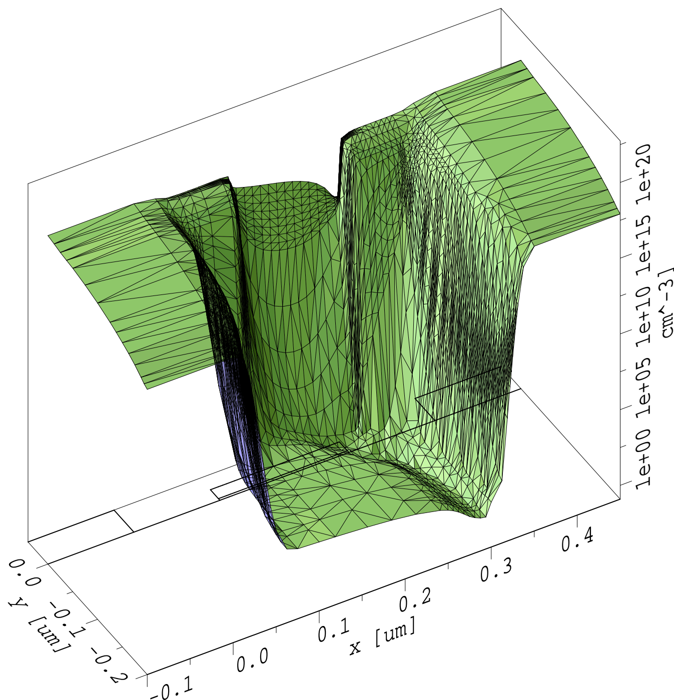

Figure 11: Electron concentration in the SOI obtained by a DD simulation.

5 Conclusion

This simulation study shows a high sensitivity of I_D to the II parameters and an unrealisticly high kink-effect with default II parameters from the literature. Careful tuning of these parameters is therefore an important issue in SOI simulation. Another observation is that reducing the strength of II (parameter b in Fig. 6) reduces the current increase, however, the desirable I/V curve (which would be the DD curve in Fig. 2) cannot be approached.

An explanation of the decrease in the output characteristic of HD simulations of SOI devices has been given. If one concludes that the Boltzmann transport equation does not predict the hot carrier spreading which causes this de-

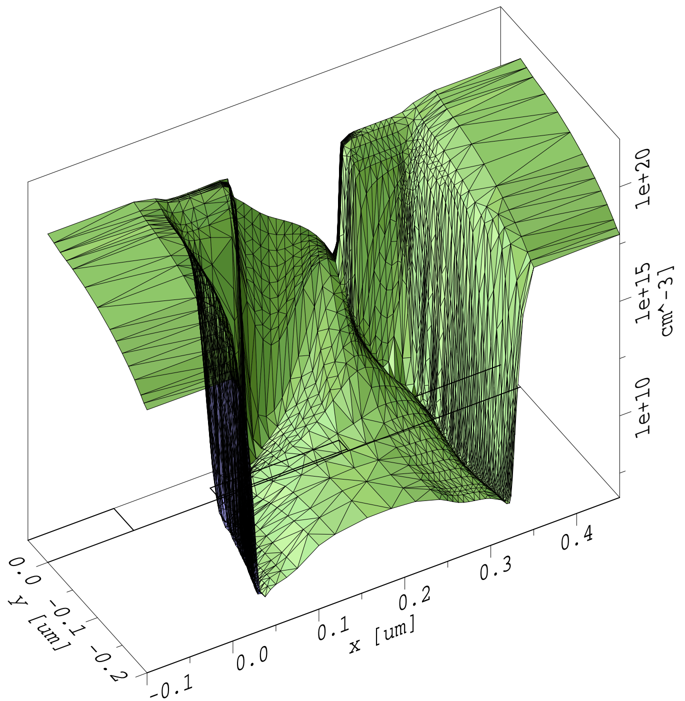

Figure 12: Electron concentration in the SOI obtained by a HD simulation.

crease, and if the HD equations derived from the Boltzmann equation do so, the problem must be introduced by assumptions made in the derivation of the HD model.

Acknowledgement

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