A SIMULATION STUDY OF PARTIALLY DEPLETED SOI MOSFETS

M. Gritsch, H. Kosina, T. Grasser, and S. Selberherr

Institute for Microelectronics, TU Vienna, Gusshausstr. 27–29, A-1040 Vienna, Austria
Phone +43-1-58801-36015, FAX +43-1-58801-36099, e-mail: Markus.Gritsch@iue.tuwien.ac.at

Abstract—We report on anomalous output characteristics 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 hydro-dynamic transport model. It is not present in drift-diffusion simulations and its occurance in measurements is questionable. The problem is investigated under various conditions and an explanation of the cause of this effect is given.

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 hydrodynamic transport models (HD) which are nowadays quite common in simulations of small bulk MOSFETs, lead to interesting problems when applied to SOI MOSFETs.

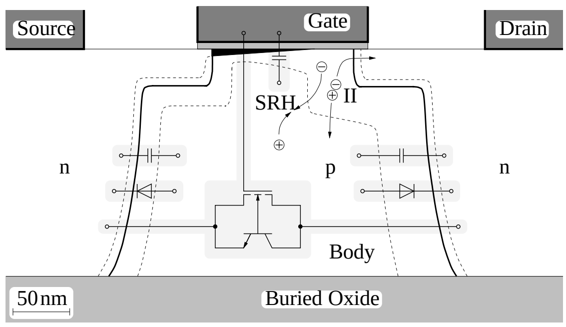

Figure 1: The geometry of the simulated SOI including the symbolic compact devices.

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 $N_D = 6 \times 10^{20}\,\mathrm{cm}^{-3}$.

SIMULATION RESULTS

While DD simulations produce output characteristics showing the typical ohmic and saturation behavior, HD give a completely different picture (Fig. 2): After a maximum, the drain current decreases considerably. It is not clear, whether this negative differen-

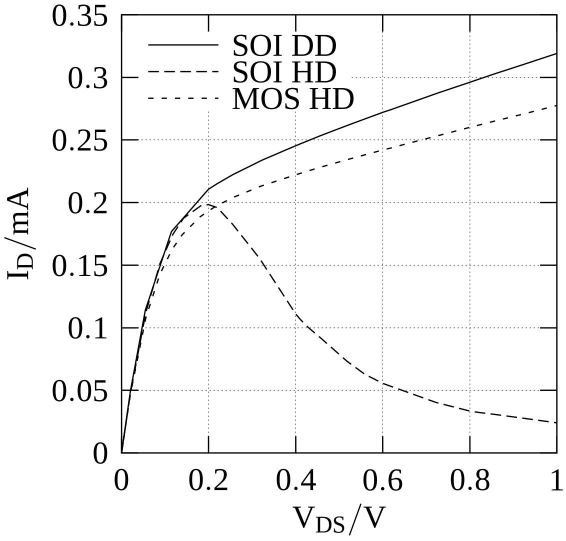

Figure 2: Output characteristics of the SOI obtained by DD an HD simulations.

tial output characteristic can be observed in measurements, or if it is just an artifact of the HD model. An implementation error can be ruled out, as this phenomenon has been observed using both MINIMOS-NT [1] and DESSIS [2] (Fig. 3). Measurements reported in [3] indicate that the decrease is a real effect.

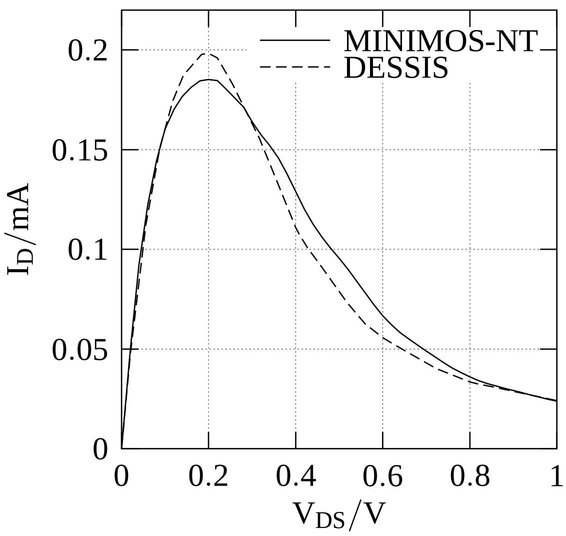

Figure 3: Output characteristics of the SOI obtained by HD simulations using MINIMOS-NT and DESSIS.

Our current picture of the responsible effects in the SOI can be explained as follows: One of the main differences between DD and HD simulations is that while the carriers stay at lattice temperature in the former one, they can reach significantly higher temperatures in the latter one. Carrier heating occurs in the pinch-off region near the drain. While the vast majority of electrons from the channel flow into the drain, some of them have enough energy due to carrier heating to diffuse into the p-doped body, where a certain percentage of them recombines with holes. The rest flows into the source and drain regions, and is of no harm. The problem is, that pair recombination causes a lack of holes and hence a steady decrease of the body potential. The difference between DD and HD can be seen in Fig. 4 and Fig. 5, respectively, where the distributed potential is shown at a vertical position of $y = 100\,\mathrm{nm}$.

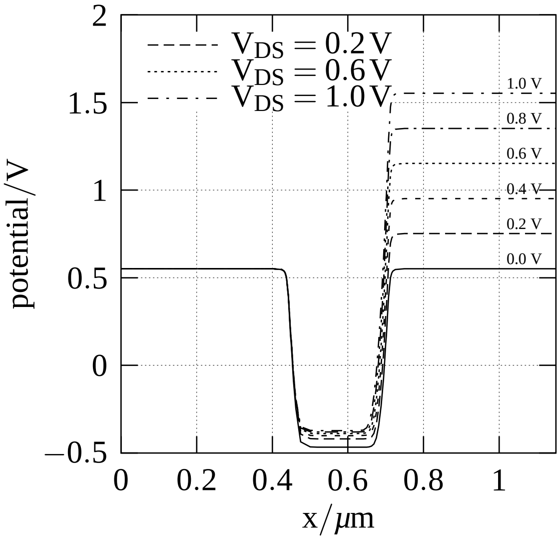

Figure 4: Lateral potential distribution of the SOI obtained by DD simulations.

To verify this hypothesis simulations of bulk MOSFETs with basically the same doping profile have been carried out. In bulk MOSFETs, where the body potential is fixed, one can observe a very small (below $1\,\mathrm{nA}$) substrate current which flows into the body (Fig. 6). Note that the real substrate current due to impact ionization would have the opposite sign. The situation of a positive substrate current shows that even in this bulk MOSFET hot electron diffusion into the p-

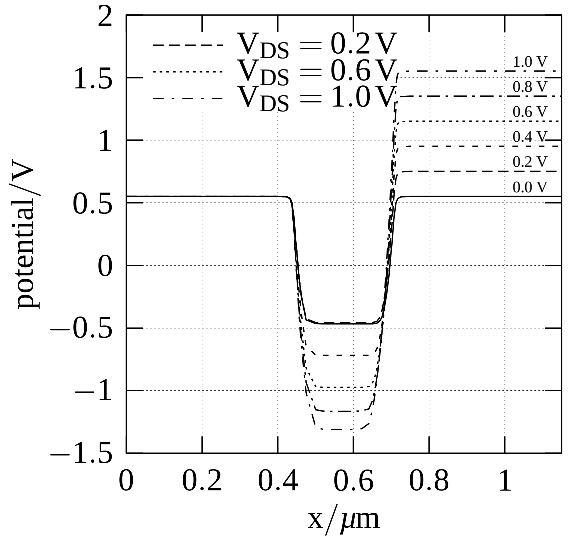

Figure 5: Lateral potential distribution of the SOI obtained by HD simulations.

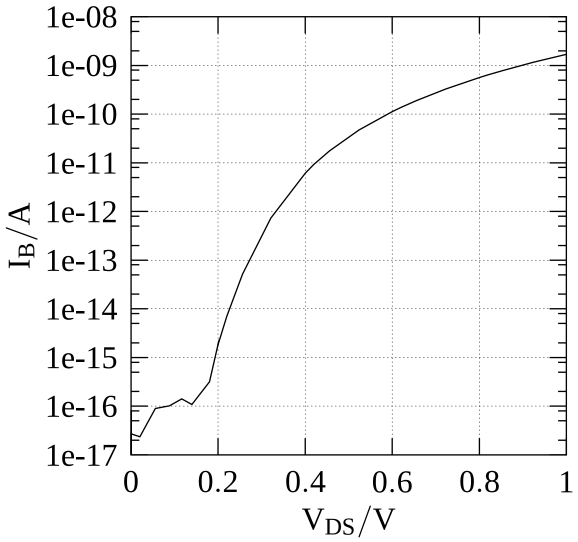

Figure 6: Bulk currents of the SOI with body contact obtained by HD simulations.

body occurs. This only happens when using the HD transport model. In a bulk MOSFET this very small recombination current has no influence on the output characteristics. In an SOI MOSFET the situation is completely different: Here this small current causes the body potential to drop, until it is low enough for the source-body junction to become reversely biased, and the junction leakage can compensate the electron current and a steady state is reached. Via the body effect the drop of the body potential causes the drain current to decrease.

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:

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

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. 7 and Fig. 10. In Fig. 10 the spread of electrons into the body is remarkable. This difference has a great impact on the SHOCKLEY-READ-HALL generation/recombination rate (SRH): Fig. 8 and Fig. 9 represent the DD regime. In the source-body junction the electrons recombine whereas they are generated in the drain-body junction. In the HD case which is depicted in Fig. 11 and Fig. 12 the situation is completely different. The electrons injected into the body recombine and cause the potential to drop. A steady state is reached when both junctions are reverse biased and thermal generation supplies holes at the same rate at which they recombine in the body.

The remaining question is whether this effect is real or only present in simulation. If it were not real, it would be interesting how the HD transport model should be modified to represent the real physics more accurately. If this cannot be achieved, the use of the HD

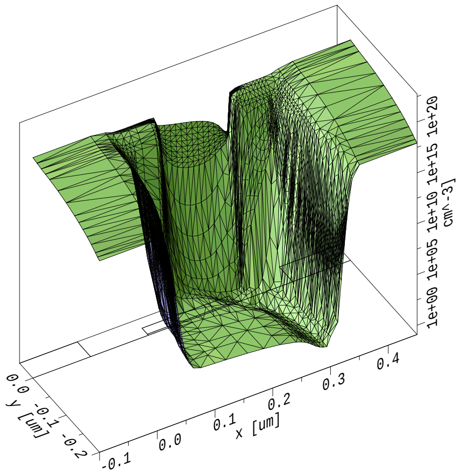

Figure 7: Electron concentration in the SOI obtained by a DD simulation.

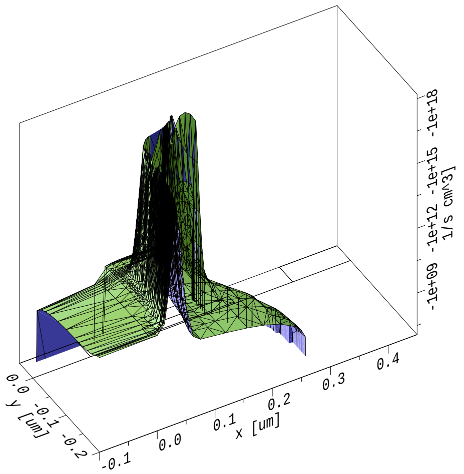

Figure 8: SRH recombination in the SOI obtained by a DD simulation.

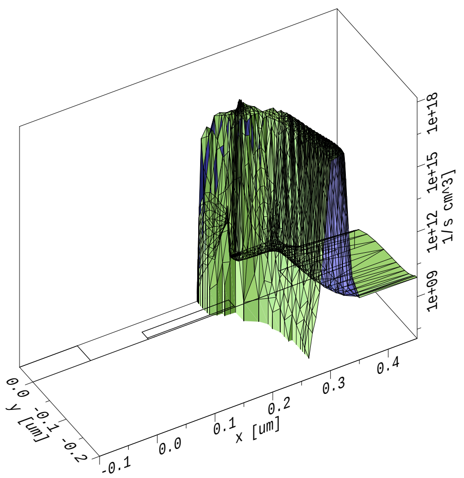

Figure 9: SRH generation in the SOI obtained by a DD simulation.

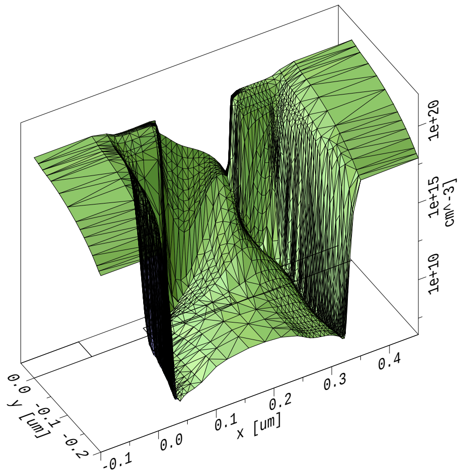

Figure 10: Electron concentration in the SOI obtained by a HD simulation.

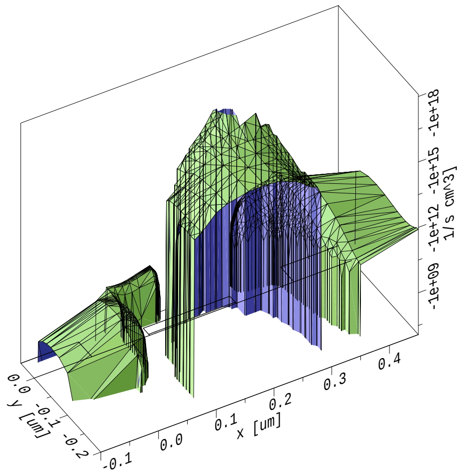

Figure 11: SRH recombination in the SOI obtained by a HD simulation.

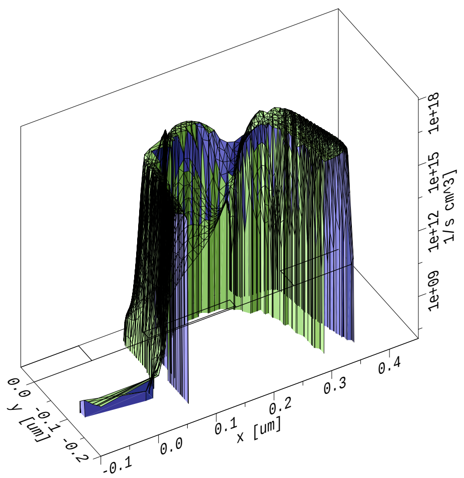

Figure 12: SRH generation in the SOI obtained by a HD simulation.

model is very questionable for the simulation of SOI MOSFETs, and the DD model should be preferred.

In order to understand the sensitivity of the problem with respect to various parameters, several simulations have been made, each one concentrating on another aspect.

Fig. 13 shows the body potential obtained by a transient simulation. Due to the

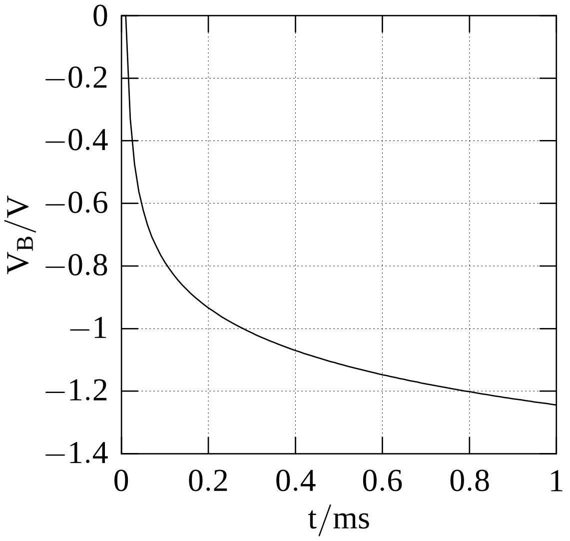

Figure 13: Body potential of the SOI obtained by a transient HD simulation.

very small current produced by the injected electrons, the decrease of the body potential is quite slow. This relatively long time constant must be taken into account, when the decrease of the drain current is to be measured. Results of simulations using a ramp-function as V_{DS} can be seen in Fig. 14 and Fig. 15. The sweep-time in this figures ranges from 100 ns to 100 ms.

The dependence on the body doping can be seen from Fig. 16. The decrease of the drain current vanishes, if the doping is reduced by about one order of magnitude. A similar result has been reported in [3]. The doping-dependence of the simulated characteristics is due partly to the change in the body and the change in the carrier lifetime,

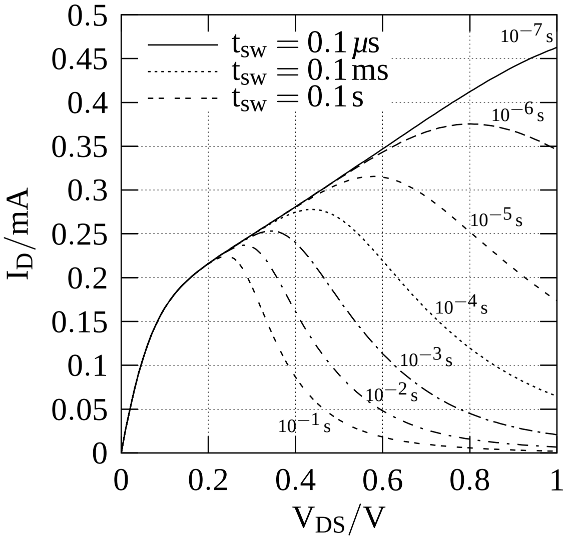

Figure 14: Drain currents of the SOI obtained by a transient HD simulation showing different sweep times.

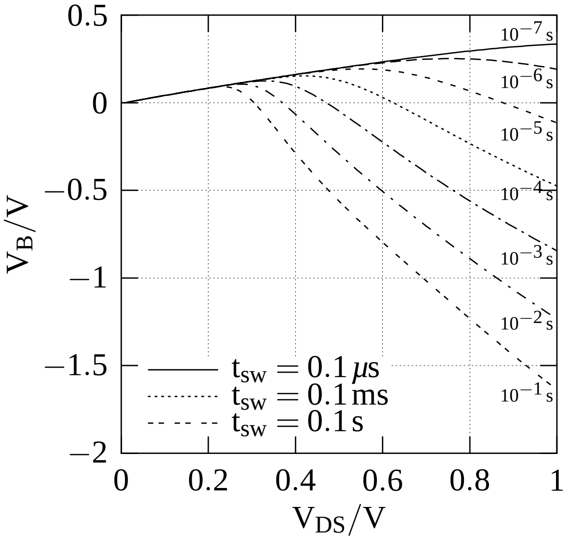

Figure 15: Body potentials of the SOI obtained by a transient HD simulation showing different sweep times.

which is modeled by the SCHARFETTER relation [4] [5]:

$$\tau(N_\mathrm{i}) = \tau_\mathrm{min} + \frac{\tau_\mathrm{max} - \tau_\mathrm{min}}{1 + (N_\mathrm{i}/\mathrm{N}_\mathrm{ref})^\gamma} \qquad (2)$$

This is the default model in DESSIS (which was used by [3]) and it is also used in our simulations, because it was only possible with this model to achieve convergence.

Furthermore the device characteristics depend sensitively on impact-ionization. In

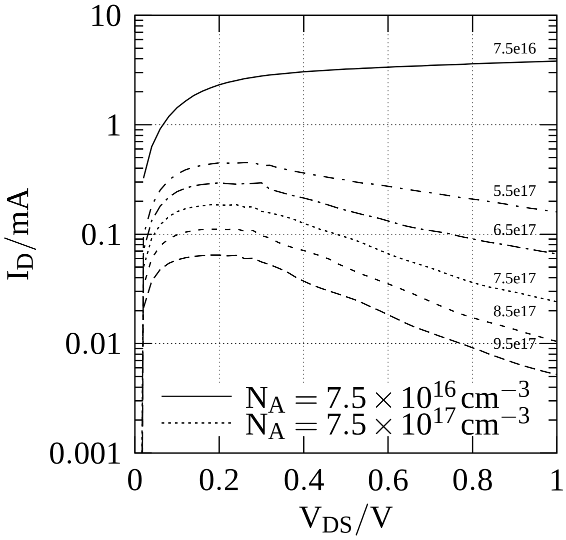

Figure 16: Drain currents of the SOI obtained by a transient HD simulation showing different body dopings.

general, the kink-effect [6] causes an increase in the drain current due to injected holes from the region near the drain where impact-ionization happens. Nevertheless the kink-effect happens at higher drain-source voltages than those where the negative differential output characteristic is observed so that the problem cannot be solved by simply by turning impact-ionization on.

CONCLUSION

A negative differential output characteristic has been produced by hydrodynamic simulations, using two different device simulators. The situation has been investigated in great detail, and an explanation of the effect has been given. Transient simulations have been made which show that measurements have to be performed relatively slow to take the big time constant into account which is involved in the body charging. On the other hand it is desirable to measure the characteristic as fast as possible to rule out self-heating. Further investigations are necessary to clarify the situation.

ACKNOWLEDGEMENTS

This work has been supported by *Intel Corp.*, Santa Clara, and the *Christian Doppler Gesellschaft*, Vienna.

REFERENCES

[1] T. Simlinger, H. Brech, T. Grave, and S. Selberherr, “Simulation of Submicron Double-Heterojunction High Electron Mobility Transistors with MINIMOS-NT,” *IEEE Trans.Electron Devices*, vol. 44, no. 5, pp. 700–707, 1997.

[2] DESSIS-ISE Users Manual, Release 6.

[3] J. Egley, B. Polsky, B. Min, E. Lyumkis, O. Penzin, and M. Foisy, “SOI Related Simulation Challenges with Moment Based BTE Solvers,” in *Simulation of Semiconductor Processes and Devices*, (Seattle, Washington, USA), pp. 241–244, Sept. 2000.

[4] J. Fossum and D. Lee, “A Physical Model for the Dependence of Carrier Lifetime on Doping Density in Nondegenerate Silicon,” *Solid-State Electron.*, vol. 25, no. 8, pp. 741–747, 1982.

[5] J. Fossum, R. Mertens, D. Lee, and J. Nijs, “Carrier Recombination and Lifetime in Highly Doped Silicon,” *Solid-State Electron.*, vol. 26, no. 6, pp. 569–576, 1983.

[6] J. Tihanyi and H. Schlötterer, “Influence of the Floating Substrate Potential on the Characteristics of ESFI MOS Transistors,” *Solid-State Electron.*, vol. 18, pp. 309–314, 1975.

KEYWORDS: partially depleted SOI MOSFET, simulation, anomalous output characteristic, negative differential output resistance, body effect