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Influence of generation/recombination effects in simulations of partially depleted SOI MOSFETs

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Abstract

Two anomalous effects seen in the simulation of partially depleted SOI MOSFETs are reported. The first is an unrealistic steep increase in the drain current due to impact ionization, predicted by both the drift-diffusion (DD) and energy transport (ET) models. Next, in ET simulations a negative differential output conductance is observed. The latter effect is neither present in DD simulations nor is it known from measurements. A comprehensive simulation study reveals that the effect is caused by an overestimation of hot carrier diffusion into the floating body. © 2001 Elsevier Science Ltd. All rights reserved.

1. Introduction

The small minimum feature size of today's 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 non-local effects such as carrier heating and velocity overshoot makes it desirable to use more sophisticated transport models. These are obtained by considering the first three or four moments of the Boltzmann equation. However, these so called energy transport (ET) models, which are nowadays quite common in the simulation of small bulk MOSFETs, lead to interesting problems when applied to SOI MOSFETs.

2. Simulation results

The ET model employed in this work is based on the first four moments of the Boltzmann equation [1]. The even moments represent conservation equations,

$$\nabla \mathbf{J}_\nu = -s_\nu q\left(\frac{\partial \nu}{\partial t} + R\right), \tag{1}$$

$$\nabla \mathbf{S}_\nu = \mathbf{E}\cdot\mathbf{J}_\nu - \frac{3}{2}k_\mathrm{B}\left(\frac{\partial(\nu T_\nu)}{\partial t} + RT_\nu + \nu\frac{T_\nu - T_L}{\tau_{\epsilon,\nu}}\right), \tag{2}$$

while the odd moments give the transport equations,

$$\mathbf{J}_\nu = q\mu_\nu\left(\nu\mathbf{E} - s_\nu\frac{k_\mathrm{B}}{q}\nabla(\nu T_\nu)\right), \tag{3}$$

$$\mathbf{S}_\nu = \frac{5}{2}\frac{\tau_{S,\nu}}{\tau_{m,\nu}}\frac{k_\mathrm{B}T_\nu}{q}(s_\nu\mathbf{J}_\nu - k_\mathrm{B}\mu_\nu \nu\nabla T_\nu). \tag{4}$$

Here, ν denotes the carrier type n or p, and s_ν the charge sign. The unknowns of this equation system are carrier concentration ν and carrier temperature T_ν. The related fluxes are the electrical current density $\mathbf{J}_\nu$ and the energy flux density $\mathbf{S}_\nu$. The relaxation times for energy, momentum and energy flux are denoted by $\tau_{\epsilon,\nu}$, $\tau_{m,\nu}$ and $\tau_{S,\nu}$, respectively.

The device simulator used primarily in this study is MINIMOS-NT. Comparative simulations of critical effects have been performed using DESSIS.

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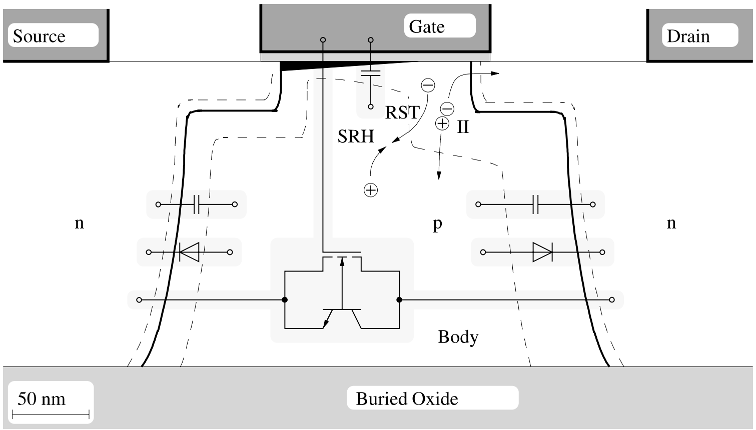

Fig. 1. Sketch of the simulated SOI MOSFET including symbolic compact devices. Important effects are SRH recombination and impact ionization (II).

2.1. Used device

A sketch of the SOI device used in the simulation study is depicted in Fig. 1. Assumed are 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-shaped n-doping under the electrodes has a maximum of $N_D = 6 \times 10^{20}\ \mathrm{cm}^{-3}$.

2.2. Drift diffusion

DD simulations show a remarkable difference in the drain current depending on whether impact ionization is turned on or off (Fig. 2). The increase in the drain current can be partially attributed to the kink effect [2]: the holes generated by impact ionization are drawn into the floating body where they raise the potential. Fig. 3 shows the lateral potential distribution in the middle of the silicon film. The increased body potential leads via the body effect to an increased drain current. The second contribution to the current increase is due to the bipolar effect. The increased body potential acts as a forward bias to the source–body diode. Electrons are injected from source to the body, diffuse through the body, and are collected by the drain.

Simulating the device without impact ionization yields a comparatively small shift in the body potential

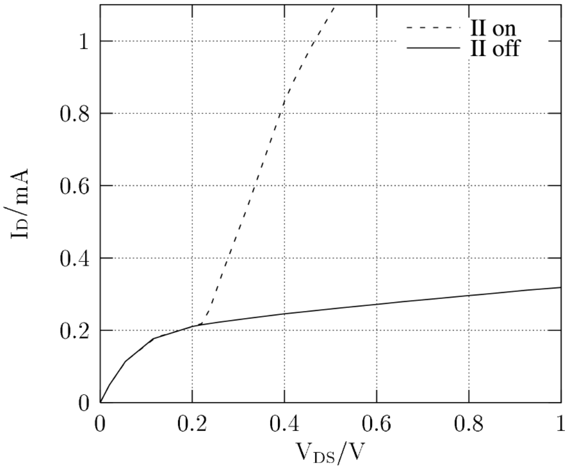

Fig. 2. Output characteristics of the SOI obtained by DD simulations with and without impact ionization. In this and the following figures $V_{GS} = 1$ V is assumed.

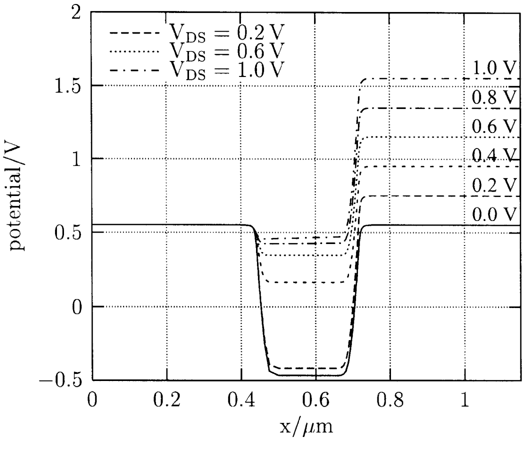

Fig. 3. Distributed potential of the SOI obtained by DD simulations with impact ionization.

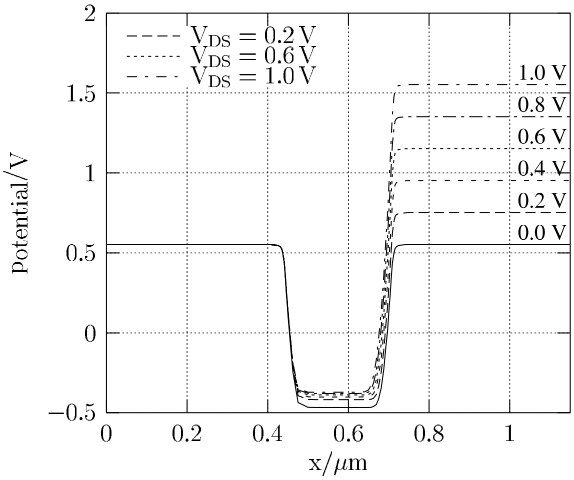

Fig. 4. Distributed potential of the SOI obtained by DD simulations without impact ionization.

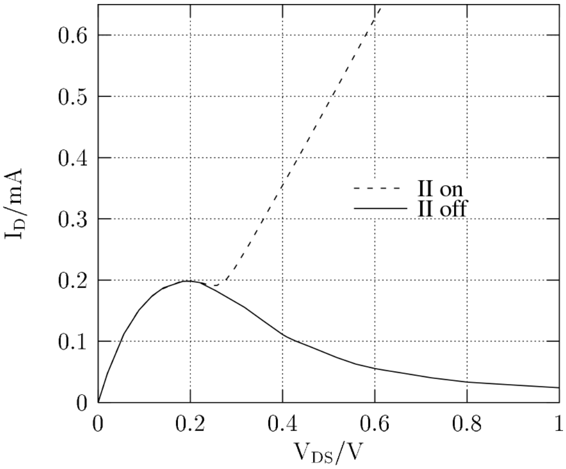

Fig. 6. Output characteristics of the SOI obtained by ET simulations using DESSIS.

as shown in Fig. 4. In this simulation condition the kink in the output characteristic does not appear (Fig. 2).

2.3. Energy transport

Carrying out ET simulations with impact ionization included yields again the steep increase in the drain current, as can be seen in Figs. 5 and 6. The carrier temperature-dependent impact-ionization model used in MINIMOS-NT is described in Ref. [5]. In all simulations of SOI devices Shockley–Read–Hall (SHR) recombination is included, because otherwise it would be difficult to achieve convergence.

If now impact ionization is turned off, the simulation gives a completely different and unexpected result (Fig. 5). After reaching a maximum at about $V_{DS} = 0.2$ V, the drain current decreases considerably. This negative differential output conductance can be observed using two different device simulators. Fig. 5 shows the results obtained from MINIMOS-NT [3], while Fig. 6 was produced using DESSIS [4]. The results are in good qualitative agreement. The small quantitative differences are due to slightly different default values for mobility and impact-ionization parameters.

In Fig. 7 lateral potential distributions are shown. An anomalous effect seen here is a drop of the body potential with increasing drain voltage. Not only is the drain–body junction reverse biased but also the source–body junction. Therefore, leakage currents from both

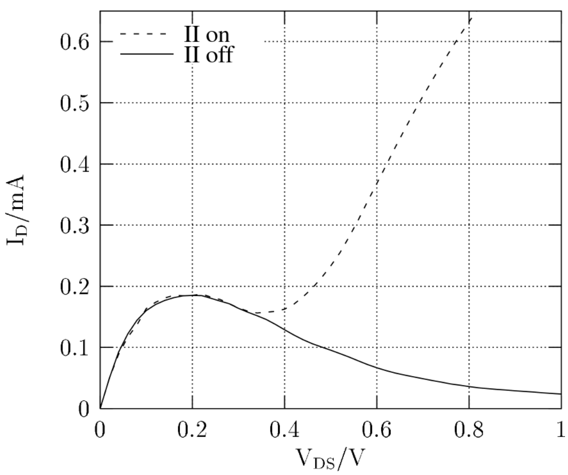

Fig. 5. Output characteristics of the SOI obtained by ET simulations using MINIMOS-NT.

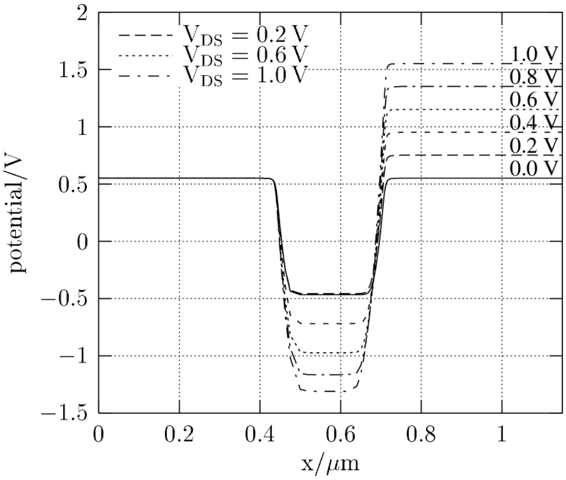

Fig. 7. Lateral potential distribution of the SOI obtained by ET simulations.

junctions flow into the floating body. Clearly, the dropping body potential affects via the body effect the drain current.

To prevent the body potential from dropping below its equilibrium value a body contact has been added to the device in the next simulation example. The results in Fig. 8 show typical MOSFET output characteristics with an onset of impact ionization. The kink in the drain current does not appear because both contributing effects are suppressed, namely the body effect and the amplification of the impact-ionization current through the bipolar effect. On the other hand, without impact ionization an expected positive output conductance is obtained.

In the considered setup an anomaly shows up in the body currents as depicted in Fig. 9. With impact ionization included one obtains the expected result that a body current flows out of the transistor ($I_B < 0$). But if in contrast impact ionization is neglected there is a body current flowing into the device ($I_B > 0$), which is several orders of magnitude smaller.

3. Discussion

Provided that impact ionization is turned off, DD simulations of the SOI MOSFET produce output characteristics showing the typical ohmic and saturation behavior, while ET simulations predict an anomalous behavior in the saturation region. An implementation error in the simulation tools can be ruled out, as this phenomenon has been observed using both MINIMOS-NT and DESSIS.

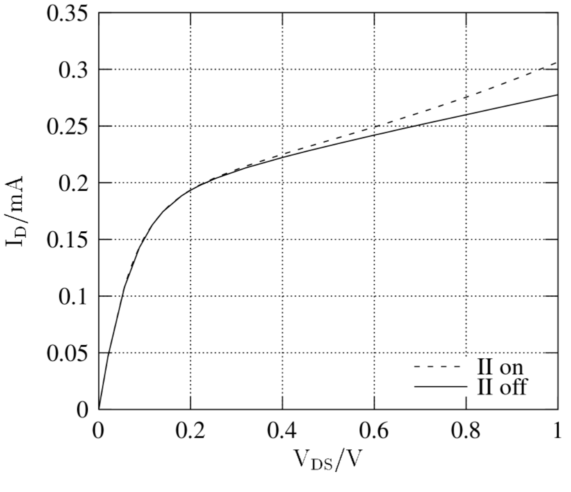

Fig. 8. Output characteristics of the SOI with a body contact obtained by ET simulations.

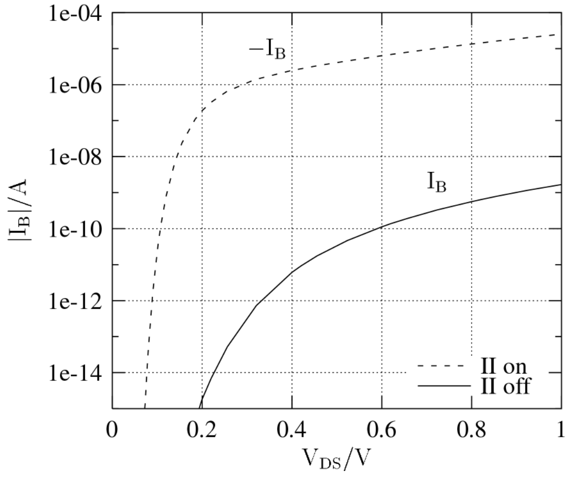

Fig. 9. Bulk currents of the SOI with body contact obtained by ET simulations.

3.1. Interpretation of the simulation results

A characteristic difference between a DD and an ET simulation of a MOSFET is seen in the carrier concentrations as shown in Figs. 10 and 11, respectively. In the ET simulation electrons reach a high temperature in the pinch-off region. Therefore, they spread farther away from the interface and diffuse into the body. The balance of the drift and diffusion currents is affected by carrier heating as follows:

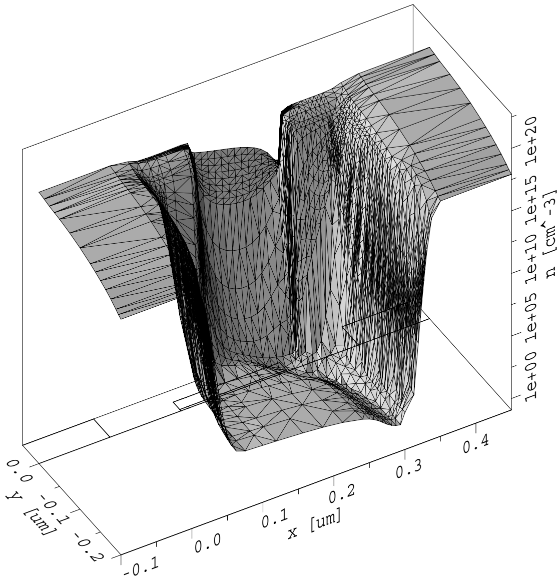

Fig. 10. Electron concentration in the SOI obtained by a DD simulation.

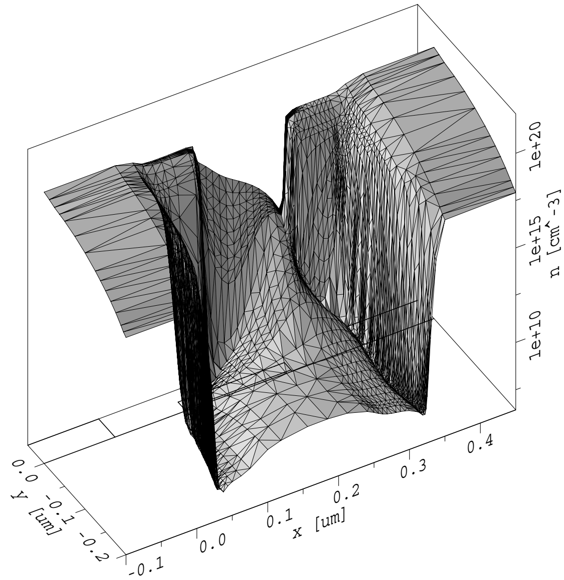

Fig. 11. Electron concentration in the SOI obtained by an ET simulation.

$$\frac{|\mathbf{J}_{\mathrm{diff}}|}{|\mathbf{J}_{\mathrm{drift}}|} = \frac{k_{\mathrm{B}} T_L}{q} \frac{|\nabla v|}{v|\mathbf{E}|} \begin{cases} 1 & \ldots \quad \mathrm{DD} \\ T_v/T_L & \ldots \quad \mathrm{ET} \end{cases}$$

This means that carrier diffusion in the ET model is enhanced by a factor T_v/T_L as compared with the DD model.

In Fig. 11 the spread of electrons into the body is remarkable. The critical area is the depletion region underneath the pinch-off region. While the DD simulation predicts carrier generation in this area, which is the expected situation in this depletion region, in the ET simulation carrier recombination takes place because of the excess electrons. As a consequence of recombination, holes are removed from the p-body. If the body is contacted, the recombining holes are substituted by holes from the body contact, leading to a small substrate current which flows into the body (Fig. 9). However, in an SOI MOSFET the situation is different. The holes removed by recombination make the body potential drop. Eventually the reverse bias of the source–body and drain–body junctions becomes large enough such that the junction leakage currents compensate for the recombination current and a steady state is reached. Via the body effect the drop of the body potential causes the drain current to decrease.

3.2. Time and doping dependence

It is not clear whether the negative differential output conductance can be observed in measurements, or is just an artifact in the ET model. Measurements reported in Ref. [6] indicate that the current decrease is a real effect. We believe that such an effect can occur in real SOI devices, but that the ET model tends to overestimate the effect. The following simulations focus on some of the conditions relevant to the measurement of the effect.

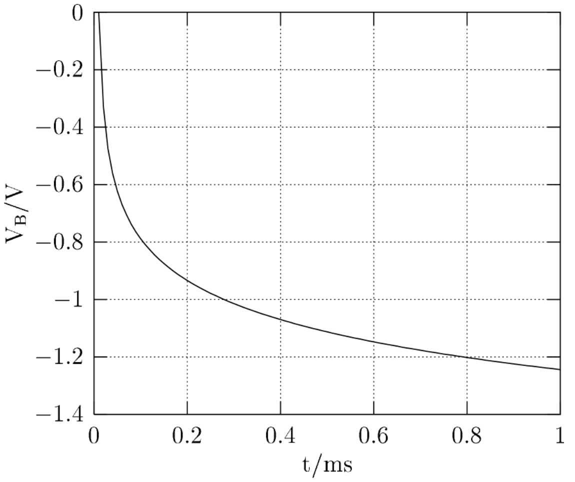

Fig. 12. Body potential of the SOI obtained by a transient ET simulation.

Fig. 12 shows the body potential as a function of time obtained by a transient simulation. Due to the very small diffusion current into the body the decrease of the body potential is quite slow. This relatively long charging time constant must be taken into account, when the decrease of the drain current is to be measured.

The drain current obtained for different ramp functions for the drain voltage can be seen in Fig. 13. The sweep time in this figure ranges from 100 ns to 100 ms. In Fig. 14 the time-dependence of the body potential is shown with the sweep time as the parameter. First the body potential increases because of the capacitive coupling to the drain. Then the parasitic DC current due to hot carrier diffusion begins to dominate over the displacement current and charges the body negatively.

The dependence on the body doping is depicted in Fig. 15. 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 Ref. [6]. The doping-dependence of the simulated characteristics is difficult to interpret because several partial effects contribute. First, the body effect parameter which plays a key role increases with doping. Second, because in Fig. 15 a transient simulation with a fixed sweep time is shown, the increase of the junction capacitances with body doping plays a role. Third, there is a doping dependence introduced through the carrier lifetimes, which are modeled by the Scharafetter relation [7,8]:

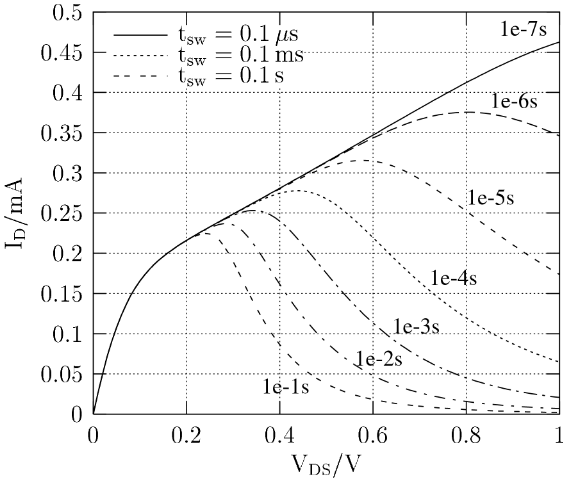

Fig. 13. Drain currents of the SOI obtained by a transient ET simulation showing different sweep times.

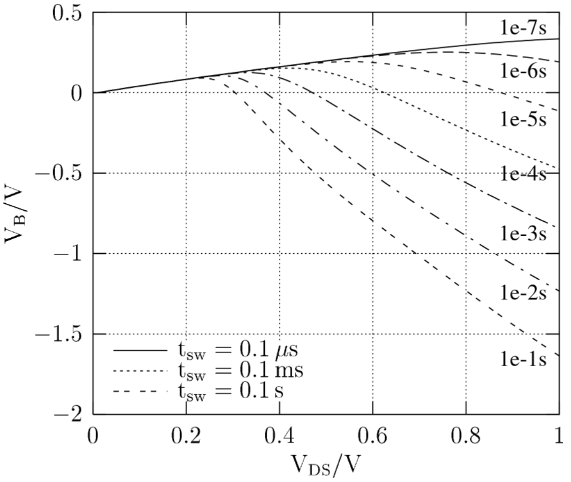

Fig. 14. Body potentials of the SOI obtained by a transient ET simulation showing different sweep times.

$$\tau(N_i) = \tau_{\min} + \frac{\tau_{\max} - \tau_{\min}}{1 + (N_i/N_{\mathrm{ref}})^{\gamma}}$$

This is the default model in DESSIS (which was used in Ref. [6]), and it is also used in the MINIMOS-NT simulations. Simulations show that with shorter lifetimes the negative differential conductance gets more pronounced.

Another issue is self-heating during the measurement. Its influence can be ruled out by measuring at small current levels. In the simulations the negative output conductance has shown up also for small gate overdrives, $V_{GS} - V_t$.

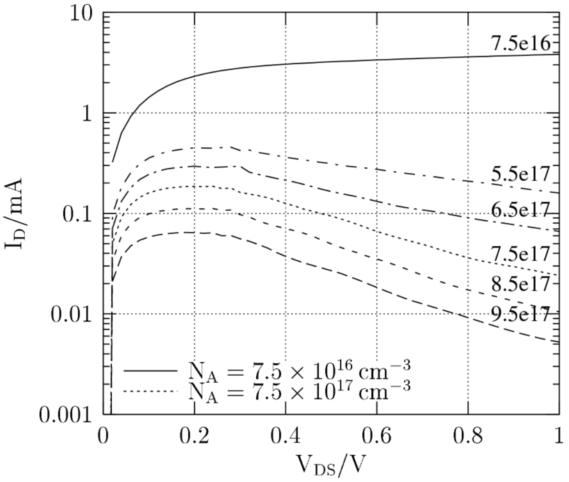

Fig. 15. Drain currents of the SOI obtained by a transient ET simulation showing different body dopings. A sweep time of 1 ms is assumed.

3.3. Impact ionization

The results shown in Fig. 9 suggest that in the simulation the problematic reverse body current could be compensated by the impact-ionization current. One problem is that the device characteristics depend sensitively on impact ionization. Furthermore, the kink effect becomes effective at higher drain voltages, such that a region with negative differential conductance can still remain (Fig. 5).

4. Conclusion

The presented simulation study of SOI MOSFETs shows a high sensitivity of the drain current to the impact-ionization parameters and an unrealistically strong kink effect. In SOI simulation more careful tuning of the impact-ionization parameters is required than for bulk MOS simulation. A negative differential output conductance has been produced by ET simulations with two different device simulators. This effect is caused by the diffusion of hot carriers from the drain-sided end of the channel into the floating body. Part of these carriers recombine with the majority carriers in the floating body, which consequently becomes reverse biased with respect to the source. Via the body effect the drain current drops.

The simulation effect is more pronounced at higher body doping levels and in short channel devices, but is also present in long channel devices. Transient simulations show that measurements have to be performed relatively slow to take into account the large charging time constant of the floating body. On the other hand it is desirable to measure the characteristics at low current levels and at shorter integration times to rule out the influence of self-heating.

Acknowledgements

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References

[1] Hänsch W. The drift diffusion equation and its application in MOSFET modeling. New York: Springer; 1991.

[2] Tihanyi J, Schlötterer H. Influence of the floating substrate potential on the characteristics of ESFI MOS transistors. Solid-State Electron 1975;18:309–14.

[3] Simlinger T, Brech H, Grave T, Selberherr S. Simulation of submicron double-heterojunction high electron mobility transistors with MINIMOS-NT. IEEE Trans Electron Dev 1997;44(5):700–7.

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

[5] Knaipp M, Kanert W, Selberherr S. Hydrodynamic modeling of avalanche breakdown in a gate overvoltage protection structure. Solid-State Electron 2000;44:1135–43.

[6] Egley JL, Polsky B, Min B, Lyumkis E, Penzin O, Foisy M. SOI related simulation challenges with moment based BTE solvers. Simulation of semiconductor processes and de-vices. Seattle, Washington, USA, September 2000. p. 241–4.

[7] Fossum JG, Lee DS. A physical model for the dependence of carrier lifetime on doping density in nondegenerate silicon. Solid-State Electron 1982;25(8):741–7.

[8] Fossum JG, Mertens RP, Lee DS, Nijs JF. Carrier recombination and lifetime in highly doped silicon. Solid-State Electron 1983;26(6):569–76.