On Negative Differential Resistance in Hydrodynamic Simulation of Partially Depleted SOI Transistors

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***Abstract*—We show that the negative differential resistance in the I_d–$V_{\rm ds}$ characteristics observed in hydrodynamic transport simulations of partially depleted silicon-on-insulator MOSFETs disappears if the nonlocality of tunneling effects are properly accounted for in the recombination–generation process.**

***Index Terms*—Modeling, MOS devices, silicon-on-insulator (SOI) technology, Simulation software.**

I. Introduction

PARTIALLY depleted silicon-on-insulator (PDSOI) transistors are widely used for high-performance VLSI CMOS, because of significantly reduced junction capacitances and an increased speed compared with bulk silicon MOSFETs. However, PDSOI suffer from floating-body effects [1]. Depending on the bias conditions and even the biasing history, generation and recombination processes can charge up the floating region. These charges act as an effective back-gate bias and change the current–voltage (*I*–*V*) characteristics of the PDSOI quite significantly.

In principle, fully depleted SOI devices and double-gate transistors are considered to be much more promising devices, because they do not suffer from these floating-body effects. However, difficulties in manufacturing fully depleted SOI and double-gate devices indicate that PDSOI devices will still be used in the near future.

Floating-body effects are determined by delicate balance between various generation and recombination mechanisms, and make numerical simulation of PDSOI devices a very challenging task. The drift-diffusion formalism, which is widely used in the industry for simulation and optimization of VLSI MOSFETs fails dramatically for sub-100-nm technology nodes, because this approach does not take velocity overshoot into account, which is quite pronounced for these technology nodes. The drift-diffusion formalism neglects also nonlocal effects in the field-dependent impact ionization model and strongly overestimates impact ionization rate. PDSOIs are very sensitive to this generation process, because it leads to an abrupt charging up of the floating-body (kink effect). Consequently, it is impossible to correctly predict floating-body effects in deep submicrometer PDSOIs within the drift-diffusion formalism even after careful calibration of parameters of recombination–generation models.

The natural alternative to the drift-diffusion is the hydrodynamic transport model, which addresses both above mentioned issues (velocity overshoot and nonlocal impact ionization). However, as it was reported in [2], hydrodynamic transport produces negative differential resistance (NDR) in I_d–$V_{\rm ds}$ characteristics in the region between saturation and the onset of the kink. In the same paper, experimental evidence in support of NDR has been reported. However, no other experimental publication in this area has confirmed the observation of NDR in the I_d–$V_{\rm ds}$ characteristics of PDSOI MOSFETs. Therefore, NDR is now considered by many to be an artifact of the hydrodynamic transport model.

Negative differential transconductance (NDT) due to band-to-band-tunneling (BTBT) have been reported in the I_d–$V_{\rm gs}$ and I_d–$V_{\rm ds}$ characteristics field-induced BTBT effect transistors (FIBTET) [3], [4]. These specially designed SOI devices feature highly doped bodies, such that the equilibrium carrier concentration in the body is degenerate. In FIBTETs BTBT is responsible for the current injection and extraction and they do not require the formation of an inversion layer. In these interesting devices band detuning leads to decrease of the BTBT current with increasing gate voltage resulting in a NDT. To a lesser extend FIBTETs also show NDR in the I_d–$V_{\rm ds}$ characteristics.

This NDT and NDR effect, however, is of a quite different nature than the NDR discussed in this paper. The devices under consideration are normal PDSOI structures without degenerate bodies. The NDR effects discussed here are predicted by certain transport models for PDSOI and are caused by changes in the potential floating-body effect. They are not related to a bias dependent modification of the BTBT rate. These NDR effects in PDSOI, however, have not been definitively confirmed experimentally and this paper discusses how to properly model PDSOI devices to avoid these NDR artifacts.

In this paper, we show that hydrodynamic transport simulations of the I_d–$V_{\rm ds}$ characteristics in PDSOIs do not exhibit NDR if the trap-assisted tunneling (TAT) of [5] and [6] is used instead of the (local) Shockley–Read–Hall (SRH) model (see e.g., [5]). The TAT generation–recombination model accounts for the nonlocality in the tunneling process. We show, further, that the accounting for the nonlocal nature of the generation–recombination increases the area of generation near the drain-to-channel junction, and thus injects more holes into the body.

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II. Negative Differential Resistance in Hydrodynamic Transport Simulations

Simulations of the I_d–V_{ds} characteristics of PDSOIs based on the hydrodynamic transport model show NDR for the following reason: During the drain voltage ramp-up electrons in the pinch-off region near the drain gain more and more energy (i.e., they become hotter and hotter). According to the Einstein relation the electron diffusion coefficient is proportional to the carrier temperature, and this increased diffusivity in the pinch-off region leads to tails of the electron distribution, which extend somewhat into the body of the PDSOI. These minority electrons recombine with the majority holes, leaving behind (negatively charged) ionized acceptors in the floating-body. The ionized acceptors decrease the body potential and, via the back-gate effect, decrease the drain current. A further increase of the drain voltage eventually activates impact ionization in the high field regions of the pn junctions. This process injects many holes into the floating-body and quickly dominates over the small amount of hot electrons diffusing into the floating-body. The additional holes lead to a sharp increase of the body potential and, in turn, drain current. (This rapid rise is known as the "kink effect" for PDSOI MOSFETs.)

The NDR is more pronounced for elevated body doping concentration (10^{17} cm^{-3} and higher) and short SRH recombination lifetimes. Note, that it is not the increased electron concentration in the body itself, which leads to NDR. The increase of the minority carrier concentration in the body is relatively small and does not significantly change body potential. If the SRH recombination process is deactivated in the simulations NDR is absent. We conclude, that NDR is caused by a combination of an increased electron thermal diffusion within hydrodynamic transport and SRH recombination.

Monte Carlo simulations for bulk MOSFETs show an increased thermal diffusion of electrons compared to the drift-diffusion transport model, but still considerably less comparing with the hydrodynamic transport model. It is therefore conceivable that the NDR is caused by an overestimation of the thermal diffusivity of hot electrons within the hydrodynamic transport model. To remedy this possible problem Gritsch *et al.* [7] proposed to suppress the spurious electron diffusion by reducing the electron diffusion coefficient in the vertical direction. However, Monte Carlo calculations of electron anisotropic diffusion coefficients reported by Jungemann *et al.* [8] do not support the decrease of electron diffusion coefficient in vertical direction. In a similar spirit Bork *et al.* [9] and Munteanu *et al.* [10] suggested to modify the (isotropic) electron diffusion coefficient to suppress the thermal diffusivity in the hydrodynamic transport model. Bork *et al.* showed that this approach results in a better agreement of the shape of the carrier distribution functions between hydrodynamic transport and Monte Carlo simulations for bulk transistors. Munteanu *et al.* showed that such modifications in PDSOI transistors suppress the NDR (at least for a given set of SRH lifetimes.)

We would like to point out, however, that the overestimation of the thermal diffusivity is not the sole reason for the NDR. In fact, the modeling of generation–recombination models has to be scrutinized as well, because NDR problem appears mainly for small values SRH lifetimes. For modern PDSOI devices, SRH lifetimes in the body are extremely small. In fact, special measures are taken during processing to decrease lifetimes, in order to suppress impact ionization, which leads to undesirable kink effect. Therefore, a successful model for large scale industrial simulations of PDSOI transistors should not produce NDR for a very wide range of lifetimes.

To our knowledge no study has been published, which shows that any modification of the hydrodynamic transport model will eliminate the NDR for small SRH lifetimes. On the contrary, it is to be expected that even if a modified hydrodynamic transport model results a lower electron concentration in the tail the NDR will reappear if the SHR lifetimes are reduced accordingly.

Munteanu *et al.* [10] investigated if the NDR could be eliminated by calibrating the energy relaxation time or the impact ionization rate. The authors report that such a calibration may eliminate the NDR for a given structure and parameter set, but that a recalibration is needed after any reconfiguration. This finding is in agreement with our own studies, in which we attempted to include and calibrate additional hole generation mechanisms to suppress the NDR. In particular, we calibrated the BTBT rate, the impact ionization rate, and the TAT model proposed by Hurkx [11]. We again found, however, that although these approaches remedy the NDR for a particular set of parameters, they fail to solve the problem in general. For example, when reducing the SRH lifetimes NDR reappeared under most circumstances.

III. TAT Model

The general functional form of the SRH recombination–generation R is

$$R = \frac{np - n_{\mathrm{i,eff}}^2}{\tau_p(n+n_1) + \tau_n(p+p_1)}. \tag{1}$$

For the regular SRH recombination–generation model (see, e.g., [5]), n and p are the local electron and hole densities, and $n_{\mathrm{i,eff}}$ is the local intrinsic carrier concentration. Within the regular SRH model the carrier lifetimes τ_n and τ_p are a function of the doping concentration only. The factors n_1 and p_1 are related to the probability for a trap to emit a carrier.

The trap assisted tunneling (TAT) model proposed by Hurkx *et al.* [11] is based on the same expression for R as given in (1), but uses a field dependent expression for the carrier lifetimes $\tau_n(F)$ and $\tau_p(F)$.

The trap assisted tunneling (TAT) model of [5] and [6] also takes the field-enhancement of the carrier lifetimes into account, but uses an expression for the enhancement factors which differs from the one proposed by Hurkx. The most important difference between the two TAT models, however, lies in the fact the Hurkx–TAT model is strictly local while the TAT of [5] and [6] accounts for nonlocalities due to tunneling.

In the low field regime, energy conservation requires the emission or absorption of several phonons for carriers to be exchanged between the trap and the conduction or valence band.

For high field regions, such the depletion regions of the pn junctions or under the gate of a MOSFET, carriers which are

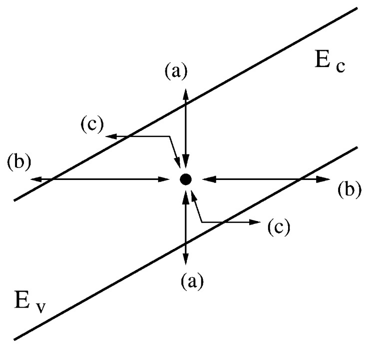

Fig. 1. Sketch of various transitions of electrons and holes from the conduction (E_c) and valance (E_v) band into the trap level (shown as solid dot). (a) Local transition requiring many phonon emission or absorptions. (b) Resonant transition, requiring tunneling over a large distance. (c) Optimal transition, involving a mix of phonon emission or absorptions and tunneling.

spatially separated from, but energetically closer to the trap can make a transition that involves tunneling into the gap to the location of the trap, as well as energy transfer to phonons (see Fig. 1).

While the additional tunneling process reduces the probability of the transition, the reduced energy transfer decreases the number of phonons in the process, and hence increases the probability. For each field, there exists an optimal mixture of tunneling and phonon interaction that maximizes the transition probability. Due to tunneling, R connects electrons and holes at different locations in the device.

Consequently, in (1) the position-dependent quantities are to be evaluated at the classical turning points of the tunnel process [5]—a treatment well in the spirit of coherent transport formulations by Tsu–Esaki [12] and Bardeen [13]. In particular, in (1) $n(\vec{r})$, $p(\vec{r})$, and $n_{\mathrm{i,eff}}^2(\vec{r})$ are to be replaced with $n(\vec{r}^-)$, $p(\vec{r}^+)$, and $n_{\mathrm{i,eff}}(\vec{r}^-)n_{\mathrm{i,eff}}(\vec{r}^+)$, where $\vec{r}^- = \vec{r} - \vec{d}_n$ and $\vec{r}^+ = \vec{r} + \vec{d}_p$ are the classical turning points, and $d_{n,p} = |\vec{d}_{n,p}|$ are the effective tunneling distance for the electrons and holes, respectively. The vector $\vec{d}_n$ points in direction of the electric field, and the value is chosen such that lifetime $\tau_p(F)$ is minimal. The exact, field dependent expression for d_n is given in [5] and [6].

After some manipulation (see the appendix) the nonlocal TAT model can be rewritten in a functional form which resembles the original (1)

$$R = \frac{\tilde{n}\tilde{p} - n_{\mathrm{i,eff}}^2}{\tau_p(F)(\tilde{n} + n_1) + \tau_n(F)(\tilde{p} + p_1)} \tag{2}$$

with

$$\tilde{n} = n(\vec{r}) \exp\left(\frac{E_{F,n}(\vec{r} - \vec{d}_n) - E_{F,n}(\vec{r})}{k_B T}\right) \tag{3}$$

where $E_{F,n}$ is the electron quasi-Fermi energy, T is the lattice temperature. Please note that the modified densities are different from the densities at the classical turning points $\tilde{n} \neq n(\vec{r}^-)$.

In low field regions the tunneling distances $d_{n,p}$ go to zero and (2) and (3) coincide with the regular SRH model. Nonlocal tunneling effects are most pronounced in depleted regions and *reverse* biased junctions, while in forward biased junctions and low field regions the field enhancement and the nonlocality are only marginal effects. With these observations in mind, (3) can be simplified further.

In depleted regions and reverse biased junction quasi-Fermi has the same direction as the electric field. It is assumed further, that the quasi-Fermi energies varies linearly over the tunneling distance. With these assumptions, (3) takes the form

$$\tilde{n} = n \exp\left(-\frac{|\nabla E_{F,n}|}{k_B T} d_n(F)\right). \tag{4}$$

A similar replacement is done for the hole density. Note that $\tilde{n}$ in (4) is always smaller than n. Hence, nonlocal effects result in a net increase in the generation rate relative to recombination. For more detail on this model, see [5], [14], and [6].

In [6] it was shown that ignoring the nonlocality of the trap assisted tunneling process leads to spurious saturation of the generation current in reverse biased pn–junctions. However, accounting for the nonlocatilty according to the scheme shown in (4) eliminates the spurious saturation and leads to better agreement with experiments [6].

IV. Simulation Results

To illustrate the NDR problem we start our investigation with a simple model structure. The body thickness of this structure is 0.1 μm and the constant acceptor concentration in the body is 5×10^{18} cm^{-3}. The source and drain regions are heavily doped with maximum doping concentration of 2×10^{20} cm^{-3} and Gaussian distributions in vertical and horizontal directions. The gate length is 1 μm, gate oxide thickness 20 Å and buried oxide thickness 0.4 μm. Strattons variant of the hydrodynamic transport model is used [15], [16] with energy relaxation time of 0.3 ps. Three different simulations are compared. The first simulation is performed with the SRH generation–recombination model [16] using doping dependent electron and hole lifetimes with a value of 10^{-8} s for low doping limit. This results in an effective value of the SRH lifetime in the body of 2×10^{-10} s. In the second simulation we neglect all generation–recombination processes. Finally, the TAT generation–recombination model of [5] and [6] is used.

In order not to mask the NDR problem with other hole generation mechanisms, neither BTBT nor impact ionization are included in simulations shown in Figs. 2 and 3. For simplicity, no size quantization effects are included in this set of simulations. Fig. 2 shows I_d–V_{ds} characteristics calculated with different generation–recombination mechanisms. Clearly, if generation–recombination processes are excluded, no NDR is observed (dash-dotted line in Fig. 2). This confirms above mentioned statement, that enhanced thermal diffusion of electrons from the channel to the body by itself does not lead to NDR. If the regular SRH generation–recombination is included, dramatic NDR is observed (dashed line in Fig. 2). However, using the TAT [see (4) and (2)] instead of the SRH generation–recombination model completely removes the NDR (solid line in Fig. 2).

Fig. 3 shows the corresponding body potential versus drain voltage. Body potential is extracted as the hole quasi-Fermi potential near the bottom silicon/oxide interface in the middle of

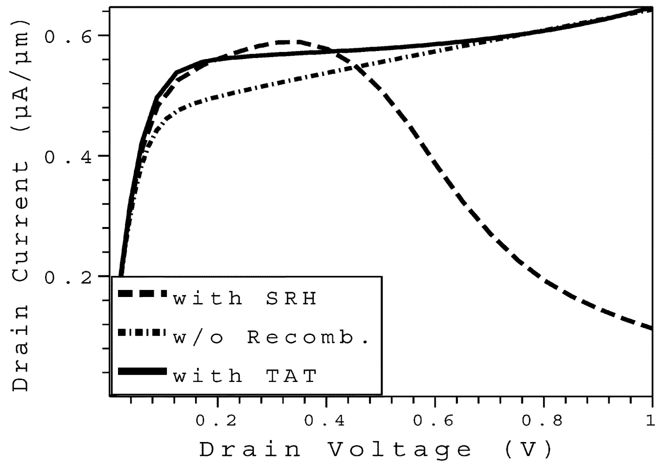

Fig. 2. Drain current versus drain voltage for a simplified 1-μm device, simulated with SRH generation–recombination (dashed line), without generation–recombination (dash-dotted line), and with the TAT generation–recombination model (solid line). The curves are simulated with DESSIS for $V_{\rm gs}$–$V_t = 50$ mV.

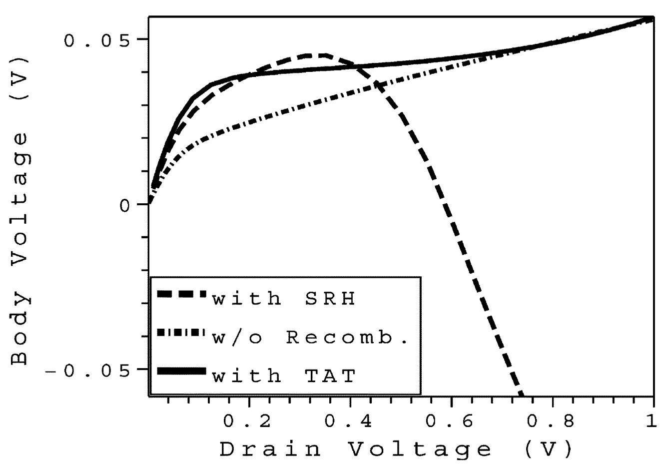

Fig. 3. Body potential versus drain voltage corresponding to the I_d–$V_{\rm ds}$ sweep shown in Fig. 2.

the device. The dash-dotted line shows that a significant decrease of the body potential is observed if the SRH generation–recombination model is used. This effective back-gate bias is responsible for NDR observed in Fig. 2.

The second example is 50-nm gate length transistor. The structure is built with the process simulator FLOOPS–ISE [17] using a realistic process flow for this technology node. For this example all relevant model have been activated: quantum effects (density gradient model [18], [16]), impact ionization, and BTBT [16]. Results are shown in Figs. 4 and 5. (For completeness also lattice self-heating effects were included in the simulations. We found, however, that for the given bias condition the current densities remain relatively low and the device temperature increases only by a small amount (<20 K), which has very little effect on the I_d–$V_{\rm ds}$ characteristics.) With respect to the NDR phenomena results are qualitatively the same as for the first simple model problem: SRH generation–recombination results in NDR, while no NDR is observed, when TAT generation–recombination is used.

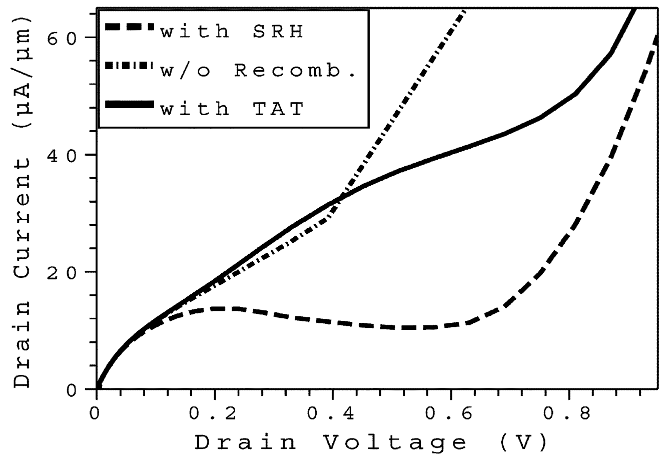

Fig. 4. Drain current versus drain voltage for a realistic 50-nm transistor, simulated with generation–recombination (dashed line), without SRH generation–recombination (dash-dotted line), and with the TAT generation–recombination model (solid line). The curves are simulated with DESSIS for $V_{\rm gs}$–$V_{\rm t} = 70$ mV.

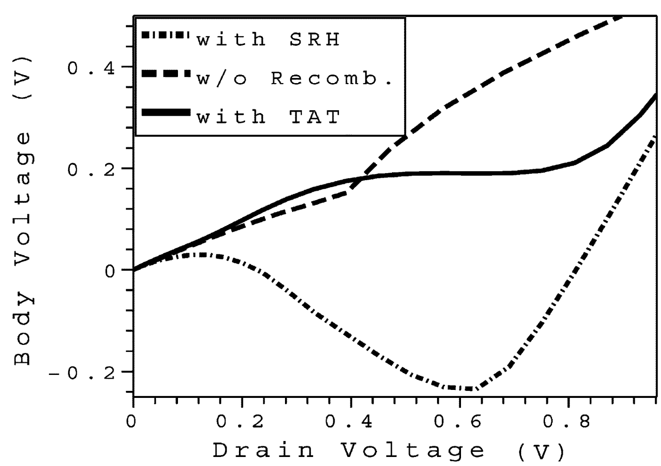

Fig. 5. Body potential versus drain voltage corresponding to the I_d–$V_{\rm ds}$ sweep shown in Fig. 4.

V. Discussion

The essential feature of the TAT model for the problem at hand is the density modification according to (4). As discussed earlier, the physical idea of this modification is that the spatial separation of tunnel-generated electrons and holes needs to be accounted for by using distribution functions on either side of the tunnel barrier.

To demonstrate the importance of the density modification, we replaced the $\tilde{n}$ and $\tilde{p}$ in (2) by the local densities n and p. We call the resulting model the "local TAT model." As Fig. 6 shows, this change causes a slight NDR to reappear. The only difference between the regular SRH recombination–generation model and the local TAT model is the field-enhancement of the carrier lifetimes $\tau_{n,p}(F)$. A comparison between the results obtained with the local TAT model (dashed line in Fig. 6) and the regular SRH model (dashed line in Fig. 2) shows that the field-induced reduction of the carrier lifetime near the drain-side pn junction greatly reduces the NDR, but does not eliminate it.

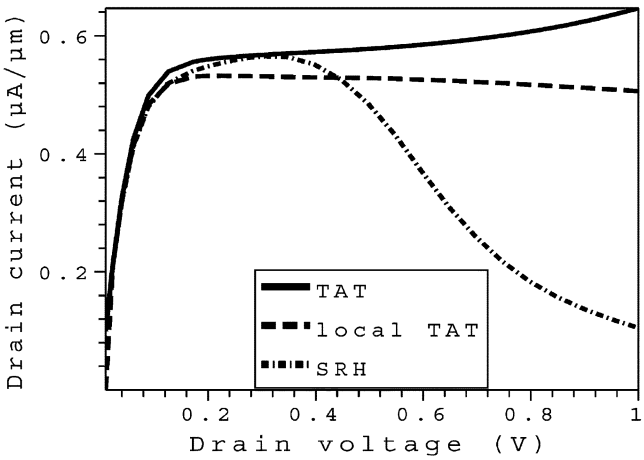

Fig. 6. Drain current versus drain voltage for the 1-μm device, using the original TAT model (solid line), the local TAT model (dashed line) and the regular SRH model (dash-dotted line).

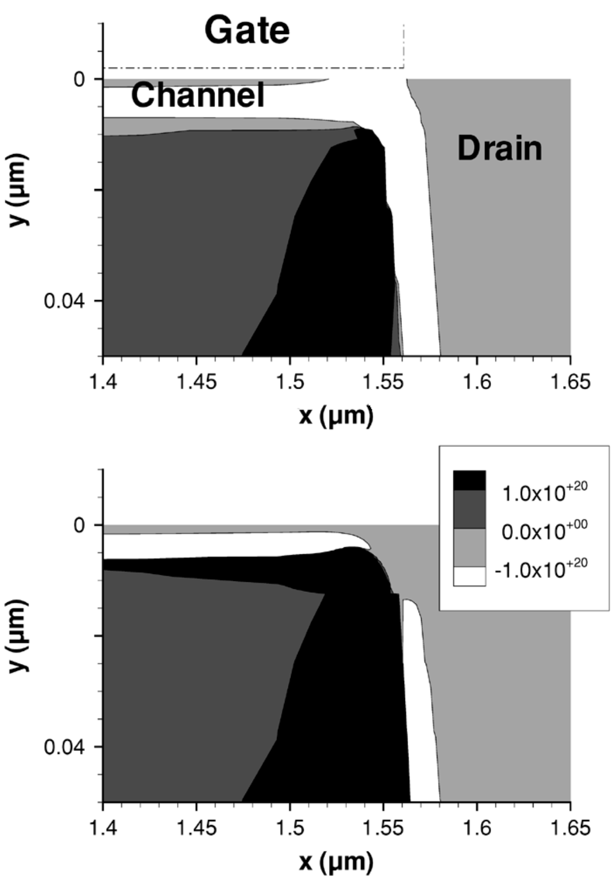

Fig. 7. Recombination–generation rates in the vicinity of the drain/channel junction the 1-μm device at $V_{\rm gs} = 1$ V. Top: Original model. Bottom: Local TAT model. Regions with recombination rate of 10^{20} pairs/cm^{3}s are shown in black, and regions with a generation rate of 10^{20} pairs/cm^{3}s are shown in white.

In Fig. 7, we compare the recombination rates obtained from the original model and the local TAT model. The most important difference appears near the drain-side pn junction, where the original TAT model gives net generation, whereas the local TAT model and other SRH-like models we tried give net recombination. The additional generation in the TAT model prevents the depletion of holes in the body, and therefore removes the NDR artifact.

This solution of the NDR problem does not require any calibration because it is based on more accurate description of the physics of the generation–recombination process in high-field regions. Some of the previous investigations in regard to the NDR problem (see, e.g., [9], [7], [10]) focused on the increased thermal diffusivity predicted by the hydrodynamic transport model, which results in long tails of the electron distribution functions. We would like to point out that solution proposed in this paper reduces the importance of the tails in the electron distribution, because the elimination of the NDR is the result of a stronger hole injection and not of a lesser electron injection. For the same reason the solution proposed in this paper is rather insensitive to the SRH lifetimes in the floating-body of the PDSOI and thus the NDR is eliminated robustly even for very short SRH lifetimes in the floating-body.

As discussed in Section III, the physical idea of the density modification (4) is that the spatial separation of tunnel-generated electrons and holes should be acknowledged by different distribution functions on either side of the tunnel barrier. Then the supply functions n and p have to be evaluated at the classical turning points of the tunnel process. Under strong generation the split of the quasi-Fermi levels causes a large increase of net generation as compared to the local model. In [6] it was demonstrated that the local formulation of a tunneling rate leads to an artificial saturation effect in reversed-biased pn junctions, where generation can even turn into recombination. There, negative-differential resistance did not occur due to self-consistency. The NDR effect in PDSOI MOSFETs is, therefore, just another device-specific consequence of the same unphysical origin.

VI. Conclusion

We have shown that the NDR observed in hydrodynamical transport simulations of the I_d–$V_{\rm ds}$ characteristics in partially depleted SOIs can be eliminated by using the TAT generation–recombination model of [5] and [6], which accounts for the nonlocality in the generation–recombination process in the high-field regions of the reverse biased drain/body junctions and the inversion channel of the MOS transistor.

Appendix

As a motivation for the expression given in (2) consider the following sketch of a derivation. Using

$$n = n_i \exp\left(\frac{E_{F,n} - E_i}{k_B T}\right)$$
$$p = n_i \exp\left(\frac{E_i - E_{F,p}}{k_B T}\right)$$

the numerator of the SRH expression (1) can be written as

$$np - n_i^2 = n_i^2 \left[\exp\left(\frac{E_{F,n} - E_{F,p}}{k_B T}\right) - 1.\right].$$

After replacing the local Fermi energies with the Fermi energies at the classical turning points we find

$$n_i^2\left[\exp\left(\frac{E_{F,n}(\vec{r}^{\,-})-E_{F,p}(\vec{r}^{\,+})}{k_BT}\right)-1\right]=\tilde{n}\tilde{p}-n_i^2.$$

For a more thorough derivation see [5].

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