Accurate Simulation of Substrate Currents by Accounting for the Hot Electron Tail Population

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Abstract

Due to the ever decreasing device geometries non-local effects gain more and more importance. It is particularly well known that impact ionization is not properly described by neither a local field nor a local energy model because it is mainly determined by the high-energy tail of the carrier distribution function. Information about the high-energy tail is lost when only the average carrier energy is taken into account. To overcome this limitation, we use the fourth moment of the distribution function to account for the population of the high-energy tail. We use a refined version of our previously published model to simulate substrate currents of n-channel MOSFETs and compare the obtained results with existing models and measurements.

1. Introduction

As device geometries are further reduced without by scaling demanded reduction of the supply voltages, the electric fields occurring inside the devices increase rapidly. In addition, strong gradients in the electric field are observed. These highly non-homogeneous field distributions give rise to distribution functions which deviate significantly from the frequently assumed Maxwellian distribution. In the case of MOS transistors the hot carriers from the channel mix with the large pool of cold carriers in the drain region. This is visible in the distribution function as a significant tail at higher energies. These hot carriers provide a primary contribution to the impact ionization rate and must be properly accounted for. Several concepts have been published so far which model this high-energy tail via a separate hot electron distribution, see for example [1, 2]. These models include two additional balance equations, one for the hot electron concentration and one for the hot electron temperature. The transition of the carriers between the cold and hot regions must be carefully modeled which, as a matter of fact, is quite difficult. Another approach is based on the extension of standard energy transport models by including the next higher order moment $\langle \mathcal{E}^2 \rangle$ of the energy distribution function as an unknown, thus obtaining a six moments model. First promising results have been obtained by Sonoda *et al.* [3] who calculated the impact ionization rate using an analytic fit to Monte-Carlo (MC) simulations.

We follow a similar approach and also use six moments to model the impact ioniza-

tion (II) rate. The second order temperature $\Theta_\nu = 2/(5\mathrm{k_B})\langle\mathcal{E}^2\rangle/\langle\mathcal{E}\rangle$ is introduced as the additional solution variable with ν being the carrier type (n or p). For a Maxwellian distribution $\Theta_\nu = T_\nu$ and thus any deviation of Θ_ν from T_ν indicates a deviation from the Maxwellian distribution. This approach has the advantage that it does not depend on any artificial splitting energy and that it requires only one additional unknown.

2. Previous II models

A commonly used assumption for modeling II is that the ionization rates depend on the local carrier temperature T_ν in the following way

$$G_{\nu_{\mathrm{ii}}} = \nu\, g_{\mathrm{ii}}\, \exp\!\left(-\frac{\mathcal{E}_C}{k_B\, T_\nu}\right) \qquad (1)$$

with g_{ii} and $\mathcal{E}_C$ being fit-factors which strongly depend on the technology and device geometry. Although a local energy model (LE) is capable of quantitatively reproducing measured integral quantities like contact currents, the predicted ionization rates *inside* the devices have been shown to deviate significantly from rigorous MC simulations [4]. This dramatically limits the usefulness of the simulations and makes predictive device simulations questionable. To overcome the limitations of LE models Sonoda *et al.* [3] derived a model for the II coefficients as a function of the averages $\langle 1\rangle$, $\langle\mathcal{E}\rangle$, and $\langle\mathcal{E}^2\rangle$ by fitting an analytical expression to their MC simulations. In addition to the LE model, their model serves as a reference model in this paper.

3. Hot electron tail (HET) model

By assuming a superposition of two Maxwellian distributions, one with lattice temperature (cold carriers) and one with T_{ν_1} we derived expressions for the tail concentration and tail temperature as a function of T_ν and Θ_ν [4]

$$T_{\nu_1} = t_\nu\,(\Theta_\nu - T_L) \qquad (2)$$

$$\frac{\nu_1}{\nu} = \frac{T_\nu}{T_\nu + t_\nu^2\,(\Theta_\nu - T_\nu)} \qquad (3)$$

$$t_\nu = \frac{T_\nu}{T_\nu - T_L} \qquad (4)$$

We used T_{ν_1} and ν_1 to replace T_ν and ν in (1). The two parameters g_{ii} and $\mathcal{E}_C$ have been derived from MC simulations as $g_{\mathrm{ii}} = 2.16\cdot 10^{13}\mathrm{s}^{-1}$ and $\mathcal{E}_C = 3.7\ \mathrm{eV}$.

The assumption of two superpositioned Maxwellian distributions is only valid for $T_\nu < \Theta_\nu$. For $T_\nu > \Theta_\nu$ the high-energy tail is underpopulated. To keep the model simple we assume $T_{\nu_1} = T_\nu$ and $\nu_1 = \nu$ for this region, which overestimates the carriers in the tail. However, the contribution of this region to the II rate was found to be marginal and thus this simplification seems to be justified.

4. Example and discussion

For the purpose of demonstration we considered two MOSFETs with gate-lengths $L_G = 1.0\ \mu\mathrm{m}$ and $L_G = 0.25\ \mu\mathrm{m}$. The six moments model and the II models were implemented in our device simulator MINIMOS-NT [5]. A comparison of the simulated II rate at $V_{\mathrm{gs}} = V_{\mathrm{ds}} = 2.5\ \mathrm{V}$ is shown in Fig. 1. As expected, the LE model predicts a different G_{ii} profile compared to the model based on six moments. In particular, the LE model predicts the maximum of G_{ii} directly at the junction whereas with the HET model the profile is shifted into the drain which is in accordance with MC simulations. This shift is important for reliability investigations. Furthermore, the steep decline of G_{ii} in the drain predicted by the LE model is completely unrealistic.

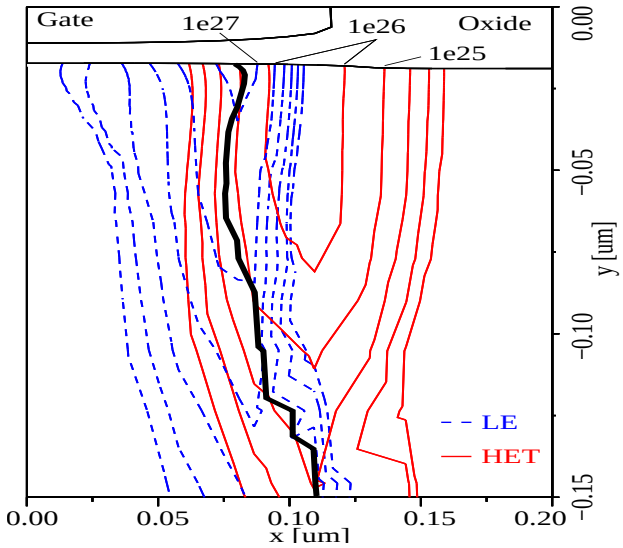

Figure 1. Comparison of G_{ii} as predicted by the LE (dashed) and our HET model (solid). Also shown is the metallurgic junction (fat line).

A comparison of the simulated substrate currents vs. measurement is given in Fig. 2 and Fig. 3. Clearly, the new model shows the best agreement. It should be pointed out that no fitting on device level had been carried out except for the LE model which has been adjusted for the short-channel device.

For the prediction of device performance at even shorter gate lengths it is important for the model to mimic physical behavior as much as possible and to avoid fitting parameters which we believe is the strength of our new model. In addition to the improved description of the shape and location of the maximum of G_{ii}, our model proved to be numerically efficient and stable.

5. Conclusions

We have refined a previously published impact ionization model based on a six moments transport description and we performed simulations of substrate currents of n-channel MOS transistors. A comparison of our method with existing approaches outlines the improvements. Due to the excellent agreement with measurements we believe that the required two model parameters are valid over a wide range which makes our new model a very good choice to accurately predict II effects for deep submicron devices.

6. Acknowledgment

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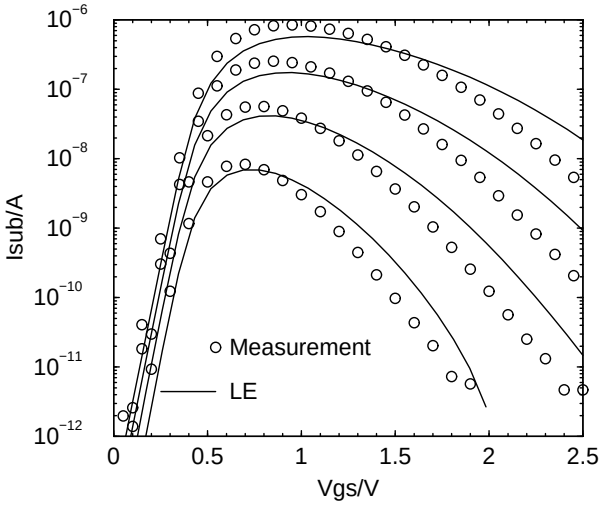
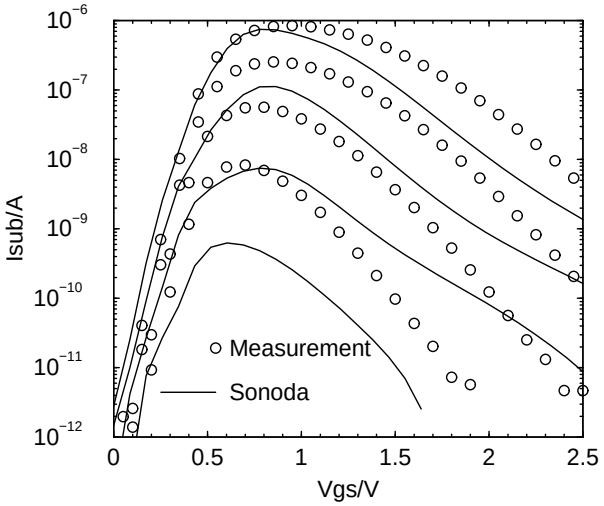




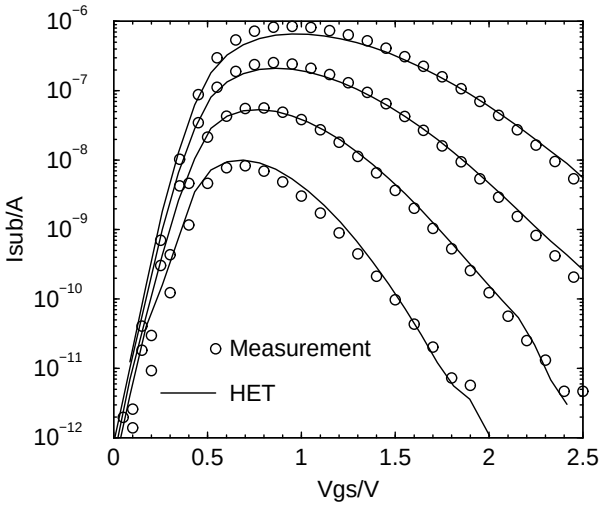
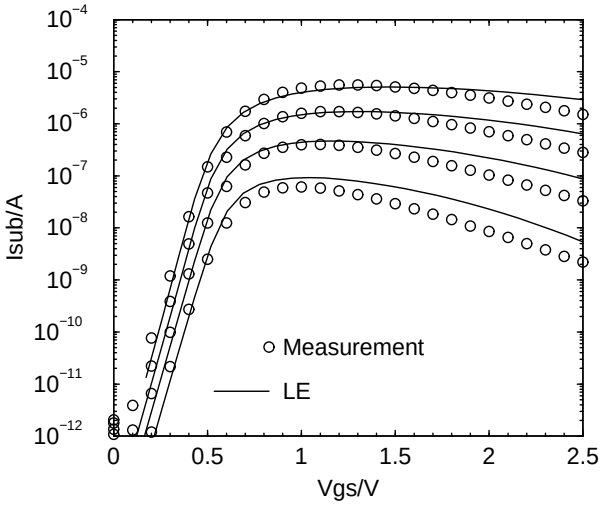
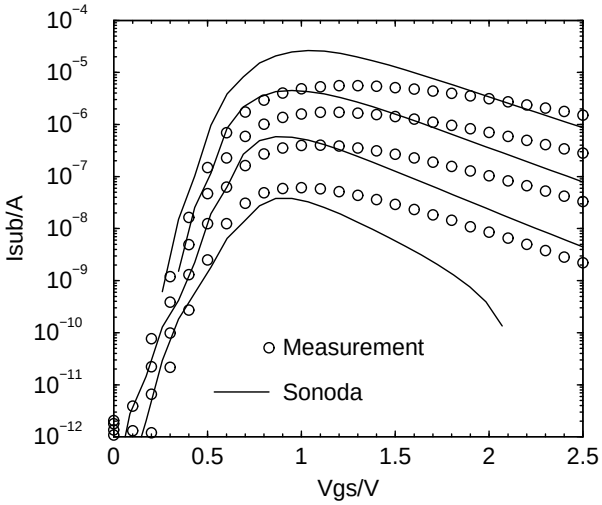


Figure 2. Comparison of the substrate currents delivered by the three models with measurements for the long-channel device.





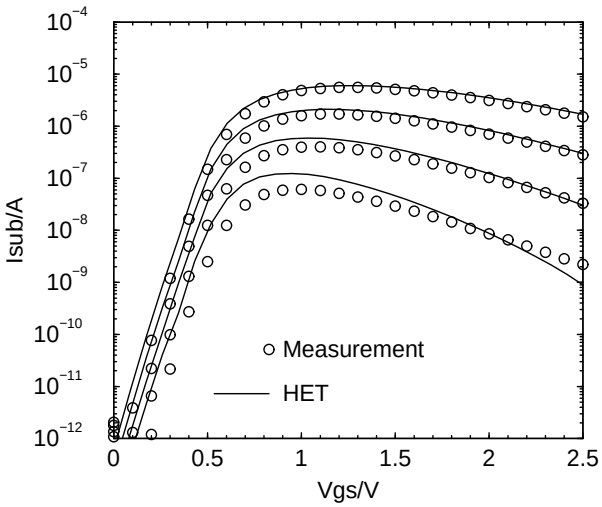


Figure 3. Comparison of the substrate currents delivered by the three models with measurements for the short-channel device.