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Parameter modeling for higher-order transport models in UTB SOI MOSFETs

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Abstract We present a two-dimensional tabularized higher-order transport model based on extracted parameters from a Subband Monte Carlo (SMC) simulator. Important effects like quantum confinement and surface roughness scattering are automatically taken into account. Device parameters like the electron temperature or the output characteristic of a SOI MOSFET are compared with the results obtained from models using bulk Monte Carlo (MC) data, where no quantization effects and no surface roughness scattering are considered.

Keywords Subband Monte Carlo · Schrödinger/Poisson solver · Method of moments

1 Introduction

The description of carrier transport in subnanometer devices based on Boltzmann's equation (BTE) is of fundamental importance. It has been shown that transport even in aggressively scaled MOSFETs with $L_g \approx 10$ nm is still predominantly classical [1], so we neglect quantum effects in transport direction and only retain the influence in transversal direction. On an engineering level a very efficient way to find approximate solutions of BTE is the method of moments, in comparison to the very time consuming MC technique [2, 3]. Considering the first two, four, and six moments, one can obtain the drift-diffusion, the energy-transport, and the six moments model respectively [4]. For these models, an accurate description of transport parameters like the carrier mobility in the drift-diffusion model is very important. One possibility is the calculation of parameter tables extracted from MC simulations for a parameter interpolation within a device simulator [4]. So far only bulk MC data has been investigated. The application of this data to MOSFET devices is problematic due to the importance of surface roughness scattering and quantization in the inversion channel [5]. In [6] surface roughness scattering on the carrier mobility has been investigated using the semi-empirical Matthiesen rule. However, the impact of quantization effects and surface roughness scattering on higher-order parameters has not been described satisfactorily yet. Here, we present a method to model these effects on higher-order transport parameters in UTB SOI MOSFETs.

2 Method

Multiplication of the BTE with weight functions like ϵ^i, $\mathbf{p}\epsilon^i$ where $i \in [0, 2]$, and integration over the two-dimensional k-space, yields the two-dimensional six moments model. With $A_0 = \mu_0 H_0$, $A_1 = -2\mu_1 H_1$, $A_2 = -6\mu_2 H_2$, and the macroscopic relaxation time approximation for the scattering operator $Q_0 = 0$, $Q_1 = -n\mathrm{k_B}(T_n - T_0)/\tau_1$, and $Q_2 = -2n/m^*\mathrm{k_B}^2(T_n^2\beta - T_0^2)/\tau_2$ the transport equations read as follows:

$$\partial_t n - \frac{1}{\mathrm{q_0}}\nabla_\mathrm{r}\mathbf{J}_n = Q_0 \tag{1}$$

$$\mathrm{k_B}\partial_t(nT_n) + \nabla_\mathrm{r}\mathbf{S}_n - \mathbf{E}\cdot\mathbf{J}_n = Q_1 \tag{2}$$

$$2\frac{\mathrm{k_B}^2}{m^*}\partial_t\left(nT_n^2\beta\right) + \frac{2}{m^*}\nabla_\mathrm{r}\mathbf{K}_n + \frac{4\mathrm{q_0}}{m^*}\mathbf{E}\cdot\mathbf{S}_n = Q_2 \tag{3}$$

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$$\mathbf{J}_n = A_0(\nabla_{\mathrm{r}}(\mathrm{k_B} n T_n) + h_0 \mathrm{q}_0 \mathbf{E} n) \tag{4}$$

$$\mathbf{S}_n = A_1 \left(\nabla_{\mathrm{r}} \left(n \frac{(\mathrm{k_B} T_n)^2}{q} \beta \right) + h_1 \mathrm{k_B} T_n \mathbf{E} n \right) \tag{5}$$

$$\mathbf{K}_n = A_2 \left(\nabla_{\mathrm{r}} \left(n \frac{(\mathrm{k_B} T_n)^3}{q} \gamma \right) + h_2 (\mathrm{k_B} T_n)^2 \mathbf{E} n \beta \right) \tag{6}$$

A discussion on the relaxation time approximation is given in [7]. Equations (1)–(3) denote the conservation equations and (4)–(6) are the fluxes. H_0, H_1, and H_2 are non-parabolic factors, and β is the kurtosis which denotes the deviation from a Maxwellian distribution function. So far this method is based on a classical approach. To model quantization effects as well as surface roughness scattering we extract transport parameters like the relaxation times in the conservation equations or the mobilities in the fluxes out of a self-consistent coupling between a SMC simulator and a SP solver. In the SMC simulator we consider non-parabolic bands, quantization effects, phonon induced scattering as well as surface roughness scattering [8]. The SP solver incorporates the quantum confinement in inversion layers [9, 10].

The extraction methodology is shown in Fig. 1. After convergence is reached, the transport parameters for high lateral fields are extracted. These loops are performed for several effective fields. A device simulator [11] utilizes these SMC tables for an interpolation in order to model classical transport through a whole device. In Fig. 3 the effective field as a function of the spatial coordinate is shown. In the case of the drift-diffusion model the mobility is calculated as a function of the effective field and the lateral field. For the higher-order models, the parameters are functions of the effective field and the temperature.

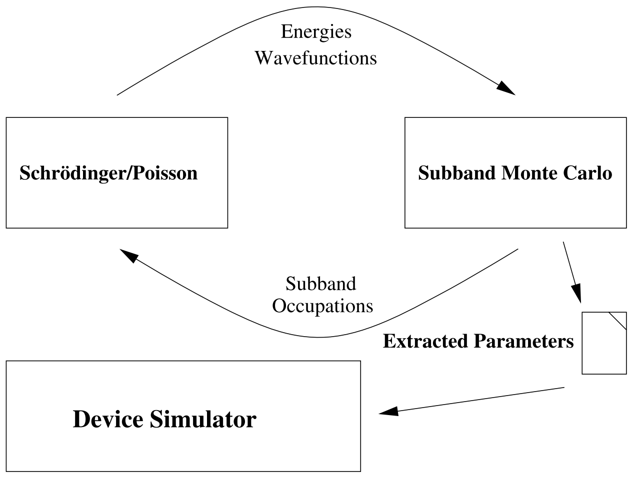

Fig. 1 The SP-SMC loop describes the transport of a two-dimensional electron gas in an inversion layer. The convergency is reached by an exchange of energy subbands, wavefunction, and subband occupations. The device simulator utilizes the extracted parameters to characterize transport through the channel of a whole device

3 Results

A fully depleted SOI MOSFET with a Si film thickness of 5 nm in ⟨100⟩ direction and a donor doping concentration of $10^{20}\,\mathrm{cm}^{-3}$ in the source and the drain regions as well as an acceptor doping in the channel of $10^{12}\,\mathrm{cm}^{-3}$ has been investigated. The geometry in lateral direction is shown as well in Fig. 3. The channel region goes from 30 nm to 70 nm. An electric field is applied in ⟨010⟩ direction. The output of the SP-SMC loop is shown in Fig. 2 and in Fig. 4. The extracted velocities and mobilities are averages over all subbands.

To show the impact of quantization effects and surface roughness scattering on higher-order transport parameters we compare our model with bulk MC data, where no quantization and no surface roughness scattering have been taken into account.

The energy relaxation time as a function of the spatial coordinate for different bias points is shown in Fig. 5. The energy relaxation time has a minimum in the middle of the channel of the bulk as well as in the subband case but are otherwise distinctly different.

This is due to high electric fields in the source and drain region. The carrier temperatures in Fig. 6 based on bulk parameters are considerably overestimated because of the missing consideration of surface roughness scattering and the impact of the inversion layer.

The output characteristic of the SOI MOSFET computed with the drift-diffusion, energy-transport, and the six moments model is shown in Fig. 7. Here we compare SMC data with bulk MC data. Due to a high velocity of the energy-transport model in the channel (see Fig. 8) the current is

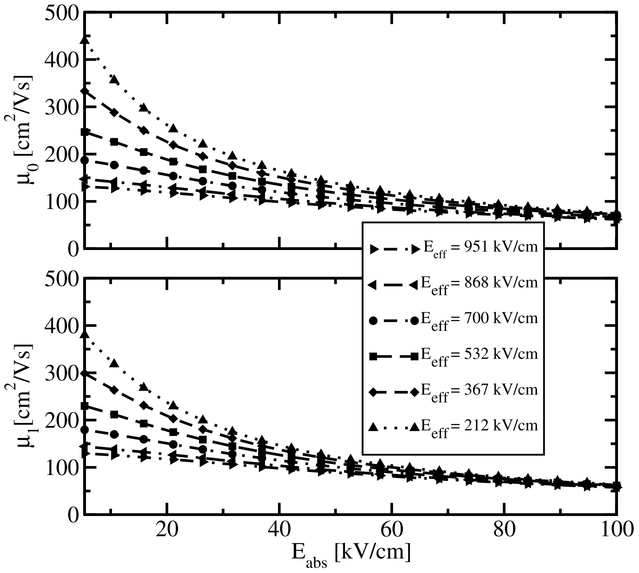

Fig. 2 A set of carrier mobilities as well as the energy mobilities as a function of the lateral field for different effective fields are plotted. An interpolation between these curves is carried out by the device simulator to model the mobilities through the whole device

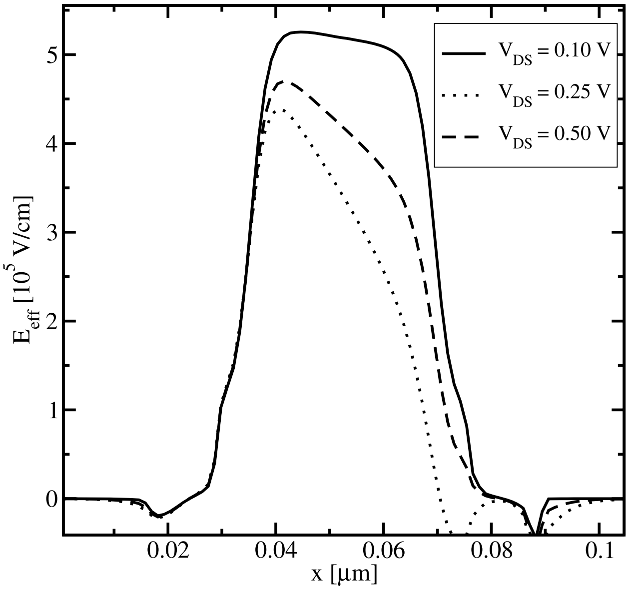

Fig. 3 The effective field through the whole device for several bias points is shown. With these fields and the SMC tables higher-order transport parameters can be modeled through the whole device

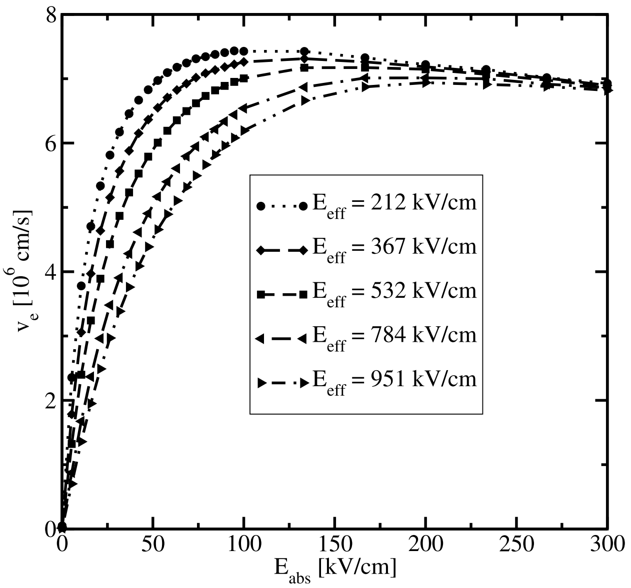

Fig. 4 The extracted velocity of the electrons as a function of the lateral field for different effective fields is plotted. Due to surface roughness scattering the saturation velocity is smaller than in the bulk (10^7 cm/s). Due to the increasing effective field the velocity decreases because of increasing surface roughness scattering rates

much higher than in the other models. The difference in the currents of bulk data and subband data is due to different MC tables and the three-dimensional transport model in the bulk case and the two-dimensional model in the subband case.

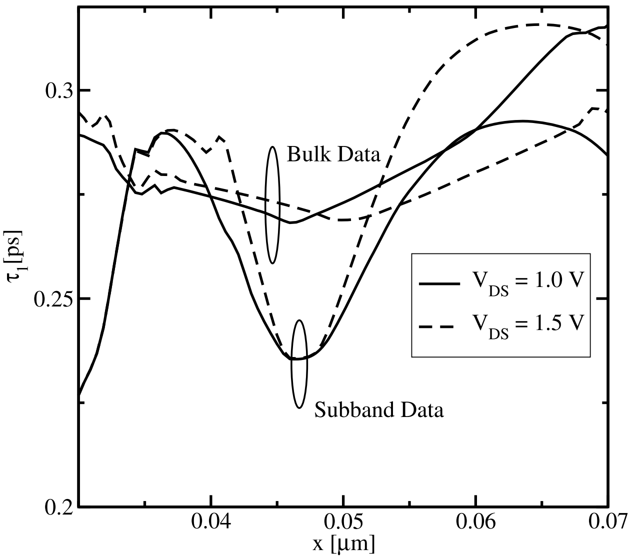

Fig. 5 A comparison of the energy relaxation time profiles of the bulk MC data and SMC data. The relaxation time is plotted over a 45 nm long channel. A gate voltage of 0.8 V is applied

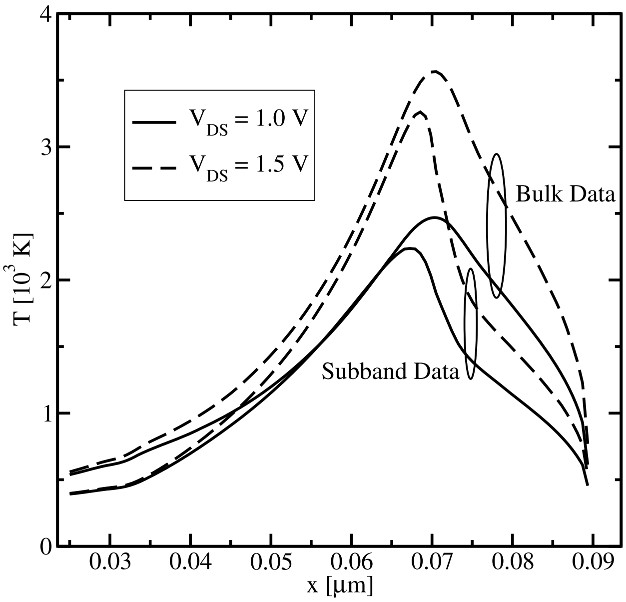

Fig. 6 A comparison of table based bulk MC data with SMC data for different bias points. The maximum peak of the temperature is at the end of the channel. The difference are due to different mobility tables

4 Conclusion

We present a method for modeling higher-order transport parameters for a two-dimensional electron gas in a UTB SOI MOSFET. This method is based on an interpolation technique between SMC tables. With this approach it is possible to consider the impact of quantization effects in an inversion layer as well as surface roughness scattering on higher-order transport parameters. We compare the output characteristic

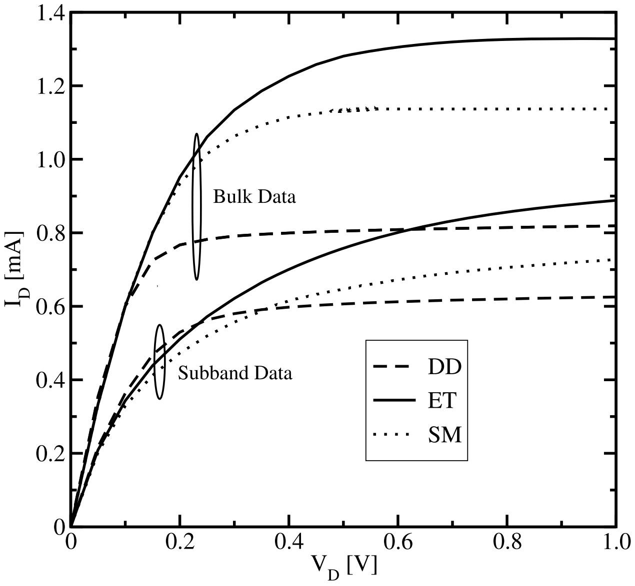

Fig. 7 The output characteristics of a fully depleted SOI MOSFET calculated with the drift-diffusion, energy-transport, and the six moments model using bulk MC data and SMC data

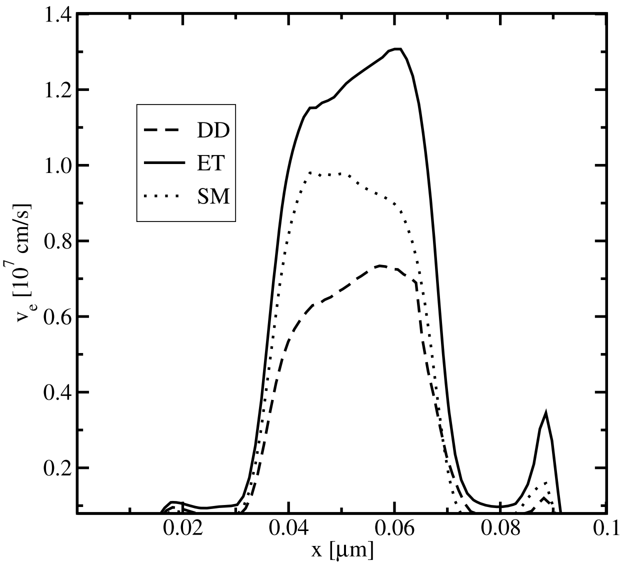

Fig. 8 The velocity profile calculated with the drift-diffusion, energy-transport, and six moments model. A drain voltage of 0.5 V is applied

of a SOI with bulk MC data where no quantization effects are considered.

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