# Simulation of Vertical CEO-FETs by a Coupled Solution of the Schrödinger Equation with a Hydrodynamic Transport Model

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## Abstract

This paper describes the simulations of vertical cleaved-edge overgrowth field effect transistors (CEO-FETs). For the simulation the device simulator SIMBA is used, which is capable to handle complex device geometries as well as several physical models represented by certain sets of partial differential equations. With a multidimensional solution of the Poisson equation the Schrödinger equation is solved either in one or in two dimensions according to the confinement of the electrons in the area where quantum mechanical effects are expected. As a new feature the involvement of a hydrodynamic (HD) transport model is implemented to include non-equilibrium transport phenomena in extremely short channels. The experimental results are compared with the simulated data of this device.

## 1. Introduction

One intention of modern semiconductor technology is the reduction of the device length and width. With the realization of these nanometer structures several quantum mechanical effects appear. The electrons and the holes can not move freely in all of the three spatial directions. The movement of the charge carriers is confined in one, two or three directions, so that 2-, 1-, or 0-dimensional electron gases arise. In heterojunctions field-effect transistors a 2-dimensional electron gas (2DEG) is used as an active transistor channel. The cleaved-edge overgrowth technique [1] offers innovative capabilities for the design of novel quantum size field-effect transistors. The self-consistent solution of the Poisson and Schrödinger equation gives an accurate model to describe quantum mechanical effects in charge carrier gases. The coupling of this microscopic model with a hydrodynamic transport model, in which short-channel and overshoot effects are taken into account, can describe the device characteristics of modern quantum sized field effect transistors. First simulations of vertical CEO-FETs have been carried out to predict the device performance and to optimize the structure.

## 2. Simulation model

For the simulations a 2D-microscopic/macroscopic algorithm is used as described in [2], which consists of the solution of the effective mass Schrödinger equation

$$-\frac{\hbar^2}{2}\nabla\cdot\left(\frac{1}{m^*}\nabla\psi\right)+\left(V-E\right)\psi=0 \tag{1}$$

(m*: effective electron mass, E: discrete energy levels, ψ: wavefunctions, V: potential energy)

together with the Poisson equation

$$\nabla\left(\varepsilon\cdot\nabla\varphi\right)=-e\cdot\left(p - n + N_D^+ - N_A^- + \rho_{ADD}\right) \tag{2}$$

( $N_D^+, N_A^-$ ionized donor and acceptor density, $\rho_{ADD}$ additionally fixed charge)

to calculate the exact electron density distribution within the two-dimensional electron gas (2DEG) channel. Schrödinger equation, Poisson equation, continuity equations

$$\nabla\cdot\mathbf{J}_p=-q\cdot\left(R-G+\frac{\partial p}{\partial t}\right) \tag{3}$$

$$\nabla\cdot\mathbf{J}_n=q\cdot\left(R-G+\frac{\partial n}{\partial t}\right) \tag{4}$$

transport equations

$$\mathbf{J}_p=-q\cdot\mu_p\cdot p\cdot\nabla\left(\varphi-\Theta_p\right)-k_B\cdot T_p\cdot\mu_p\cdot\nabla p-k_B\cdot p\cdot\mu_p\cdot\nabla T_p \tag{5}$$

$$\mathbf{J}_n=-q\cdot\mu_n\cdot n\cdot\nabla\left(\varphi+\Theta_n\right)+k_B\cdot T_n\cdot\mu_n\cdot\nabla n+k_B\cdot n\cdot\mu_n\cdot\nabla T_n \tag{6}$$

and energy balance equations (HD transport model),

$$\nabla\cdot\mathbf{S}_p=\mathbf{J}_p\cdot\mathbf{E}^*-\frac{3}{2}k_B\cdot p\cdot\frac{\left(T_p-T_L\right)}{\tau_{wp}}-\frac{3}{2}k_B\frac{\partial}{\partial t}\left(p\cdot T_p\right)-\frac{3}{2}k_BT_p\left(R-G\right) \tag{7}$$

$$\nabla\cdot\mathbf{S}_n=\mathbf{J}_n\cdot\mathbf{E}^*-\frac{3}{2}k_B\cdot n\cdot\frac{\left(T_n-T_L\right)}{\tau_{wn}}-\frac{3}{2}k_B\frac{\partial}{\partial t}\left(n\cdot T_n\right)-\frac{3}{2}k_BT_n\left(R-G\right) \tag{8}$$

both for electrons and holes are solved self-consistently in the Gummel algorithm to simulate the device characteristics at different bias conditions. R and G are the recombination and generation rate, $\Theta_p$ and $\Theta_n$ are so called band parameter for holes end electron respectively.

## 3. Results

The device structure used for the simulation is presented in Fig. 1 together with the doping densities. Fig. 2 and Fig. 3 show the calculated output and transfer characteristics, respectively. Additionally the results of a Schrödinger-Poisson solver coupled with a drift-diffusion (DD) model are inserted. The considerable differences show that short-channel and overshoot effects are taken into consideration by the HD transport model. Currently first experimental data are available for CEO-FETs operating at T = 4.2 K. The measured output characteristics (Fig. 4) correspond qualitatively to the calculated data at T = 300 K.

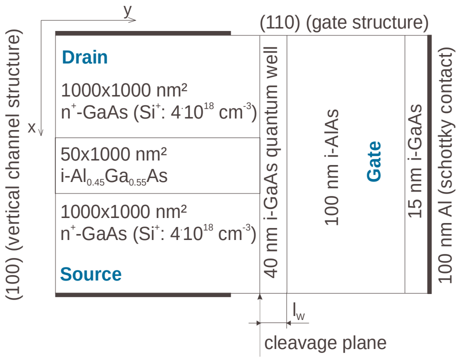

**Fig. 1** Structure of the vertical CEO-FET

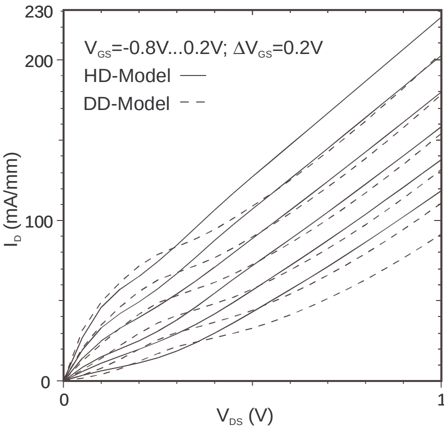

**Fig. 2** Output characteristics for different simulation models

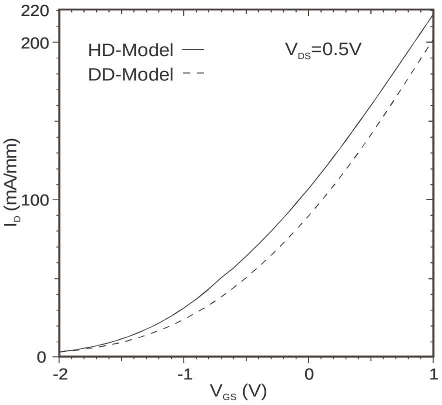

**Fig. 3** Transfer characteristics for different simulation models

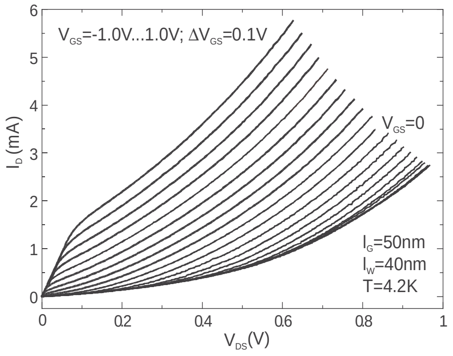

**Fig. 4** Experimental CEO-FET output characteristics

The electron temperature in the channel region is depicted in Fig. 5. A strong increase of the temperature can be detected at the drain side near the channel edge. A plot of the conduction band around the quantum well formed in the middle of the gate shows Fig. 6. The discrete energy levels are marked within the quantum well. The transit frequency $f_T = 14$ GHz and the maximum frequency of oscillation $f_{max} = 31$ GHz are obtained at the bias point $V_{DS} = 1$ V, $V_{GS} = 0$. These insufficient values of the non-optimized structure result mostly from the overlap capacities in the gate-source and gate-drain region. The capability of device simulation contains the possibility to investigate scaling effects. The performance, especially the output and transfer characteristics, of CEO-FETs has been evaluated as a function of channel width ($l_W$) in the range from $l_W = 10$ nm to $l_W = 40$ nm. In Fig. 7 the output and in

Fig. 8 the transfer characteristics are illustrated for different channel widths at $V_{GS} = 0$.

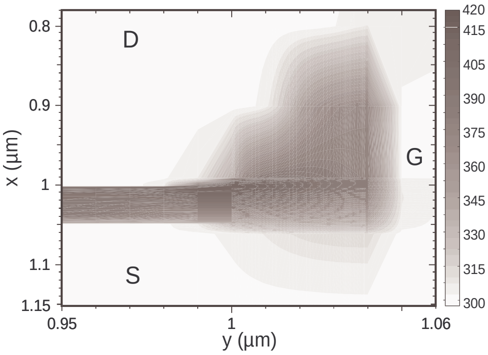

**Fig. 5** Electron temperature $T_e$ (K) in the channel region ($V_{GS} = 0$; $V_{DS} = 1.0$ V)

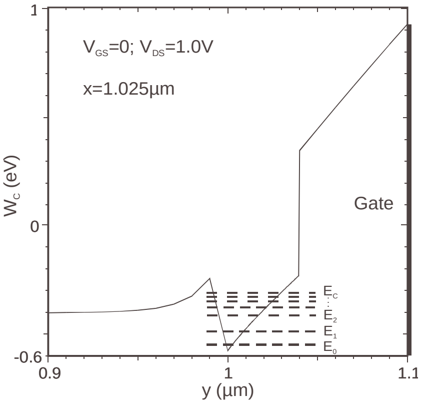

**Fig. 6** Conduction band and discrete energies

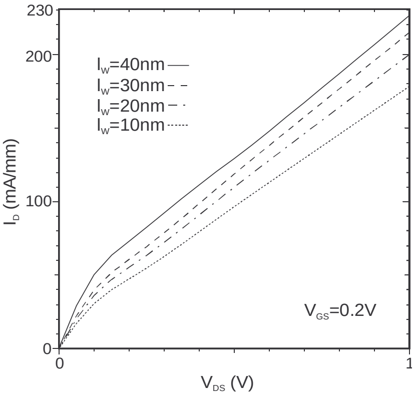

**Fig. 7** Output characteristic for different gate widths

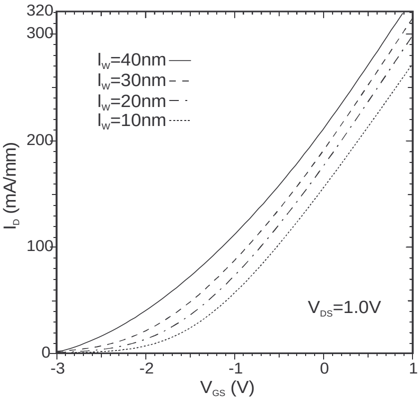

**Fig. 8** Transfer characteristic for different gate widths

## 4. Conclusions

Numerical 2D-simulations of vertical CEO-FETs have been carried out. For the calculations, a coupled solution of Schrödinger equation with a hydrodynamic transport model is deployed. The non-optimized structure shows scaling effects, like short-channel and overshoot behaviour in the device characteristics. The variations of the channel width shows a increase the drain current with the channel width.

## References

[1] Pfeiffer L.N., West K.W., Stormer H.L., Eisenstein J.P., Baldwin K.W., Gershoni G., Spector J. : Appl. Phys. Lett. 56, 1990, pp. 1697-1699.

[2] Pigorsch C., Klix W., Stenzel R.: Microelectronic Engineering 43-44, 1998, pp. 325-333.