Design and Optimization of Vertical CEO-T-FETs with Atomically Precise Ultrashort Gates by Simulation with Quantum Transport Models

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Abstract. The cleaved-edge overgrowth (CEO) technique offers an innovative approach to designing novel quantum sized field-effect transistors (FETs) with a T-like gate-to-channel structure. Numerical simulations of vertical CEO-T-FETs have been carried out to optimize the structure and predict device performance. For the simulation the 2D/3D device simulator SIMBA is used, which is capable of dealing with complex device geometries as well as with several physical models represented by certain sets of partial differential equations.

INTRODUCTION

One intention of modern semiconductor technology is the reduction of device length and width. With the realization of these nanometer scale structures several physical effects appear such as short channel effects and overshoot behaviour, as well as quantum mechanical effects. With the CEO technique it is possible to produce vertical CEO-T-FETs based on AlGaAs/GaAs heterostructures with atomically precise ultrashort gates that eliminate short channel behavior [1]. The idea of a CEO-T-FET is to build up a planar epitaxial structure with source, barrier, atomically precise ultrashort gate, barrier and drain. In the second growth step, a conducting channel, a supply and a cap layer are grown perpendicular to the original planar layers. Numerical investigations of this CEO-T-FET show good device behaviour without short channel effects.

SIMULATION MODELS

The simulation models of our device simulator SIMBA are described. The equations are shown only for electrons. SIMBA calculated the equations for electron and holes. The Poisson equation

$$\nabla\left(\varepsilon_s\varepsilon_0\nabla(\varphi)\right) = -q\left(p - n + N_D - N_A\right) \qquad (1)$$

where N_D^+, N_A^- are the ionized donor and acceptor densities, the continuity equation

$$\nabla \cdot \mathbf{J}_n = q\left(R - G + \frac{\partial n}{\partial t}\right) \qquad (2)$$

and the transport equation

$$\begin{aligned}\mathbf{J}_n = -qn\mu_n\nabla\left(\varphi + \lambda_n + \Theta_n\right) + \\ D_n q\nabla(n) + k_B n\mu_n\nabla(T_n)\end{aligned} \qquad (3)$$

are solved self-consistent in the Gummel algorithm to get the device characteristics at different bias conditions. In the drift gradient of the transport equation an accessory expression is included. This additional equation describes a quantum potential for the carriers

$$\lambda_n = \frac{\gamma_n \hbar^2}{6\, m_n\, q}\frac{\nabla^2\sqrt{n}}{\sqrt{n}} \qquad (4)$$

where m_n is the constant effective mass. The problem of the anisotropic effective mass is handled by the fitting factor γ_n. Non-equilibrium device phenomena, like short-channel and overshoot behaviour are taken into account by the energy balance equation and the energy flux density, which are included as additional equations in the self-consistent Gummel algorithm. The energy flux density equation

$$\mathbf{S}_n = -\kappa_n \nabla(T_n) + \frac{5}{2}\frac{k_B}{q}T_n\mathbf{J}_n + \frac{3}{2}\lambda_n\mathbf{J}_n \qquad (5)$$

and the energy balance equation

$$\nabla\cdot\mathbf{S}_n = \mathbf{J}_n\mathbf{E}^* - \frac{3}{2}k_B n\frac{(T_n-T_L)}{\tau_{wn}} - \frac{3}{2}k_B\frac{\partial}{\partial t}(nT_n) - \frac{3}{2}k_B T_n(R-G) + \frac{1}{2}q\lambda_n\left(\frac{n}{\tau_{wn}}-(G-R)\right) + \frac{1}{2}q\frac{\partial}{\partial t}(n\lambda_n) \qquad (6)$$

are likewise extended to include quantum effects by the same quantum correction potential for the carriers. τ_{wn} is the energy relaxation time. With the quantum hydrodynamic model it is possible to consider quantum mechanical effects. The Poisson equation (1), the continuity equation (2) and the transport equation (3) without the temperature gradient is described together as quantum drift diffusion (QDD) model. The quantum potential do not account for the classical hydrodynamic (HD) and drift diffusion (DD) models.

RESULTS

Figure 1 shows the CEO-T-FET structure with a gate length of L_G = 20 nm that was used for simulation together with the doping densities as well as the layer thicknesses.

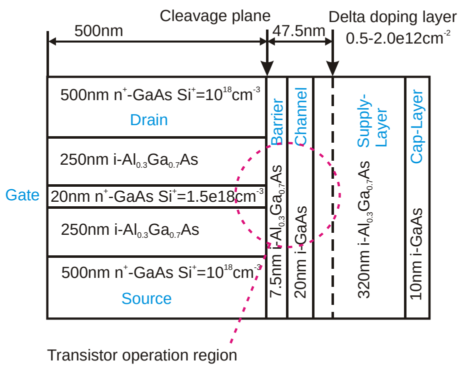

FIGURE 1. Structure of the 20nm CEO-T-FET.

The calculated output and transfer characteristics are represented in Fig. 2 and 3. They are simulated with two classical models and do not indicate short channel or overshoot effects. The transfer characteristics for different γ_n of the QDD model are shown in Fig. 4. The increase of the drain current at lower gate-source voltage results from tunneling and leakage currents through the gate and can be calibrated by γ_n in the QDD model. The lower drain current results from the smaller calculated electron density distribution by the QDD model.

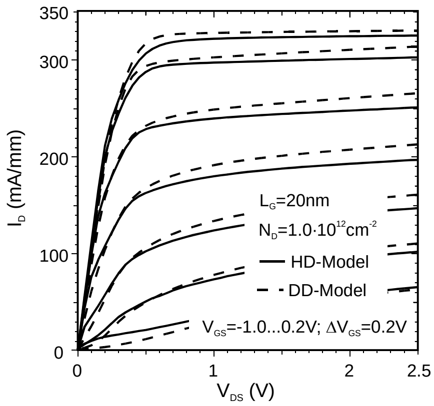

FIGURE 2. Output characteristics.

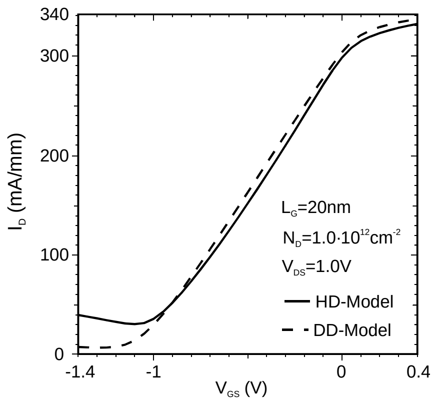

FIGURE 3. Transfer characteristics.

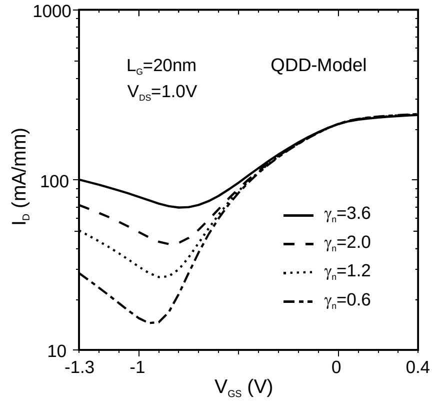

FIGURE 4. Transfer characteristics for different γ_n.

REFERENCES

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