Two-Dimensional Simulation of a Pseudomorphic HEMT with MINIMOS-NT

H. Brech*, T. Simlinger**, T. Grave*, and S. Selberherr**

*Corporate Research and Development, Siemens AG
Otto-Hahn-Ring 6, D-81739 München, Germany

**Institute for Microelectronics, TU Vienna
Gußhausstraße 27-29, A-1040 Vienna, Austria

Simulations and measurements of a submicron pseudomorphic high electron mobility transistor (HEMT) are presented. For the simulations the generic device simulator MINIMOS-NT [1] 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. A description of the structure of the simulator is given. The principle of splitting the device geometry into distinct regions, referred to as segments, is shown. Within these regions, arbitrary material properties and physical models, i.e., partial differential, can be defined independently. The segments are linked together by interface models. The simulated characteristics of a HEMT with a gate length of 240 nm are compared with the measured data. Essential physical effects which determine the behavior of the device can be identified in the output and transfer characteristics.

The electrical behavior of the HEMT is mainly determined by the epitaxialy grown structure of the device. Several distinct layers of different semiconductor alloys are combined. The material and electrical properties change almost abruptly at the heterojuntion interface. Inside a layer the material properties and the electrical quantities are continuous. For these layers the well known Poisson and continuity equations are used. Additionally, to account for short channel effects, a hydrodynamic model describing the energy transport is implemented. Therefore the current density J_n is defined as

$$J_n = q \cdot \mu_n \cdot n \cdot \left[\nabla\left(\frac{E_c}{q} - \Psi \right) + \frac{k}{q} \cdot \frac{N_c}{n} \cdot \nabla \frac{n \cdot T_n}{N_c} \right], \tag{1}$$

and for the HD model the equation governing the energy transport is

$$\nabla \vec{S}_n + \frac{\partial (n \cdot \omega_n)}{\partial t} - \nabla\left(\frac{E_c}{q} - \Psi \right) \cdot \vec{J}_n + n \cdot \frac{\omega_n - \omega_0}{\tau_{\omega n}} + \omega \cdot R = 0 \tag{2}$$

where the energy flux $\vec{S}_n$ of electrons reads

$$\vec{S}_n = -\kappa_n \cdot \nabla T_n - \frac{1}{q} \cdot (\omega_n + k \cdot T_n) \cdot \vec{J}_n . \tag{3}$$

The same formulae hold for holes with the corresponding parameters. n is the carrier density, μ the mobility, ω the energy, κ the thermal conductivity and T the temperature of the corresponding carriers. Ψ denotes the electrostatic potential and k is the Boltzman constant.

The discontinuities of the interfaces between the layers have to be treated by specific interface models to link the layers together. A thermionic-field emission model, which includes tunneling, is implemented to enable electrons to cross the interface between the channel and the barrier layers. Considering the interface between segment 1 and segment 2, the thermionic field emission model determines the electron current density J_{n1} leaving segment 1, the electron current density J_{n2}

entering segment 2, the electron flux density S_{n1} leaving segment 1, and the electron energy flux density S_{n2} entering segment 2:

$$J_{n2} = J_{n1}, \tag{4}$$

$$S_{n2} = S_{n1} + \frac{1}{q} \cdot (\Delta E_c - \delta E_c) \cdot J_{n2}, \tag{5}$$

$$J_{n2} = q \cdot v_{n2}(T_{n2}) \cdot n_2 - q \cdot \frac{m^*_{n2}}{m^*_{n1}} \cdot v_{n1}(T_{n1}) \cdot n_1 \cdot \exp\left(-\frac{\Delta E_c - \delta E_c}{k \cdot T_{n1}}\right), \tag{6}$$

$$S_{n2} = -2 \cdot k \cdot T_{n2} \cdot v_{n2}(T_{n2}) \cdot n_2 + 2 \cdot \frac{m^*_{n2}}{m^*_{n1}} \cdot k \cdot T_{n2} \cdot v_{n1}(T_{n1}) \cdot n_1 \cdot \exp\left(-\frac{\Delta E_c - \delta E_c}{k \cdot T_{n1}}\right), \tag{7}$$

where

$$v_{n1,2}(T_{n1,2}) = \sqrt{\frac{2 \cdot k \cdot T_{n1,2}}{\pi \cdot m^*_{n1,2}}} \tag{8}$$

denotes the "emission velocity", and $m^*_{n1,2}$ are the effective masses for segment 1 and 2, respectively. Tunneling of electrons through the energy barrier is taken into account by barrier height lowering of δE_c, which is modeled as

$$\delta E_c = \begin{cases} q \cdot E_\perp \cdot x_{eff}, & E_\perp > 0 \\ 0, & E_\perp \le 0 \end{cases} \tag{9}$$

where $E_\perp$ is the electric field perpendicular to the interface in segment 2 and x_{eff} is the effective tunnel length.

A representative Scanning Electron Microscopy (SEM) profile of the device simulated in this study is shown in Fig. 1. As is can be seen, the alloying process of the ohmic contacts does not lead to complete penetration of the cap. Thus we assume that the underlying heterostructures are not destroyed. Therefore, the schematic structure shown in Fig. 2 where the ohmic metal is placed on top of the cap layer is used for simulation. The gate length of the device is 240 nm.

The mixed model simulation is performed with a hydrodynamic model within the channel region and a drift-diffusion (DD) model within the other layers. The measured transfer characteristic for a drain-source voltage of 2 V is shown in Fig. 3 along with two simulated I-V curves, one with plain DD model simulation, the other with mixed model simulation. As depicted in this figure, the mixed model simulation and the measured data agree very well.

The transfer characteristic can be devided up into 3 operation regimes, each regime owing to a major physical effect. Firstly, the pinch off regime, i.e. the regime of negative gate voltage where the electron concentration in the channel is low but is starting to rise with the gate voltage increasing. Most of the current flowing is conducted in the lower barrier layer. The second regime is the one of most interest for device applications. The drain current increases rapidly with the gate voltage exhibiting the maximum in g_m as shown in Fig. 4. For gate voltages higher than 0.3V, marking the 3rd regime, the I-V curve in Fig. 3 drops since the electrons heat up and start to surmount the energy barrier layer above. This effect is commonly known as real space transfer

(RST) of the electrons. Hence an increasing fraction of the electron transport takes place within the barrier layers where the electron mobility is much lower than within the channel.

Looking at g_m of Fig. 4 it becomes evident that the mixed model simulation covers the major effects whereas the plain DD simulation lacks the important RST leading to an almost constant g_m over a wide range of V_{GS}.

A quarter micron delta doped HEMT is simulated with the generic device simulator MINIMOS-NT. A new method is used which divides the device into several subdomains, referred to as segments, each segment with its characteristic physical models. Mixed model as well as plain DD simulations were performed. It is shown that for a proper simulation of the transfer characteristics it is necessary to perform hydrodynamic simulation in the channel.

Reference

[1] T. Simlinger, H. Kosina, M. Rottinger, and S. Selberherr, "MINIMOS-NT: A Generic Simulator for Complex Semiconductor Devices," in ESSDERC'95 - 25th European Solid State Device Research Conference (H. de Graff and H. van Kranenburg, eds.), (Gif-sur-Yvette Cedex, France), pp. 83-86, Editions Frontiers, 1995.

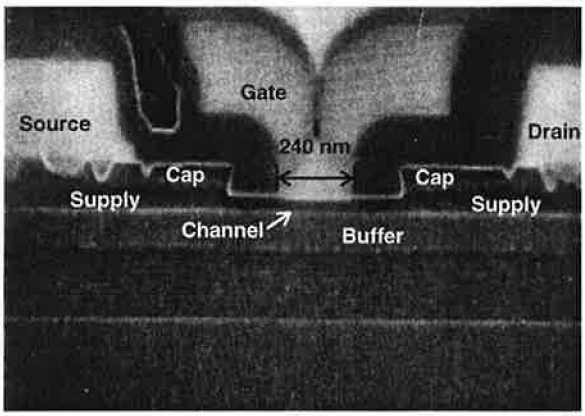

Fig. 1: SEM profile of the simulated HEMT.

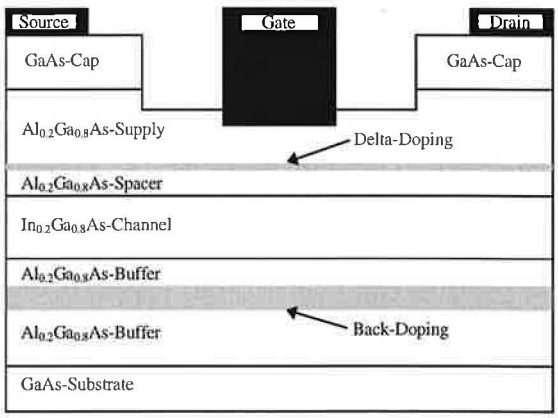

Fig. 2: Schematic of the simulated HEMT.

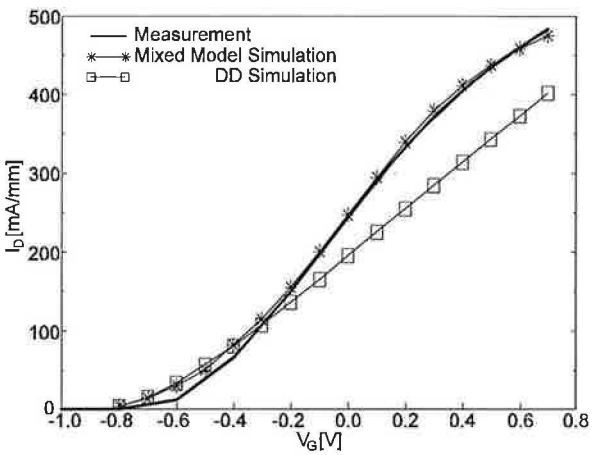

Fig. 3: Transfer curves of the HEMT.

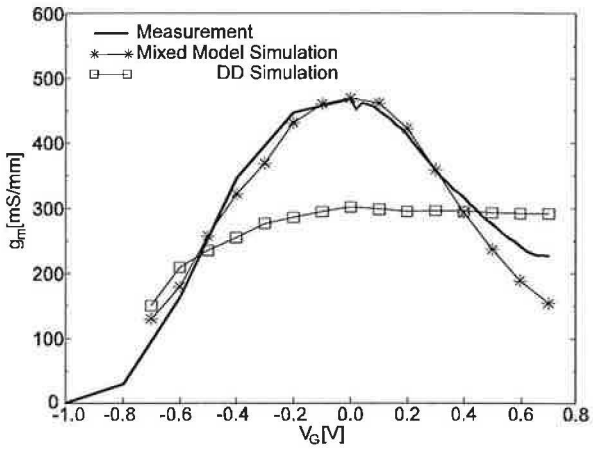

Fig. 4: Transconductance of the HEMT