# Highly Efficient Simulation of HEMTs and MESFETs Based on Quantum Mechanics

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**Abstract**

A new, quasi-two-dimensional physical device model was developed which allows the DC small- and large-signal microwave characteristics of HEMTs and MESFETs to be obtained based on device geometry and process data. It is easily applied to a wide variety of HEMT structures including pHEMT, AlGaAs/GaAs and multichannel structures.

## I. Introduction

Field effect transistor physical models can be used in several electronic engineering areas, including device and circuit design. Analytical models, due to there simplicity, can not reliably predict device performance whereas two dimensional models (both hydrodynamic and Monte Carlo) are certainly predictive and usually accurate, but computationally very demanding. Quasi-two-dimensional (Q2D) modelling offers a good compromise as it is up to 1000 times faster than full-two-dimensional modelling and still reasonably accurate. In practice I-V characteristics and microwave S parameters can be obtained in a few minutes on a personal computer with a 80486 processor. Our program can also determine simultaneously the elements of non-linear quasi-static equivalent circuit model. S parameters are calculated using a time-domain version of the physical model.

The Q2D approach is based upon the fact that the equipotential lines in the active channel (i.e. outside the depleted region) of a HEMT or MESFET are fairly parallel, perpendicular to the free surface. Therefore the analysis of the device can be subdivided into establishing the charge control law by the gate in the direction perpendicular to the gate (y direction) and calculating the current transport in the direction parallel to the gate (x direction).

## II. Charge Control Law

In the charge control model a vertical cross-section of the device is analysed (considered as a Schottky-diode). The calculation of the sheet electron and ionised donor concentrations are achieved by self-consistently solving Poisson's equation with Fermi statistics and the Schrödinger equation. Fast convergence can be achieved using Newton's algorithm. Up to nine Eigen energies can be evaluated when solving the Schrödinger equation though for practical reasons usually only two or three are calculated, while the rest of the electrons are treated as those belonging to the three-dimensional electron population. When the quantum well is not very deep, as is often the case, it is possible to by-pass the quantum mechanical calculations which makes the simulation even faster.
An advantage of this approach is accuracy and generality, as opposed to the triangular well

or square well approximations, which usually contain an empirical fitting parameter in order to improve accuracy [1].

At the end of calculations a look-up table is produced which contains the gate voltages and the sheet electron and ionised donor concentrations in each epitaxial layer. In case of pseudomorphic structures the effect of strain on the band gap, conduction band edge discontinuity, dielectric constant and effective mass is calculated.

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gate width: 1.0 mm
gate length: 0.3 μm
source gate distance: 1.0 μm
gate drain distance: 1.3 μm
layer structure:
AlGaAs(electron supplying layer): 30 nm, Al content: 20%, donor concentration: $1.2 \times 10^{24} m^{-3}$
AlGaAs (spacer layer): 3 nm, Al content: 20%, donor concentration: $1 \times 10^{20} m^{-3}$
InGaAs (active layer): 18 nm, In content: 15%, donor concentration: $1 \times 10^{20} m^{-3}$
GaAs (buffer layer): 150 nm, donor concentration: $1 \times 10^{20} m^{-3}$

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Table 1.: The structure and properties of the simulated pHEMT device

For a pseudomorphic AlGaAs/InGaAs/GaAs HEMT (see Fig.1. and Table 1) the conduction band edge and the electron concentration is shown in Fig.2 and Fig.3 for zero gate bias. The dependence of sheet electron and ionised donor concentration on the voltage applied to the Schottky-diode is shown in Fig.4. It can be seen that at negative gate biases (close to pinch-off) the sheet electron concentration is several orders of magnitude lower than in Fig.3. .

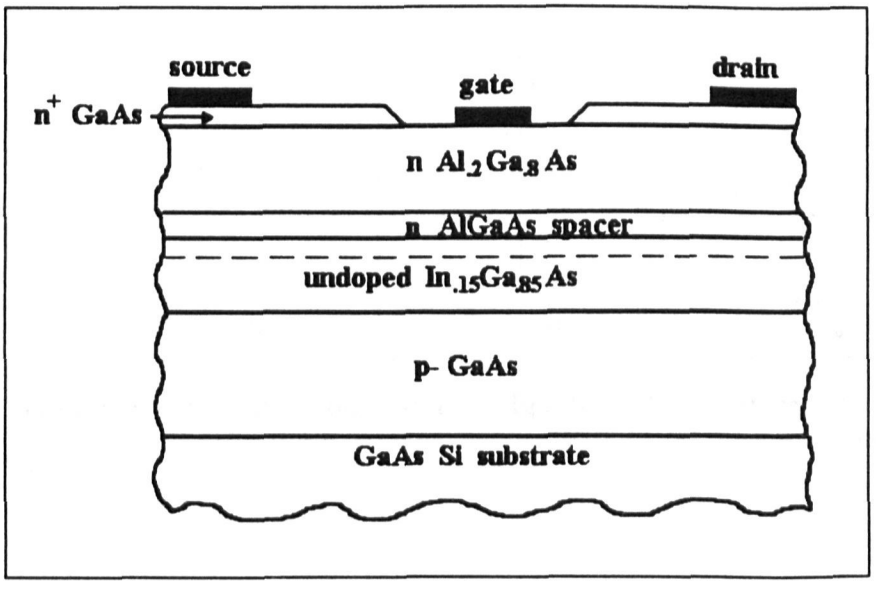


Figure 1. Structure of a typical pseudomorphic HEMT

The quantum mechanical calculations were not by-passed in the present simulation (in favour of Fermi statistics), as it would have led to about 20% overestimation of the sheet electron concentration in the InGaAs layer and 10% overestimation of the total sheet electron density.

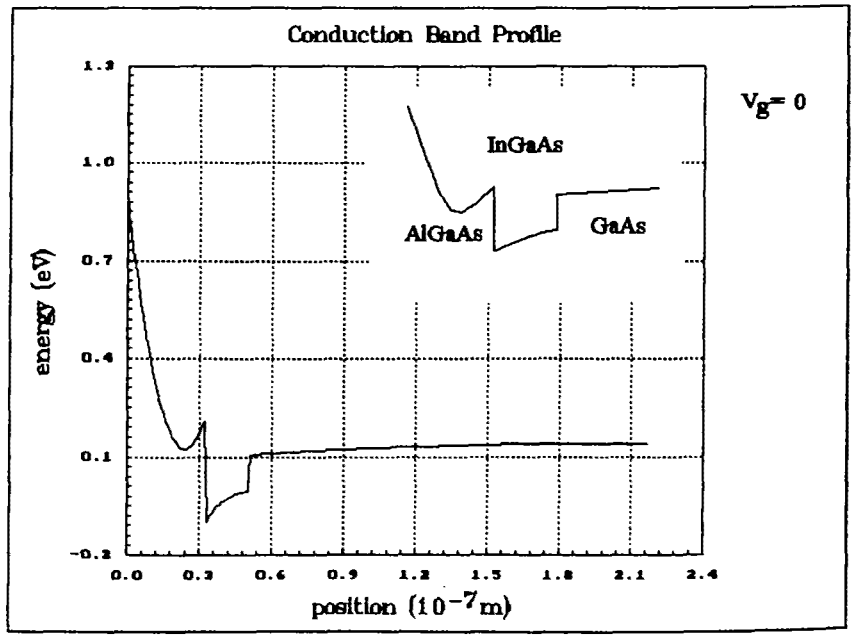


Figure 2. Energy-band diagram of a vertical section below the gate of the pHEMT in Table 1.

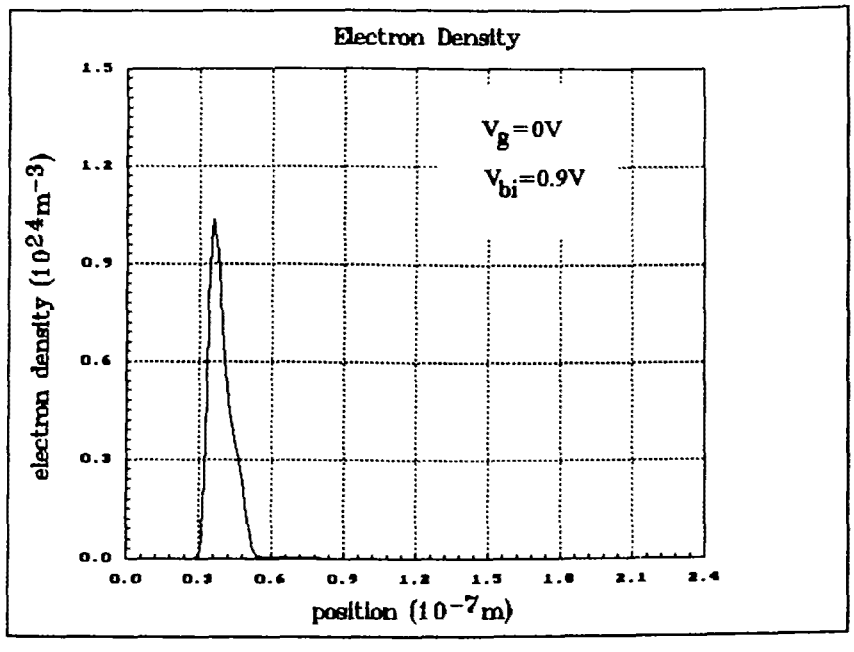


Figure 3. Electron density for the cross-section of a pHEMT corresponding to the conditions shown in Figure 2.

## III. Channel Simulator

In the channel simulator Poisson's equation and the transport equations are solved self-consistently in the x-direction assuming the gradient of the Fermi level to be one-dimensional. The transport equations are simplified versions of the first three moments of the Boltzmann equation, the particle (current continuity), momentum and energy conservation equations [2]. The terms describing the scattering of free electrons are calculated based on analytical fits to

Monte Carlo simulation results [3], and are all considered to be the function of average electron energy.

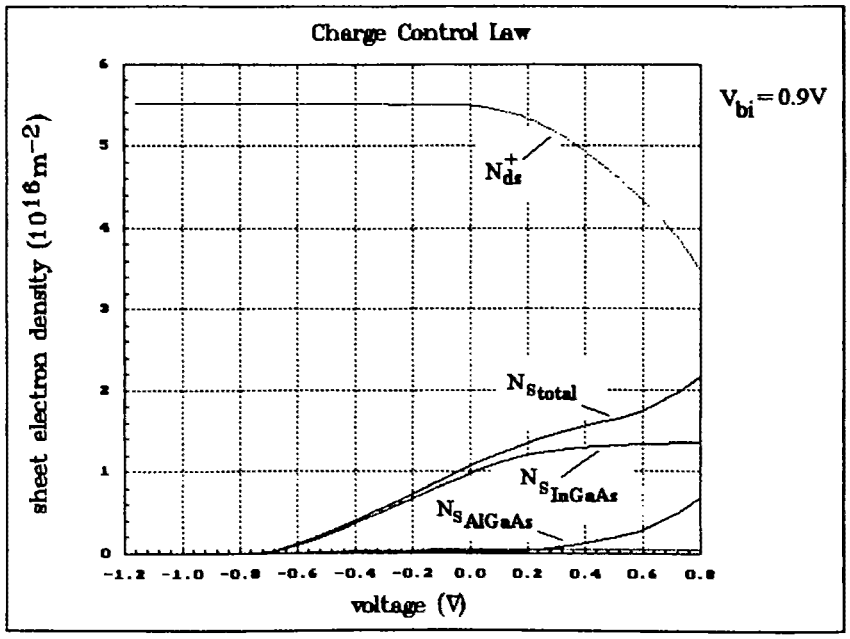


Figure 4. Charge control law: sheet electron concentration and ionised donor concentration in each layer

The sheet electron and ionised donor concentration is found from the above look-up table, based on the difference of channel and gate (or surface) potential, with a correction arising from the gradient of electric field in the x-direction. As this term can be quite large, especially around the drain end of the gate, more accurate calculations should use a double subscripted look-up table for the sheet charge densities to include the grad($E_x$) dependence. Due to the large memory requirement this approach is more suitable for simulations running on workstations than on PCs, therefore an analitic approximation was used in this work.

Unlike other recently published models, our model can simulate parasitic MESFET conduction, allowing a more accurate representation of device operation. In fact, HEMT and MESFET devices with an arbitrary number of different layers can be simulated.

The calculations at a specified source current proceed from source to drain using a simple forward differencing scheme, after omitting the diffusion term in the momentum conservation equation based on the considerations in [2]. The combination of Poissons's equation and the transport equations yields a quadratic equation for the electric field or the drift velocity. The drain voltage corresponds to the channel potential at the drain and is obtained integrating the electric field along the channel (Fig.5). The I-V characteristics of the pHEMT is shown in Fig.6.

**Acknowledgement**

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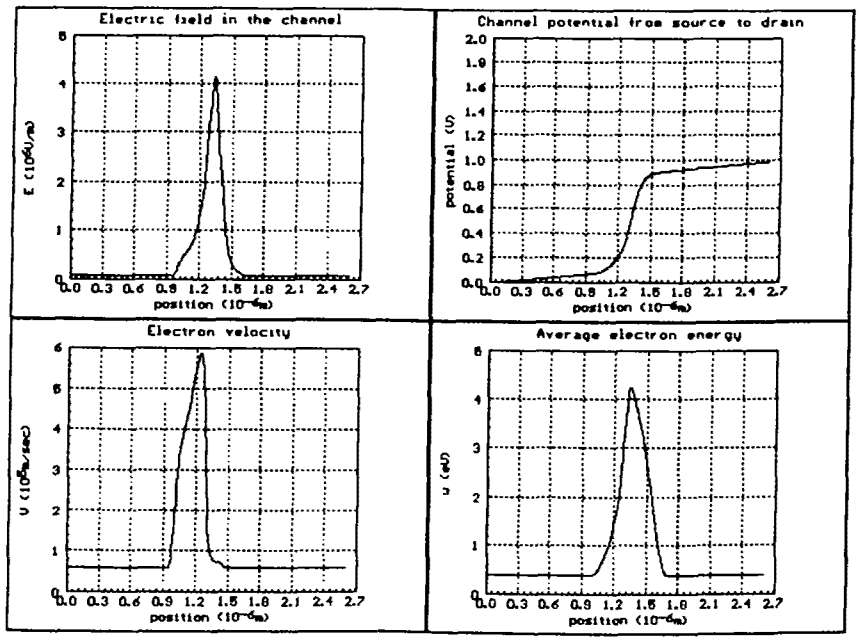


Figure 5. The electric field, channel potential, average electron energy and drift velocity in the conduction channel at bias point: $V_{gs}$ = -0.4 V, $V_{ds}$ = 1.0V

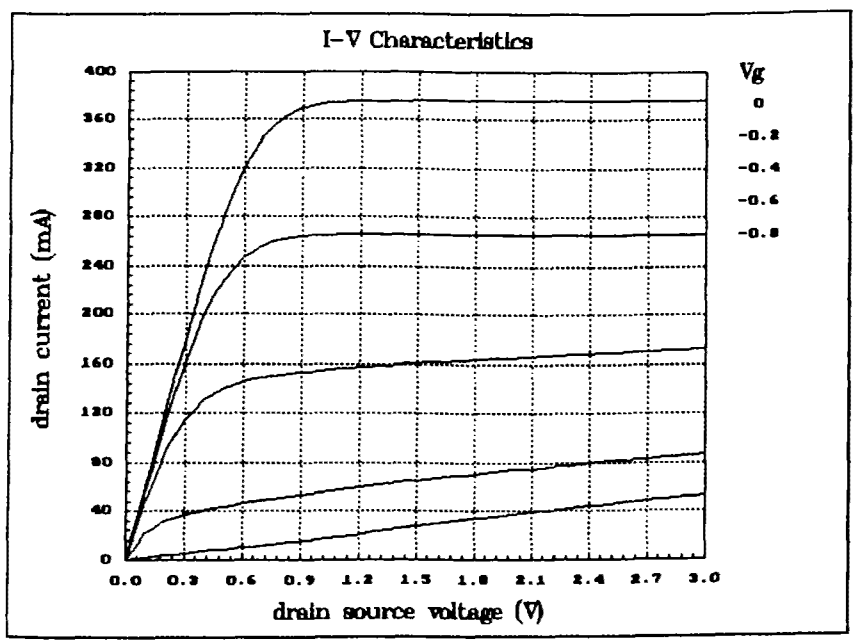


Figure 6. DC characteristics of the simulated pHEMT device

## References


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