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A New Quasi-two Dimensional HEMT Model

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Abstract

A Quasi-two Dimensional HEMT model is presented which for the first time describes accurately the I-V characteristics close to device pinch-off and at high drain current. The model uses a new analytical model for describing the injection of charge into the buffer material. This analytical description works in conjunction with an asymptotic boundary condition in the charge control solution to drastically increase the computational efficiency of the model. Electron temperature is also included in the charge control model to calculate the degeneracy factor of the electron gas under the gate where velocity overshoot occurs.

1 Introduction

The needs of the microwave engineer have changed dramatically over the last few years. Present-day MMICs and MMMICs generally make use of GaAs-based MESFETs or HEMTs which need to be characterized thoroughly at DC and RF in order to carry out a 'single point' circuit design. The availability of foundry information on process tolerances also provides the possibility of design centering for yield optimization [1]. It is in this area where physical models offer great potential, being able to build up a picture for the active device performance variations across the wafer from theoretical rather than experimental results [2]. Furthermore, the predictive nature of physical models makes it possible to optimise the transistor design as well as the circuit design for a specific application.

2 Model Description

The model described here uses a 'Quasi-two Dimensional' approach for modelling HEMTs in which it is assumed that the driving force for electron transport (electric field) is essentially in the x-direction only (source to drain) [3]. The carrier conservation, momentum and energy balance equations are used to describe electron dynamics in the conducting channel. This calculation is coupled to a solution for the electron sheet density in the y-direction (surface to substrate) using a charge-control look-up table. A highly developed charge-control model [4] is used to generate the look-up table which solves the coupled Poisson-Schrödinger equations in the y-direction but also includes the variation of x-directed field, dE_x/dx, to maintain consistency between the decoupled simulations[5]. The charge-control model makes use of an asymptotic boundary condition,

$$E_y(y) = \mp \left(\frac{2q}{\epsilon_0 \epsilon_r}\right)^{\frac{1}{2}} \left(N_c F_{\frac{3}{2}}(V) - \bar{N} V + c\right)^{\frac{1}{2}} \qquad (1)$$

where E_y is the electric field in the y-direction and V is electrostatic potential. This boundary condition is used in conjunction with the Shooting Method and enables the solution domain end to be located at the lower heterointerface (see Figure 1). The boundary condition is derived by integrating Poisson's equation and describes an exact asymptotic solution to the flat-band condition in the buffer when the constant of integration, c, is evaluated for $E_y = 0, V = V_{fb}$. The term, $\bar{N}$, accounts for both net doping density and dE_x/dx in the buffer layer.

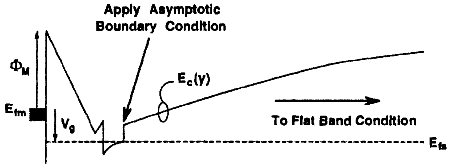

Figure 1: The asymptotic boundary condition.

The inclusion of dE_x/dx in the charge-control calculation describes elegantly the injection of electron charge into the buffer [6]. An analytical model is used to describe the buffer injection [6] which greatly improves the computational efficiency of the solutions and gives excellent pinch-off at high drain voltage : this problem has plagued previous Quasi-two Dimensional HEMT simulations.

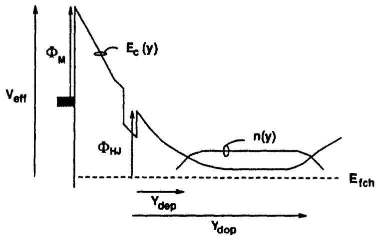

Figure 2: The analytical substrate injection model.

Figure 2 shows the implementation of the analytical substrate model. The potential, Φ_{HJ} at the lower heterojunction is first evaluated either analytically (when the channel is depleted of carriers) or numerically from the charge-control simulation. The depletion region penetration can then be calculated from the lower heterojunction and used to obtain the sheet electron charge in the buffer using the abrupt junction approximation.

Electron temperature is included in the charge control model via the Fermi-Dirac Function to calculate the degeneracy factor of the electron gas under the gate using,

$$\gamma = \frac{1}{n_s} \int_{channel} \frac{F_{\frac{3}{2}}(\eta)}{F_{\frac{1}{2}}(\eta)} n(y) dy \tag{2}$$

where n_s is the net sheet electron density and F corresponds to the family of well known Fermi-Dirac integrals. In this calculation it is assumed that electrons reside predominantely in the Γ-valley under the gate electrode. The degeneracy factor is then used in the energy equation [7] via the sink term,

$$S_w = \frac{w - \frac{3}{2} k T_0 \gamma}{\tau_w(w)} \tag{3}$$

where T_0 is the lattice temperature and $\tau_w(w)$ is the energy relaxation time.

3 Simulation Results

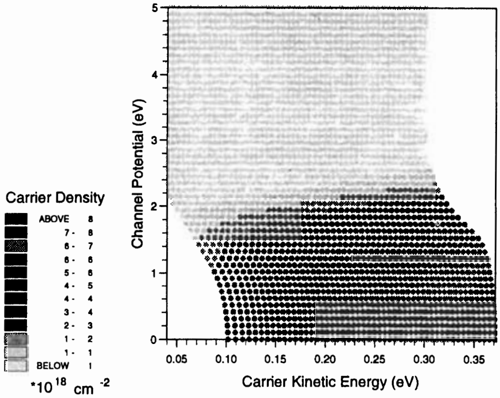

Figure 3: Shift in carrier kinetic energy due to degeneracy.

Figure 3 shows the shift in kinetic energy of the electron gas as the sheet electron density increases beyond the non-degnerate boundary. The maximum kinetic energy shift corresponds to around 0.06eV above the classical thermal energy of an ideal gas.

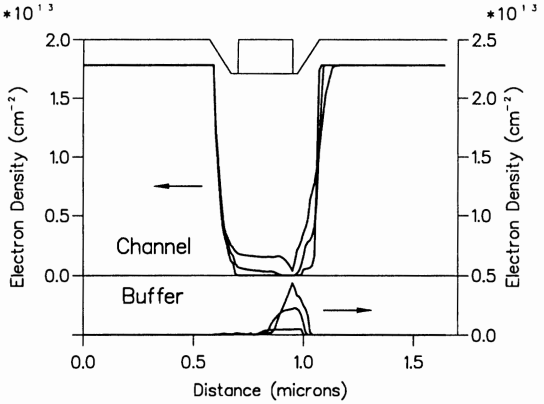

Figure 4: Carrier density profile variation as V_{GS} changes from 0V to device pinch-off.

Figure 4 shows the sheet electron density profile in the channel and in the buffer which are calculated from the charge control model and analytical substrate penetration models respectively. The diagram shows the evolution of the profiles as the gate bias is swept from zero volts to device pinch-off. Clearly the penetration of the conduction path into the buffer plays an important role in describing both the DC *and* RF operation of the HEMT. This point is reflected in Figure 5 which shows excellent pinch-off of the DC I-V characteristics and also the ability of the model to predict device breakdown at high currents and voltages.

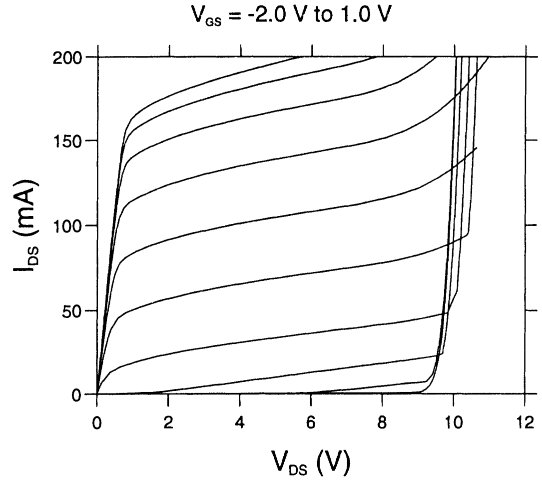

Figure 5: DC I-V characteristics for 0.25 × 150 μm pseudomorphic HEMT.

4 Conclusions

The new implementation of a Quasi-two Dimensonal HEMT model presented in this paper has for the first time made it possible to predict device pinch-off at high drain bias. The execution time of the simulations remains extremely fast, making the model well suited to consideration of large signal device/circuit design.

References

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