FAST AND ACCURATE HFET MODELLING FOR MICROWAVE CAD APPLICATIONS

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ABSTRACT

A new *quasi-two-dimensional* HFET model has been developed that solves the physical device equations in a more rigorous fashion than previously reported. The model incorporates a quantum mechanical description of the free electron concentration, self-consistently solving Schrödinger's and Poisson's equations, making it applicable to devices with scale lengths smaller than 20nm. The conventional one-dimensional charge control simulation is shown to be inadequate at the drain edge of the gate and is replaced by a quasi-two-dimensional version that more accurately describes the channel under drain-source bias. This modification produces much improved pinch-off characteristics which are essential for digital and low-noise characterisation.

I. INTRODUCTION

Quasi-two-dimensional (Q2D) FET models are based upon the fact that in the active region of the device the equipotential lines are essentially parallel, normal to the free surface, allowing the full two-dimensional device equations to be separated into their x and y components [1,2]. Conventional HFET models then proceed to solve these equations in terms of a charge-control law, taken perpendicular to the heterojunction(s), and a 'channel simulation' involving the carrier dynamics. The charge-control element typically consists of a self-consistent solution of Poisson's equation with the charge density (1) but with the first term, $\partial\mathscr{E}_x/\partial x$, set to zero.

$$\frac{\partial(\varepsilon_r \mathscr{E}_x)}{\partial x} + \frac{\partial(\varepsilon_r \mathscr{E}_y)}{\partial y} - \frac{q}{\varepsilon_0}.\left(N_D^+ - n\right) = 0 \tag{1}$$

The channel simulation then solves the full Poisson equation together with the current-continuity and the energy and momentum conservation equations. Here the values for $\partial\mathscr{E}_y/\partial y$ and N_D^+ obtained from the charge-control law are used, and the equations solved in a 'current-driven' form. However, the omission of the $\partial\mathscr{E}_x/\partial x$ term in the charge-control equation leads to important errors. When the $\partial\mathscr{E}_x/\partial x$ term tends to $-\infty$ the electron density increases indefinitely to compensate, but when the opposite extreme is approached, $\partial\mathscr{E}_x/\partial x$ tending to $+\infty$, the electron density can only be reduced to zero. The equations described above do not operate in this fashion since as the $\partial\mathscr{E}_x/\partial x$ term in the channel simulation increases to $+\infty$ they predict the sheet electron density tends to $-\infty$, which is clearly wrong. This leads to poor simulation of the pinch-off characteristics where the most extreme fields are produced.

II. THE QUASI-TWO-DIMENSIONAL MODEL

The new scheme described in this paper modifies the charge-control law, making the $\partial\mathcal{E}_y/\partial y$ and N_D^+ terms functions of $\partial\mathcal{E}_x/\partial x$. This is performed by supplementing the one-dimensional Poisson equation used in the charge-control law with a constant term representing $\partial\mathcal{E}_x/\partial x$ which is applied to the channel and substrate penetration regions, Figure 1.

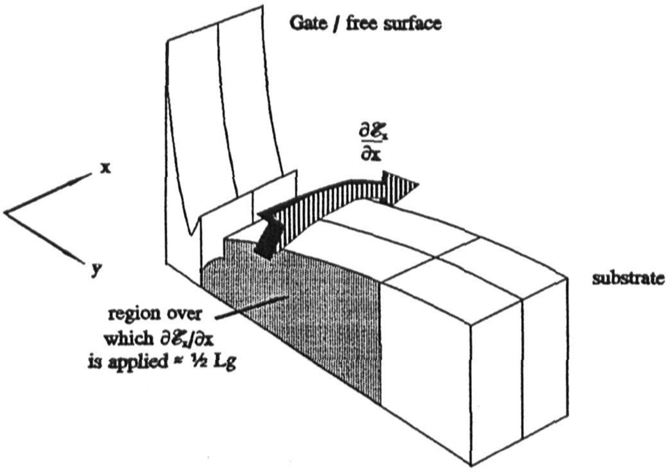

Figure 1 Slice of the conduction band edge illustrating the region over which the constant term, $\partial\mathcal{E}_x/\partial x$, is applied.

This produces typical conduction band-edge diagrams illustrated in Figure 2. Here the $\partial\mathcal{E}_x/\partial x$ term is varied illustrating the effect at extreme biases.

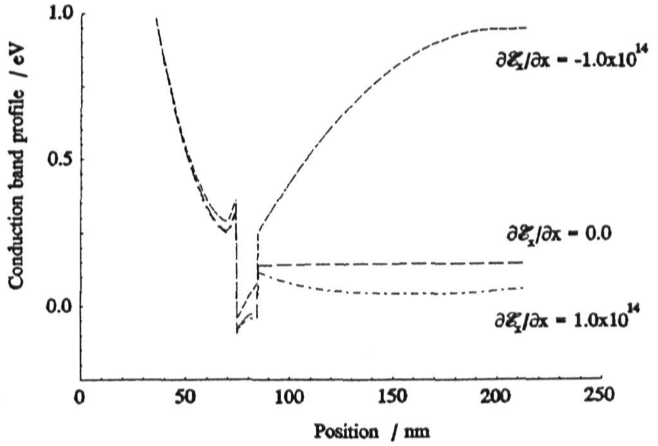

Figure 2 Conduction band profiles for various values of $\partial\mathcal{E}_x/\partial x$

To accommodate the small scale lengths associated with heterostructure devices quantum mechanics is introduced by including Schrödinger's equation in the charge-control law. The self-consistent solution of Poisson's and Schrödinger's equations is performed within the framework of a modified Newton-Raphson iterative scheme that rapidly, accurately and robustly solves the equations over all appropriate biases. This method requires the partial derivatives of λ and Ψ with respect to electrostatic potential [3]. Applying perturbation theory to Schrödinger's equation, these parameters turn out to be -1 and 0 respectively (2).

$$\frac{\partial \lambda}{\partial V} = -1 \ , \ \frac{\partial \Psi}{\partial V} = 0 \tag{2}$$

The equations are then solved for a range of biases and the results stored in a look-up table. This produces the two-dimensional surface illustrated in Figure 3, where the two-dimensional nature of this term is apparent. Here the 'effective sheet electron density' listed on the z axis represents the integral of $\partial \mathscr{E}_y/\partial y + N_D^+$ over the whole of a vertical slice. The two-dimensional look-up table is then used in the channel simulator which extracts the value of this combined term using a two-dimensional cubic spline routine.

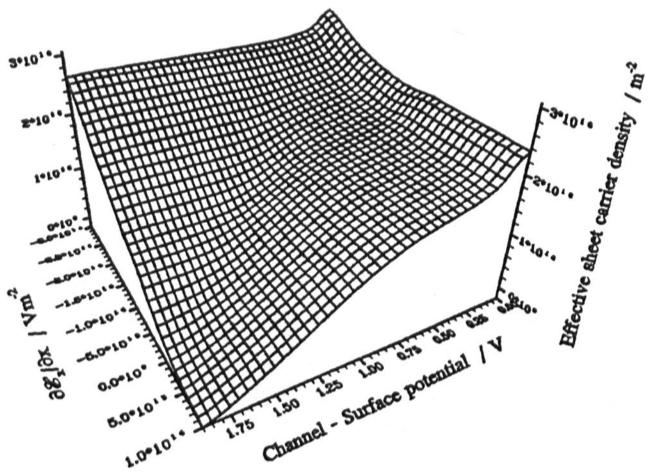

Figure 3 Two-dimensional variation of the effective sheet electron density ($\int \partial \mathscr{E}_y/\partial y + N_D^+ .dy$)

Figure 4 illustrates the effect the two-dimensional charge control law has on the pinch-off characteristics of a simulated device. Here the poor pinch-off of the conventional scheme is illustrated and compared with the improved results of the new model. It is worth noting that accurate simulation of pinch-off is essential for digital device modelling and also that most low-noise devices are operated in this region.

III. Microwave simulation

The S-parameter calculation requires the microwave gate current to be calculated together with the access capacitances. The first term is proportional to the capacitance associated with the charge-control law and turns out to be relatively independent of the $\partial \mathscr{E}_x/\partial x$ term. Hence a one-dimensional look-up table is sufficient. This method provides an accurate estimate of the gate current evident in the good agreement between measured and simulated S-parameters illustrated in Figure 5.

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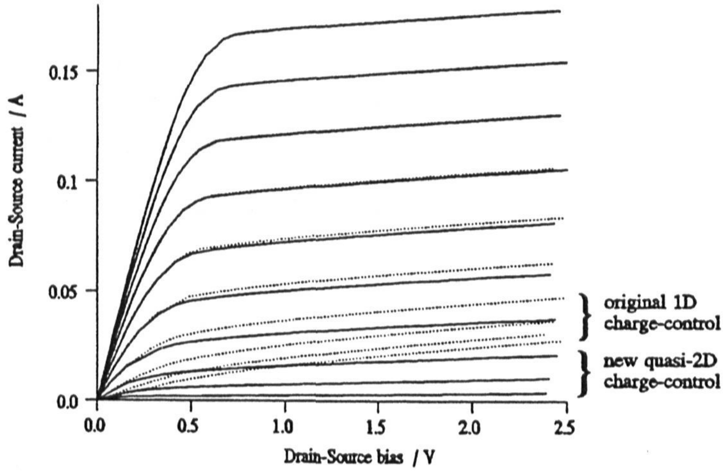

Figure 4 I_{DS}-V_{DS} curves for old and new charge-control schemes

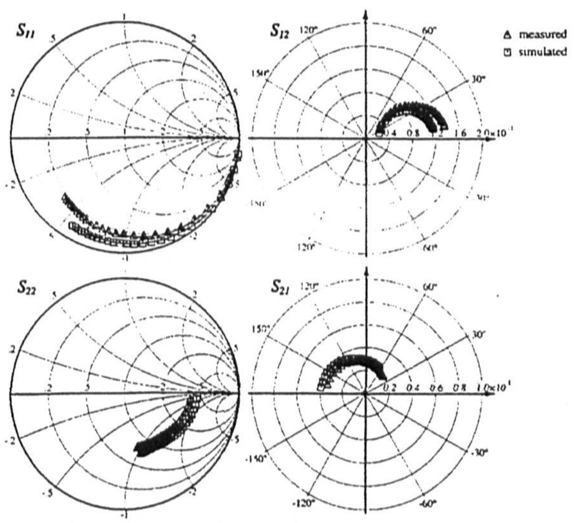

Figure 5 Comparison of measured and simulated S-parameters for a British Telecom AlGaAs/GaAs HEMT

IV. REFERENCES

[1] C.M. Snowden and R.R. Pantoja, "Quasi-Two-Dimensional MESFET Simulations for CAD", *IEEE Trans Electron Devices*, Vol. ED-36, No. 9, pp. 1564-1574, September 1989

[2] R.R Pantoja, M.J. Howes, J.R. Richardson and C.M. Snowden, "A Large-Signal Physical MESFET Model for Computer-Aided Design and Its Applications", *IEEE Trans Microwave Theory and Techniques*, Vol MTT-37, No. 12, pp. 2039-2045, December 1989

[3] R. Drury, C.M. Snowden and R.E. Miles, "A New Fast Full 2D Quantum Model for Heterojunction Field Effect Transistors", *International Workshop on Computational Electronics*, Leeds, England, August 1993