COMPARISON OF QUASI-2D AND ENSEMBLE MONTE CARLO SIMULATIONS FOR DEEP SUBMICRON HEMTS

Chris G. Morton, Hewlett-Packard Co., Santa Rosa, CA, USA
and Christopher M. Snowden, The University of Leeds, Leeds, UK

Abstract

In this paper, we present corroborative material indicating the accuracy of our quasi-2D HEMT model when applied to the analysis of deep sub-micron devices. We compare our modelling results with those derived from Ensemble Monte Carlo simulations, and demonstrate excellent agreement in the velocity profiles for 0.5, 0.25 and 0.05 micrometre gate-length devices.

I Introduction

The motivation for this work stems from the need for fast and accurate simulation of microwave and millimeter-wave HEMTs. For device simulation to provide significant benefit to the engineer it needs to exhibit execution times that are of the order of minutes rather than hours or days. The focus of this study is on the ultimate limits of the quasi-2D (Q2D) approach in describing operation of short-gate-length devices typically used in present-day monolithic ICs. Our focus is specifically on the description of velocity overshoot in sub-micron HEMTs, an effect which is well known for its impact on high-frequency device performance. We use as a reference the analysis of Kizilyalli *et al.* [1], which is based on the solution of the coupled Boltzmann Transport and Poisson equations using the ensemble Monte-Carlo method. We consider the results

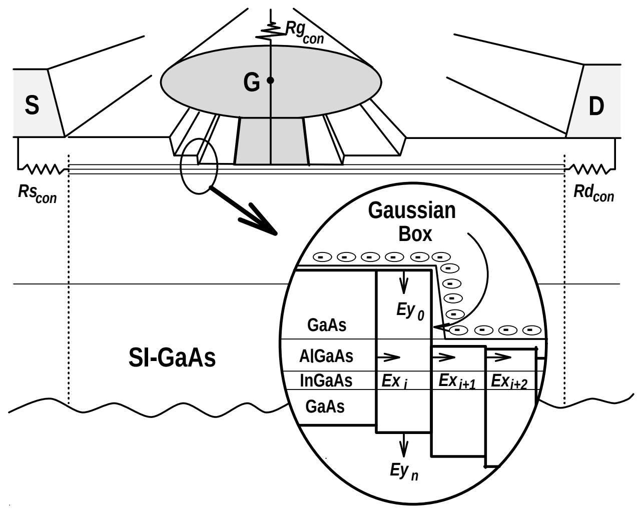

Figure 1: Schematic of Q2D approach for the HEMT

derived from this approach to be a suitable reference for identifying any fundamental limitations with our Q2D model. Application of our model to the simulation of real devices has been reported elsewhere [2].

II Modelling Approach

The basis of the Q2D approach is the assumption that carrier transport takes place predominantly in a single spatial dimension (defined here as the x-direction) from the source to the drain contact [3]. This assumption relies on the fact that the equipotential lines in the active channel

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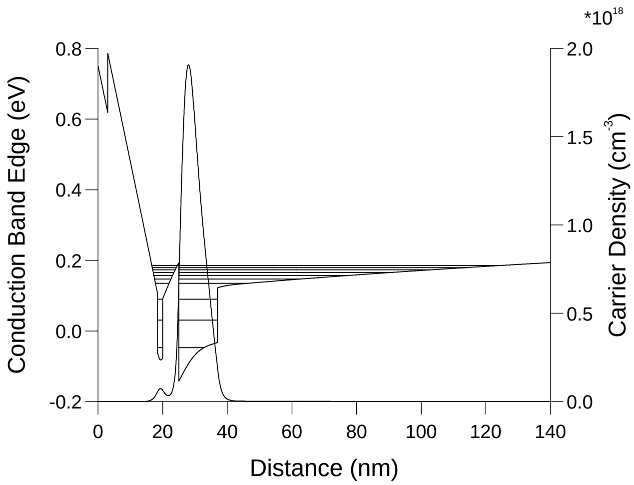

Figure 2: Channel profile at source side of gate contact

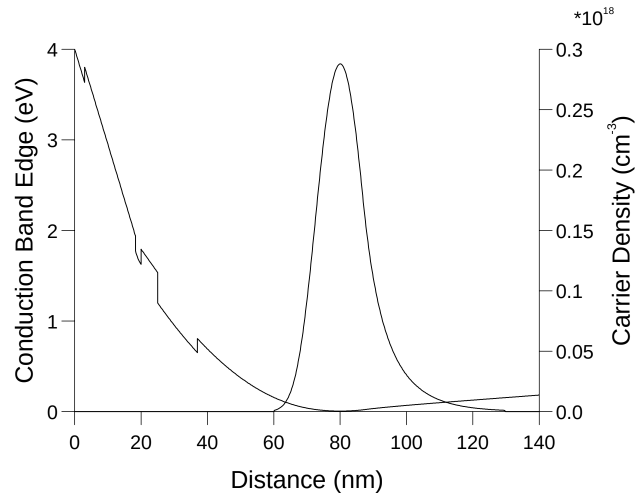

Figure 3: Channel profile at drain side of gate contact

of the HEMT are parallel. Once this assumption has been made, the electric field profile from source to drain can be calculated based on the propagation of a Gaussian box from the source to the drain as shown in Figure 1. Velocity overshoot is included through the well-known hydrodynamic approach as documented for the Q2D formulation in [3]. The charge within the Gaussian box is calculated from a solution of the coupled Poisson-Schrödinger equations and is influenced by the box height, the structure of the active layers, and the gradient of x-directed electric field, dE_x/dx, [2] and references therein. Figure 2 shows a cross-section of the active layers of a HEMT at the source side of the gate where we see that carriers are located primarily in the device channel. Figure 3 shows a cross-section taken at the drain side of the gate. In this case, the depletion region extends beyond the channel so that the only path for carriers is through the buffer. The carrier density distribution in the buffer is formed by the sharply increasing field on the drain side of the gate which results in a non-zero value of dE_x/dx. Figure 4 shows how this mechanism is integrated into device operation. Here we see that, under certain bias conditions, carriers are injected into the buffer (depicted by n_{buf}) from the channel, close to the source side of the gate, due to the sharp increase in the field, E_x. We also see that the reduction in carrier velocity v_x, following overshoot, gives rise to a substantial increase in the buffer carrier density, driven by the condition of current continuity.

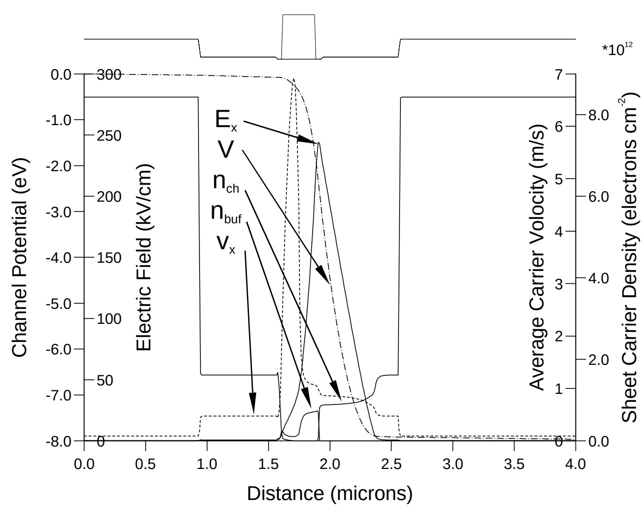

Figure 4: Device profiles derived from Q2D simulation

III Analysis

Figure 5 shows the device structure used in the comparison of the Q2D and Monte-Carlo models. Our structure differs slightly from that used

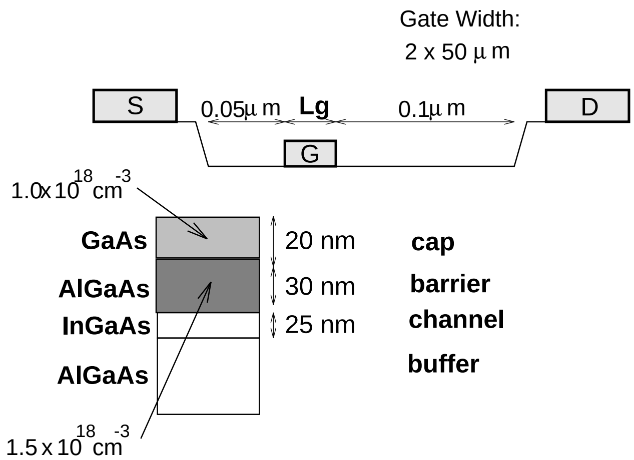

Figure 5: Test structure used in model comparisons

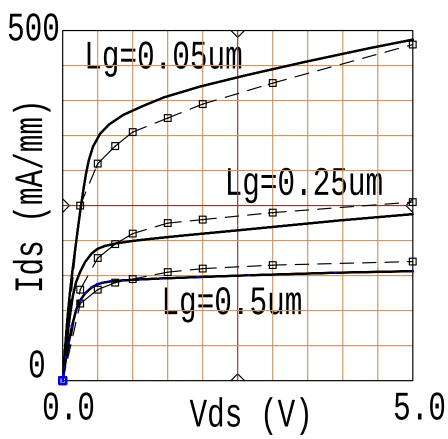

Figure 6: Model comparison using DC I-V, $V_{GS} = 0.4$V (dashed Monte Carlo, continuous Q2D)

in [1] due to the difficulty of introducing an n^+ layer in the channel at the edges of the solution domain. Instead, we have used a heavily-doped cap layer to produce a similar sheet carrier density at source and drain edges of the solution domain. Figure 6 shows a comparison of I-V characteristics, derived from Monte Carlo and Q2D solutions, for an applied gate-source voltage of 0.4V. For each of the three gate lengths, reasonable agreement is observed, both in the current level and output conductance of the devices. Slight discrepancies between the results could be attributed to differences in the test structure or material parameters used in the simulations. Certainly, the inclusion of size-quantization in our calculation does not explain the differences between simulation results, since the channel thickness is too large to make quantum-mechanical effects important. Figures 7 and 8 show the channel sheet carrier density and average carrier ve-

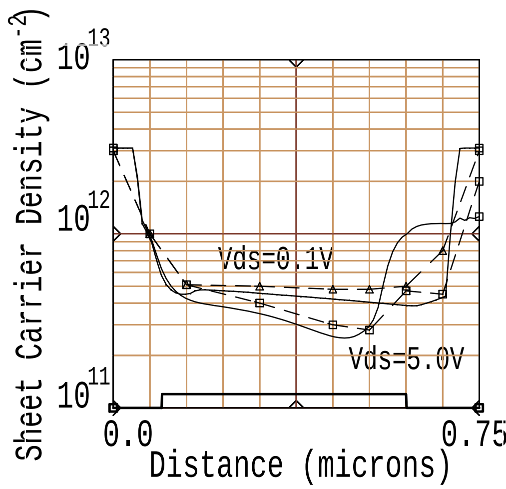

Figure 7: Model comparison using channel sheet carrier density $L_g = 0.5\mu$m (dashed Monte Carlo, continuous Q2D)

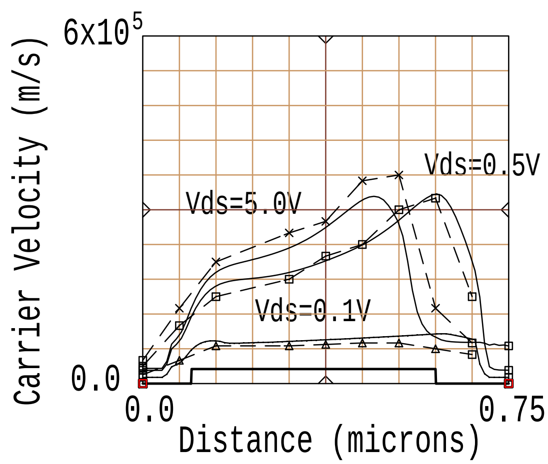

Figure 8: Model comparison using average carrier velocity $L_g = 0.5\mu$m (dashed Monte Carlo, continuous Q2D)

locity across the 0.5 μm device. A similar analysis is shown in Figures 9 and 10 for the 0.05 μm device. Here we see excellent agreement, both in terms of peak velocity and the general shape of the responses. There are some discrepancies in carrier density on the drain side of the device, after the point of overshoot, where we see a considerable build-up of charge in our simulation. In fact, the Monte Carlo simulation also predicts a large build-up of carriers on the drain side of the device, but in the buffer (not shown here) rather than across the active layers. We do not attribute this discrepancy to any fundamental limitation with our approach, however, since we have already shown that buffer injection can also be predicted by the Q2D simulation. Instead, we attribute this discrepancy to the difference between our recessed geometry and the planar geometry, used together with the artificial n^+ regions, which could lead to differing lateral extensions of the depletion region on the drain side of the device.

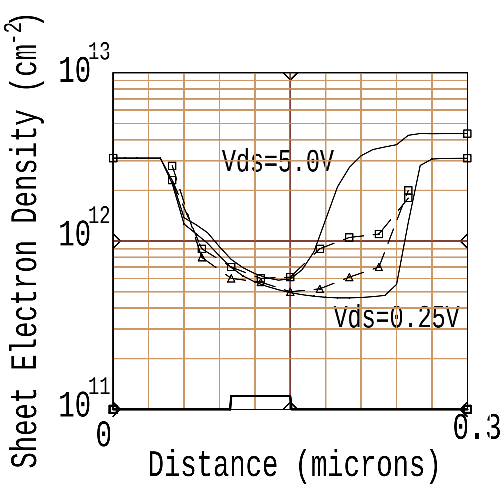

Figure 9: Model comparison using channel sheet carrier density $L_g = 0.05\mu\text{m}$ (dashed Monte Carlo, continuous Q2D)

1 IV Conclusions

In summary, we have demonstrated the accuracy of our Q2D model, particularly in the description of velocity overshoot. Our findings suggest that the model formulation is capable of describing deep sub-micron device operation without the

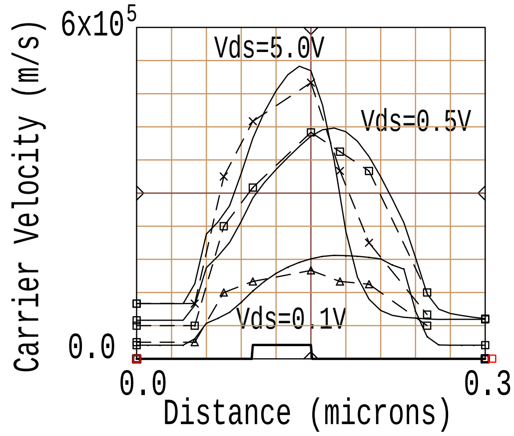

Figure 10: Model comparison using average carrier velocity $L_g = 0.05\mu\text{m}$ (dashed Monte Carlo, continuous Q2D)

need for resorting to more precise and computationally intensive solution schemes.

References

[1] I. C. Kizilyalli, M. Artaki, and A. Chandra. Scaling properties and short-channel effects in submicrometer AlGaAs/GaAs MODFETs: A Monte Carlo study. *IEEE Trans. Elec. Dev.*, 40(2):234–249, February 1993.

[2] C.G. Morton, J.S. Atherton, C.M. Snowden, R.D. Pollard, and M.J. Howes. A large-signal physical HEMT model. *Proceedings of MTT Symposium*, June 1996.

[3] C. M. Snowden and R. R. Pantoja. Quasi-two-dimensional MESFET simulations for CAD. *IEEE Trans. Elec. Dev.*, 36(9):1564–1574, September 1989.