A full 3D TCAD framework for nanosheet transistors including quantum-confined channels

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Introduction

Nanosheet FETs utilizing ultrathin, quantum-confined semiconductor channels, offer a promising solution for sub-10 nm scaling for high-speed digital logic [1] and may also provide a path to high-speed RF power electronics using wide bandgap materials such as GaN. Simulating nanosheet FETs in TCAD is essential for understanding their physics and guiding device design. While previous approaches using NEGF and Monte Carlo methods are accurate, their high computational cost limits their practicality for device design exploration. This paper introduces a computationally efficient 3D TCAD framework for simulating nanosheet FETs, taking into account the quantum confinement in the channel. The presented framework integrates the Schrödinger equation to account for quantum subbands in the channel and couples the real-space transport of 2D electrons in these subbands with 3D charge transport in the surrounding bulk materials.

TCAD Framework

Figure 1 presents the schematic of a test GaN nanosheet HEMT structure, featuring a 12 nm GaN channel and a 5 nm $Al_{0.3}Ga_{0.7}N$ barrier, with n^+ GaN bulk regions beneath the source/drain contacts. The 3D transport in the bulk is modeled by solving the moments of the Boltzmann Transport Equation (BTE) using the Fermi Kinetics Transport (FKT) solver, a TCAD framework developed at the Air Force Research Laboratory [2]. Unlike conventional BTE solvers, FKT employs an alternative formulation of electronic heat flow based on heat capacity of ideal Fermi gas, offering superior numerical stability and convergence properties. In the quantum-confined channel, the Schrödinger is solved along confinement direction self-consistently with Poisson's equation to compute the subbands (see Figure 2 for wavefunctions). The 2D transport along the channel length is treated classically by adapting the FKT framework to two dimensions using the 2D moments of the BTE. The 3D bulk transport and the 2D channel transport are coupled through ballistic thermionic emission, linking the bulk conduction band with the channel subbands, as shown in Figure 3. Furthermore, FKT can incorporate the full bandstructure with transport simulations taking into account the various scattering mechanisms [3]. The 3D transport model utilizes bulk GaN band structure derived from empirical pseudopotential method (EPM), while the integration of 2D band structure with the 2D transport will be addressed in future work (the methodology to do so is indicated in Figure 4).

Results

To demonstrate the superior electrostatics of the nanosheet device particularly for scaled gate lengths, we compare the subthreshold characteristics of nanosheet HEMTs with bulk HEMTs for gate lengths ranging from 100 nm to 10 nm. As illustrated in Figures 5-7, nanosheet HEMT consistently demonstrates reduced leakage currents and improved subthreshold swing as gate length decreases, outperforming the bulk HEMT. The on-current of the nanosheet device can be improved in structures where multiple sheets are integrated in parallel, providing additional conduction channels [4]. The nanosheet HEMT was simulated using the effective mass approximation with constant mobility, which is reasonable for estimating the subthreshold characteristics; nevertheless, the inclusion of the full bandstructure in 2D FKT is currently ongoing and will be presented in the future.

Conclusion

This work introduced a 3D TCAD framework to simulate nanoscale devices with quantum-confined channels. By incorporating Schrödinger's equation and coupling it with real-space Boltzmann transport, the framework accurately captures the essential quantum and classical transport phenomena. This versatile approach is well-suited for designing next-generation nanosheet-based devices. As a case study, the simulator was used to highlight the superior electrostatics of a GaN nanosheet HEMT over its bulk counterpart at reduced gate lengths.

References

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[3] Grupen, M., "Energy Transport Model with Full Band Structure for GaAs Electronic Devices," in Journal of Computational Electronics, vol. 10, no. 3, pp. 271–290, 2011.

[4] Tunga, A., Li, X., Rakheja, S., "Modeling-Based Design and Benchmarking of Al-rich AlGaN 3D Nanosheet MOSFET and MOSHEMTs for RF Applications," in 2021 Device Research Conference (DRC), 2021, pp. 1–2.

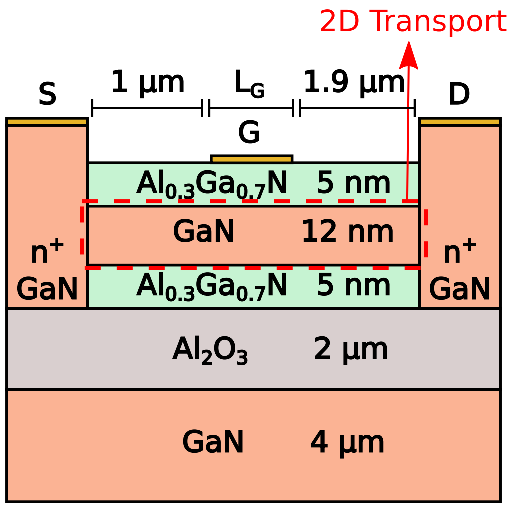

Fig. 1. Schematic of nanosheet GaN HEMT. The dotted box indicates the region where 2D transport is solved. L_G is varied from 100 nm to 10 nm in the simulations.

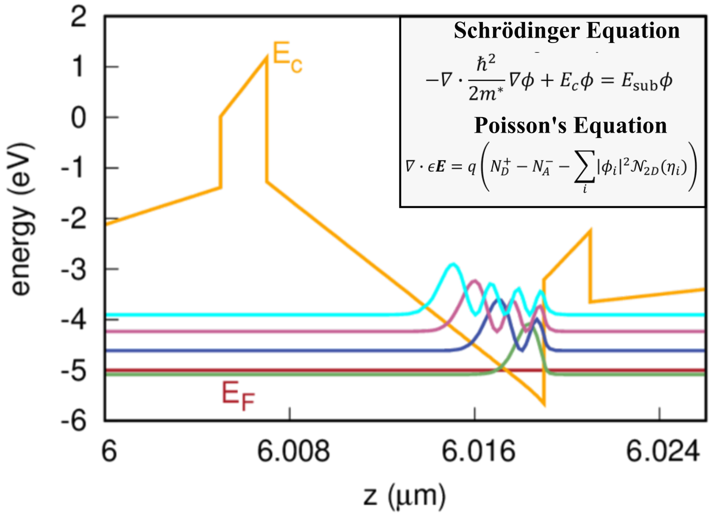

Fig. 2. Wavefunctions in the channel at the center of the gate at equilibrium, obtained from self-consistent solution of coupled Schrödinger-Poisson equation.

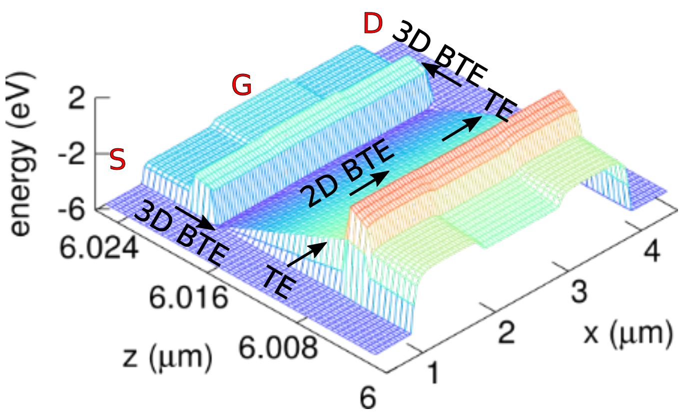

Fig. 3. Coupling 3D BTE in the bulk region with the 2D BTE in the nanosheet channel through thermionic emission (TE). The horizontal plane represents the device cross-section, and the vertical axis is the conduction band energy.

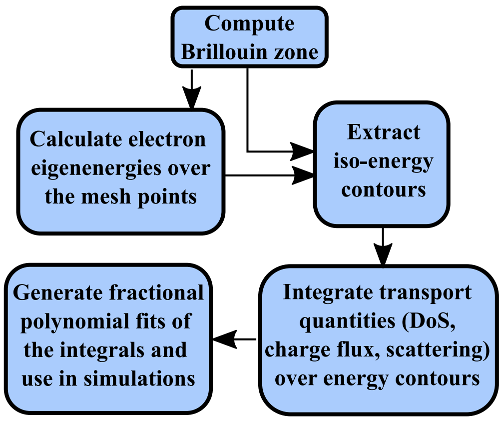

Fig. 4. Methodology to incorporate full band-structure in transport simulations.

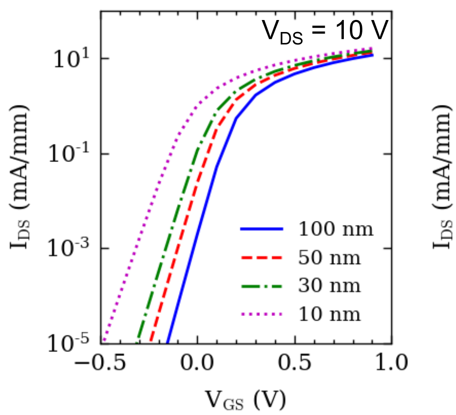

Fig. 5. Transfer characteristics of nano-sheet GaN HEMT for varying gate lengths.

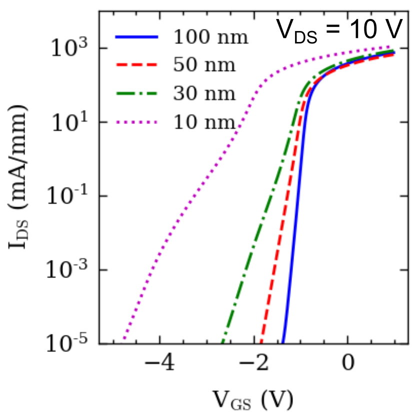

Fig. 6. Transfer characteristics of bulk GaN HEMT for varying gate lengths.

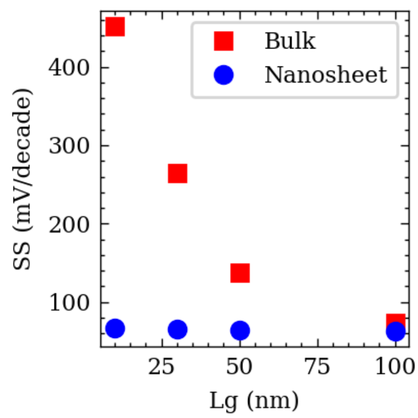

Fig. 7. Subthreshold swing of bulk and nanosheet HEMTs with varying gate lengths.