Evolution of Current Transport Models for Engineering Applications

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The continuous minimum feature size reduction of microelectronic devices, institutionalized by the ITRS roadmap, has been partly enabled by the support of TCAD tools. Device modeling tools have been established on base of the ground-breaking work of Scharfetter and Gummel [1]. Since then, numerous transport models of increasing complexity have been proposed, see Fig. 1. From an engineering point of view, the drift-diffusion model [2] has proven amazingly successful due to its efficiency, numerical robustness, and the feasibility to perform two- and three-dimensional studies on fairly large unstructured grids. However, several shortcomings of this model are critical for miniaturized devices. Hot-carrier effects motivated the development of higher-order transport models such as the hydrodynamic, energy-transport, and six-moments model [3], which allow the electron energy distribution function to be described beyond the Maxwellian approximation (see Fig. 2). The full-band Monte Carlo method got accepted as a calibration tool for these models, since it precisely accounts for the various scattering processes [4]. Fig. 3 shows a comparison of different macroscopic simulation approaches [5]. Macroscopic transport models are used routinely in commercial and academic general-purpose device simulators. However, the fabrication of structures in the nanometer regime triggered the development of quantum-mechanical modeling tools. This comprises quantum-mechanical one-dimensional capacitance-voltage simulators which are established tools for the characterization of gate dielectrics. The semi-classical transport models have been augmented by tunneling models [6]. Furthermore, purely quantum-mechanical device simulators have been developed which may be based on the Non-Equilibrium Green's Function formalism [7], the quantum transmitting boundary method [8], the transfer-matrix method [9], or the Kohn-Sham set of equations [10]. These simulators, however, are usually limited to specific geometries, restrictive grids, or small length scales. Typical applications are double-gate MOSFETs as shown in Fig. 4. Modern microelectronic devices, however, are characterized by the transition between large reservoirs with strong carrier scattering, and small regions where quantum effects dominate. This explains the general interest to incorporate both classical and quantum-mechanical modeling approaches into macroscopic device simulators. To first order, quantum correction models can account for these effects. A more rigorous approach is to derive macroscopic transport models from the Wigner equation, which leads to the Density-Gradient model [11], or to self-consistently couple Schrödinger-Poisson solvers with the transport model used [9]. Even more rigorously, the Wigner equation can directly be solved by means of the Wigner Monte Carlo method, as shown in Fig. 5 [12]. An overview and examples of these approaches, namely higher-order transport models, the different quantum correction approaches, and the Wigner Monte Carlo method will be presented.

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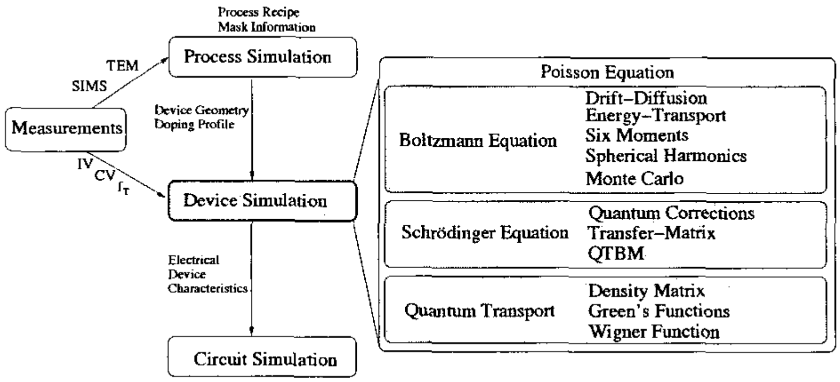

Figure 1: Hierarchy of process, device, and circuit simulation in TCAD modeling.

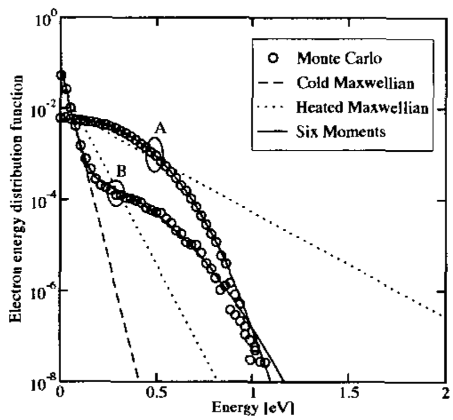

Figure 2: Distribution function in a MOSFET near source (A) and near drain (B).

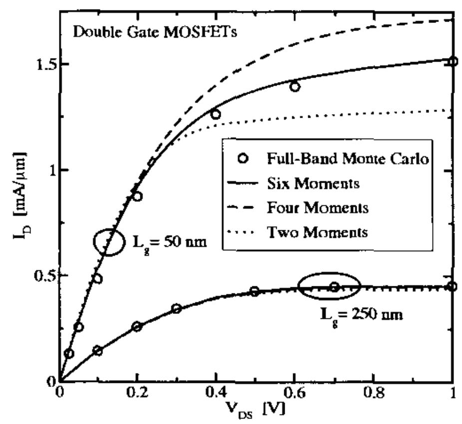

Figure 3: Comparison of macroscopic transport models with full-band Monte Carlo [5].

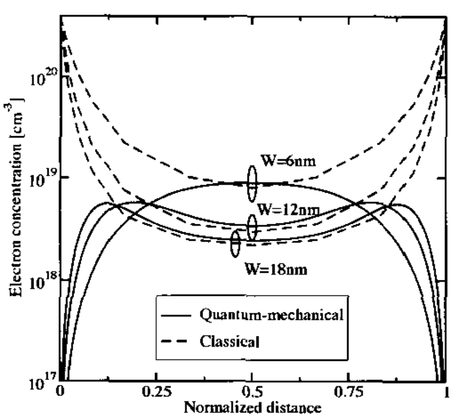

Figure 4: Carrier concentration in ultrathin DG-SOI devices with different widths (W).

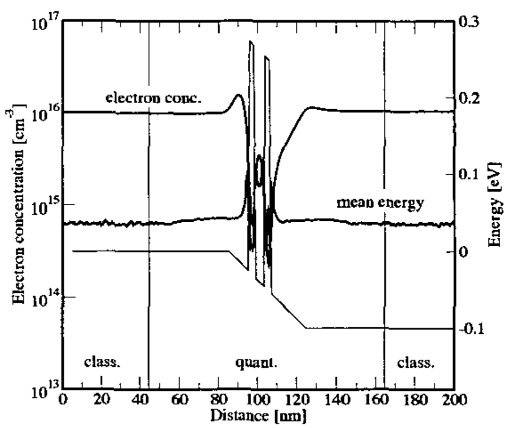

Figure 5: Wigner Monte Carlo results for a resonant tunneling diode [12].