PHYSICS-BASED COMPACT MODELING OF QUASI-BALLISTIC TRANSISTORS

ABSTRACT

This Ph.D. study deals with the development of physics-based compact models for advanced semiconductor devices with a focus on quasi-ballistic (QB) transistors. The initial part of the thesis deals with Fermi potential modeling of III-V (InGaAs)-based High Electron Mobility Transistors with rectangular quantum well. The III-V material based devices usually have higher mobility due to their large mean free path (λ). When compared to silicon-based devices, the large λ devices show a faster onset of ballistic effects with channel length scaling. The drift-diffusion (DD) based devices are scattering limited whereas the QB devices are limited by the injection velocity. The mobility (μ), which is defined in a scattering dominant environment, loses its validity in QB regime. Hence, the DD based models cannot be used to study the physics of devices operating in QB regime. Similarly, the QB models in literature fail to capture the DD device physics. The current literature lacks models that exclusively study the DD to QB transition even though DD and QB devices have been well modeled individually.

In the major part of this thesis, critical length (δ), defined based on the thermal energy drop with respect to the virtual source, is presented as a better parameter for ballisticity. The δ is derived from the Quasi-2D solution of the Poisson equation and captures the device parameter (oxide thickness, body thickness, doping, and channel length) dependencies. The proposed model is validated with extracted Monte-Carlo simulation results from the literature. The model can be used to predict the onset of ballistic behavior based on the relative magnitude of the δ to λ. The δ model is further used to calculate the apparent μ, which could be used similarly to diffusive μ to predict the electrical characteristics in QB regime. To exclusively study the DD to QB transition, the velocity vs. electric field characteristics of the DD devices is extended to the QB regime. This new approach is used for an in-depth analysis of the transition region in conceptual MOS devices. The impact of various material parameters like λ, thermal velocity, and saturation velocity are well studied at different channel length scales. The proposed model tallies well with the DD and QB regime device physics. The model is also tested for its temperature dependence, which is, to the best of our knowledge, the first in literature. The model is validated with SOI measurement data for channel lengths spanning from DD to QB regimes.

The last part of the thesis focuses on the study of QB transport on the low-frequency noise (LFN). A modified $(g_m/I_d)^2$ method for the subthreshold regime is proposed to aid in characterizing the LFN origin. Also, the recent measurement results on devices operating in ballistic regime show LFN scaling trend that cannot be explained using the well-established carrier number (CNF) and correlated mobility fluctuation (CMF) theories developed for DD devices. The CNF/CMF theory is extended to the QB regime to give a physical explanation for the anomalous LFN scaling behavior. The proposed models are validated with measurement data extracted from the literature.