

# Preface

With the size shrinking down to the submicrometer scale and working frequency rising up to the subterahertz range modern semiconductor devices are performing under strong and/or rapidly time-varying electromagnetic fields. In these circumstances not only fails the conventional linear relationship between the current density and the electric field, but the drift-diffusion model, which has so far been the main basis for most device simulations, is no longer valid for describing the carrier transport in devices. The development of modern microfabrication techniques has been forcing people to bring the quantal condensed-matter physics directly into the arena of electronics yet intending the transport process to be expressed in a way as concise as possible.

Since 1950s physicists have been proposed many transport theories based on the many-particle quantum and statistical mechanics and using innovative techniques such as superoperators, path integrals, correlation functions, Feynman diagram expansions, nonequilibrium Green's functions, Wigner distribution functions, etc. These theories have been great success, but are often formidable to deal with accurately and few of them seems to offer a simple transport dynamics embodying scattering mechanisms in a realistic semiconductor. Over the years, with quantal ingredients putting in from time to time, the Boltzmann-type equations for the distribution function of microscopic particles remain almost the only theoretical tool capable of generating useful performance-oriented information in a device. As a statistical but complete description of carrier transport the distribution function can, in principle, be solved from the Boltzmann equation under the condition of given electric and magnetic fields and given impurity, phonon and intercarrier scatterings, and then all the transport quantities are obtained. In practice, solving the Boltzmann integro-differential equa-

tion is a very hard job for realistic scattering mechanisms especially in the presence of electron–electron interactions. Drastic approximations, such as relaxation-time treatment, are usually taken in order to obtain quasi-analytical results.

With the development of modern computational capacity, Monte Carlo and other numerical techniques have been employed in transport calculations. They allow numerical solution to the Boltzmann equation with less approximations and have become powerful tools in investigating semiconductor transport and device modeling. However, pure numerical methods having intrinsic shortcomings in offering physical insights and systematic analyses, can never replace an analytical or quasi-analytical theory.

In many cases, for the calculation of concerned transport quantities it is sufficient to know a partial relevant information of transport rather than the distribution function containing the complete information. With this in mind people derive moment equations of finite orders from the Boltzmann-type equation and, under some further approximations, establish hydrodynamic transport theories. These theories have been playing very important roles in simulating carrier dynamics in various semiconductor devices.

In 1984, C.S. Ting and the author of the present book proposed a balance-equation scheme based on the separation of the integrative mechanic motion of the whole carrier system (the center of mass) from the statistical motions of individual carriers and developed a transport theory using the average carrier drift velocity as the control parameter. Contrary to most existing dynamic response theories (such as Boltzmann-type theory) in which the current density and other transport quantities (e.g. the conductivity) are calculated from the distribution function obtained as the response to a given electric field, in the balance-equation theory the electric field is derived to balance the frictional force for a given carrier drift velocity thus the transport property (e.g. the resistivity) is obtained as a function of the drift velocity or the current density, a physical quantity most affecting the conduction behavior and most direct controlled in the experiment.

Because of technical difficulties, electron–electron interactions, which can be of vital importance, are often ignored in most of transport treatments. The admission to including electron–electron interaction introduces considerable complication. However, there is a substantial simplification in the situation when electron–electron interactions are large enough to induce rapid thermalization of the carriers about their drifted transport state. This opens the possibility of a quasi-analytic description of transport in the

strong electron–electron scattering limit in the balance-equation theory.

Due to its simplicity and effectiveness, the balance-equation approach has become a useful tool to deal with many realistic transport phenomena in semiconductors, and provided a reliable basis for developing theories, modeling devices and explaining experiments.

This book is devoted to a systematic, comprehensive and up-to-date description of the physical basis of the balance-equation theory and its applications to various transport problems in various types of semiconductors. The different aspects of the balance-equation method were reviewed in the volume entitled “Physics of Hot Electron Transport in Semiconductors” (edited by C.S. Ting, World Scientific, 1992). Since then, the balance-equation theory has been further developed and extensively applied to investigate various new transport phenomena, such as transport in nonparabolic systems, spatially inhomogeneous transport and device modeling, miniband transport of semiconductor superlattices, radiation-induced transport and magnetotransport, effects of impact ionization in high-field dc and high-frequency transport, microwave-induced magnetoresistance oscillation, radiation-induced electron cooling, etc. The present book complements the volume of “Physics of Hot Electron Transport in Semiconductors” and part of the material is a direct extension of the first review article written by me and N.J.M. Horing in that book.

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