PHYSICS OF HOT ELECTRON TRANSPORT IN SEMICONDUCTORS

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edited by

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PREFACE

The development of submicrometer semiconductor devices during the past decade has underscored the need for a better theoretical understanding of carrier transport in these small sized systems. Even a few volts applied across the device can lead to a rather high electric field on the order of 10^4 V/cm. In these circumstances, the relationship between current and voltage is no longer linear, and the statistical temperature of the charge carriers becomes higher than that of the heat bath. Thus, the carrier dynamics under a strong electric field are characterized as "hot electron transport" Since the first survey on this subject by E. M. Conwell in her review *High Field Transport in Semiconductors* (New York: Academic Press, 1967), where the experimental data were analyzed with the phenomenological Boltzmann equation, many new experimental techniques and theoretical methods have been developed or proposed to study hot electron transport in various semiconductors. In particular, Monte Carlo simulation methods have been introduced to solve the Boltzmann equation numerically. A useful review of such developments can be found in the book *Hot Electron Transport in Semiconductors* edited by L. Reggiani (New York: Springer-Verlag, 1985). However, in the present volume, we shall review primarily analytical approaches developed since 1984 for treating various kinds of hot electron transport problems.

The balance equation method, originally proposed by X. L. Lei and myself in 1984 for the purpose of investigating steady state hot electron transport, has subsequently been extended to study thermal noise, time dependent transport, and other subjects relating to charge carriers in strong electric fields. The predicted theoretical results are in good agreement with both experimental measurements and Monte Carlo numerical simulations. Much of the simplicity of the mathematical structure of the balance equation approach arises in conjunction with its effectiveness in dealing with many-electron systems having strong inter-carrier collisions, and it is particularly powerful in this respect. Extensive reviews of this method are given by the first two articles, which deal with it in the absence and presence of a magnetic field. When hot electrons are confined to a quantum well, the proper treatment of the electron-phonon-coupling involving phonons which propagate in three dimensions requires special care, because phonon heating produces a bottleneck in the rate energy transfer from electrons to phonons. This subject is carefully reviewed in Article 3. During the past decades, the intra-collisional field effect (ICFE), which has been promoted as a major ingredient of quantum transport theory, has drawn tremendous theoretical efforts in the attempt to understand its influence on hot electron transport (see Section 16, Article 1). Nevertheless, all the numerical calculations to date seem to indicate that this effect yields almost no correction to steady state transport up to a field strength of 10^7 V/cm except possibly minor modifications to the classical overshoot behavior within a time scale $t > 10^{12}$ sec. ($\sim$ electron-phonon scattering time) in the transient region respond to a step electric field. Within the framework of the balance equation formulation, the intra-collisional field term is simply embedded in the structure of the memory

function wherein the drift velocity of the charge carriers is taken in its time dependent form — accelerated by the electric field, even with the neglect of contributions from the electron-phonon interaction and other scattering mechanisms. This feature will be discussed in Article 4, where the memory effect is demonstrated to be very important for investigating nonlinear high frequency conductivity. The method of nonequilibrium statistical operators (NSO), developed by Zubarev in the early sixties, has subsequently been employed by Kalashnikov in 1970 to study hot electron transport. In Article 5, it will be shown that had the problem been done correctly, the results obtained from NSO would reduce exactly to those of the balance equation method as described in Article 1. In this connection, I wish to emphasize that Articles 1 to 5 in this book assume charge carriers with strong carrier-carrier collisions. These collisions may originate directly from Coulomb interaction and/or indirectly from phonon mediated electron-electron interaction, with the strength of such interaction mandating a relatively high carrier density. On the other hand, for the case of very low carrier density, the charge carriers are far apart and collisions between carriers are negligible. In this situation, the transport problem needs to be treated in terms of single carrier transport, which will be discussed in Article 6 using the nonequilibrium Green's function techniques and the Feynman path integral theory. At this stage, it is of interest to note that the linear isothermal (I) impurity resistivity derived from the balance equation method outlined in Articles 1 to 5 yields the expression $\rho_i^I = \frac{m}{Ne^2} \langle \frac{1}{\tau} \rangle$, with $\frac{1}{\tau}$ and $\langle \dots \rangle$ as defined in Equations (15.38) and (15.39) of Article 1. This form is different from the standard adiabatic (A) result based upon the Kubo formula or the Boltzmann equation in the absence of carrier-carrier scattering, wherein $\rho_i^A = \frac{m}{Ne^2(\tau)}$. Although ρ_i^A and ρ_i^I are practically identical with each other at low temperatures, they are quite different at higher temperatures. The question of which formula should be used to compare with experimental measurements has been the subject of debate in the literature for quite some time. In Article 7, the authors introduce an inter-carrier collision time τ_{in} and show that ρ_i^I and ρ_i^A are derived respectively under the conditions $\tau_{in} \ll \tau$ (strong inter-carrier collisions) and $\tau_{in} \gg \tau$ (weak inter-carrier collisions). Finally, in the last paper, the dynamic conductivity and the shot noise suppression of a double-barrier resonant tunneling system, which is of great current interest (but having no links to the previous articles,) is also reviewed.

Finally, I wish to thank all the contributors to this volume for their cooperation and special efforts in writing their review articles to meet the highest standards of quality in research, as well as pedagogical clarity. Acknowledgement is also due to the Texas Center for Superconductivity at the University of Houston for support in every respect.

C. S. Ting

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