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Hot-Electron Transport in Semiconductors

Edited by L. Reggiani

With Contributions by
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Preface

In a heuristic approach the concept of hot electrons is associated with a temperature of the electron gas which is higher than that of the host lattice. This is usually realized by applying electric fields of sufficiently high strength, and the study of charge-carrier dynamics under such a condition is commonly called hot-electron transport.

Owing to the growing importance which semiconductor devices are assuming in the technology of computers and telecommunications, hot-electron transport in semiconductors is rapidly developing as a research subject. Indeed, modern microelectronics has now entered the submicrometer scale of miniaturization, and it is easy to understand that even a few volts in the applied voltage can lead to very high electric fields of the order of 10,000 V/cm. These high fields, by leading to values of the carrier drift velocity of the order of 10^7 cm/s, are also at the basis of devices operating at frequencies as high as 100 GHz.

Physical understanding of most of the microscopic processes which underlie the performances of semiconductor devices at high electric fields is provided by research into hot-electron phenomena. A first survey, describing theoretical and experimental findings up to 1965, is given in Conwell's well-known book *High Field Transport in Semiconductors*, issued as supplement in the Solid State Physics Series (Academic, New York 1967). Since then, a notable amount of work has been done. New experimental techniques have been used and different materials have been characterized. Also new theoretical methods have been introduced, enabling exact numerical solutions of the Boltzmann equation.

The purpose of this volume is to give a unifying physical interpretation of the main results which have appeared in the literature of the past 20 years on hot-electron transport in bulk semiconductors. This aim is pursued by a combination of tutorial and educational background material, and up-to-date applications to problem areas of current interest.

Many authors with international recognition have contributed to make this book highly beneficial for the reader.

Together with the description of different theoretical and experimental techniques, a great effort has been devoted to the collection and display of the most reliable data, not otherwise available in a single textbook, on the drift velocity, the diffusion coefficient and the equivalent noise temperature associated with velocity fluctuations of the best known semiconductors. Furthermore, the microscopic models pertaining to different materials have been widely discussed and summarized in useful tables. The content of the book should therefore satisfy the basic requirement of offering an up-to-date microscopic description of hot-electron phenomena, and could be destined to become a helpful standard of reference. It may be of particular interest to researchers and graduate students in the field of microelectronics, VLSI, and device modeling, in particular. It may thus be recommended as a textbook for graduate courses in physics of electronics, and electrical engineering departments.

Finally, the editor would like to express his thanks to Professor M. Cardona for having solicited this effort, to Dr. H. Lotsch for his cooperation in the editing procedure, to the authors who have contributed to this volume and to the colleagues in the Physics Department for having provided a critical scientific environment of high standard. Also acknowledged are the Computer Center of the Modena University, the Ministero della Pubblica Istruzione (MPI) and the European Research Office (ERO) for their financial support.

Modena, October 1984 *Lino Reggiani*

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1. Introduction

Lino Reggiani

1.1 Historical Survey and Scientific Motivations

For about 40 years now hot electron transport has been a fruitful subject in the field of solid-state physics both for theory and experiments. This is easily understandable in view of the determinant role that semiconductor devices are continuously playing in the developing fields of computers and telecommunications. Modern microelectronics has by now entered the submicrometer scale of miniaturization, and it can easily be seen that even a few volts in the applied voltage can lead to very high electric fields of the order of 10,000 V/cm. These high fields, by leading to values of the carrier drift velocity v_d of the order of 10^7 cm/s, are also at the basis of devices operating at frequencies as high as 100 GHz.

One should emphasize that this subject has taken advantage of most of the knowledge in the parallel field of transport in an ionized gas [1.1,2], in many cases offering valuable testing of theoretical models. Indeed, the electron gas can be confined within very small volumes (typically a few cubic millimeters) of the host crystal, which in turn can be shaped appropriately, by making use of the sophisticated technology borrowed from electrical engineering.

This has enabled scientists to devise and develop a wide series of experiments which hitherto seems to be limited only by the ingenious imagination of researchers.

From an historical point of view, the beginning of systematic analysis in hot-electron problems could be dated to the end of the 40's. At that time the scientific motivation was related to the study of dielectric breakdown in insulators, from which the concept of hot electron was originally introduced [1.3,4]. Subsequently, taking impetus from the discovery of the transistor, the study of the nonlinear behaviour of current-voltage characteristics (deviation from Ohm's law) [1.5] and of instability phenomena (the Gunn effect) [1.6] was carried out on a few semiconductors, Ge and GaAs in particular. Even if these pioneering measurements were somewhat incomplete (for instance, diffusion data were not available and the range of electric field strengths and temperatures was too limited) and the theoretical interpretation suffered from too rough analytical approximations, the agreement between theory and experiments appeared to be reasonably satisfactory. The possibility of superimposing on a static electric field other fields such as magnetic, strain, etc. enlarged the subject, which received a first general survey up to about 1965 in *Conwell's* book [1.7].

In the following years, 1965–80, the availability of fast computers enabled numerical methods for an exact solution of the Boltzmann equation, which were soon developed to a high degree of refinement, "in primis" the Monte Carlo method [1.8,9] and the iterative procedure [1.10]. These, in turn, led to a more rigorous interpretation of experiments [1.11]. In the same period new experimental techniques were introduced, and the materials which were more interesting and promising for application purposes (e.g., Si, Ge, GaAs and related III–V and II–VI compounds) were systematically characterized. In particular, new techniques were developed which, for the first time, enables reliable measurements of the diffusion coefficient to be performed.

Thus, these years witness, on the one hand, systematic analysis of results associated with bulk properties and, on the other, the opening up of a new area of research centered upon super-lattice (multi-layered) structures [1.12,13]. With respect to hot electron transport in bulk materials, we can retrospectively identify three "grouping arguments" which have catalyzed the researchers' efforts.

The first one is the generalization to arbitrary field strength of the basic kinetic coefficients: mobility μ, diffusion coefficient D, and spectral density of velocity fluctuations, S_v. At equilibrium these coefficients are related to each other by the fluctuation-dissipation theorem [1.14]. In its macroscopic formulation this theorem can be expressed by the Einstein relation (fluctuation-dissipation theorem of first kind) and by the Nyquist relation (fluctuation-dissipation theorem of second kind) [1.15]. For carrier concentrations far from degeneracy and neglecting the quantum correction factor (i.e., $\hbar\omega \ll K_B T_0$ will be assumed), these are, respectively, given by

$$D = \frac{1}{e}\,\mu K_B T_0 \tag{1.1}$$

$$S_v(\omega) \equiv 2\pi\,\frac{\overline{(\delta v)^2}}{\delta\omega} = \frac{4}{e}\,K_B T_0\,\mathrm{Re}\,\{\mu^*(\omega)\}. \tag{1.2}$$

Here e is the electron charge, K_B the Boltzmann constant, T_0 the absolute temperature of the thermal bath, v a component of the carrier velocity, ω the angular frequency; the bar signifies a time average, and the frequency dependent differential mobility $\mu^*(\omega)$ (in this case field independent) is expressed as a complex number in accordance with the usual notation. (It has to be noted that, owing to the assumed linearity with respect to external fields, the zero frequency chord mobility $\mu = v_d/E$ and $\mathrm{Re}\,\{\mu^*(\omega)\} = dv_d/dE$ coincide for $\omega\tau \ll 1$, τ being of the order of the momentum relaxation time). Thus, for thermal equilibrium, an independent determination of the noise spectral density or of the diffusion coefficient does not add information not otherwise available from the mobility.

A generalization to a high electric field of the Einstein relation was proved under the two auxiliary conditions [1.14]: (i) the system, seen as a two-terminal device, is electrically stable, that is $\mathrm{Re}\,\{\mu^*(\boldsymbol{E},\omega)\} > 0$, (in this case μ^* is field dependent); (ii) two-particle interaction is neglected.

Under these conditions the Price relationship [1.16] can be written as

$$D(\boldsymbol{E},\omega)=\frac{1}{e}\,\mathrm{Re}\,\{\mu^*(\boldsymbol{E},\omega)\}K_BT_n(\boldsymbol{E},\omega). \qquad (1.3)$$

Here the noise temperature T_n is a convenient way to express the spectral density of velocity fluctuations when the system is displaced from equilibrium due to the application of an external electric field. Its macroscopic meaning is related to the measurable quantity $K_BT_n\Delta f$, Δf being the frequency bandwidth, which is the maximum noise power at frequency f, which can be displayed by the network in an output circuit [1.17]. T_n represents a property of the ensemble of charge carriers which is, in general, different from both its "energy temperature" T_e (conveniently defined as $T_e=\langle\mathscr{E}\rangle 2/(3K_B)$, $\langle\mathscr{E}\rangle$ being the carrier average-energy) and from the thermal bath temperature T_0. The hot-electron condition is therefore responsible for the introduction of kinetic coefficients which depend upon the electric field strength and are related to each other through (1.3).

The latter represents a generalization of the fluctuation-dissipation theorem under conditions far from equilibrium [1.18, 19]. The determination of these coefficients for different materials in a wide range of field strengths (up to 200,000 V/cm) and temperatures (from 6 up to 430 K) has been carried out successfully in these last years.

Furthermore, the satisfactory agreement with the macroscopic interpretation [1.20] has enabled improved knowledge of the different scattering mechanisms which charge carriers undergo in their motion in the crystal.

A second grouping argument is the analysis of instabilities related to the condition of negative differential mobility. Under this condition it is well known that a random fluctuation of carrier density produces a space charge that grows exponentially in time [1.21]. As a result direct conversion of energy from a dc to a microwave frequency (ac) is made possible. This self-organized phenomenon can give rise to interesting examples of broken symmetry [1.22, 23] when the band structure of the material is of many-valley type.

A third grouping argument is concerned with the analysis of transport properties in the streaming-motion limit. This physical condition, which corresponds to a carrier distribution function needle-shaped along the field direction, is made possible when the dominant scattering process is through optical-phonon emission. Thus the ensemble of carriers is characterized by the time a carrier takes to reach the optical phonon energy starting from rest, and the net effect of the external applied field is to order the carrier motion which, at equilibrium, is randomly spread. Under such a condition a lot of peculiar transport phenomena become possible, for instance, the practical vanishing of diffusion processes and the saturation of the drift velocity of charge carriers [1.24].

With regard to hot-electron phenomena in superlattices and related submicrometer structures, this argument represents a new area, of considerable practical interest, and presently in rapid development. As such, we are not in a position to set out this argument systematically, as in the case of bulk phenomena. Aside from this, two grouping arguments are attracting researcher's attention and these we shall propose for the attention of the reader. They are usually referred to as real-space transfer [1.25] and ballistic transport [1.26].

Real-space transfer can be obtained in semiconductors heterostructures which are modulation-doped; the $Al_x Ga_{1-x}$ As-GaAs heterostructure can be taken as prototype.

If the $Al_x Ga_{1-x}$ As component is doped, then electrons move towards the GaAs which is the material with the lower band gap, provided that the band edge discontinuity between the materials is sufficiently large. The electrons are then separated from their parent donors and experience a much reduced impurity scattering. Under hot-electron conditions, when a high field is applied parallel to the heterolayer, the electrons are accelerated until they attain enough energy to propagate perpendicular to the layers and reunite with their parent donors. Therefore, the electrons experience strong impurity scattering and negative differential resistance can occur. This is the real-space analogy (real-space transfer) to the Gunn effect.

Ballistic transport can occur in submicrometer structures, a simple prototype being of the type n^+-n-n^+, with the active region n of submicrometer length. When the active-region length becomes comparable to or less than the carrier mean free path, transport may occur without collision (ballistic motion) in a perfect analogy with the case of vacuum diodes.

This phenomenon, which seems to have the inherent possibility of improving device performances in terms of low power dissipation and high speed logic, is becoming highly attractive from an applied point of view.

1.2 Outline of the Book

The book is ideally divided into three parts which are intended to develop the "grouping arguments" briefly reviewed above.

Part 1 (Chap. 2) presents the general theory underlying hot-electron transport and serves as the foundation of the subsequent chapters of the book. The first principles of such a theory rely on the Boltzmann equation, the band structure and the scattering mechanisms. The fundamental quantities, drift velocity, diffusion coefficient and white noise temperature associated with velocity fluctuations are rigorously defined. Then, their dependence upon electric field strength and temperature is investigated for simple but valuable models and for some real cases of interest.

Part 2 (Chaps. 3–6) reviews the most interesting results which have been obtained to date for bulk properties and whose microscopic interpretation seems to be well established. More emphasis has been given to the quantities measured and their physical interpretation than to the materials under investigation, through contributions in which the experiments and theory are appropriately balanced.

Accordingly, Chap. 3 describes the time-of-flight technique, an experimental set-up which has provided quite reliable measurements of both drift velocity and diffusion coefficient. Furthermore, several results obtained on different materials are reported together with the available theoretical interpretation. Chapter 4 analyzes hot carrier transport and fluctuation phenomena as obtained through microwave carrier heating. Together with the determination of microwave conductivity and related relaxation effects, nonhomogeneous carrier heating is also investigated. In particular, this technique is shown to be complementary with the time-of-flight technique for the determination of the diffusion coefficient, thus providing an experimental proof of the Einstein and Price relationships, see (1.1, 3).

Chapter 5 is devoted to the study of the instabilities related to negative differential conductivity in the case of covalent many-valley semiconductors. The conditions for the existence of a multivalued electron distribution are discussed in the light of theoretical models which well agree with experiments. Chapter 6 deals with the properties of hot-electron transport under streaming motion conditions.

Starting from the simplest situation, when only an applied electric field is present, the inclusion of a transverse magnetic field is then considered. In this way a situation of population inversion occurring in the continuum of the energy band is shown to be possible. Furthermore, the case of intense microwave electric field coupled with a magnetic field is shown to predict a carrier bunching in momentum space.

Part 3 (Chaps. 7 and 8) deals with phenomena related to superlattices and submicrometer structures and gives some insight into their potential applicability to devices. Accordingly, Chap. 7 presents the general features of band structure and scattering mechanisms in multilayer structures, then treats of real space transfer. Furthermore, the possible microelectronic applications of multidimensional superlattices and heterostructures are discussed. Chapter 8 analyzes carrier transport under non-steady state conditions as it occurs in the presence of a very short time or very small space configuration of the electric field. New features are then found which characterize the carrier dynamics, and some interesting phenomena, such as ballistic motion, overshoot and undershoot of drift velocity, and negative diffusivity, are predicted. All these new aspects, which still await full experimental evidence, are expected to introduce a significant improvement in the performances of future devices.

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