Transport in Nanostructures

Second Edition

Providing a much-needed update on the latest experimental research, this new edition has been thoroughly revised and develops a detailed theoretical framework for understanding the behavior of mesoscopic devices.

The second edition now contains greater coverage of the quantum Hall effect, in particular, the fractional quantum Hall effect; one-dimensional structures, following the growth of research in self-assembled nanowires and nanotubes; nanoscale electronic devices, due to the evolution of device scaling to nanometer dimensions in the semiconductor industry; and quantum dots.

The authors combine reviews of the relevant experimental literature with theoretical understanding and interpretation of phenomena at the nanoscale. This second edition will be of great interest to graduate students taking courses in mesoscopic physics or nanoelectronics, and researchers working on semiconductor nanostructures.

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Preface

The original edition of this book grew out of our somewhat disorganized attempts to teach the physics and electronics of mesoscopic devices over the past decade. Fortunately, these evolved into a more consistent approach, and the book tried to balance experiments and theory in the current, at that time, understanding of mesoscopic physics. Whenever possible, we attempted to first introduce the important experimental results in this field followed by the relevant theoretical approaches. The focus of the book was on electronic transport in nanostructure systems, and therefore by necessity we omitted many important aspects of nanostructures such as their optical properties, or details of nanostructure fabrication. Due to length considerations, many germane topics related to transport itself did not receive full coverage, or were referred to only by reference. Also, due to the enormity of the literature related to this field, we did not include an exhaustive bibliography of nanostructure transport. Rather, we tried to refer the interested reader to comprehensive review articles and book chapters when possible.

The decision to do a second edition of this book was reached only after long and hard consideration and discussion among the authors. While the first edition was very successful, the world has changed significantly since its publication. The second edition would have to be revised extensively and considerable new material added. A decision to go ahead was made only after welcoming Jon Bird to the author's team. Once this was done, we then carefully discussed the revison and its required redistribution of material among several new chapters. Even so, the inclusion of this considerable material has meant that a lot of material has been left out of this second edition, in order to bring it down to a tractable size. This even included a considerable amount of material that was in the first edition, but no longer appears. We hope that the reader is not put off by this; as the first edition was so successful, we anticipate many of the readers will already have that tome. But, it was essential to include more up-to-date material and topics while maintaining a rational size for the book. Thus, the decision was in principle already made for us.

Currently, we still are teaching a two semester graduate sequence (at ASU) on the material contained in the book. In the first course, which is suitable for first-year graduate students, the experiments and simpler theory, such as that for tunneling, edge states, quantum Hall effect, quantum dots, and the Landauer–Büttiker method, are introduced. This covers parts of each of the chapters, but does not delve into the topic of Green's functions. Rather, the much more difficult treatment of Green's functions is left to the second course, which is intended for more serious-minded doctoral students. Even here, the developments of the zero-temperature Green's functions now in Chapter 3, followed by the Matsubara Green's functions in Chapter 8, and the nonequilibrium (real-time) Green's functions in Chapter 9, are all coupled closely to the experiments in mesoscopic devices.

In spite of the desire to consistently increase the level of difficulty and understanding as one moves through the book, there remain some anomalies. We have chosen, for example, to put the treatment of the recursive Green's functions in the chapter with waveguide transport and the recursive solutions to the Lippmann–Schwinger equation, since these two treatments of quantum transport are closely coupled. Nevertheless, the reader would be well served to go through the introduction of the Green's functions prior to undertaking an in-depth study of the recursive Green's function. This, of course, signals that topics have been grouped together in the chapters in a manner that relies on their connection to one another in physics, rather than in a manner that would be optimally chosen for a textbook. Nevertheless, we are convinced that one can use this book in graduate coursework, as is clear from our own courses.

Chapter 1 is, of course, an introduction to the material in the entire book, but new material on nanodevices has been added, as progress in silicon technology has brought the normal metal-oxide-semiconductor field-effect transistor (MOSFET) into the mesoscopic world. Additionally, a new introduction to nanowires and carbon nanotubes is given. Chapter 2 remains a discussion of quantum confined systems, but now focuses more on the one-dimensional structures rather than the two-dimensional ones. New material here includes a discussion of numerical solutions to the Schrödinger equation and Poisson's equation as well as non-self-consistent Born approximations to scattering in quasi-one-dimensional systems. Chapter 3 remains focused upon very low temperature transport, but now includes the introduction to the different approaches to (equilibrium) quantum transport. Chapter 4 is a completely new chapter focused upon the quantum Hall effect and the fractional quantum Hall effect.

Chapter 5 is also a new chapter which focuses upon quantum wires, and includes some of the modern investigations into various effects in these wires. Chapter 6 focuses upon quantum dots with new material on the role of spin. The focus upon single electron tunneling remains, but considerable new material on coupled dots has been added. Then, Chapter 7 discusses weakly disordered systems. New material on (strong) localization is presented so that weak localization can be placed in its context in relation to this material.

Chapter 8 is mostly carried over from the first edition and discusses the role of temperature. Here, the Matsubara Green's functions are introduced in addition to the semiclassical approach. Finally, Chapter 9 discusses nonequilibrium transport and nanodevices. Here, considerable new material on semiconductor nanodevices has been added. Device simulation via the scattering matrix implementation based upon the Lippmann–Schwinger equation appears as well as the treatment with nonequilibrium Green's functions.

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