BOOKS: APPLIED PHYSICS

Quantum Devices

Leo Kouwenhoven

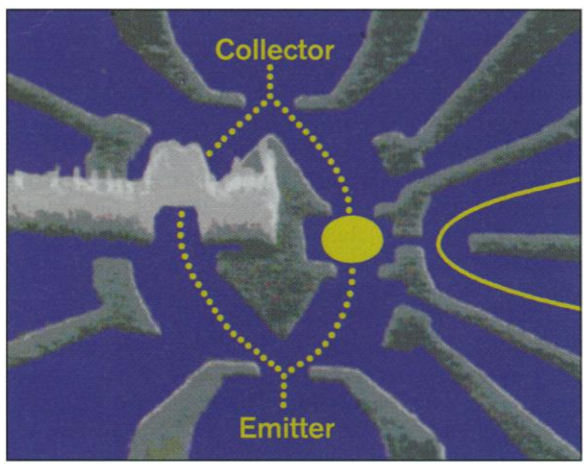
Transport in Nanostructures. DAVID K. FERRY and STEPHEN M. GOODNICK. Cambridge University Press, New York, 1997. xii, 512 pp., illus. $100. ISBN 0-521-46141-3. Cambridge Studies in Semiconductor Physics and Microelectronic Engineering, 6.

This 50-year jubilee for the transistor has given us many reviews on the development of this remarkable solid-state device. One impressive aspect of progress in this area is the speed of miniaturization. Extrapolation of this trend predicts that, in 20 to 30 years time, chips will contain devices on nanometer size scale, so that connecting wires will then be about 10 atoms wide. During the last 15 years, the research field known as mesoscopic physics has focused on the fundamental phenomena associated with nanostructures. The results of these studies have revealed that the properties of such structures are very different from those of present-day transistors. Given that the basics are now understood, it is valuable to have these results collected in textbooks.

Let me first introduce the three nanodevices that constitute the tiny quantum circuit shown in the figure. These structures illustrate the core phenomena in mesoscopic physics. First, consider the ring. In classical mechanics, a particle entering such a ring must choose which of the two possible paths to take. The quantum mechanical wave nature of an electron, however, allows it to take both paths simultaneously. Part of the electron travels along one path, and part travels along the other. At the opposite end of the ring, the recombination of the two parts gives rise to interference. The resistance of the ring is low or high for, respectively, constructive or destructive interference.

A great advantage of working with solid-state materials is one's ability to engineer the potential landscape. For instance, the interface between certain materials forms a potential well in which electrons are captured and form a two-dimensional electron gas. The width of the well is just a few nanometers. Additional confinement can be obtained by fabrication of a narrow wire. The quantum point contact in the figure (the second nanodevice in the circuit) is an example of a short wire with a controllable width between zero and a few hundred nanometers. In semiconductors, these widths are comparable to the wavelength of electrons, making the wire effectively one dimensional. A zero-dimensional structure is realized when electrons are confined in all three directions, such as in the quantum dot structure (the third nanodevice) in the figure. Electrons in quantum dots can occupy only discrete energy states, similar to the discrete states of atoms.

It is not only the wave nature of electrons but also the discreteness of charge in units of e that can be important. The capacitance, C, of nanostructures can be so small that the charging energy, e^2/C, for adding a single electron to, for instance, a quantum dot exceeds the thermal energy. A large charging energy can prevent the addition to (or removal from) a nanostructure of even one electron, resulting in transport effects such as Coulomb blockade for tunneling. Single-electron transistors have been developed in which a switch from an on to an off state is induced, as the name implies, by just one electron.



Tiny quantum circuit. Image shows metallic gates on an (Al)GaAs semiconductor, containing a ring (yellow dots indicate two possible paths for electrons traveling from emitter to collector), a quantum dot in the right arm of the ring (indicated by the yellow disk), and a quantum point contact (electrons can travel through the quantum point contact along the solid yellow curve).

Quantum interference, quantum confinement, and single-electron charging are three general phenomena that apply, in various combinations, to all types of nanostructures. In fact, it does not matter whether the nanostructures are manufactured by semiconductor band-gap engineering, whether they consist of superconductors or normal metals, or whether they comprise just a single molecule. Thus, an important discovery of mesoscopic physics is that these seemingly different systems share the same basic physics. On the other hand, each system is governed by a unique mixture of these concepts. The diversity of systems has resulted in a large research field—so large, in fact, that it is difficult to cover in a single book. *Transport in Nanostructures* by David Ferry and Stephen Goodnick—both professors of electrical engineering at Arizona State University—focuses on small structures defined in semiconductors. I find this a wise and logical choice. Wise because, by focusing on semiconductor nanostructures, the book has become a coherent description of mesoscopic phenomena. Logical because the research careers of both authors have focused on semiconductor devices—in addition, the book is in the series of *Cambridge Studies in Semiconductor Physics and Microelectronic Engineering*. What I do not understand is why this choice is not made clear, either by mention in the preface or, better, by including the word "semiconductor" in the title. The book skips too many subjects (mesoscopic superconductors and metals; atom-scale systems made and measured by scanning probe techniques; clusters, grains, and molecules) to be marketed as a general book on nanostructures. However, if you are interested in small semiconductor systems, keep reading this review.

The book can be divided into two parts: one focusing on clean structures, in which electrons move ballistically without encountering impurities; the other covering disordered structures, in which electrons move diffusively as a result of many collisions with impurities. Clean semiconductors are beautiful examples—in my opinion, even better than the historic textbook examples—of fundamental quantum mechanics. Ferry and Goodnick exploit this and provide a well-written tutorial on solving the Schrödinger equation and determining wave functions, energy eigenvalues, and density of states for several examples of the electrostatic potential landscape. Also, solutions for the case of a

The author is in the Department of Applied Physics, Delft University of Technology, P.O. Box 5046, 2600GA Delft, the Netherlands. E-mail: leo@qt.tn.tudelft.nl

magnetic field are derived step by step.

Often avoided in textbooks, but not here, is an emphasis on screening and self-consistent solutions. The theory of quantum transport is introduced pedagogically by starting with the simple case of tunneling through a barrier and then building up a matrix formulation of resonant tunneling through double-barrier structures. This approach naturally leads to the successful and easy-to-understand Landauer-Büttiker formalism for electron transport. The importance of Coulomb interactions between electrons is added to the discussion when single-electron charging effects in quantum dots are described. Again, a pedagogical approach is taken by first giving step-by-step derivations for the non-interacting single-particle states in dots. The interaction problem is introduced by discussing two interacting electrons in detail, outlining the Hartree and Hartree-Fock approximations for more electrons, and providing a thorough description of the Coulomb blockade model.

Halfway through, the book makes a transition from clean to disordered systems. An illuminating semiclassical description of weak-localization and universal conductance fluctuations is provided. The authors discuss in depth the temperature dependence of fluctuations. However, an explanation of the often used concept of the Thouless energy and a connection to results obtained with random matrix theory were not included. I find this omission somewhat unfortunate given that recent results from random matrix theory could have provided a smooth connection between the clean- and disordered-structure parts of the book. For instance, when moving from symmetrically confined quantum dots to non-symmetrical dots, one can smoothly go from repulsion between two levels to level statistics characterized by Wigner-Dyson distributions. At this point, nonsymmetrical dots and chaos perhaps ought to have been related to wires with impurities, thus providing a natural introduction to universal conductance fluctuations. (I must admit that this complaint is to some extent motivated by a recurrent misspelling of this reviewer's name in this section.)

Throughout the book, helpful introductions to commonly used theoretical approaches are provided. Step-by-step examples are given for calculations of scattering mechanisms and transmission probabilities for all types of geometries. In addition to physically transparent approaches such as the Boltzmann equation, wave function mode-matching, and the Landauer-Büttiker formalism, much attention is paid to powerful methods based on Green's functions.

This book shows a substantial overlap in subject with *Electronic Transport in Mesoscopic Systems* by Supriyo Datta, which appeared in the same Cambridge series. However, the two books differ markedly in character. Datta's book is really an introductory textbook; it never uses more words than necessary to allow a basic understanding of the subject and it provides exercises for basic training. The book by Ferry and Goodnick is also introductory, but it has more of the character of a review than of that of a textbook. Exercises are not provided. Overall, this book goes into much more detail, and it provides many references and experimental examples (although, the examples are chosen somewhat too often from the authors' own or affiliated work to represent the field as a whole). Both books discuss only established mesoscopic physics; almost everything covered was known 5 years ago. I would have liked to have seen introductions to today's issues in semiconductor mesoscopic physics, such as composite Fermions, skyrmions, Luttinger liquids, developments on artificial atoms, shot noise, and surface-acoustic and other high-frequency effects.

Altogether, I think *Transport in Nanostructures* provides a well-written introduction to the basic phenomena associated with mesoscopic semiconductors. I am convinced that much of the fundamental theory described in this book is also the theory that will underlie the commercial devices of the next century. The subject definitely deserves to be taught at universities, and this book is currently the most accurate review on mesoscopic semiconductors. The book can serve as a good reference that contains all the basics—not only for students but also for rusty researchers.

Browsings

1001 Things Everyone Should Know About the Universe. William A. Gutsch, Jr. Doubleday, New York, 1998; 353 pp., illus., $25.95, ISBN 0-385-48223-X.

A survey of the spectacular from astronomy in the form of 1001 concise explanations of topics that range from the effects of light pollution on telescope locations to instructions for talking to extraterrestrials.

Causality in Crisis? Statistical Methods and the Search for Causal Knowledge in the Social Sciences. Vaughn R. McKim and Stephen Turner, Eds. University of Notre Dame Press, Notre Dame, IN, 1997. 410 pp., $38, ISBN 0-268-00813-2; paper, $22, ISBN 0-268-00824-8.

In this book stemming from a 1993 conference on techniques of causal modeling, scholars of social sciences, statistics, and philosophy of science reassess current methods and evaluate the future of determining causal relationships from correlational statistical data. At issue is whether cause can be ascertained by non-experimental research.

Georges Cuvier, Fossil Bones, and Geological Catastrophes. New Translations and Interpretation of the Primary Text. Martin J. S. Rudwick. University of Chicago Press, Chicago, IL, 1997. 318 pp., illus. $34.95 or £27.95, ISBN 0-226-73106-5.

This modern translation of Cuvier's paleontological writings includes his most famous (the "Preliminary Discourse" of 1812) and two previously unpublished pieces. Rudwick's interpretive commentary places the work in its scientific and social context. Rather than being the proponent of a biblical catastrophism (as depicted by a poor original translation and its editorial slant), Cuvier made lasting contributions to the theory and practice of biology.

Vignette

Etymology of bugs

"The metaphorical bugs that Hoover wrote about in 1952 are the same ones that computer engineers and programmers worry about today (notwithstanding stories that the term 'bug' derives from an actual moth found in an early computer and preserved to this day either in Lucite in the U.S. Naval Research Laboratory or taped in a logbook kept at Harvard). In fact the term *bug* was familiar to Thomas Edison, who understood that the success of his elecric light depended upon his anticipating how it could fail. ...In a letter dated November 13, 1878, and addressed to Theodore Puskas, one of the agents representing Edison abroad, he was explicit about bugs tending to crawl into the development process:

> 'The first step is intuition, and it comes with a burst, then difficulties arise—this thing gives out and then that—'Bugs'—as such little faults and difficulties are called—show themselves and months of intense watching, study and labor are requisite before commercial success—or failure—is certainly reached.' "

—*Henry Petroski*, in *Remaking the World: Adventures in Engineering* (Knopf)