Preface

Nanostructures are among the most actively studied systems in present day research. Theoretical and experimental studies of these small systems have uncovered remarkable phenomena due to fundamental interactions and the reduction in dimensionality. Such nanostructures can be made out of well known materials such as metals or semiconductors by lithographic procedures. In addition, novel material systems, e.g. semiconducting heterostructures, or even molecular-like materials, e.g. carbon nanotubes, can represent nanostructures in which electron–electron interactions are of importance.

The discoveries of quantum Hall effects offered an initial glimpse into the striking phenomena that may occur in these low-dimensional structures. Extensive research since then, made possible by enormous advances in fabrication technologies, have revealed a large class of unexpected behaviors in nanostructures. The rapid technological progress in the last two decades has led to great excitement among both applied and basic physicists. The hope that miniaturization of such devices will lead to a new age of smaller and faster computers has motivated extensive work, trying to understand the basic physics involved, an imperative step towards any future application.

During this research many surprising experimental effects have been found, including the integer and the fractional quantum Hall effect, weak localization, conductance quantization in point contacts, universal conductance fluctuations and Coulomb oscillations in quantum dots. In many cases the experimental observations were unexpected. Theoretical progress was important in facilitating understanding of the effects discovered. A deep understanding of the observed phenomena and a consistent picture of the underlying physics are not only important from the basic research point of view, but will also prove crucial for our ability to design and control the operation of novel devices. All the discovered, intriguing effects, which are understood as arising from microscopic quantum interactions, represent remarkable macroscopic scale quantum phenomena. Current research offers some answers to fundamental issues, and it reveals many puzzles that remain to be explained. Studies of these phenomena are among the most active areas of research at the advancing frontiers of physics. In addition to the fundamental issues involved, research is also driven by commercial aspects since it is assumed that present-day silicon technology will reach some ultimate limits within the next 20 years. Therefore, worldwide efforts are underway in search of alternatives for improvement or replacement of silicon technology.

For example, the Coulomb oscillations in quantum dots have demonstrated the ability to change the current through such a device by four or five orders of magnitude by an externally controllable parameter, e.g. a gate voltage. At almost any gate voltage an electron must have a finite energy in order to overcome the on-dot Coulomb repulsion and to be able to tunnel into the dot. Therefore, the conductance through the device is suppressed. The exceptions are the points of charge degeneracy. At these points, two charge states of the dot have the same energy, and an electron can hop on and off the dot without paying an energy penalty. This dramatic effect promptly led to suggestions that the device could be used as a single-electron tunneling transistor. Such a system with a quantum dot coupled via tunnel junctions to two leads serves simultaneously as a model system for electronic transport through strongly interacting mesoscopic systems. Quantum dots are zero-dimensional systems with a fully discrete level spectrum justifying calling them 'artificial atoms'. By changing a gate voltage the number of electrons confined in a quantum dot can be varied in a defined way. Thus, a single-electron transistor with a quantum dot provides a well-controlled object for studying quantum many-body physics. In many respects, such a device resembles an atom embedded into a Fermi sea of electrons.

By increasing the system size one can move from zero-dimensional quantum dots to one-dimensional quantum wires. The electronic properties of one-dimensional systems have attracted considerable attention in theory and experiment. Starting with the work of Tomonaga in 1950 it has become clear that the electron–electron interaction destroys the sharp Fermi surface and leads to a breakdown of the ubiquitous Fermi liquid theory pioneered by Landau for systems of higher dimensionality. Recent years have seen a large number of theoretical and experimental works to study the consequences of these interactions in quantum wires, where ballistic conduction has also been observed. Future applications of these quantum wires might be connected with the need for perfect leads in new electronic devices.

Another alternative to standard silicon technology could conceivably be based on molecular electronics. This field understood as information processing via single molecules, was initiated in the 1970s. As time passed, the manipulation of single molecules appeared to be more difficult than expected and interest faded away. Nowadays, molecular electronics is experiencing a revival, since technology has progressed with the invention of scanning techniques, etc. Connecting a single molecule was proven to be feasible. A second reason for this renewed interest and exciting progress is the discovery of very stable, long and at the same time electronically very versatile molecules: carbon nanotubes. Within a few years, many applications of carbon nanotubes were proposed. They cover quite diverse fields ranging from novel material for storage of hydrogen, application as artificial muscle through to molecular electronics. On the other hand, from a more fundamental point of view it became clear that carbon nanotubes can serve as perfect model systems for the study of interacting electrons in nanostructures. Carbon nanotubes appear to be perfect one-dimensional systems which can be designed to be a one-dimensional metal or a semiconductor.

Applications of quantum mechanics in nanostructures are always related to the manipulation of wave functions. People envisage using quantum mechanics in totally new computer concepts by calculating with entangled states. Several proposals were made to also use nanostructures in such quantum computing concepts. The possibility of manipulating wave functions relies on a certain coherence of the wave function. Coherence is especially important in such quantum computing concepts, but it is at the same time a very fundamental problem. Therefore, the coherence of wave functions, possible dephasing and relaxation processes have been studied theoretically and experimentally in nanostructures in recent years.

Total wave functions carry orbital and spin components. By involving the effects of interacting spins, additional degrees of freedom emerge for the design of new devices. One example of an effect caused by interacting spin systems is the recently discovered Kondo effect in quantum dots. It has been known for many years that the interaction between the spin of a magnetic impurity and the spins of the electrons in a metal can lead to anomalies in transport. Similar effects were predicted for the interaction between the spin of an electron in a quantum dot and the electrons in the leads. Recently, several groups have succeeded in observing this Kondo effect in tunneling through a quantum dot.

Spin effects are also important in ferromagnets. In current information technology, semiconductors and ferromagnets play complementary roles. The low carrier densities in semiconductors facilitate modulation of electronic transport properties by doping or external gates, whereas ferromagnets allow large changes in magnetic and transport properties through the reorientation of magnetic moments in small magnetic fields. Semiconductors are traditionally used for information processing, whereas ferromagnets have their application in storage devices. Recently, the prospect of synergies between electronic and magnetic manipulation of transport properties has raised interest in spin electronics in semiconductors. This interest is also driven by great improvements in material science with the success in growing ferromagnetic semiconductors. New concepts for devices based on spin effects are appearing and a new term has even been coined: spintronics.

Proposals for new device concepts also make use of the interplay between the electronic and the mechanical properties of a system. Such ideas are possible due to the tremendous advances in nanotechnology which allow one to purpose design mechanical properties of small systems. Again it will be important to treat these small systems in a fully quantum mechanical way. Quantum mechanics brings a new quality to the system, so that these nano-electromechanical systems are not just extensions of micro-mechanics. Nano-electromechanical systems are investigated because of their promising features with regard to applications in sensors and communication technology.

This book is based on contributions of a workshop held in Bad Honnef, Germany, from 13–16 June 2000. At the workshop key scientists convened to present their most recent research and thus created a forum for the in-depth discussion of exciting new results. Several of the talks resulted in not only lively but truly controversial discussions. For this book a selection of 12 topics from the workshop was chosen. Leading scientists have contributed carefully prepared chapters to cover the most interesting aspects of interaction effects in nanostructures. In a few cases it was even possible to bring together experimentalists and theoreticians enabling an especially comprehensive view of a particular topic. The 12 articles are arranged into the six parts of this book. The first part concentrates on electronic transport through quantum dots. It is followed by a part about interaction effects in quantum wires. Electronic transport through molecules is the subject of the next part. Effects of phase coherence are discussed in the following part. A further part covers spin electronics and magnetism, and the last demonstrates the connection to nano-mechanics. In this way the current, most exciting problems in the field of nanostructures are well represented in this book.

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