Nanowire Transistors

Physics of Devices and Materials in One Dimension

From quantum mechanical concepts to practical circuit applications, this book presents a self-contained and up-to-date account of the physics and technology of nanowire semiconductor devices. It includes:

- An account of the critical ideas central to low-dimensional physics and transistor physics, suitable to both solid-state physicists and electronic engineers.
- Detailed descriptions of novel quantum mechanical effects such as quantum current oscillations, the semimetal-to-semiconductor transition, and the transition from classical transistor to single-electron transistor operation are described in detail.
- Real-world applications in the fields of nanoelectronics, biomedical sensing techniques, and advanced semiconductor research.

Including numerous illustrations to help readers understand these phenomena, this is an essential resource for researchers and professional engineers working on semiconductor devices and materials in academia and industry.

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For Cindy and Sue, to our children, and to the memory of our parents

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Jean-Pierre Colinge and James C. Greer
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Preface

After the era of bulk planar CMOS, trigate field-effect transistors (FinFETs), and fully depleted silicon-on-insulator (SOI), the semiconductor industry is now moving into the era of nanowire transistors. This book gives a comprehensive overview of the unique properties of nanowire transistors. It covers the basic physics of one-dimensional semiconductors, the electrical properties of nanowire devices, their fabrication, and their application in nanoelectronic circuits.

The book is divided into seven chapters:

Chapter 1: Introduction serves as an introduction to the other chapters. The reader is reminded of the exponential increase in complexity of integrated circuit electronics over the last 50 years, better known as "Moore's law." Key to this increase has been the reduction in transistor size, which has occurred in a smooth, evolutionary fashion up to the first decade of the twenty-first century. Despite the introduction of technology boosters such as metal silicides, high-κ dielectric gate insulators, copper metallization, and strained channels, evolutionary scaling reached a brick wall called "short-channel effects" in the years 2010–2015. Short-channel effects are a fundamental device physics showstopper and prevent proper operation of classical bulk MOSFETs at gate lengths below 20 nm. The only solution to this problem is the adoption of new transistor architectures such as fully depleted silicon-on-insulator (FDSOI) devices [1,2] or trigate/FinFET devices [3]. Ballistic transport of channel carriers, which replaces classical drift-diffusion transport, is also introduced in this chapter.

Chapter 2: Multigate and nanowire transistors first explains the origin of the short-channel effects that preclude the use of bulk MOS transistors for gate lengths smaller than 20 nm. Based on Maxwell's electrostatics equations, this chapter shows how the use of multigate and gate-all-around nanowire transistor architectures will allow one to push the limits of integration to gate lengths down to 5 nm and possibly beyond, provided the diameters of the nanowires are decreased accordingly. In semiconductor nanowire with diameters below approximately 10 nm (this value is temperature dependent and varies from one semiconductor material to another), the coherence length of electrons and holes can become comparable to or larger than the wire cross-sectional dimensions, and

[1] J.P. Colinge, *Silicon-on-Insulator Technology: Materials to VLSI*, 3rd edition, Kluwer Academic Publishers/ Springer (2004).
[2] O. Kononchuk and B.-Y. Nguyen (eds.), *Silicon-on-Insulator (SOI) Technology Manufacture and Applications*, Woodhead Publishing (2014).
[3] J.P. Colinge (ed.), *FinFETs and Other Multi-Gate Transistors*, Springer (2007).

one-dimensional (1D) quantum confinement effects become observable. The formation of 1D energy subbands in narrow nanowire transistors gives rise to several effects such as an increase of energy band gap, oscillations of drain current when gate voltage is increased, and oscillations of gate capacitance with gate voltage (quantum capacitance effect). Some collateral effects can be predicted, such as a semimetal-to-semiconductor transition in thin semimetal nanowires, and a MOSFET to single-electron transistor transition in nanowire transistors with non-uniform channel properties.

Chapter 3: Synthesis and fabrication of semiconductor nanowires lists the different top-down and bottom-up techniques used to grow or etch and pattern nanowires. Vertical nanowires can be grown by the VLS (vapor–liquid–solid) technique or confined epitaxy, or formed using lithography and etching. Horizontal nanowires can also be grown using the VLS technique, by patterning an SOI layer, or by patterning heteroepitaxial layers, such as Si/SiGe/Si. Examples of nanowire transistor fabrication processes are given. Chapter 3 also describes methods for smoothing and thinning down silicon nanowires. The properties of heterojunction nanowires (core-shell nanowires and axial heterojunctions) are described. Finally, strain effects in nanowires are explored, including carrier mobility enhancement, Young's modulus, and fracture strength.

Chapter 4: Quantum mechanics in one dimension provides a résumé of the physical description of one-dimensional systems in quantum mechanics. A brief summary of the principles of quantum mechanics is given. Particular emphasis is given to topics that are related to describing nanowire transistors including momentum eigenstates, energy dispersion, scattering states in one dimension, probability current density, and transmission at potential energy barriers. A description of materials and nanowires using the concept of electronic band structures is provided and calculation of simple band structures is provided using simple examples such as a linear chain of atoms. The relation of electronic band structures to the density of states and how the density of states can be used to characterize three-dimensional (3D) bulk, two-dimensional (2D) electron and hole gases, and (1D) nanowire material systems is presented.

Chapter 5: Nanowire electronic structure examines in greater detail the impact of fabricating nanometer scale devices with one or more critical dimension comparable to or smaller than the Fermi wavelength of the confined charge carriers. The crystal structure of semiconductors commonly used in electronics such as silicon, germanium, and gallium arsenide are introduced. Mention is made of two-dimensional materials such as graphene and the transition metal dichalcogenides, and carbon nanotubes are briefly discussed in relation to applications in electronics. Emphasis is placed on the experimental measurement and theoretical calculation of electronic structure. Quantum mechanical effects become apparent below 10 nm critical dimensions and below 6 nm confinement and surface effects begin to dominate silicon nanowire properties. A greater understanding of the dependence of orientation, surface chemistry, disorder, doping effects, and other factors arising for nanopatterned materials is needed to optimize the use of nanowires in transistor configurations. This chapter highlights how these factors can influence electronic structure and demonstrates their impact with examples for silicon nanowires with diameters below 10 nm.

Chapter 6: Charge transport in quasi-1D nanostructures investigates how charge carriers flow through nanowires. The operation of voltage sources as charge carrier reservoirs interacting with nanowires is introduced, and the relationship of voltage to current flow on the nanometer length scale leads to conductance quantization and the Landauer conductance formula. Charge carrier mobility is introduced and the length scales associated with scattering mechanisms leading to macroscopic mobilities are outlined. For charge transport on length scales shorter than the scattering lengths, ballistic and quasi-ballistic charge transport emerges. The chapter ends with a brief introduction to the Green's function approach to charge transport in nanowires as it possesses the capability to describe charge transport from quantum ballistic to classical drift and diffusion regimes.

Chapter 7: Nanowire transistor circuits describes the potential and performances of nanowire transistors in logic, analog, and RF circuit applications. This includes an in-depth analysis of SRAM and flash memory cells. New types of circuit architectures are enabled by the use of nanowire devices, such as crossbar circuits and "nanoscale application specific integrated circuits" (NASICs). The large surface area-to-volume ratio of nanowires makes them ideal for sensing minute amounts of chemicals and biochemicals. Nanowire transistors have proven to be efficient sensing devices, capable of detecting chemicals in concentrations as low as a few tens of attomoles.