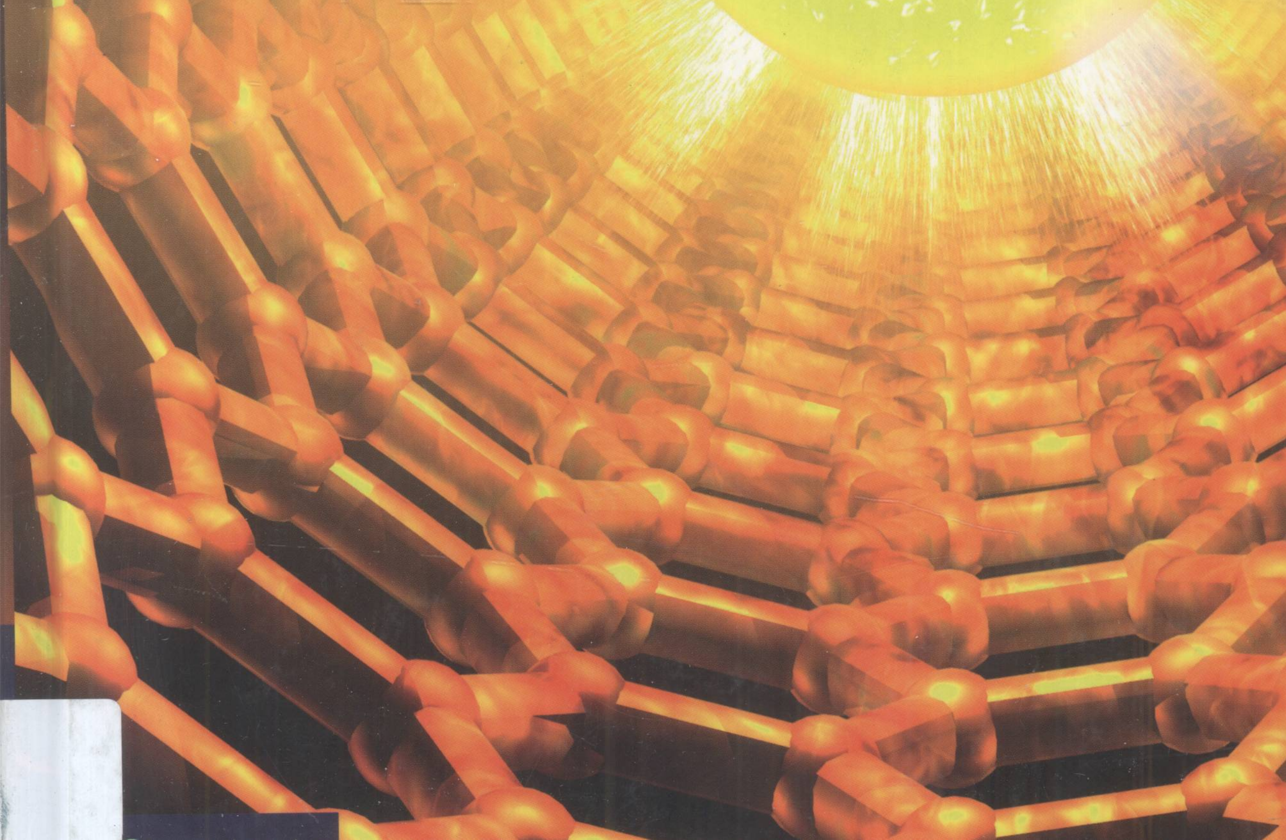
Introduction to Nanoelectronics

Science, Nanotechnology, Engineering, and Applications

Vladimir V. Mitin
Viatcheslav A. Kochelap
Michael A. Stroscio



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VLADIMIR V. MITIN
University of Buffalo, State University of New York
VIATCHESLAV A. KOCHELAP
Institute of Semiconductor Physics National Academy of Sciences, Ukraine
MICHAEL A. STROSCIO
University of Illinois at Chicago

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Introduction to Nanoelectronics

Increasing miniaturization of devices, components, and integrated systems requires developments in the capacity to measure, organize, and manipulate matter at the nanoscale. This textbook is a comprehensive, interdisciplinary account of the technology and science that underpin nanoelectronics, covering the underlying physics, nanostructures, nanomaterials, and nanodevices.

Without assuming prior knowledge of quantum physics, this book provides a unifying framework for the basic ideas needed to understand the recent developments in the field. Following an introductory description of recent trends in semiconductor and device nanotechnologies, as well as novel device concepts, materials for nanoelectronics are treated, covering methods of growth, fabrication and characterization. Treatment then moves to an analysis of nanostructures, including recently discovered nanoobjects, and concludes with a discussion of devices that use a "simple" scaling-down approach to copy well-known microelectronic devices, and nanodevices based on new principles that cannot be realized at the macroscale.

Numerous illustrations, homework problems and interactive Java applets help the student to appreciate the basic principles of nanotechnology, and to apply them to real problems. Written in a clear yet rigorous and interdisciplinary manner, this textbook is suitable for advanced undergraduate and graduate students in electrical and electronic engineering, nanoscience, materials, bioengineering, and chemical engineering.

Further resources for this title, including instructor solutions and Java applets, are available online at www.cambridge.org/9780521881722.

Vladimir V. Mitin is a Professor and Chair of the Department of Electrical Engineering at the University of Buffalo, State University of New York. He has co-authored eight books, and over 400 professional publications, including ten patents.

Viatcheslav A. Kochelap is Professor and Head of the Theoretical Physics Department at the Institute of Semiconductor Physics National Academy of Sciences, Ukraine. He has published over 200 journal articles.

Michael A. Stroscio is a Professor in the departments of Electrical and Computer Engineering, and Bioengineering, at the University of Illinois at Chicago. He is a Fellow of the IEEE, the American Physical Society, and the AAAS.

Preface

Welcome to the amazing *nanoworld*! In this book you will find fundamental principles in nanoscience and basic techniques of measurement, as well as fabrication and manipulation of matter at the nanoscale. The book discusses how these principles, techniques, and technologies are applied to the newest generation of electronics, known as *nanoelectronics*.

The science of atoms and simple molecules, and the science of matter from microstructures to larger scales, are both well established. A remaining, extremely important, size-related challenge is at the nanoscale – roughly the dimensional scales between 10 and 100 molecular diameters – where the fundamental properties of materials are determined and can be engineered. This field of science – nanoscience – is a broad and interdisciplinary field of emerging research and development.

Nanotechnology is concerned with materials, structures, and systems whose components exhibit novel and significantly modified physical, chemical, and biological properties due to their nanoscale sizes. A principal goal of nanotechnology is to control and exploit these properties in structures and devices at atomic, molecular, and supramolecular levels. To realize this goal, it is essential to learn how to fabricate and use these devices efficiently. Nanotechnology has enjoyed explosive growth in the past few years. In particular, nanofabrication techniques have advanced tremendously in recent years. Obviously, revolutionary changes in the ability to measure, organize, and manipulate matter on the nanoscale are highly beneficial for electronics with its persistent trend of downscaling devices, components, and integrated systems. In turn, the miniaturization required by electronics is one of the major driving forces for nanoscience and nanotechnology.

Practical implementations of nanoscience and nanotechnology have great importance, and they depend critically on training people in these fields. Thus, modern education needs to address the rapidly evolving facets of nanoscience and nanotechnology. A new generation of researchers, technologists, and engineers has to be trained in the emerging nanodisciplines. With the purpose of contributing to education in the nanofields, we present this textbook providing a unifying framework for the basic ideas needed to understand recent developments underlying nanoscience and nanotechnology, as applied to nanoelectronics. The book grew out of the authors' research and teaching experience in these subjects. We have found that many of the ideas and achievements in fields underlying nanoscience and nanotechnology can be explained in a relatively simple setting, if the necessary foundational underpinnings are presented properly. We have designed this textbook mainly for *undergraduate students*, who will be trained in diverse fields including nanoscience, physics of material devices, electrical and optical engineering, materials science and engineering, and mechanical engineering. It can be helpful also for training students in bioengineering and chemical engineering. To reach such a broad audience, materials are presented in such a way that an instructor can choose the level of presentation depending on the backgrounds of the students. For example, we have included Chapters 2 and 3 in part for students who have not taken a quantum mechanics course. An analogy with wave fields – elastic waves and optical waves – is exploited widely to introduce wave mechanics of particles and quantum principles, which play key roles in the interpretation of the properties of nanomaterials.

One of us (V.V.M.) has taught the course for students in the second semester of their sophomore year. For students at this level, Chapters 2 and 3 were covered in detail and, consequently, there was not enough time to cover all of the devices that are discussed in Chapter 8. If students using the book have previously taken courses on quantum mechanics and electromagnetics, the instructor may start from Chapter 4. This book may be also used as an introductory graduate or senior undergraduate course. Another of us (M.A.S.) has used Chapters 2 and 3 as the introduction to a graduate course on nanoelectronics for a class with students drawn from electrical engineering, materials engineering, chemical engineering, mechanical engineering, and physics. By covering Chapters 2 and 3 at the beginning of the course, the students can then proceed from this common basis in quantum mechanics and other underlying areas of physics to cover more advanced topics, either in the current text or in other texts such as *Quantum Heterostructures* by V. Mitin, V. Kochelap, and M. Stroscio. The latter approach has been used by M.A.S. in teaching nanoelectronics to graduate students with diverse backgrounds in many disciplines within engineering and the physical sciences. For this purpose, we include details of derivations and mathematical justification of concepts in some sections. These details can be omitted from an undergraduate curriculum.

The book contains homework problems on various subjects. These problems illustrate the basic material and help students to understand and learn the basic principles of the nanoscience and the nanotechnology.

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Essentially, the chapters are organized into three main groups.

Chapters 1–3 are of an introductory character. In Chapter 1, we present in concise form the main subject of the book. The recent and diverse trends in semiconductor and device nanotechnologies, as well as novel concepts of nanodevices, are reviewed. These trends make it clear why understanding the fundamentals of nanoscience is of great importance.

Chapters 2 and 3 are written for students who have not taken a quantum mechanics course. An analogy with wave fields (elastic waves and optical waves) is exploited widely to introduce wave mechanics of particles and the quantum principles, which play key roles in the interpretation of the properties of nanomaterials.

In Chapter 2, we explain that the fundamental laws of physics governing particles and material fields in the nanoworld are different from those that apply to familiar macroscopic phenomena. Starting with an analysis of an arbitrary wave field (elastic vibrations in solids, electromagnetic fields, etc.), we find particle-like behavior of this wave field for small wave amplitudes and (or) for spatial scales larger than the wavelength. By analyzing particle motion, we show that at small spatial scales a particle can not be characterized by exact coordinates and momentum and that it behaves rather as an extended wave-like object. This analysis establishes the essence of the wave–particle duality which is an underlying principle of nanophysics.

In Chapter 3, we discuss the basic physical concepts and equations related to the behavior of particles in the nanoworld. We introduce the Schrödinger wave equation for particles and determine the ways in which to calculate observable physical quantities. Keeping in mind the diverse variants of nanostructures, by using wave mechanics we analyze a number of particular examples, which highlight important quantum properties of particles. Many of the examples analyzed can serve as the simplest models of nanostructures and are exploited in later chapters.

Chapters 4 and 5 are devoted to materials used in nanoelectronics, methods of their growth, and fabrication and characterization techniques.

In Chapter 4, we present an overview of the basic materials that are exploited in nanoelectronics. We start with semiconductor materials as the principal candidates for use in nanoelectronics, because they offer great flexibility in the control of the electronic and optical properties, and functions, of nanoelectronic devices. We show how, through proper regimes of growth, doping by impurities, and sequent modifications and processing, one can fabricate nanostructures and nanodevices starting from "bulk-like" materials. Then, we introduce other materials that have properties of great potential in nanoelectronics. Organic semiconductors and carbon nanotubes are discussed.

In Chapter 5, the principal methods of materials growth and nanodevice fabrication are presented. We start with an analysis of fabrication of nanodevices on the basis of perfect materials and continue by considering processing techniques. All stages of fabrication and methods of processing are considered in detail. Then, we discuss special regimes of material growth, when nanostructures (mainly quantum dots) are formed spontaneously due to the growth kinetics. These approaches to the production of nanostructures and nanoelectronic devices actually represent "evolutionary" improvements in the growth and processing methods applied previously in microelectronics. Nanoscale objects like carbon nanotubes and biomolecules require, in general, other techniques for production. These innovative techniques are also highlighted in this chapter.

We pay special attention to the most important characterization techniques, such as atomic-force microscopy, scanning tunneling microscopy, and transmission electron microscopy, among others.

Also in Chapter 5, we review advances in nanotechnology that came from synthetic chemistry and biology. These include chemical and biological methods of surface nanopatterning for preparing nanostructured materials with predefined and synthetically programmable properties. The basic ideas related to these chemical and biological approaches are discussed. Finally, we study the methods of fabrication of a new class of devices commonly known as nanoelectromechanical systems (NEMS).

Chapters 6–8 include analyses of electron properties of nanostructures, traditional low-dimensional systems, and recently discovered nano-objects.

In Chapter 6, transport of charge carriers is analyzed. Important aspects of transport regimes are elucidated by comparing the time and length scales of the carriers with device dimensions and device temporal phenomena related to operating frequencies. Then, we consider the behavior of the electrons in high electric fields, including hot-electron effects. For short devices, we describe dissipative transport and the velocity overshoot effect as well as semiclassical ballistic motion of the electrons. We present ideas on quantum transport in nanoscale devices.

To distinguish the nanostructures already having applications from the newly emerging systems, we refer to the former as traditional low-dimensional structures (quantum wells, quantum wires, and quantum dots). These structures are considered in Chapter 7.

In Chapter 8, we consider newly emerging electronic, optical, and electromechanical devices based on nanostructures. First, we discuss the devices which resemble well-known microelectronic devices using a "simple" scaling-down approach. Examples include such heterostructure devices as the field-effect and bipolar transistors as well as injection bipolar lasers. Then, we study nanodevices based on new physical principles, which can not be realized in microscale devices. Among these are resonant-tunneling devices, hot-electron transistors, single-electron-transfer devices, monopolar injection cascade lasers, nanoelectromechanical devices, and quantum-dot cellular automata. We understand that there are more devices to be reviewed. For example, not enough attention has been paid to progress in silicon device technology. The ideas and results presented provide an understanding of near-future developments in nanoelectronics and optoelectronics that are occurring as a result of advances in nanotechnology. This will encourage students to learn more about nanoelectronics.

The authors have many professional colleagues and friends from numerous countries who must be acknowledged. Without their contributions and sacrifices this work would not have been completed. Special thanks go to the Division of Engineering Education and Centers (EEC) in the Directorate for Engineering and to the Division of Materials Research (DMR) in the Directorate for Mathematical and Physical Sciences (MPS), and especially to the program manager Mary Poats at the National Science Foundation for the partial support of this work through the Nanoscale Science and Engineering (NSE) Nanotechnology in Undergraduate Education (NUE) Program. The help of Dr. Nizami Vagidov in preparing figures and editing the text is especially appreciated.

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Notation

Symbols

$\mathbf{A}$ – amplitude of wave
$\langle A \rangle$ – average value of A
a – lattice constant
a_0 – length of carbon–carbon bond in carbon nanotubes
$\mathbf{a}_1$, $\mathbf{a}_2$, $\mathbf{a}_3$ – basis vectors
$\mathbf{a}_i$ – basis vectors of lattice
$\mathbf{B}$ – magnetic field
C – capacitance
$\mathbf{d}$ – translation vector
D – diffusion coefficient
d_{sp} – spacer thickness
E – energy of a particle
E_{F} – Fermi level
E_{g} – bandgap
e – elementary charge
$\mathbf{F}$ – electric field
F_0 – amplitude of electric field
f – frequency
f_{SET} – frequency of Bloch oscillations
$\mathbf{f}$ – vector of force
$\mathcal{F}$ – distribution function
$\mathcal{F}_{\mathrm{F}}$ – Fermi distribution function
G – conductance
G_0 – quantum of conductance
$\hat{\mathcal{H}}$ – Hamiltonian operator
$\mathbf{H}$ – magnetic field
$\mathbf{H}$ – direction of the nearest-neighbor hexagon rows
$\mathcal{H}$ – total energy, Hamiltonian function
h – Planck's constant
h – wave energy density
h_{1D} – wave energy density for a one-dimensional medium
$\hbar$ – Planck's constant divided by 2π

J – current density
I – current
I_{T} – tunnel current
$\mathcal{I}$ – wave intensity
$\mathbf{i}$ – quantum-mechanical flux of the particles
$\mathbf{k}$ – wavevector
k_{B} – Boltzmann's constant
L – inductance
L_T – thermal diffusion length
l_{e} – mean free path between two elastic collisions
l – orbital quantum number
$\mathbf{l}$ – angular momentum
l_{ϕ} – coherence length
L_{E} – inelastic scattering length
L_x, L_y, L_z – dimensions of a sample
M – mass of resonator
$\mathbf{M}$ – magnetic dipole moment
m – magnetic quantum number
m^* – effective mass of electron
m_0 – mass of an electron in vacuum
m_{HH} – heavy-hole mass
m_{LH} – light-hole mass
m_{SH} – split-off hole mass
N_{s} – sheet concentration of donors
N_{depl} – sheet concentration of ionized acceptors
n – principal quantum number
n_{s} – sheet concentration of electrons
$P(\xi)$ – Hermite polynomial
P_{b} – Probability of finding electron under the barrier
$\mathbf{q}$ – wavevector
Q – quality factor
Q – amount of deposited material
R – radial function
r – magnitude of radius vector
$\mathbf{r}$ – coordinate vector
r_0 – Bohr's radius
R – radius of quantum dot
R – tube radius of carbon nanotube
R – reflection coefficient
$\mathbf{S}$ – spin – intrinsic angular momentum
S – cross-section
S_z – projection of the spin of electron
s – distance between tip and surface
s – phase velocity of traveling wave

s – spin of electron
t – time
t_{tr} – transit time
T – time period
$\mathbf{T}$ – vector corresponding to tube axis of carbon nanotube
T – ambient temperature
T_e – electron temperature
T_d – translation operator
$u_{\mathbf{k}}(\mathbf{r})$ – Bloch periodic function
u – displacement of atoms from their equilibrium positions
V – potential energy
V – volume
V_b – barrier height
V_0 – volume of primitive cell
v_d – average(drift) velocity
v – velocity
v_h – velocity of hole
W – crystalline potential
U_M – potential energy
z_0 – characteristic length
Z – atomic number
α – dimensionality factor
β – spring constant
$\delta(x)$ – Dirac's delta-function
ϵ – relative mismatch of lattice constants of the substrate and epilayer
ϵ – dielectric constant of the medium
ϵ_0 – permittivity of free space
ε – energy
Φ – potential
Φ_b – built-in Schottky voltage, Schottky barrier
Φ_0 – applied voltage
ϕ – phase
ϕ – polar angle
γ – gyromagnetic ratio
Λ_{1D} – elastic modulus of string
λ – wavelength
μ – electron mobility
μ_{ph} – partial electron mobility, determined by phonon scattering
μ_{im} – partial electron mobility, determined by impurity scattering
ν – set of quantum numbers
ξ – vector of polarization
ξ – dimensionless coordinate
Ω – angular frequency of a particle
Ω – ohm

ω – frequency
ω_q – frequency of harmonic oscillator
$\Psi(\mathbf{r}, t)$ – non-stationary wavefunction
$\Psi^*(\mathbf{r}, t)$ – complex conjugate of wavefunction $\Psi(\mathbf{r}, t)$
$\psi(\mathbf{r})$ – stationary wavefunction
ρ – three-dimensional density
ρ_{1D} – linear density of string
ϱ – density of states
σ – conductivity
Θ – theta-function
θ – polar angle
τ_{E} – mean free time between two inelastic collisions
τ_{d} – decay time of flexural vibrations
τ_{e} – mean free time between two elastic collisions
$\chi(z)$ – wavefunction
χ – electron affinity

Abbreviations

BT – bipolar transistor
CMOS – complementary MOS, i.e., NMOS and PMOS on the same chip
DPN – dip-pen nanolithography
FET – field-effect transistor
JBT – homojunction BT
JFET – junction FET
HBT – heterojuction BT
HEMT – high-electron-mobility transistor
HFET – heterojunction FET
HOMO – highest occupied molecular orbit
LUMO – lowest unoccupied molecular orbit
MES – metal–semiconductor
MESFET – metal–semiconductor FET
MODFET – modulation-doped FET
MOS – metal–oxide–semiconductor
MOSFET – metal–oxide–semiconductor FET
QUIT – quantum interference transistor
RTD – resonant-tunneling diode
SIMOX – separation by implantation of oxygen
SMS – semiconductor–metal–semiconductor
VMT – velocity-modulation transistor

Contents

1 Toward the nanoscale

This book provides the foundations and the main ideas emerging from research that underlies the applied field called *nanoelectronics*. Nanoelectronics promises to improve, amplify, and partially substitute for the well-known field of *microelectronics*. The prefix *micro* denotes one *millionth* and, as applied to electronics, it is used to indicate that the characteristic sizes of the smallest features of a conventional electronic device have length scales of approximately a micrometer. The prefix *nano* denotes one *billionth*. Thus, in nanoelectronics the dimensions of the devices should be as many as a thousand times smaller than those of microelectronics.

Such a revolutionary advance toward miniaturization of electronics is based on the recently developed ability to measure, manipulate, and organize matter on the nanoscale – 1 to 100 nanometers, i.e., 1 to 100 billionths of a meter. At the nanoscale, physics, chemistry, biology, materials science, and engineering converge toward the same principles and tools, and form new and broad branches of science and technology that can be called *nanoscience* and *nanotechnology*.

Advancing to the nanoscale is not just a step toward miniaturization, but requires the introduction and consideration of many additional phenomena. At the nanoscale, most phenomena and processes are dominated by quantum physics and they exhibit unique behavior. Fundamental scientific advances are expected to be achieved as knowledge in nanoscience increases. In turn, this will lead to dramatic changes in the ways materials, devices, and systems are understood and created. Innovative nanoscale properties and functions will be achieved through the control of matter at the level of its building blocks: atom-by-atom, molecule-by-molecule, and nanostructure-by-nanostructure. The molecular building blocks of life – proteins, nucleic acids, carbohydrates – are examples of materials that possess impressive properties determined by their size, geometrical folding, and patterns at the nanoscale. Nanotechnology includes the integration of manmade nanostructures into larger material components and systems. Importantly, within these larger-scale systems, the active elements of the system will remain at the nanoscale.

The driving forces underlying developments at the nanoscale have at least two major complementary components – scientific opportunities and technological motivations.

Scientific opportunities

The progress in physics, chemistry, and biology at the nanoscale represents a natural step in advancing knowledge and understanding Nature. Scientific perspectives on this route are conditioned first of all by new quantum phenomena in atomic- and molecular-scale structures and by the interaction of large numbers of these small objects. Indeed, the fundamental laws of physics in the nanoworld differ from those that apply to familiar macroscopic phenomena. Instead of classical physics, that works so well for macroscopic phenomena, the motion of particles and systems in the nanoworld is determined by the so-called wave mechanics or quantum mechanics. A basic principle of nanophysics is the fundamental concept that all matter, including electrons, nuclei, atoms, electromagnetic fields, etc., behaves as both waves and particles. This wave–particle duality of all matter is strikingly apparent at the nanoscale. For dealing with a large number of particles or systems, the statistical laws are important. Statistical physics on the nanoscale is also fundamentally different from that on the macroscale. In general, phenomena that involve very large numbers of small interacting particles or systems follow different rules from those involving only a few of them. Cooperative behavior of many-object systems is revealed clearly at the nanoscale. Besides the phenomena just discussed, there are other classes of phenomena that are important for science at the nanoscale.

It is appropriate here to refer to the famous 1959 lecture of the Nobel Prize laureate Professor Richard Feynman with the title "There is plenty of room at the bottom," where he discussed "the problem of manipulation and controlling things on a small scale." Feynman did not just indicate that there is "room at the bottom," in terms of decreasing the size of things, but also emphasized that there is "*plenty* of room." In his lecture, Feynman justified the inevitable development of concepts and technologies underlying the nanoworld and presented his vision of exciting new discoveries and scientific perspectives at the nanoscale.

Technological motivations

Achievements in nanoscience and nanotechnology will have tremendous multidisciplinary impact. The benefits brought by novel nanotechnologies are expected for many important practical fields of endeavor. These include materials and manufacturing, electronics, computers, telecommunication and information technologies, medicine and health, the environment and energy storage, chemical and biological technologies, and agriculture. Having stated the purpose of this text, we consider now more detailed motivations for the development of electronics at the nanoscale.

In general, progress in electronics is stimulated, in part, by the enormous demands for information and communication technologies as well as by the development of numerous special applications. The continuous demands for steady growth in memory and computational capabilities and for increasing processing and transmission speeds of signals appear to be insatiable. These determine the dominant trends of contemporary microelectronics and optoelectronics. One of the main trends of the progress in electronics was formulated by Intel co-founder Dr. Gordon Moore as the following empirical observation: *the complexity of integrated circuits, with respect to minimum component cost, doubles every 24 months*. This statement formulated forty years ago is known as *Moore's law* and provides an estimate of the rate of progress in the electronics industry. Specifically, Moore's law predicts that the number of the basic devices – transistors – on