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 a microchip doubles every one to two years. This is possible only if progressive scaling down of all electronic components is realized.

Electronics exploits the electrical properties of solid-state materials. A simple and intuitive classification of solids makes a distinction between dielectrics and metals, i.e., dielectrics are non-conducting materials whereas metals are good conducting materials. Semiconductors occupy the place in between these two classes: semiconductor materials are conducting and optically active materials with electrical and optical properties varying over a wide range. Semiconductors are the basic materials for microelectronics and remain the principal candidates for use in nanoelectronic structures because they exhibit great flexibility in terms of allowing the control of the electronic and optical properties and functions of nanoelectronic devices. Accordingly, to a large extent, we will analyze the trends of electronics in the context of semiconductor technology.

It is instructive to illustrate these trends and achievements through the example of Si-based electronics. Indeed, contemporary microelectronics is based almost entirely on silicon technology, because of the unique properties of silicon. This semiconductor material has high mechanical stability as well as good electrical isolation and thermal conductivity. Furthermore, the thin and stable high-resistance oxide, SiO_2, is capable of withstanding high voltages and can be patterned and processed by numerous methods. Silicon technology also enjoys the advantage of a mature growth technology that makes it possible to grow Si substrates (wafers) of larger areas than for other semiconductor materials. The high level of device integration realizable with Si-based electronics technology may be illustrated by the important integrated circuit element of any computer, controller, etc. – the dynamic random access memory (DRAM). The main elements of DRAM based on complementary metal–oxide–semiconductor technology (Si-CMOS) are metal–oxide–semiconductor field-effect transistors (MOSFETs). For Si MOSFETs, channels for flow of electric current are created in the Si substrate between the source and drain contacts, and the currents are controlled by electrodes – metal gates – which are isolated electrically by very thin SiO_2 layers, which have become thinner than 10 nm.

Figure 1.1 illustrates the evolution of the DRAM size and transistor gate size as functions of time. Besides transistors and capacitors, the chip contains metallic line connections: local, intermediate, and global wiring. Figure 1.1 illustrates the steady scaling down of all characteristic sizes and increasing levels of integration. For example, the 64-Mbit DRAM chip contains approximately 10^8 transistors per cm^{-2}, each with feature sizes of the order of 0.3 μm. The transistors in this DRAM as well as those of the more highly integrated 256-Mbit chip operate as conventional devices and obey the laws of classical physics. The next generation of devices is entering the nanoscale regime where quantum mechanics is important; indeed, as we will discuss in this book, quantum mechanics becomes dominant on the scale of approximately one to ten nanometers for devices that operate at room temperature. According to Fig. 1.1, today's technology has already reached the nanoscale and newer device concepts should be implemented before 2010.

One of the factors driving the huge production and wide use of microelectronic systems is the relatively low cost of their fabrication. Moreover, despite their increasing

Table 1.1 A roadmap for Si-based microelectronics (predictions of the Semiconductor Industry Association)

	1995	1998	2001	2004	2007	2010
Memories, DRAM						
Bits per chip	64 M	256 M	1 G	4 G	16 G	64 G
Cost per bit (milli-cent)	0.017	0.007	0.003	0.001	0.0005	0.0002
Cost per chip (US$)	11	18	30	40	80	130
Logic, microprocessors						
Transistors per cm^2	4 M	7 M	13 M	25 M	50 M	90 M
Cost per transistor (milli-cent)	1	0.5	0.2	0.1	0.05	0.02
Power supply (V)	3.3	2.5	1.8	1.5	1.2	0.9
Parameters						
Minimum feature size (μm)	0.35	0.25	0.18	0.13	0.10	0.07
Wafer size (in.)	8	8	12	12	16	16
Electrical defect density per m^2	240	160	140	120	100	25

The data are from U. König, *Physica Scripta*, **T68**, 90, 1996.

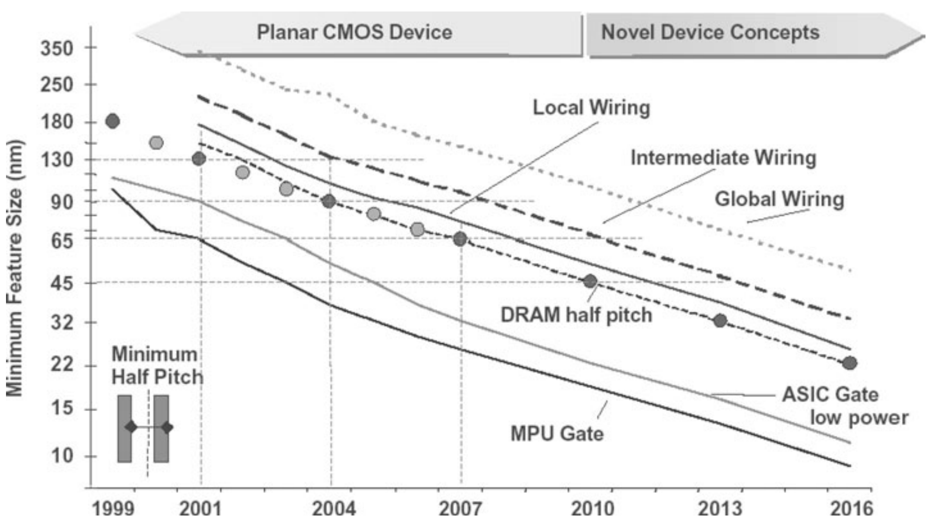

Figure 1.1 Technology nodes and minimum feature sizes from application ITRS Roadmap: MPU, Micro Processing Unit; ASIC, Application-Specific Integrated Circuit. Used with permission, from W. Klingenstein (2002). *Technology Roadmap for Semiconductors.* http://broadband02.ici.ro/program/klingenstein_3d.pdf, page 15. © InfineonTechnologies AG, 2002.

complexity, microelectronic systems continue to be produced at lower costs. In Table 1.1 the costs per bit and costs per chip as well as the associated performance levels are given as functions of the integration level. One can see that every three years the number of bits per chip has increased by a factor of four (even faster than predicted by Moore's law) and the cost per bit has decreased by a factor of two or more.

In the same table, the integration levels of logic circuits and microprocessors are forecast. We see that, for this case, device integration is also large but will increase slightly slower than for DRAMs. The cost of the principal elements of logic circuits – transistors – is significantly greater, but it also tends to decrease. The forecast for the necessary power supply presented in the table portrays a slow, but persistent, decrease. Thus, one can expect favorable trends for the power consumption of microelectronic systems.

The bottom of the table presents the necessary technological parameters for ultra-high integration: minimum feature sizes, diameters of wafers, and electrical defect densities. The large wafer size allows a greater number of devices to be fabricated on a chip. The density of electrical defects (i.e., crystal imperfections which affect electrical properties) is characteristic of the quality of the wafers. Table 1.1 forecasts that wafer diameters will be continuously increased, while the defect density decreases by a factor of six per decade; currently, they must be limited to several tens per m^2.

After this overview of the dominant driving forces in nanoscale development, we will mention briefly other general issues important for this field. These include improving materials, fabrication and measurement techniques on the nanoscale, and novelties in the operation principles of nanodevices.

Improving materials on the nanoscale

In the processes of achieving minimum device sizes and ultra-high levels of integration it is necessary to identify the limiting and critical parameters for improved performance. In reality, these parameters depend on the integrated elements of each individual material system. For example, for transistors two parameters of the host material are of special importance: the ultimate electron velocity and the limiting electric field which does not induce electric breakdown. Further improvements in the parameters can be achieved through materials engineering.

Silicon plays the central role in electronics. However, semiconductors other than silicon can be used. In particular, compound semiconductors constitute a general class of semiconductors that has been used increasingly in recent decades. As examples of forming compound semiconductors, every particular element in column III of the periodic table of elements may be combined with every element in column V to form a so-called III–V compound, which is semiconducting. Then, two or more discrete compounds may be used to form alloys. A common example is aluminum–gallium arsenide, $Al_xGa_{1-x}As$, where x is the fraction of column III sites in the crystal occupied by Al atoms, and the fraction $1 - x$ is occupied by Ga atoms. As a result, it becomes possible not only to make discrete compounds, but also to realize a *continuous range* of materials for tailoring necessary electronic properties. As for Si technology, the growth of silicon–germanium (Si_xGe_{1-x}) alloys facilitates the control of the properties of materials over a considerable range of the electrical parameters. These techniques are exploited widely in microelectronics.

Further revolutionary modification and engineering of materials can be accomplished by using *heterostructures* with nanoscale features. Heterostructures are structures with two or more abrupt interfaces at the boundaries between the different semiconductor materials. With modern material-growth techniques, it is possible to grow structures with transition regions between adjacent materials that have thicknesses of only one or two atomic monolayers. This allows one to fabricate multilayered semiconductor structures with nanoscale thicknesses.

The simplest multilayered structure has a single heterojunction, i.e., a single-heterojunction structure is made of two different materials. At the interface of such a heterojunction, the electronic properties are changed to improve selected physical characteristics. In particular, electrons can be confined in a thin layer near the interface. In fact, the layers with confined electrons can be made so thin that wave-like behavior – that is, quantum-mechanical behavior – of the electrons becomes apparent. The same phenomena occur for diverse multilayered nanoscale structures that can be grown with high quality.

By using nanostructures, it is possible to modify the electronic properties of a great variety of a nanoscale devices. Indeed, we live in a three-dimensional world, where a particle can, in principle, move in all three directions. Quantum effects on the nanoscale determine the properties of electrons in nanostructures: the nanostructures can be made in such a way that the electron motion becomes *two-dimensional, one-dimensional, or even zero-dimensional*. These nanostructures are known as *low-dimensional* quantum heterostructures and are called quantum wells, quantum wires, and quantum dots, for the cases where the electrons are confined in one, two, and three dimensions, respectively. Such an impressive example of manipulation of the properties of the current-carrying particles clearly illustrates fundamentally new possibilities for electronics that become viable at the nanoscale.

Fabrication techniques on the nanoscale

The progress in heterostructure technology has been made possible largely as a result of new advances in fabrication techniques. In Table 1.2, we provide a very brief summary of some important steps now used in the growth, characterization, and processing of heterostructures. In the period of the 1970s and 1980s, molecular-beam epitaxy was invented, developed, and employed to fabricate high-quality and ultra-thin layers and superlattices. Qualitative electron-beam and X-ray microscope technologies were used to characterize the perfectness of structures, including interface disorder. During this period, lithographic and etching methods suitable for microscale and nanoscale devices were proposed and realized. In the 1980s and later, new epitaxial techniques were developed; these included metal–organic vapor-phase epitaxy and metal–organic molecular-beam epitaxy, among others. These innovations made possible the fabrication of layers with atomic-level accuracy. Lithography and etching methods were improved to the point that they can be used for nanoscale structuring. Desirable spatial-modulation doping by impurities has become possible, including δ-doping – that is, doping of one or a few atomic monolayers.

These approaches to the production of nanostructures and nanoelectronic devices represent "evolutionary" improvements in the growth and processing methods applied previously in microelectronics. Advances in nanotechnology allow, in principle, the utilization of methods and concepts from other areas of science and engineering. Synthetic

Table 1.2 Advances in growth, characterization, and processing of quantum heterostructures

1970s–1980s	Growth and fabrication methods Molecular-beam epitaxy Ultra-thin-layer fabrication Superlattice fabrication
	Characterization methods Lithographic microstructuring Qualitative electron-beam and X-ray microscopies
1990s–2000s	Growth and fabrication methods Metal–organic vapor-phase epitaxy Metal–organic molecular-beam epitaxy Fabrication to atomic-layer accuracy δ-Doping Controlled strained layers Fabrication methods based on chemistry and biology Assembling inorganic nanoblocks with biomolecules
	Characterization methods Lithography and etching for nanostructuring Dip-pen nanolithography Quantitative electron-beam and X-ray microscopies Scanning tunneling microscopy (STM) Atomic force microscopy (AFM) Picosecond and femtosecond spectroscopy Terahertz time-domain spectroscopy

chemistry and even biology have much to offer for emerging nanotechnologies. Some fundamental concepts coming from these fields can successfully be exploited for the synthesis of nanomaterials and nanodevices. These include chemical and biological methods of growth of nanoscale objects – such as carbon nanotubes and biomolecules – surface nanopatterning, and preparing nanostructured materials with predefined, synthetically programmable properties from common inorganic building blocks with the help of DNA interconnect molecules, etc.

Improvement in characterization methods for the nanoscale

Progress in the refinement of fabrication techniques for making nanostructures depends on the great improvements made in characterization methods. Some of these methods are indicated in Table 1.2. In particular, composition and dopant distribution, lattice strain, and other parameters within nanostructures must be known with atomic-scale precision. Currently, the manipulation of a single atom (ion) in a solid is possible. New tools – scanning tunneling microscopy and atomic-force microscopy – which portend numerous applications in high-precision fabrication have emerged. Picosecond and femtosecond spectroscopy have progressed substantially and they have been applied to characterize the electronic and lattice properties of heterostructures. Finally, terahertz time-domain spectroscopy was developed, which makes it possible to measure electric signals with time resolution at the level of 10^{-12} seconds.

New principles of device operation at the nanoscale

Fundamental questions arise when conventional principles of device operation fail as a result of entering the nanoscale domain. One of the effects is almost *collisionless* motion – frequently called ballistic motion – of electrons flying through short devices. As mentioned previously, the nanoscale domain is the "realm" of quantum physics. Indeed, scaling down of devices and their integration above the level corresponding to 250 Mbits on a single chip makes it necessary to take into account new regimes and even to modify the principles underlying device operation. Further device downscaling and higher integration densities for information capacities exceeding 1 Gbit per chip imply the need to investigate using *quantum regimes* of operation in future years. Quantum-mechanical effects are not only important for operation of future integration circuits, but also are already used for generation of ultra-high-frequency electromagnetic emission. A relevant example is that of resonant-tunneling phenomena in nanoscale multilayered structures, which creates a foundation for microwave emission up to 1000 GHz.

A number of such device-related quantum effects has been discovered. New physics and new quantum effects always pass ahead of new devices exploiting these effects that have made a substantial impact on device technology. We mention here just a few quantum effects: 1970, the proposal of multilayered structures; 1974, the resonant-tunneling effect; 1978, the modulation doping effect; 1980, conduction of polymers; 1985, the discovery of the buckyball, C_{60}; 1993, the discovery of single-walled carbon nanotubes; and 1996, nanoelectromechanical systems (NEMSs). Some of these effects will be analyzed in this book. Here is a short list of some of the novel quantum devices: 1979, the injection quantum-well laser; 1983; the Microwave DBRTD Oscillator; 1984, the hot-electron transistor; 1998, the quantum-wire carbon nanotube field-effect transistor; 1998, polymer-based transistors and light-emitting devices; 2001, sensors based on NEMSs; 2001, sub-terahertz III–V compound nanoscale field-effect transistor; and 2006, sub-terahertz InP and SiGe bipolar transistors. There is a "delay time" between the discovery of the effect and the device concept, but the delay time is decreasing steadily. The following examples show this tendency. The effect of resonant tunneling was discovered in 1974; the device – the microwave double-barrier resonant-tunneling diode (DBRTD) oscillator – was realized in 1983. The first quantum wires with one-dimensional electron motion were studied in 1986; their first application in lasers occurred in 1995. In both cases the "delay time" was 9 years. The discovery of single-walled carbon nanotubes was made in 1993 and in only 5 years the carbon nanotube transistor was fabricated. The same is valid for the development of nanoelectromechanical systems and their applications for a number of sensors, etc. Thus, for contemporary electronics there is an evident acceleration of the implementation of fundamental physical effects.

Besides quantum effects, reducing device dimensions results in a decrease in the number of electrons participating in the transfer of an electric signal. As a result, nanoscale devices may operate on the basis of single-electron transfer. Various novel single-electron devices have been proposed and demonstrated. By reducing the sizes of quantum dots to 100 Å or less, it is possible to operate with single electrons at temperatures near or close to room temperature.

The great technological advances brought about in mainstream microelectronics and nanoelectronics can be used for the fabrication of other classes of nanodevices. One such approach is based on quantum dots arranged in locally interconnected cellular-automata-like arrays. The fundamental idea of operation of cellular automata is to encode information using the charge configuration of a set of quantum dots. Importantly, in the quantum-dot cellular-automata approach, the information is contained in the arrangement of charges of the dots, rather than in the flow of the charges, i.e., electric current. It can be said that the devices interact by direct Coulomb coupling rather than via the current through the wires.

Another approach employs both electrical and mechanical properties of nanostructures. The new generation of devices and systems based on this approach is commonly referred to as *nanoelectromechanical systems* (NEMSs). Indeed, on the nanoscale a strong enhancement of coupling between electronic and mechanical degrees of freedom occurs. This electromechanical concept may be used for the development of a new class of devices that includes nanomachines, novel sensors, and a variety of other new devices functioning on the nanoscale. Thus, NEMSs may supplement the traditional electronics that works solely with electrical signals.

Nanotechnology for optoelectronics

Thus far, we have reviewed nanoscience and nanotechnology as applied to *electronic* devices, i.e., devices in which electrical properties are exploited and which operate with electrical input and output signals. Another class of devices is comprised of *optoelectronic devices*, which are based on both electrical and optical properties of materials and operate with both optical and electrical signals. An important and growing trend is that optoelectronics complements microelectronics in many applications and systems. First of all, optoelectronics provides means to make electronic systems compatible with lightwave communication technologies. Furthermore, optoelectronics can be used to accomplish the tasks of acquisition, storage, and processing of information. Advances in optoelectronics make significant contributions to the transmission of information via optical fibers (including communication between processing machines as well as within them), to the high-capacity mass storage of information on laser disks, and to a number of other specific applications. Clearly, optoelectronic devices have a huge number of diverse applications.

The principal components of optoelectronic systems are light sources, sensitive optical detectors, and properly designed light waveguides, for example, optical fibers. These devices and passive optical elements are fabricated with optically active semiconductor materials. Semiconductor nanostructures and, in particular, quantum heterostructures provide new means to enhance many optical and electro-optical effects. For example, both of the most widely used light sources – light-emitting diodes and laser diodes –

may be improved greatly when nanostructures such as quantum wells, quantum wires, and quantum dots are exploited as active optical elements.

As for the previously studied case of microelectronics, the trends in optoelectronics involve scaling down the sizes of these devices as well as achieving high levels of integration in systems such as arrays of light diodes, laser arrays, and integrated systems with other electronic elements on the same chip. Optoelectronics benefits substantially through the use of nanotechnology and becomes competitive with its microelectronic counterpart.

In conclusion, the current and projected trends in electronics lead to the use of nanostructures and to the reliance on novel quantum effects as an avenue for realizing further progress. These recent and diverse trends in semiconductor and device technologies as well as in novel device concepts are driving the establishment of a new subdiscipline of electronics based on nanostructures, i.e., nanoelectronics. This subdiscipline and its foundations are studied in this book.

More general information on nanoscience, nanotechnology, and nanostructures, and their potential, may be found in the following reviews:

R. Feynman, “There’s plenty of room at the bottom,” American Physical Society Meeting, Pasadena, CA, 29 December 1959; originally published in Caltech’s *Engineering and Science Magazine*, February 1960; reprinted as R. P. Feynman, “Infinitesimal machinery,” *Microelectromechanical Systems*, **2**, 1 (1993); (see, for example, www.zyvex.com/nanotech/feynman.html).

National Nanotechnology Initiative: The Initiative and Its Implementation Plan, National Science and Technology Council, Committee on Technology, Washington DC, 2000 (see, for example, www.nano.gov).

H. Kroemer, “Quasielectric fields and band offsets: teaching electrons new tricks,” *Rev. Mod. Phys.*, **73**, 783 (2001).

The International Technology Roadmap for Semiconductors (Semiconductor Industry Association, San Jose, CA, 2002 – update).