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Vladimir V. Mitin, Viatcheslav Kochelap and Michael A. Stroscio
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Trends in Microelectronics and Optoelectronics

This book is intended to provide the foundations of the physics and engineering of quantum heterostructures and the physics of novel microelectronics and optoelectronics devices.

A wide variety of quantum heterostructures and devices has become possible because of dramatic improvements in semiconductor materials and technology as well as because of a deeper understanding of the underlying physics and the new device concepts. Progress in each of these areas has been stimulated, in part, by the enormous demands for information and communication technologies as well as by 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. They have determined the dominant trends of contemporary microelectronics and optoelectronics – two components of the rapidly growing information industry. In this chapter we briefly analyze some of these trends and discuss the use of quantum heterostructures and quantum physics to realize electronic devices with greatly enhanced performance. Then we discuss new quantum effects discovered in heterostructures as well as their impact on the operation of conventional devices and on new device concepts.

To trace how the dominant trends are evolving, Fig. 1.1 illustrates the relationships among end-use technologies, physics of materials and devices, and new device concepts. The upper level of this schematic presents end-use technologies. As is well known, these information and communication technologies are essential to the functions and progress of society. There are also other special applications based on microelectronics and optoelectronics; these applications underlie many high-technology industries including those supporting aeronautics, space, and the military. These end-use technologies are based on supporting technical capabilities.

The next level of Fig. 1.1 focuses on the general demands for technical capabilities and systems. Modern information technology depends heavily on the systems that are highly integrated with great numbers of devices per unit area or on a single chip; moreover, there are increasing demands for high-speed operation and low power consumption. Communication technology relies on microwave and optical-fiber transmission and is based on systems operating with both high-frequency electrical and optical signals. Special applications result in additional

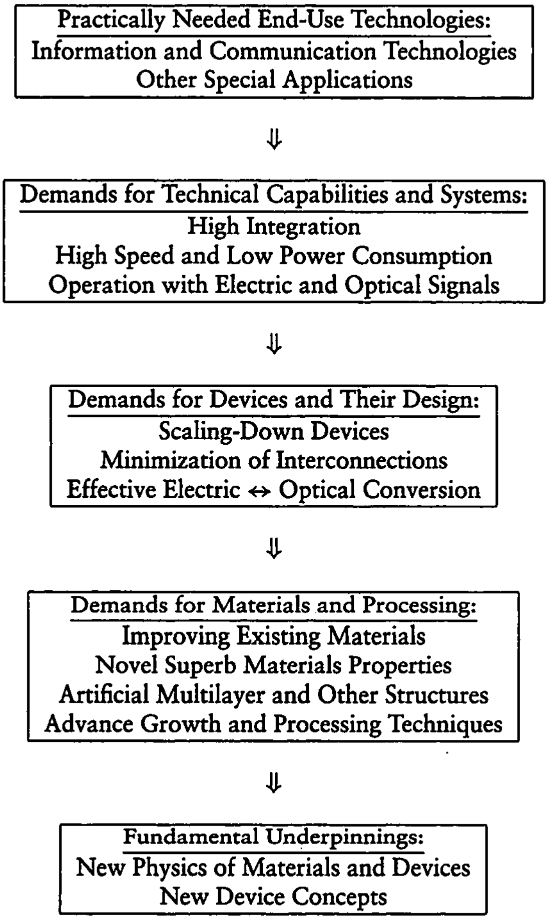

Figure 1.1. This schematic illustrates the relationships among end-use technologies, technical systems, single devices, material science and engineering, physics, and new device concepts and systems.

demands such as high-temperature operation and the handling of high-power signals. The technical systems consist of active devices, passive elements, a number of interdevice connections, and so on. The next level of Fig. 1.1 highlights the demands on single devices. For high-performance systems, single devices have to be as small as possible, and it is highly desirable to minimize interconnections on chip. Clearly, efficient conversion from electric to optical signals and vice versa are necessary. It is possible to achieve many of these goals through advances in materials and processing, as presented in the next level of Fig. 1.1. This includes improving existing semiconductor and optical materials, growing new materials with superb properties and perfectness, and the fabrication of artificial structures like multilayered structures and other semiconductor heterostructures. Techniques for processing materials and heterostructures are essential for these advances. Currently, processes such as patterning, etching, implantation, metallization, and others are carried out with nanoscale control. Finally, the basis for future progress in all these technologies is the physics of new materials, structures, and devices. A principal task for researchers in these fields is to establish the fundamental properties of materials, to model processes in devices, and to find ultimate regimes and operation limits for devices. Equally important, scientists and engineers must generate new conceptual ideas of devices.

It is instructive to illustrate these trends and achievements through the example of Si-based electronics. Contemporary microelectronics is based almost entirely on Si technology because of the unique properties of Si. 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 voltage and can be patterned and processed by numerous methods. Si technology also enjoys the advantage in that one can grow larger-area Si substrates (wafers) than for other semiconductor materials. The high level of device integration realizable with Si-based electronics technology is illustrated for the important integrated circuit element of any computer, controller, etc. – the dynamic random-access memory (DRAM). We shall consider DRAMs based on the Si complementary metal-oxide-semiconductor (CMOS) technology. The main elements of such DRAMs are metal-oxide-semiconductor (MOS) field-effect transistors (FETs) and passive capacitors. For Si MOSFETs, current channels are created in the Si substrate between the source and the drain contacts, and the currents are controlled by electrodes – metal gates – that are isolated electrically by very thin SiO_2 layers, typically ~100 Å thick. In a CMOS, the storage element uses two MOSFETs with p and n channels. Figure 1.2 illustrates the evolution of such DRAMs: the minimum MOSFET feature size is presented as a function of time for DRAMs with different integration levels and capabilities. The chip also contains, besides MOSFETs, capacitors, metallic line connections, etc. The number of such devices and elements increases progressively with increasing information capability of the DRAM chip. Figure 1.2 illustrates the steady scaling down of the devices as well as increasing levels of integration. For example, the modern 64-Mbit DRAM chip contains approximately 10^8 MOSFETs/cm^2 and these MOSFETs have feature sizes of the order of 0.3 μm. The MOSFETs 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 going to be in a transition regime and further in a quantum regime of operation.

One of the factors driving the huge production and wide use of microelectronic systems is the relatively low cost of their fabrication. Moreover, despite an increase in 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 3 years the bit number per chip increases by a factor of 4 and the cost per bit decreases by a factor of 2 or more.

In Table 1.1, the integration levels of logic circuits and microprocessors are forecast. We see that for this case, device integration is also large but it will increase slightly slower than for DRAMs. The cost of the principal elements of logic circuits – transistors – is sufficiently greater, but it also tends to decrease.

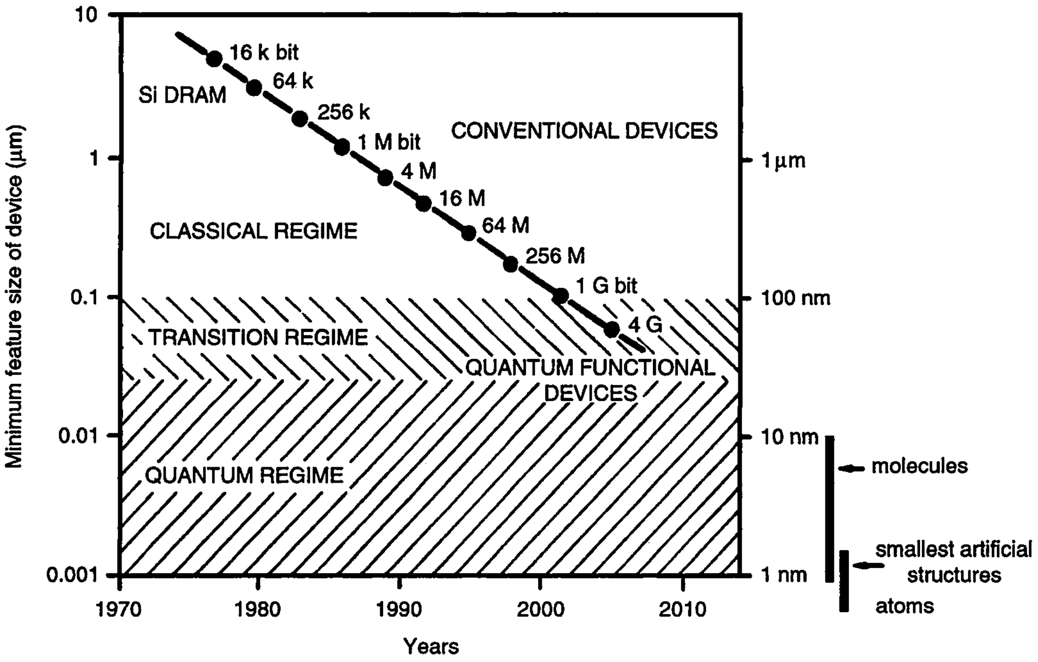

Figure 1.2. Evolution of Si-based DRAM chips as a function of time. The ordinate presents the minimal feature sizes of MOSFETs. The number of bits per chip is indicated as a function of time. Regimes of electron transport in FETs, classical, transitional, and quantum-mechanical devices are identified in terms of relevant feature sizes. For comparison, the sizes of large molecules, the smallest artificial systems, and atoms are presented. [After H. Lüth, "Nanostructures and semiconductor electronics," Phys. Status Solidi B 192, pp. 287–299 (1995).]

In the table, a forecast for the necessary power supply is presented that shows a slow, but persistent, decrease. Thus one can expect favorable trends for the power consumption of microelectronic systems.

At the bottom of the table the necessary technological parameters for ultra-high integration are presented; these include minimum feature sizes, diameters of wafers, and electrical defect densities. It is anticipated that by 2001 feature sizes of ~ 0.18 μm will be realized; at this dimensional scale, the lithographic technique must be changed. For larger sizes, optical (ultraviolet) lithography is applicable, while for small dimensions, innovative tools such as x-ray and electron-beam lithography will have to be used. As is well known, wafers cut from monocrystalline Si ingots are used as substrate materials for subsequent processing and device fabrication; the larger the wafer size, the greater the number of devices that can be fabricated on chip. Table 1.1 forecasts that wafer diameters will increase by a factor of 2 and the defect density will decrease by a factor of 6.

Such ultra-large-scale integration is possible only for Si-based electronics because of the unique properties of Si. Other advanced semiconductor technologies based on III–V compounds also facilitate high integration, but they cannot match Si technology in terms of applicability to ultra-large-scale integration.

Table 1.1.
Roadmap for Si-Based Microelectronics: Predictions of the Semiconductor Industry Association

Years	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 (millicent)	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 (millicent)	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
Electric defect density ($1/m^2$)	240	160	140	120	100	25

The data are taken from U. König, Phys. Scripta T68, 90 (1996). M, $\times 10^6$; G, $\times 10^9$.

Concerning speed of operation and lower power consumption for a single device, the scaling of III–V devices to small dimensions appears to offer potential advantages compared with the figures of merit for Si-based electronics. The potential advantages of III–V devices stem from higher mobilities and hence higher electron velocities.

It is worth emphasizing that quantum effects appear in III–V-based devices for larger device features than for their Si-based counterparts. Achieving high-speed operation of integrated circuits also requires the minimization and the optimization of interconnections on chips. An alternative way to satisfy this demand is to use optically active semiconductor materials, as is discussed below.

In the processes of achieving minimum device sizes and ultrahigh 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 – the so-called saturated velocity – and the limiting electric field that does not induce electric breakdown – the so-called dielectric breakdown strength. Further improvements in the parameters are possible to achieve through materials engineering; examples include growing alloys and fabricating high-quality artificial multilayered structures.

The simplest multilayered structure has a single heterojunction, that is, a single-heterojunction structure is made of two different materials. At the interface of such a heterojunction, the electronic properties can be changed to improve selected physical characteristics. In particular, electrons can be confined in a thin

Table 1.2.
Advances in Growth, Characterization, and Processing of Quantum Heterostructures

1960s–1970s	Molecular-beam epitaxy
	Ultra-thin-layer fabrication
	Superlattice fabrication
	Qualitative electron-beam and x-ray microscopies
	Lithographic microstructuring
1980s–1990s	Metal-organic vapor-phase epitaxy
	Metal-organic molecular-beam epitaxy
	Atomic layer accuracy fabrication
	δ doping
	Controlled strained layers
	Quantitative electron-beam and x-ray macroscopies
	Scanning tunneling microscopy
	Atomic force microscopy
	Lithography and etching for nanostructuring
	Picosecond and femtosecond spectroscopy

layer near the interface and spatially separated from their parent impurities; this so-called modulation doping greatly enhances electron mobility. In fact, the layers with confined electrons are so thin that electrons become quantized, that is, they obey the laws of quantum physics. The same is valid for different multilayered structures, which can be grown with high quality. Two- and one-dimensional electron channels, including quantum wells and quantum wires, as well as cells for electrons known as quantum boxes or dots, are currently fabricated in many laboratories throughout the world. Such structures are known as quantum semiconductor heterostructures. The progress in heterostructure technology has been made possible largely as a result of new advances in fabrication techniques. In Table 1.2, we give a brief summary of some important steps now used in the growth, characterization, and processing of heterostructures.

In the 1960s and the 1970s, molecular-beam epitaxy was invented, developed, and used to fabricate high-quality and ultrathin 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 devices were proposed and realized. In the 1980s and later, new epitaxial techniques were developed; these included metal-organic vapor-phase epitaxy, metal-organic molecular-beam epitaxy, and others. These innovations made possible the fabrication of layers with atomic-level accuracy. Desirable spatial-modulation doping by impurities has become possible, including δ doping: doping of one or a few atomic monolayers. The thin-layer fabrication technique facilitated atomic-scale control and the use of materials with quite different lattice parameters. Such layers are strained, but in many cases they can be almost perfect. New tools – scanning-tunneling microscopy (STM) and atomic force microscopy (AFM) – emerged that portend numerous applications in high-precision fabrication. Lithography and etching methods were improved to the point that they can be used for nanoscale structuring. Finally, picosecond and femtosecond spectroscopy progressed substantially, and they were applied to characterize the electronic and lattice properties of heterostructures.

Perfect heterostructures can have properties superior to those of bulk materials and alloys. Currently, they have become key elements of microelectronics technology. Initially, quantum heterostructures were developed on the basis of III–V materials. Heterostructure FETs, which are also known as high-electron-mobility transistors (HEMTs), heterostructure bipolar transistors (HBTs), double-barrier resonant-tunneling diodes (DBRTDs) for microwave applications, real-space transfer (RST) transistors, hot-electron transistors (HETs), and other microelectronic devices have been fabricated with high-performance characteristics. For example, these devices can operate in the high-frequency range up to hundreds of gigahertz. Furthermore, heterostructures based on Si/Ge have significant potential for being compatible with Si technology. Many properties of these structures portend devices with advantages over Si devices. In particular, Si/Ge heterostructure bipolar transistors can operate at frequencies up to 100 GHz, which substantially exceeds the frequencies of operation of homostructure Si bipolar transistors. A variety of different devices may be fabricated with these Si/Ge heterostructures. These developments may lead to major extensions of current Si-based electronics technology.

Fundamental questions arise when conventional principles of device operation fail as a result of entering the small-scale domain of quantum physics. In Fig. 1.2 the feature sizes corresponding to classical (conventional), transitional, and quantum-mechanical regimes of operation are indicated. One can see that integration above 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 of Si-based chips lead to information capacities exceeding 1 Gbit/chip and imply the need to explore by use of quantum regimes of operation in future years. 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. A variety of novel single-electron devices has been proposed and demonstrated. These devices are fabricated on the basis of III–V and Si/Ge heterostructures. When the sizes of quantum dots are reduced to 100 Å or less, it is possible to operate with single electrons at temperatures near or close to room temperature.

In conclusion, the current and the projected trends in microelectronics lead to the use of quantum heterostructures and to the reliance on novel quantum effects as an avenue to realizing further progress. A number of such relevant quantum effects have been discovered. In Table 1.3 we present the list of some of these

Table 1.3.
Physical Effects in Quantum Structures and Associated Microelectronic (ME) and Optoelectronic (OE) Devices

	Physics		Devices
1970	Proposal for multilayered structures (superlattices) (Chapters 3, 4)	1979	(OE) Injection quantum well laser (Chapter 12)
1974	Resonant-tunneling Effect (Chapter 8)	1980	(ME) HEMT and other transistors (Chapter 9)
1974	Quantum-well-size quantization effect (Chapters 3, 4)	1983	(ME) Microwave DBRTD oscillator (Chapters 8, 9)
1978	Modulation doping effect (Chapters 4, 6, 7)	1984	(OE) Self-electron-optic-effect device (Chapters 11, 12)
1981	Quantum-confined Stark effect (Chapters 11, 12)	1984	(ME) Resonant HET (Chapters 8, 9)
1986	Quantum wires and waveguides (Chapters 3, 6, 7)	1984	(OE) Quantum-well, nonlinear (conventional) etalon (Chapters 11, 12)
1987	Quantum point contact (Chapter 2)	1987	(OE) Quantum-well infrared photodetector (Chapters 10, 12)
1987	Stark ladder transitions in superlattices (Chapter 11)	1989	(OE) Surface-emitting laser (Chapters 10, 12)
1990	Single-electron tunneling (Chapter 8)	1991	(OE) II–VI blue laser (Chapter 12)
1991	Quantum microcavities (Chapters 10, 12)	1994	(OE) Quantum-cascade laser (Chapter 12)
		1995	(OE) Quantum-box laser (Chapter 12)
		1995	(OE) GaN blue laser

effects and identify novel devices that use them; we include those effects that are analyzed in this book. Some other important phenomena observed in quantum structures such as the quantum Hall effect, the suppression of shot noise, and so on, are not presented.

In this book we study conditions associated with the transition between classical and quantum regimes of operation as well as quantum physics and new microelectronic devices and concepts based on the underlying physics. In Table 1.3, we identify the chapters in which these effects and devices are analyzed.

Now we briefly consider optoelectronic systems that are frequently referred to as photonic systems. Optoelectronics complements microelectronics in many applications and systems. First, optoelectronics provides means to make electronic systems compatible with light-wave 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 by means of optical fibers (including communication between processing machines as well as within them), to the high-capacity mass storage of information in laser disks, and to a number of other specific 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. The III–V, IV–VI, and II–VI compounds belong to this group; most of these compounds have direct bandgaps, which make them suitable materials for optoelectronic devices. For comparison, Si is an indirect-energy-gap material, and it is not suitable for conventional optical applications. With direct-bandgap semiconductor materials, two main types of light sources have been developed: light-emitting diodes (LEDs) that produce spontaneous incoherent emission and lasers that emit stimulated coherent light. In both cases, electrical energy is converted into light energy. General goals for these devices include electric control, high-speed optical tuning, and achieving operation in the desired optical spectral range.

Optoelectronic devices and systems use a variety of different optical and electro-optical effects. Quantum heterostructures provide a means to enhance many of the effects known in bulklike materials, such as excitonic effects and optical nonlinearities near the fundamental edge of optical absorption. Quantum heterostructures also exhibit the new optical effects listed in Table 1.3.

Semiconductor junction lasers are quantum devices. They have superior properties compared with those of LEDs and are preferable for many technologies. These lasers are quite compact and are highly compatible with semiconductor electronic circuits. The original semiconductor lasers were homojunctions, i.e., they were made of one material, usually GaAs, doped to form a *p*–*n* junction. For these lasers, the injection of electrons and holes from both sides of the junction into the active region provided the population inversion necessary for lasing, and stimulated emission occurred because of radiative recombination of highly nonequilibrium electrons and holes in the active region. The next generation of the lasers used two heterojunctions. These double-heterojunction structures served both to confine electrons and holes in a precisely defined active region and to provide a waveguide for the stimulated emitted light. These lasers were designed successfully for different spectral ranges. For example, AlGaAs/GaAs double-heterostructure lasers operated in the 0.75–0.9-μm range, while GaInAsP/InP lasers covered the 1.2–1.6-μm range, which is ideally suited for low-attenuation optical-fiber transmission. There are several different critical parameters of semiconductor lasers: the threshold current, temperature sensitivity, modulation bandwidth, speed of modulation, coherence, and so on. All these demands can be met if nonequilibrium electrons and holes are squeezed together in such a narrow active region; accordingly, quantum effects in electron transport become significant. The demand for advanced semiconductor lasers promotes the reliance on various heterostructure materials. Devices with low costs and long

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life are required as well. In Table 1.3 several new types of heterostructure lasers are highlighted: quantum-well injection lasers, surface-emitting lasers, quantum-wire and quantum-dot lasers, quantum-cascade lasers, and short-wavelength injection lasers.

As for the previously studied case of microelectronics, the trends in optoelectronics are scaling down the sizes of these devices and 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. Note that there is a fundamental limit to the size scaling of optical devices: light can not be spatially confined below λ/n_{ref}, where λ is the wavelength of light in vacuum and n_{ref} is the refractive index of optical material. Light confinement on scales of the order of λ/n_{ref} is possible in waveguides or specially designed optical microcavities such as a Fabry–Perot resonator with highly reflective multilayered mirrors.

Generally, there are two approaches to device operation with optical signals. The first, currently the most widely used, is optical-to-electrical signal conversion and subsequent processing by electronic means; these systems are referred to as hybrid optoelectronic systems. To achieve this goal, one needs optical detectors; in addition, optical modulators, optical gates, and other electrically controlled devices are to be used. The essential performance requirements are fast response, high sensitivity, and high quantum efficiency. Electro-optical devices based on heterostructures satisfy these conditions and play a leading role in optoelectronics. A particular example is provided by the so-called self-electro-optic-effect devices (SEEDs). These quantum heterostructure optoelectronic devices serve as multifunctional devices and facilitate the realization of optical set–reset latches, differential logic gates, differential modulators or detectors, and so on. Another approach to optical signal processing is based on nonlinear optical elements that make light-by-light control possible and exhibit all necessary functions for all-optical addressed systems. The latter should include such devices as optical switches, dynamic optical memory, and optical transistors. A digital hybrid optoelectronic or all-optical addressed system should use two-dimensional arrays of lasers, optical switches (optical gates), and optical detectors, as well as such optic elements as lenses and light splitters. The benefits of this approach are the substantial decrease in the number of optical-to-electrical and electrical-to-optical conversions, the dramatically decreased number of interdevice connections, and powerful parallel processing of signals.

Special techniques for the growth of optical semiconductor materials and their processing were developed to fabricate these optoelectronic devices with sizes close to the above-mentioned fundamental optical limit and with sizes that led to confining electrons and holes in the quantum limit. Large arrays of emitting diodes or lasers, nonlinear elements, and optical detectors have been fabricated for this purpose. Their fabrication is based on the heterostructure manufacturing and processing techniques presented in Table 1.2 and tends to provide devices with long lifetimes for low costs. In Table 1.3, we indicate several heterostructure devices used for optical signal processing: SEEDs, conventional nonlinear multilayered optical photodetectors, and quantum-well photodetectors.