1 Some Trends in Optoelectronics

This book is intended to provide the foundations of the physics and engineering of the optical properties of quantum heterostructures and the basics of optoelectronics devices.

A wide variety of quantum heterostructures and devices has become possible due to dramatic improvements in semiconductor materials and technology as well as to a deeper understanding of the underlying physics and new device concepts. This variety of heterostructures and devices is enhanced by the recently discovered single- and few-monolayer crystals (true two-dimensional materials). 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.

In this chapter we analyze briefly trends in the optics and optoelectronics of quantum heterostrucures and two-dimensional crystals and discuss the use of these nanostructured materials to realize devices with greatly enhanced performance.

In order to trace how the dominant trends are evolving, Fig. 1.1 illustrates the relationships between end-use technologies, the physics of the materials and devices, and new device concepts. The upper level of this chart presents end-use technologies. As is well known, these information and communication technologies are essential to the present-day functioning and progress of society. There are also other special applications based on 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 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 high-frequency electrical and optical signals. Special applications result in additional 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 inter-device connections, etc. 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 the number of interconnections on a chip. Clearly, efficient conversion from electrical to optical signals and vice versa is necessary.

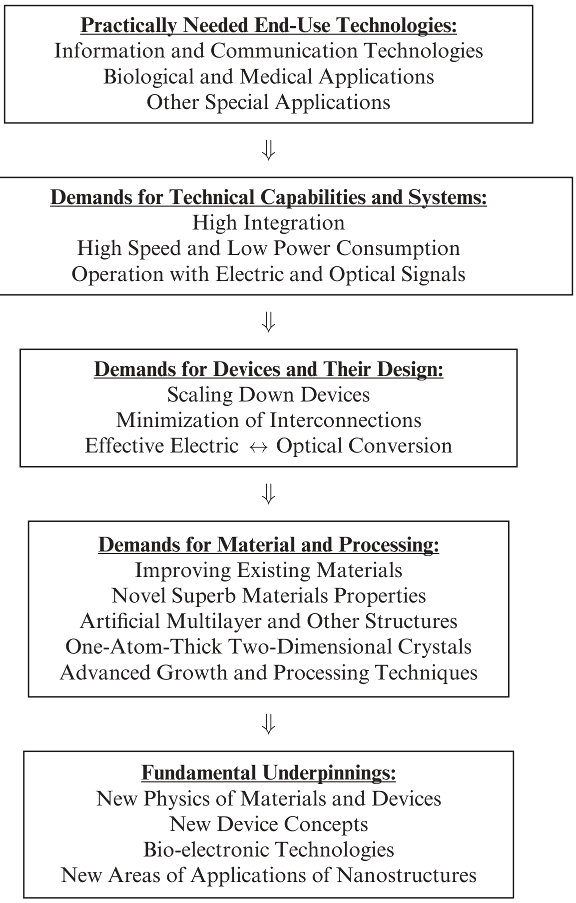

Figure 1.1 The relationships between end-use technologies, technical systems, single devices, material science and engineering, physics and new device concepts, and systems.

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, developing new materials with superb properties and “perfectness”, and fabricating artificial structures such as multilayered structures and other semiconductor heterostructures. Techniques for the processing of 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 the new materials, structures, and devices. A principal task for researchers in these fields is to establish the fundamental properties of the materials, to model processes in devices, and to find ultimate regimes and operation limits for devices. It is equally important that scientists and engineers generate new conceptual ideas of devices.

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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. It is known now that it is possible to achieve improvements in the parameters through materials engineering. Examples include growing alloys and fabricating high-quality artificial multilayered nanostructures composed of single- and few-monolayer crystals.

The simplest multilayered structure has a single heterojunction; 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 layer near the interface and spatially separated from their parent impurities; this so-called modulation doping greatly enhances the 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 quantum dots, are currently being fabricated on large wafers and used in electronic and optoelectronic devices. 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 1.1, we give a very brief summary of some of the important steps now used in the growth, characterization, and processing of heterostructures.

In the 1960s and 1970s, 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 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 – the doping of one or a few atomic monolayers. Thin-layer fabrication techniques 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 and atomic-force microscopy – emerged, which 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, femtosecond spectroscopy progressed substantially, moving into ottosecond spectroscopy, and became heavily used to characterize heterostructures.

Heterostructures based on Si/Ge have significant potential since these structures are compatible with Si technology. Many properties of these structures portend

Table 1.1 Advances in growth, characterization, and processing of quantum heterostructures

1970s–1980s	***Growth and fabrication methods***
	Molecular-beam epitaxy
	Ultrathin-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
	Atomic-layer-accuracy fabrication
	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
2000s–2018	***Growth and fabrication methods***
	Methods of fabrication of quantum wires and quantum dots of controllable compositions and sizes
	Micromechanical cleavage techniques for extraction of two-dimensional crystals
	Extreme ultraviolet interference lithography for tens of nanometers resolution
	Fabrication of structures for subwavelength optics
	Methods of generation and detection of THz emission
	Characterization methods
	Angle-resolved photoemission spectroscopy
	Near-field optical spectroscopy which uses plasmonic effects
	Sub-femtosecond spectroscopy
	Time-delay spectroscopy

devices with advantages over Si devices. In particular, Si/Ge heterostructure bipolar transistors can operate at frequencies up to the sub-terahertz range.

Recently, another type of heterostructure – silicon on insulator – has received a great deal of attention and has significant promise. The term silicon-on-insulator technology refers to the exploitation of a layered silicon–insulator–silicon substrate instead of the conventional silicon substrates widely used in the semiconductor

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industry. In silicon-on-insulator systems, the silicon junction is located above an electrical insulator, typically silicon dioxide or sapphire. The choice of insulator depends largely on the intended application. For example, silicon on sapphire is used for high-performance radio frequency applications, while silicon on silicon dioxide is used in nanoelectronic devices and in silicon optoelectronics. Indeed, the growing demand for instant and reliable communication requires the integration of microelectronic and optical devices in optoelectronic circuits. Silicon-on-insulator structures facilitate the fabrication of optical waveguides and other optical devices. For example, the buried insulator enables the propagation of infrared light in the silicon layer, on the basis of total internal reflection.

The very first two-dimensional crystal – graphene – was discovered in 2004. After that, various other two-dimensional crystals were discovered. Two-dimensional crystals are atomically thin materials with atoms strongly bound in one crystal plane. Owing to the reduced dimensionality, charge carriers in these materials are strongly confined to one crystalline plane. This leads to a significant modification of the electronic band structure and, in particular, radical changes in optical behavior, giving rise to exciting new physical effects. These effects indicate the great potential for applications of two-dimensional materials in optoelectronics over a very wide spectral range (from terahertz to ultraviolet electromagnetic spectra).

Very recently novel ways to confine and control light (electromagnetic emission in general) on dimensional scales smaller than the light wavelength have been proposed. In such cases, one can exploit the interaction of light and conduction electrons at an interface between a dielectric and a conducting material (metal or semiconductor). In many instances such interaction is associated with surface localized plasmons – collective oscillations of the electrons against a fixed background of positive-ion cores. As the result of the interaction of light waves and plasmons, coupled excitations – plasmon-polaritons – are formed. The corresponding research branch is known as plasmonics. The most intriguing plasmonic effects are an enhancement of the optical fields in the subwavelength domain and the possibility of light control on subwavelength scales. Plasmonics promises a number of new optoelectronic devices and applications.

In this book, we will study the conditions associated with the transition between the classical and quantum regimes of operation, as well as the quantum physics of new microelectronic devices and concepts.

Now, we consider briefly optoelectronics, which 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 the acquisition, storage, and processing of information. Advances in optoelectronics have made 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 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–IV, and II–VI compounds belong to this group; most of these compounds have a direct bandgap, which makes them suitable materials for optoelectronic devices. Using direct-bandgap semiconductor materials, two main types of light sources have been developed: light-emitting diodes, which produce spontaneous incoherent emission; and lasers, which emit stimulated coherent light. In both cases, electrical energy is converted into light energy. The 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 employ a variety of different optical and electro-optical effects. Quantum heterostructures provide a means to enhance many of the effects known in bulk-like materials, such as excitonic effects and optical nonlinearities near the fundamental edge of optical absorption. Quantum heterostructures also exhibit new optical effects.

The original semiconductor light-emitting diodes were homojunctions, i.e., they were made of one material, usually GaAs, doped to form a p–n junction. For these light-emitting diodes, the injection of electrons and holes from both sides of the junction into the active region provides the population inversion necessary for light emission. It is necessary to have a very high current density in order to achieve stimulated emission due to the radiative recombination of highly nonequilibrium electrons and holes in the active region. Semiconductor heterojunction lasers are quantum devices. They have superior properties to homojunction light-emitting diodes and are preferable for many technologies. These lasers employ two heterojunctions, and they are quite compact and are highly compatible with semiconductor electronic circuits. Double-heterojunction structures confine electrons and holes in a precisely defined active region and provide a waveguide for the stimulated emitted light. Such lasers have been designed successfully for different spectral ranges. For example, AlGaAs/GaAs double-heterostructure lasers operate in the 0.75–0.9 μm range while GaInAsP/InP lasers cover the 1.2–1.6 μm range, which is ideally suited for low-attenuation optical-fiber transmission.

Some optoelectronic applications require efficient short-wavelength emitting devices, which may be realized with the use of wide-bandgap semiconductor materials and their heterostructures. The direct-bandgap group-III nitrides present a suitable class of materials for such emitting devices. Recent progress in the fabrication of high-quality single-crystal GaN and ternary and quaternary alloys such as AlGaN, InGaN, and AlGaInN and the successful development of p-type doping technologies for these wide-bandgap materials have facilitated the realization of short-wavelength emitting devices.

There are several different critical parameters of semiconductor lasers: the threshold current, temperature sensitivity, modulation bandwidth, speed of modulation, coherence, etc. All these demands can be met if nonequilibrium electrons and holes are squeezed together in a sufficiently narrow active region; accordingly,

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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 life are required as well. There are several types of heterostructure laser: quantum well injection lasers, surface emitting lasers, quantum wire and quantum dot lasers, quantum-cascade lasers, and short-wavelength injection lasers.

The trends in optoelectronics are toward scaling down the sizes of these devices and achieving high levels of integration in systems such as arrays of light-emitting diodes, laser arrays, and integrated systems with other electronic elements on the same chip. Of particular importance is that there is a fundamental limit to the size scaling of optical devices: light cannot be spatially confined below λ/n_{ref}, where λ is the wavelength of light in vacuum and n_{ref} is the refractive index of the 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–Pérot 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 used. The essential performance requirements are fast response, high sensitivity, and high quantum efficiency.

Special techniques for the growth of optically active semiconductor materials and their processing are being developed to fabricate these optoelectronic devices with sizes close to the previously mentioned fundamental optical limit and with sizes that lead to the confinement of 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 1.1 and tends to provide devices with long lifetimes for low costs. Thus, we can conclude that optoelectronics benefits substantially through the use of quantum heterostructures and becomes competitive with its microelectronic counterpart.

These recent and diverse trends in semiconductor heterostructures and device technologies as well as in novel device concepts are driving the establishment of new subdisciplines of optoelectronics based on quantum structures. These subdisciplines and their foundations will be studied in the following chapters.

The rest of this book is organized as follows. In Chapter 2, we consider the different materials used in optoelectronic applications. We start with the classification of dielectrics, semiconductors, and metals and define electron energy spectra, which determine the basic optical properties of crystals. For optoelectronic and optical applications, a critical issue is the engineering of electron spectra, which can be realized in heterostructures. Thus, we analyze the principles of such engineering of the spectra in semiconductor heterostructures. In Chapter 3 we present the basic electronic properties of quantum heterostructures: i.e., quantum wells, quantum wires, and quantum dots, as well as two-dimensional crystals. Key concepts of the quantum physics necessary for understanding the properties of quantum heterostructures are given in Appendix A. In Chapter 4, we discuss the properties of light and light–semiconductor interactions, review the optical properties of bulk semiconductors, and define the major optical characteristics of semiconductors with an emphasis on the specifics of direct- and indirect-bandgap semiconductors. The optical properties of quantum structures are studied in Chapter 5, where we analyze stimulated emission and other optical effects in quantum structures and one- and few-monolayer crystals. In Chapter 6, we study electro-optical and nonlinear optical effects for quantum heterostructures, including quantum wells, double- and multiple-quantum-well structures, and superlattices. We show that these effects have a great potential for optoelectronic applications. In Chapter 7, we analyze the applications of quantum heterostructures to devices emitting near-infrared, visible, and ultraviolet light; these devices exploit phototransitions between the valence and conduction bands, i.e., interband phototransitions. Finally, in Chapter 8 optoelectronic devices which exploit intraband phototransitions are presented. These include unipolar cascade lasers operating in the mid-infrared and terahertz ranges, and quantum-structure photodetectors. We also present the topic of silicon optoelectronics, which is important for communication technologies. This chapter concludes with a discussion of the prospective applications of two-dimensional crystals in optoelectronics.