Introduction to Optical and Optoelectronic Properties of Nanostructures

Get to grips with the fundamental optical and optoelectronic properties of nanostructures. This comprehensive guide makes a wide variety of modern topics accessible, including up-to-date material on the optical properties of monolayer crystals, plasmonics, nanophotonics, ultraviolet quantum well lasers, and wide-bandgap materials and heterostructures. The unified, multidisciplinary approach makes it ideal for those in disciplines spanning nanoscience, physics, materials science, and optical, electrical, and mechanical engineering.

Building on work first presented in *Quantum Heterostructures* (Cambridge 1999), this volume draws on years of research and teaching experience. Rigorous coverage of basic principles makes it an excellent resource for senior undergraduates, and detailed mathematical derivations illuminate concepts for graduate students, researchers, and professional engineers. The examples with solutions included in the text and end-of-chapter problems allow students to use this text to enhance their understanding.

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Preface

There are many monographs and textbooks devoted to nanostructures and nanoelectronics. It is generally accepted that microstructure science and technology deal with microstructures with sizes down to 0.1 micrometer, while sizes below 100 nm (0.1 micrometer) are considered in nanoscience and nanoelectronics. Nanoelectronics was and is predominantly driven by applications in processors and memories of computers and their follow-on systems. This is why the overwhelming majority of textbooks deal with the progress in the technology, covering so-called top-down technology which produces nanostructures and nanostructure devices whose critical dimensions are reduced to less than 100 nm. Textbooks have devoted less attention to the optical properties and optoelectronics of nanostructures, the subject of this book.

A new burst of basic research and applications of nanostructures was stimulated in 2004 by a "scotch tape" technology in which a single layer of graphene was obtained by peeling it from a graphite surface. The simplicity of "scotch tape" technology and the very unusual properties of graphene initiated interest in structures with a thickness of one atomic layer. Many materials have weak bonding between the layers, and monolayers or bilayers can easily be produced with "scotch tape" technology. In spite of the fact that the "scotch tape" technology is not applicable for industrial production, it is convenient and inexpensive for wide use in research. These monolayer structures demonstrated interesting electrical, optical, and optoelectronic properties. Today different methods of fabrication of graphene have been developed, including epitaxial technologies. A number of other one-atom-thick material structures have been discovered and studied. These monolayer materials constitute a new class of two-dimensional crystals which complements conventional two-dimensional heterostructures. Industrially applicable technologies for these structures are currently under active development.

Modern educational programs need 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 nano-disciplines. With the purpose of contributing to education in the nano-fields, we present this textbook providing a unifying framework for the basic ideas needed to understand recent developments underlying the optical and optoelectronic properties of nanostructures. This book grew out of the authors' research and teaching experience in these subjects. We have found that many of the ideas and achievements can be explained in a relatively simple setting. We have designed this textbook primarily for senior undergraduate students and first-year graduate students, who will have been trained in different fields, including nanoscience, physics and optical engineering, materials science and engineering, and mechanical 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. We include details of derivations and the mathematical justification of concepts in some sections. These detailed sections may be omitted in an undergraduate curriculum. The book contains some solved examples in the text and control questions for student self-evaluation at the end of each chapter.

Although this book has been written basically for the student, the material presented in Chapters 4–8 should be useful for a wide audience of researchers working on different subjects within the multidisciplinary area of nanoscience. The core of this textbook is in Chapters 4–8 but, in order to make the book self-contained, we give in Chapters 1–3 the relevant background material on nanostructures and their electronic properties. Appendix A discusses the Schrödinger wave equation for particles and contains major relations and equations from quantum mechanics. Appendix B includes tables of units as well as major physical constants.

In Chapter 1, we present in concise form the main subject of the book, namely the recent and diverse trends in nanotechnologies; novel concepts of nanodevices are also reviewed briefly. These trends make it clear why understanding the fundamentals of the optics and optoelectronics of nanostructures is of great importance. Chapters 2 and 3 have been written for students who have not taken courses in nanoelectronics.

In Chapter 2, we present an overview of the basic materials that are exploited in nanoelectronics. We introduce the major properties of semiconductors and materials that demonstrate great potential for application in nanoelectronics and optoelectronics. Special attention is paid to carbon nanotubes, graphene, transition-metal dichalcogenides and other single-atomic-layer materials.

In Chapter 3, we discuss the basic physical concepts related to the behavior of particles in the nanoworld. Keeping in mind the diverse variants of nanostructures, we analyze a number of particular examples which highlight important quantum properties of particles in heterostructures. Recently, substantial efforts in research have been made in the area of reconfigurable materials. The last section in Chapter 3 briefly describes three examples of reconfigurable materials based on nanostructures, namely on graphene, quantum wells, and quantum dots. Many of the examples analyzed can serve as the simplest underlying models of nanostructures that are exploited in later chapters.

For supplemental information on the fundamentals presented in Chapters 2 and 3, students can refer to the following recent books: *Quantum Mechanics for Nanostructures*, V. Mitin, D. Sementsov, and N. Vagidov, Cambridge University Press, 2010, *Introduction to Nanoelectronics: Nanotechnology, Engineering, Science, and Applications*, V. Mitin, V. Kochelap, and M. Stroscio, Cambridge University

Press, 2008, and *Quantum Heterostructures: Microelectronics and Optoelectronics*, V. Mitin, V. Kochelap, and M. Stroscio, Cambridge University Press, 1999.

Chapter 4 covers the properties of light and light–semiconductor interactions. We start with a brief review of the basic concepts of electromagnetic fields. We define the classical characteristics of electromagnetic fields, such as the energy, intensity, and density of states, and we introduce the concept of the quanta of these fields – the photons. By analyzing electromagnetic fields in free space and in optical resonators, we show that resonators drastically change the structure and the behavior of electromagnetic fields. Next we study the interaction of light with matter and define three principal optical processes: spontaneous emission, stimulated emission, and stimulated absorption. We review the optical properties of bulk semiconductors and define the major optical characteristics of semiconductors, with specific emphasis on the III–V compounds.

Chapter 5 emphasizes that the electrodynamics of heterostructures differs from that of bulk materials. The spatial nonuniformity causes specific characteristics of the interaction of light with matter, including light propagation, absorption, etc. We introduce several parameters which characterize the interaction of light with matter for different cases of light propagation. The parameters for light absorption are calculated for type-I heterostructure quantum wells. The optical properties of monolayer materials are discussed. Various factors affecting the optical properties of low-dimensional electrons, such as the broadening of spectra due to intraband scattering processes, excitonic effects, etc., are analyzed in this chapter.

Chapter 6 discusses the influence of an external electric field on the refractive index and the absorption coefficient, i.e., the effect of the electric field on the propagation of light through a material or on the reflection of the light, which is known as the electro-optical effect. We study the electro-optical effect for quantum heterostructures including quantum wells, double- and multiple-quantum-well structures, and superlattices. We consider the quantum-confined Stark effect, the Burstein–Moss effect, and the effect of destroying excitons in gated heterostructures. We show that electro-optical effects have great potential for optoelectronic applications using the electric field to control light and for realizing the tunable generation of microwave emission. We consider nonlinear optical effects in quantum heterostructures that occur at high intensities of light. Also in Chapter 6 we present a new emerging branch of the subject – plasmonics for optoelectronics. We discuss subwavelength light phenomena, which involve surface plasmons and plasmon excitation in low-dimensional electron gases.

Chapters 7 and 8 are devoted to the applications of nanostructures. We analyze the effect of optical confinement. Our discussion focuses on heterostructures which facilitate the simultaneous formation of optical modes and the realization of laser oscillations which convert electric power into laser emission. A variety of different laser designs are analyzed, such as: quantum well and quantum wire lasers, including devices operating in the terahertz (THz), infrared, visible, and ultraviolet spectral regions; the quantum cascade laser; and single-monolayer photodetectors and emitters. In particular, we consider ultraviolet-emitting devices based on the group-III-nitride materials. We discuss the use of plasmonic effects for optoelectronic devices of subwavelength scale. Other emerging optoelectronic devices based on nanophotonic effects are highlighted in Chapter 8. For example, special attention is paid to silicon photonics. Chapter 8 concludes with a brief discussion of adaptive photodetectors.

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