NANOSTRUCTURES

Raúl J. Martín-Palma
Departamento de Física Aplicada, Universidad Autónoma de Madrid, Spain

Akhlesh Lakhtakia
Department of Engineering Science and Mechanics, The Pennsylvania State University, USA

Keywords: artificial atom, confined state, chemical vapor deposition, eigenfunction, Landauer transport theory, nanofabrication, quantum engineering, quantum size effect, Schrödinger equation, surface plasmon resonance

Contents

Summary

When one or more of the dimensions of a solid are reduced sufficiently in size, its physico-chemical behavior departs significantly from that of the bulk state. With reduction in size, different and often new electrical, mechanical, chemical, magnetic and optical properties emerge. The resulting structure is a low-dimensional structure. The typical dimensions are usually in the range of a few nanometers. The confinement of particles in a low-dimensional structure leads to a dramatic change in their behavior and to the manifestation of novel size-dependent effects which usually fall into the category of quantum size effects.

Nanostructures are low-dimensional structures. Quantum size effects appear in their

electrical, thermal, magnetic and optical properties, depending on the dimensionality, and offer a rich palette of phenomena to be technological exploited. Several old techniques have been improved and several new techniques have been devised to fabricate and characterize nanostructures.

1. Introduction

Low-dimensional structures exhibit properties that are different from those of the miniature versions of bulk structures. Although the value of the minimum size needed to obtain new properties depends on many factors for a specific material, the value usually falls in the range of a few nanometers. For this reason, a nanostructure can be described as having at least one dimension in the range of few nanometers and displaying new physico-chemical properties not shown by the same material in bulk. Thus, nanostructures constitute a bridge between molecules and bulk materials. Suitable control of the properties and response of nanostructures can lead to new devices and technologies. Accordingly, nanoscience and nanotechnology primarily deal with the synthesis, characterization, exploration and exploitation of nanostructured materials.

In the following section, the basic properties of low-dimensional structures and nanostructures are described. Concepts are presented rigorously but not in depth, since the aim is to provide the tools required to describe and understand the performance of low-dimensional structures, with an eye towards particular applications in such different fields as microelectronics and optoelectronics or medicine. For an in-depth and rigorous discussion of these structures, the reader is encouraged to refer to specific textbooks and review articles, several of which are referenced at the end of this chapter, as well as to other entries in this encyclopedia.

In Section 3, the reduction of the extent of a solid in one or more dimensions is shown to lead to a dramatic alteration of its overall behavior, thereby yielding new electrical, magnetic, optical and thermal properties. The fundamental electronic and vibrational excitations of a nanostructure become quantized, and these excitations determine many of the most important properties of nanostructured materials. This makes nanostructures a subject of both fundamental and practical interest, since their physico-chemical properties can be tailored by controlling their size and shape on the nanometer scale.

Finally, Section 4 deals with available techniques for the growth and characterization of nanoparticles and nanostructures.

2. Low-dimensional Structures

As sizes approach the atomic scale, the relevant physical laws change from the classical to the quantum -mechanical laws of physics. Physical behavior at the nanometer scale is accurately predicted by quantum mechanics, as represented by the Schrödinger equation, which therefore provides a quantitative understanding of the properties of low-dimensional structures.

In the Schrödinger description of quantum mechanics, a particle (electron, hole, exciton, etc.) or physical system (i.e., an atom, …) is described by a wavefunction $\psi(\vec{r},t)$, which depends on the variables describing the degrees of freedom of the system, and is interpreted as the probability amplitude of finding a particle at spatial location $\vec{r}=\left(x,y,z\right)$ and time t. Thus, while the state of motion of a particle in classical mechanics is specified by the particle's position and velocity, in quantum mechanics the state of motion is specified by the particle's wavefunction, which contains all the information that may be obtained about the particle. Thus, in quantum mechanics, the idea of a trajectory must be eliminated in favor of a more subtle description in terms of quantum states and wavefunctions.

The wavefunction of an uncharged particle with no spin satisfies the Schrödinger equation

$$\left(-\frac{\hbar^2}{2m}\nabla^2+V(\vec{r},t)\right)\psi(\vec{r},t)=i\hbar\frac{\partial\psi(\vec{r},t)}{\partial t}, \qquad (2.1)$$

where $\nabla^2\equiv\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}+\frac{\partial^2}{\partial z^2}$ is the Laplacian operator, m is the mass of the particle, $\hbar$ is the reduced Planck constant, and $V(\vec{r},t)$ is the spatiotemporally varying potential influencing the particle's motion. The Hamiltonian $H(\vec{r},t)=-\frac{\hbar^2}{2m}\nabla^2+V(\vec{r},t)$ is implicit in this non-relativistic equation. The first part of the Hamiltonian corresponds to the kinetic energy, the second to potential energy. The Hamiltonian thus describes the total energy of the system. As with the force in Newton's second law, the exact form of the Hamiltonian is not provided by the Schrödinger equation and must be independently formulated from the physical properties of a given system.

For many real-world systems, the potential does not depend on time, i.e. $V(\vec{r},t)=V(\vec{r})$. Then, the dependence on time and spatial coordinates of $\psi(\vec{r},t)$ can be separated as

$$\psi(\vec{r},t)=e^{-iEt/\hbar}\psi(\vec{r}) \qquad (2.2)$$

where $\psi(\vec{r})$ is a function of space only, and E is the energy of the system of interest. On using thus representation of the wavefunction in the Schrödinger Eq. (2.1), the time-independent Schrödinger equation

$$\left(-\frac{\hbar^2}{2\mathrm{m}}\nabla^2+V(\vec{r})\right)\psi(\vec{r})=E\psi(\vec{r}) \qquad (2.3)$$

is obtained. Equation (2.3) is analogous in wave mechanics to Hamilton's formulation of classical mechanics for time-independent potentials, i.e., conservative systems.

Low-dimensional systems are usually classified according to the number of reduced dimensions. More precisely, the dimensionality refers to the number of degrees of freedom in the momentum. Accordingly, depending on the dimensions of the system, different cases can be distinguished:

- Three-dimensional (3D) system or bulk system: No quantization of the particle motion occurs, i.e., the particle is free.
- Two-dimensional (2D) system or quantum well: Quantization of the particle motion occurs in one direction, while the particle motion is free in the other two directions.
- One-dimensional (1D) system or quantum wire: Quantization occurs in two directions, leading to free movement along only on direction.
- Zero-dimensional (0D) system or quantum dot (sometimes called "quantum box"): Quantization occurs in all three directions.

In the following subsections, two-, one-, and zero-dimensional systems are discussed and solutions to the Schrödinger equation are given in terms of eigenfunctions and eigenenergies which define the physical behavior of the considered systems.

2.1. Two-dimensional Structures: Quantum Wells

In two-dimensional structures, particles are confined to a thin sheet of thickness L_z along the z axis by infinite potential barriers that create a quantum well (Figure 1). The particles cannot escape from the quantum well $0 \leq z \leq L_z$ and lose no energy on colliding with its walls $z = 0$ and $z = L_z$. In real systems, confinement can be due to electrostatic potentials (generated by external electrodes, doping, strain, impurities, etc.), the presence of interfaces between different materials (e.g., in core-shell nanocrystals), the presence of surfaces (e.g., semiconductor nanocrystals), or a combination of these. Motion of the particles in the two other directions (i.e., in the xy plane) inside the quantum well is free.

A one-dimensional potential profile for electrons can be physically implemented by using two heterojunctions. Figure 1 (right) shows the most comprehensively studied quantum-well structure to date. It consists of a layer of GaAs inserted between two $Al_uGa_{1-u}As$ $(0 \leq u \leq 1)$ barrier layers. The energy difference between the valence band and conduction band in a semiconductor is called the bandgap. The layer of GaAs is a quantum well because the barrier layers are made of a material with a larger bandgap than GaAs. By adjusting the aluminum content of the barrier layers and the thickness of the GaAs layer at the time of growth, quantum wells with electronic properties tailored to the user's specifications can be created. This practice is referred to as quantum engineering.

The infinitely deep one-dimensional potential well is the simplest confinement potential to treat in quantum mechanics. In classical mechanics, the solution to the problem is trivial, since the particle will move in a straight line always at the same speed until it reflects from a wall at an equal but opposite angle. However, in order to find the quantum-mechanical solution many fundamental concepts need to be introduced.

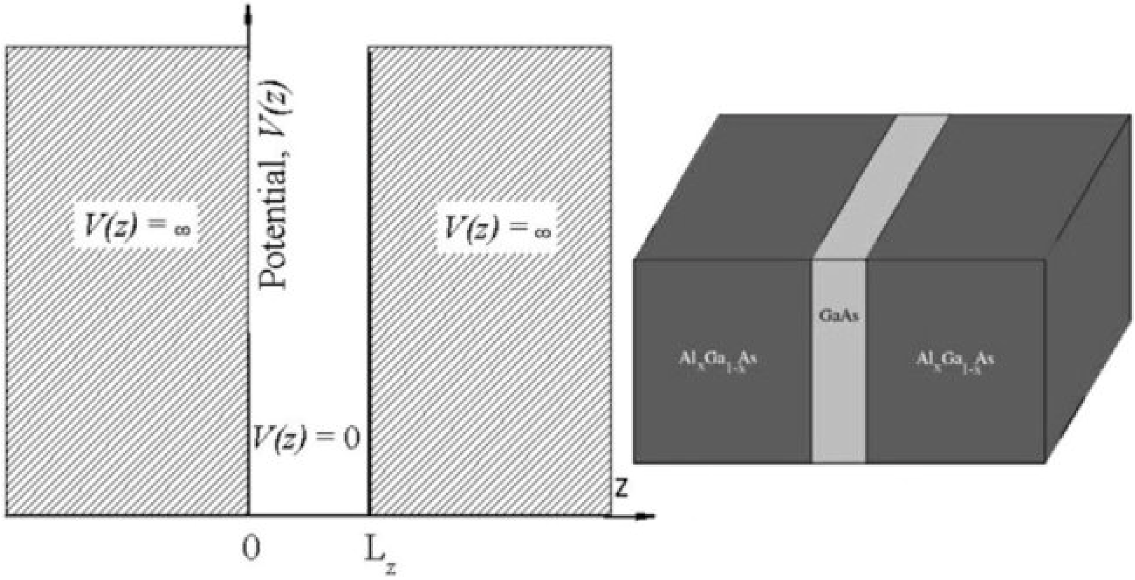

Figure 1. (left) Two-dimensional structure represented by infinite potential barriers that create a quantum well. (right) GaAs quantum well inserted between two $Al_xGa_{1-x}As$ barrier layers.

On restricting analysis to an infinitely deep, one-dimensional potential well aligned along the z axis (Figure 1) of the form

$$V(z) = \begin{cases} 0, & 0 < z < L_z \\ \infty, & z \le 0 \text{ or } z \ge L_z \end{cases} \tag{2.4}$$

the time-independent Schrödinger equation can be written as

$$-\frac{\hbar^2}{2m}\frac{d^2}{dz^2}\psi(z) + V(z)\psi(z) = E\psi(z)\,. \tag{2.5}$$

Outside the chosen potential well, the potential is infinite; hence, the only possible solution is $\psi(z) = 0,\ z \le 0$ or $z \ge L_z$, which in turn implies that all values of the energy E are allowed. Within the infinitely deep potential well, the Schrödinger equation simplifies to

$$-\frac{\hbar^2}{2m}\frac{d^2\psi(z)}{dz^2} = E\psi(z), \qquad 0 < z < L_z \tag{2.6}$$

Taking into account the appropriate boundary conditions, the solutions of this equation are infinitely many in number. These solutions, called eigenfunctions, may be written down as

$$\psi_{n_z}(z) = \sqrt{\frac{2}{L_z}}\sin\left(\frac{n_z \pi z}{L_z}\right), \;\; 0 < z < L_z, \;\; n_z = 1, \; 2, \; 3, \; \ldots \tag{2.7}$$

Note that the index $n_z = 0$ is ruled out since in this case $\psi(z) = 0$ for all $z \in (-\infty, \infty)$, corresponding to the case where there is no particle is in the infinitely deep potential well. Negative values of n are also neglected, since they merely change the sign of the sine function. The complete solution is a superposition of all eigenfunctions and is given by the sum

$$\psi(z) = \sum_{n_z=1}^{\infty} A_n \psi_{n_z}(z), \quad 0 < z < L_z, \tag{2.8}$$

where A_n are the coefficients of expansion. The determination of the values of these coefficients lies outside the scope of this chapter.

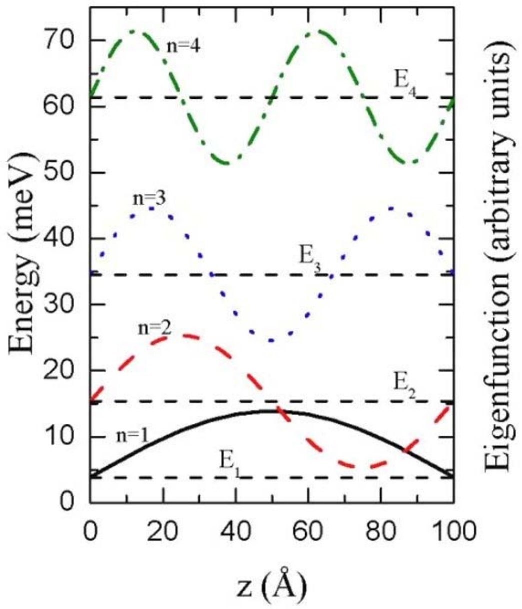

Figure 2. First four eigenfunctions (solid line) and eigenenergies (dashed line) of an electron confined to a 100 Å-thick infinitely deep potential well of Si. An eigenfunction-eigenenergy pair constitutes a quantum state. Computer codes from P. Harrison were used for the calculations.

Figure 2 shows the first four eigenfunctions (2.7) of the Schrödinger Eq. (2.6) for an electron in a 100 Å-thick, infinitely deep potential well of Si. The effective mass of the electron in Si is $m^* = 0.98m_0$, m_0 being the electron rest mass. Although the eigenfunctions were determined for a low-dimensional Si structure, the discussion can be extended to any other material such as GaAs, since eigenfunctions will show a qualitatively similar behavior. Figure 2 shows that the chance $\left|\psi_{n_z}(z)\right|^2$ of an electron obeying the nth eigenfunction being found at a specific value of z in the infinitely deep potential well is not uniform. There are certain locations (antinodes) in the potential well where the electron might be found most easily, but there are also locations (nodes) where the probability of finding the electron is zero. This result contrasts sharply with the predictions of classical mechanics where in the probability of finding an electron is the same for all z inside the infinitely deep potential well.

Each eigenfunction may be taken to describe a confined state. The eigenenergy of the nth eigenfunction is given by

$$E_{n_z} = \frac{\hbar^2}{2m}\left(\frac{n_z \pi}{L_z}\right)^2, \quad n_z = 1,\ 2,\ 3, \ldots \qquad (2.9)$$

An eigenfunction-eigenenergy pair constitutes a quantum state labeled by the principal quantum number n_z.

Quantum size effects are apparent for reduced size. Thus, a particle confined to an infinitely deep potential well has only specific (discrete) energy levels and the zero-energy level is not one of them. The lowest possible energy level of the particle is usually called the zero-point energy or confinement energy, which can be understood in terms of the Heisenberg uncertainty principle as follows. Because the particle is constrained within a finite region, the variability in its position has an upper bound. As the variability in the particle's momentum cannot then be zero due to the uncertainty principle, the particle must contain some energy that increases as the width L_z of the infinitely deep potential well decreases. Figure 2 also shows the first four energy levels (eigenenergies) of an electron confined to a 100 Å-thick, infinitely deep potential well of Si.

The infinitely deep potential well is of great interest since it describes qualitatively the behavior of real systems and has served as a platform for developing the physics of two-dimensional structures. In the more realistic case of a potential well of finite depth, wherein a particle is confined to a well with finite-potential wells, the results are comparable to those of infinitely deep potentials. However, unlike the infinite-potential well, there is a probability associated with the particle being found outside the finite-potential well. The quantum-mechanical interpretation is unlike the classical interpretation, where if the total energy of the particle is less than potential-energy barrier of the walls it cannot be found outside the box. In the quantum interpretation, there is a probability of the particle being outside the box even when the energy of the particle is less than the potential energy barrier of the walls.

-
-
-

Bibliography

A. D. Yoffe (2002). Low-Dimensional Systems: Quantum Size Effects and Electronic Properties of semiconductor Microcrystallites (Zero-Dimensional Systems) and Some Quasi-Two-Dimensional Systems. *Advances in Physics* 51(2), 799-890. [Extensively surveys low-dimensional structures.]

A. D'Andrea, R. Del Sole and K. Cho (1990). Exciton Quantization in CdTe Thin Films. *Europhysics Letters* 11(2), 169-174. [Describes physical properties of excitons in two-dimensional structures].

A. Hernando (2003). Magnetism in Nanocrystals, *Europhysics News* 34(6), 209. [Briefly reviews some key magnetic properties in low-dimensional structures.]

A. Lakhtakia and R. Messier (2005). *Sculptured Thin Films: Nanoengineered Morphology and Optics*. SPIE Press, Bellingham, WA, USA. [Surveys thin-film morphology and relates it to optical response characteristics.]

A. Ozpineci and S. Ciraci (2001). Quantum Effects of Thermal Conductance through Atomic Chains. *Physical Review* B 63(12), 125415. [Presents the electrical and transport properties of one-dimensional systems.]

B. J. van Wees, H. van Houten, C. W. J. Beenakker, J. G. Williamson, L. P. Kouwenhoven, D. van der Marel and C. T. Foxon (1988). Quantized Conductance of Point Contacts in a Two-Dimensional Electron Gas. *Physical Review Letters* 60(9), 848-850. [A key paper on quantum conductance in two-dimensional structures.]

C. Cohen-Tannoudji, B. Diu and F. Laloë (1977). *Quantum Mechanics*. Wiley, New York, NY, USA. [Introduces quantized systems and quantum principles.]

C. Kittel (2005). *Introduction to Solid State Physics* (8th ed.), Wiley, New York, USA. [A classic text on solid-state physics, in this edition including the basic physical properties of low-dimensional structures.]

C. N. R. Rao and A. K. Cheetham (2006). Materials Science at the Nanoscale. *Nanomaterials Handbook*, (Ed. Y. Gogotsi), CRC Press, Boca Raton, FL, USA. [Surveys general properties of low-dimensional systems.]

C. Weisbuch and B. Vinter (1991). *Quantum Semiconductor Structures. Fundamentals and Applications*. Academic Press, San Diego, CA, USA. [Covers the basics of electronic states as well as the fundamentals of optical interactions and quantum transport in two-dimensional quantized systems.]

D. J. Griffiths (2004). *Introduction to Quantum Mechanics* (2nd ed.). Prentice-Hall, New York, NY, USA. [Introduces quantum theory.]

D. M. Eigler and E. K. Schweizer (1990). Positioning Single Atoms with a Scanning Tunneling Microscope. *Nature* 344, 524-526. [Shows the capabilities of scanning tunneling microscopy.]

E. L. Wolf (2004). *Nanophysics and Nanotechnology: An Introduction to Modern Concepts in Nanoscience*. Wiley-VCH, Weinheim, Germany. [Introduces physical concepts, techniques and applications of nanoscale systems.]

G. Binning, C. F. Quate and Ch. Gerber (1986). Atomic Force Microscopy. *Physical Review Letters* 56(9), 930-933. [A key paper on scanning tunneling microscopy.]

G. Binning, H. Rohrer, Ch.Gerber and E. Weibel (1982). Surface Studies by Scanning Tunneling Microscopy, *Physical Review Letters* 49(1), 57-61. [A key paper on scanning tunneling microscopy.]

H. L. Störmer (1984). The Fractional Quantum Hall Effect (Experiment). *Physica B+C* 126(1-3), 250-253. [A key paper on the fractional quantum hall effect.]

H. Lüth (2003). Electronic Properties and Quantum Effects. *Nanoelectronics and Information Technology. Advanced Electronic Materials and Novel Devices* (2nd ed.), (Ed. R. Waser). Wiley-VCH, Weinheim, Germany. [Introduces electronic materials and device concepts for current and future information technology.]

J. D. Patterson and B. C. Bailey (2007). *Solid-State Physics. Introduction to the Theory*. Springer, Berlin, Germany. [Presents the physical characteristics of solid materials.]

J. I. Gersten and F. W. Smith (2001). *The Physics and Chemistry of Materials*. Wiley, New York, NY, USA. [Provides background information on a host of material properties and their applications.]

J. M. Martínez-Duart, R. J. Martín-Palma and F. Agulló-Rueda (2006). *Nanotechnology for Microelectronics and Optoelectronics*. Elsevier, Amsterdam, The Netherlands. [A general text on low-dimensional structures and their applications in the field of micro- and optoelectronics.]

J. R. Hook and H. E. Hall (1991). *Solid State Physics* (2nd ed.). Wiley, Chichester, United Kingdom. [Provides the fundamentals of solid-state physics.]

K. von Klitzing (1984). The quantized Hall effect. *Physica B+C* 126(1-3), 242-249. [A key paper on the quantized Hall effect.]

K. von Klitzing (1986). The quantized Hall effect. *Reviews of Modern Physics* 58(3), 519-531. [A key paper on the quantized Hall effect.]

P. Ehrhart (2005). Film Deposition Methods. *Nanoelectronics and Information Technology: Advanced Electronic Materials and Novel Devices* (2nd ed.), (Ed. R. Waser). Wiley-VCH, Weinheim, Germany. [Reviews current techniques for growing thin films.]

P. Harrison (2000). *Quantum Wells, Wires and Dots: Theoretical and Computational Physics*, Wiley, Chichester, United Kingdom. [Provides essential information, both theoretical and computational, to calculate the electronic, optical and transport properties of quantum wells, wires and dots.]

P. Y. Yu and M. Cardona (2001). *Fundamentals of Semiconductor Physics and Materials Properties* (3rd ed.). Springer, Berlin, Germany. [Fills the gap between general solid-state-physics textbooks and research papers by providing detailed explanations of the electronic, vibrational, transport and optical properties of semiconductors.]

P.K. Basu (1997). *Theory of Optical Processes in Semiconductors: Bulk and Microstructures*. Oxford University Press, Oxford, United Kingdom. [Provided basic understanding of physical phenomena involved in semiconductor optoelectronic devices, and simple quantum-mechanical explanations of important optical processes].

R. B. Laughlin (1984). Excitons in the Fractional Quantum Hall Effect. *Physica B+C* 126(1-3), 254-259. [Presents excitonic effects in low-dimensional structures.]

R. Dingle, W. Wiegmann and C. H. Henry (1974). Quantum States of Confined Carriers in Very Thin $Al_xGa_{1-x}As$-GaAs-$Al_xGa_{1-x}As$ Heterostructures. *Physical Review Letters* 33, 827-830. [A classic paper that presents quantum levels as consequences of carrier confinement to a two-dimensional system].

R. Landauer (1957). Spatial Variation of Currents and Fields due to Localized Scatterers in Metallic Conduction. *IBM Journal of Research and Development* 1(3), 223-231. [A classic paper on quantum conductance.]

R. Landauer (1989). Conductance Determined by Transmission: Probes and Quantized Constriction Resistance. *Journal of Physics: Condensed Matter* 1(43), 8099-8110. [Describes quantum conductance.]

S Ciraci, A Buldum and I. P. Batra (2001). Quantum Effects in Electrical and Thermal Transport through Nanowires. *Journal of Physics: Condensed Matter* 13(29), R537–R568. [Provides a detailed treatment of electrical and transport properties in one-dimensional systems.]

S. C. Tjong and H. Chan (2004). Nanocrystalline Materials and Coatings. *Materials Science and Engineering R* 45(1-2), 1-88. [Reviews the physico-chemical properties of low-dimensional structures.]

S. M. Reimann and M. Manninen (2002). Electronic Structure of Quantum Dots. *Reviews of Modern Physics* 74(4), 1283-1342. [Reviews the electronic structure of zero-dimensional systems.]

S. Okazaki and J. Moers (2005). Lithography. *Nanoelectronics and Information Technology. Advanced Electronic Materials and Novel Devices* (2nd ed.), (Ed. R. Waser). Wiley-VCH, Weinheim, Germany. [Describes the state-of-the-art lithographic techniques.]

S. Schmitt-Rink, D. A. B. Miller and D. S. Chemla (1987). Theory of the Linear and Nonlinear Optical Properties of Semiconductor Microcrystallites. *Physical Review B* 35(15), 8113-8125. [Brief review of optical properties of low-dimensional systems.]

S. Y. Chou, P. R. Kraus and P. J. Renstrom (1996). Imprint Lithography with 25-Nanometer Resolution. *Science* 272, 85-87. [Describes the basics of imprint lithography.]

V. V. Mitin, V. A. Kochelap and M. A. Stroscio (1999). *Quantum Heterostructures. Microelectronics and Optoelectronics*. Cambridge University Press, Cambridge, United Kingdom. [Describes key physical and engineering principles of quantum semiconductor structures.]

W. A. Harrison (2000). *Applied Quantum Mechanics*. World Scientific, Singapore. [Covers quantum theory from an engineering viewpoint.]

Y. Imry (2002). *Introduction to Mesoscopic Physics* (2nd ed.). Oxford University Press, Oxford, United Kingdom. [Presents the physics of structures larger than a nanometer but smaller than a micrometer.]

Y. Meir, N. S. Wingreen and P. A. Lee (1991). Transport through a Strongly Interacting Electron System: Theory of Periodic Conductance Oscillations. *Physical Review Letters* 66(23), 3048-3051. [Explains the conductance of an assembly of quantum dots.]

Y. Xia, P. Yang, Y. Sun, Y. Wu, B. Mayers, B. Gates, Y. Yin, F. Kim and H. Yan (2003). One-Dimensional Nanostructures: Synthesis, Characterization and Applications. *Advanced Materials* 15(5), 353-389. [General paper on several basic properties of one-dimensional structures.]

Biographical Sketches

Raúl J. Martín-Palma has a M.S. Degree in Applied Physics (1995) and a Ph.D degree in Physics (2000) from the Universidad Autónoma de Madrid (Spain). He has been a post-doctoral fellow at the New Jersey Institute of Technology (Newark, NJ, USA) and a visiting Professor at the Pennsylvania State University (University Park, PA, USA). He is currently Professor of Physics at Universidad Autónoma de Madrid. He is the author of over seventy research publications, most of them on electrical, optical and optoelectronic properties of nanostructured materials. In addition, he is coauthor of the book *Nanotechnology for Microelectronics and Optoelectronics* (Elsevier, 2006). He has received several awards for young scientists for his research on nanostructured materials from the Materials Research Society (USA), European Materials Research Society and Spanish Society of Materials. Prof. Martín-Palma is member of the *Real Sociedad Española de Física* (RSEF, Spain) and SPIE.

Akhlesh Lakhtakia is the Charles Godfrey Binder (Endowed) Professor of Engineering Science and Mechanics at the Pennsylvania State University. He is the Editor-in-Chief of SPIE's online Journal of Nanophotonics. He obtained B.S. (1979) and D.Sc. (2007) degrees in electronics engineering from the Institute of Technology, Banaras Hindu University, India, and M.S. (1981) and Ph.D. (1983) degrees in electrical engineering from the University of Utah, USA. He has published over 625 journal papers; is the author or co-authors of over 200 conference presentations and publications; and has edited, co-edited, authored or co-authored 12 books and 8 conference proceedings. The University of Utah made him a

Distinguished Alumnus in 2007. He won the PSES Outstanding Research Award (1996), the PSES Premier Research Award (2008), and the PSES Outstanding Advising Award (2006). Penn State gave him the 2006 Faculty Scholar Medal in Engineering. His research won two Nano 50 Awards from Nanotech Briefs. He is a Fellow of the Optical Society of America, SPIE, and the Institute of Physics (UK). He is also a Professional Fellow of the Institute of Nanotechnology. He has expertise in the following fields: wave-material interaction, isotropic chiral materials, anisotropic and bianisotropic materials, negative phase-velocity materials, structurally chiral materials, sculptured thin films, carbon nanotubes, nanomodeling, and fractals.