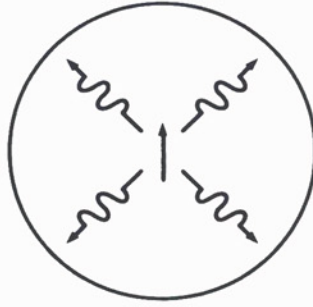


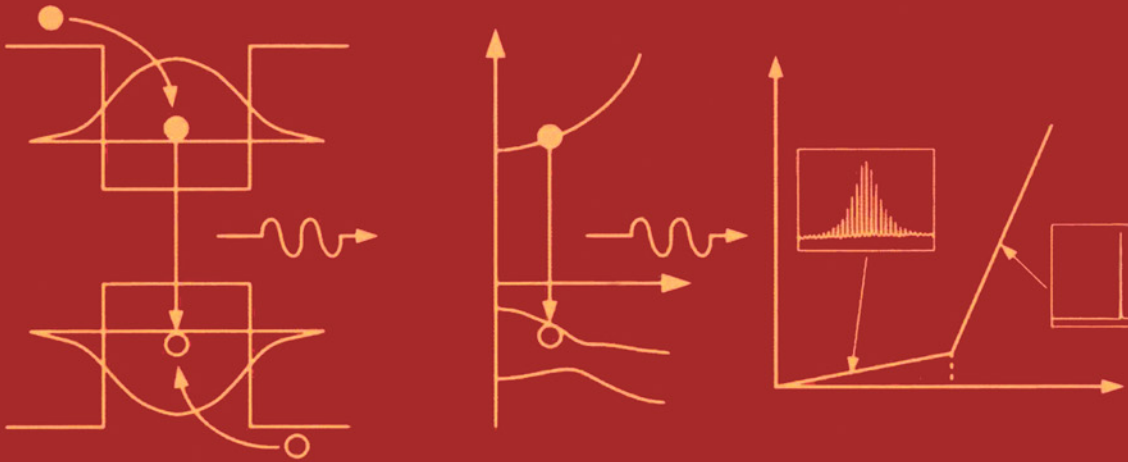
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# PHYSICS OF PHOTONIC DEVICES



SHUN LIEN CHUANG

 WILEY



# Physics of Photonic Devices

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# Physics of Photonic Devices

Second Edition

**SHUN LIEN CHUANG**

Professor of Electrical and Computer Engineering  
University of Illinois at Urbana-Champaign



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*To My Wife, Shu-Jung, with Love*



# Contents

<b>Preface</b>	<b>xiii</b>
<b>Chapter 1. Introduction</b>	<b>1</b>
1.1 Basic Concepts of Semiconductor Band and Bonding Diagrams	1
1.2 The Invention of Semiconductor Lasers	4
1.3 The Field of Optoelectronics	8
1.4 Overview of the Book	15
Problems	19
References	19
Bibliography	21
<b>PART I FUNDAMENTALS</b>	<b>25</b>
<b>Chapter 2. Basic Semiconductor Electronics</b>	<b>27</b>
2.1 Maxwell's Equations and Boundary Conditions	27
2.2 Semiconductor Electronics Equations	30
2.3 Generation and Recombination in Semiconductors	40
2.4 Examples and Applications to Optoelectronic Devices	48
2.5 Semiconductor $p$ - $N$ and $n$ - $P$ Heterojunctions	53
2.6 Semiconductor $n$ - $N$ Heterojunctions and Metal–Semiconductor Junctions	69
Problems	73
References	74
<b>Chapter 3. Basic Quantum Mechanics</b>	<b>77</b>
3.1 Schrödinger Equation	78
3.2 The Square Well	80
3.3 The Harmonic Oscillator	90
3.4 The Hydrogen Atom and Exciton in 2D and 3D	95
3.5 Time-Independent Perturbation Theory	97
3.6 Time-Dependent Perturbation Theory	104
Appendix 3A: Löwdin's Renormalization Method	107
Problems	110
References	111

<b>Chapter 4. Theory of Electronic Band Structures in Semiconductors</b>	<b>113</b>
4.1 The Bloch Theorem and the $\mathbf{k} \cdot \mathbf{p}$ Method for Simple Bands	113
4.2 Kane's Model for Band Structure: The $\mathbf{k} \cdot \mathbf{p}$ Method with the Spin–Orbit Interaction	118
4.3 Luttinger–Kohn Model: The $\mathbf{k} \cdot \mathbf{p}$ Method for Degenerate Bands	126
4.4 The Effective Mass Theory for a Single Band and Degenerate Bands	130
4.5 Strain Effects on Band Structures	132
4.6 Electronic States in an Arbitrary One-Dimensional Potential	144
4.7 Kronig–Penney Model for a Superlattice	152
4.8 Band Structures of Semiconductor Quantum Wells	158
4.9 Band Structures of Strained Semiconductor Quantum Wells	168
Problems	172
References	174
<b>PART II PROPAGATION OF LIGHT</b>	<b>179</b>
<b>Chapter 5. Electromagnetics and Light Propagation</b>	<b>181</b>
5.1 Time-Harmonic Fields and Duality Principle	181
5.2 Poynting's Theorem and Reciprocity Relations	183
5.3 Plane Wave Solutions for Maxwell's Equations in Homogeneous Media	186
5.4 Light Propagation in Isotropic Media	186
5.5 Wave Propagation in Lossy Media: Lorentz Oscillator Model and Metal Plasma	189
5.6 Plane Wave Reflection from a Surface	197
5.7 Matrix Optics	202
5.8 Propagation Matrix Approach for Plane Wave Reflection from a Multilayered Medium	206
5.9 Wave Propagation in Periodic Media	210
Appendix 5A: Kramers–Kronig Relations	220
Problems	223
References	224
<b>Chapter 6. Light Propagation in Anisotropic Media and Radiation</b>	<b>227</b>
6.1 Light Propagation in Uniaxial Media	227
6.2 Wave Propagation in Gyrotropic Media: Magneto optic Effects	239

6.3	General Solutions to Maxwell's Equations and Gauge Transformations	246
6.4	Radiation and the Far-Field Pattern	249
	Problems	254
	References	256
<b>Chapter 7. Optical Waveguide Theory</b>		<b>257</b>
7.1	Symmetric Dielectric Slab Waveguides	257
7.2	Asymmetric Dielectric Slab Waveguides	268
7.3	Ray Optics Approach to Waveguide Problems	271
7.4	Rectangular Dielectric Waveguides	273
7.5	The Effective Index Method	279
7.6	Wave Guidance in a Lossy or Gain Medium	281
7.7	Surface Plasmon Waveguides	285
	Problems	290
	References	293
<b>Chapter 8. Coupled-Mode Theory</b>		<b>295</b>
8.1	Waveguide Couplers	295
8.2	Coupled Optical Waveguides	300
8.3	Applications of Optical Waveguide Couplers	307
8.4	Optical Ring Resonators and Add-Drop Filters	311
8.5	Distributed Feedback (DFB) Structures	322
	Appendix 8A: Coupling Coefficients for Parallel Waveguides	332
	Appendix 8B: Improved Coupled-Mode Theory	333
	Problems	334
	References	339
<b>PART III GENERATION OF LIGHT</b>		<b>345</b>
<b>Chapter 9. Optical Processes in Semiconductors</b>		<b>347</b>
9.1	Optical Transitions Using Fermi's Golden Rule	347
9.2	Spontaneous and Stimulated Emissions	353
9.3	Interband Absorption and Gain of Bulk Semiconductors	360
9.4	Interband Absorption and Gain in a Quantum Well	365
9.5	Interband Momentum Matrix Elements of Bulk and Quantum-Well Semiconductors	371
9.6	Quantum Dots and Quantum Wires	375
9.7	Intersubband Absorption	384
9.8	Gain Spectrum in a Quantum-Well Laser with Valence-Band Mixing Effects	391

Appendix 9A: Coordinate Transformation of the Basis Functions and the Momentum Matrix Elements	398
Problems	401
References	405
<b>Chapter 10. Fundamentals of Semiconductor Lasers</b>	<b>411</b>
10.1 Double-Heterojunction Semiconductor Lasers	412
10.2 Gain-Guided and Index-Guided Semiconductor Lasers	428
10.3 Quantum-Well Lasers	432
10.4 Strained Quantum-Well Lasers	446
10.5 Strained Quantum-Dot Lasers	457
Problems	472
References	474
<b>Chapter 11. Advanced Semiconductor Lasers</b>	<b>487</b>
11.1 Distributed Feedback Lasers	487
11.2 Vertical Cavity Surface-Emitting Lasers	502
11.3 Microcavity and Photonic Crystal Lasers	515
11.4 Quantum-Cascade Lasers	530
11.5 GaN-Based Blue–Green Lasers and LEDs	548
11.6 Coupled Laser Arrays	571
Appendix 11A: Hamiltonian for Strained Wurtzite Crystals	578
Appendix 11B: Band-Edge Optical Transition Matrix Elements	581
Problems	583
References	584
<b>PART IV MODULATION OF LIGHT</b>	<b>603</b>
<b>Chapter 12. Direct Modulation of Semiconductor Lasers</b>	<b>605</b>
12.1 Rate Equations and Linear Gain Analysis	605
12.2 High-Speed Modulation Response with Nonlinear Gain Saturation	611
12.3 Transport Effects on Quantum-Well Lasers: Electrical versus Optical Modulation	614
12.4 Semiconductor Laser Spectral Linewidth and the Linewidth Enhancement Factor	622
12.5 Relative Intensity Noise Spectrum	629
Problems	632
References	632
<b>Chapter 13. Electrooptic and Acousto-optic Modulators</b>	<b>639</b>
13.1 Electrooptic Effects and Amplitude Modulators	639
13.2 Phase Modulators	648

13.3	Electrooptic Effects in Waveguide Devices	652
13.4	Scattering of Light by Sound: Raman–Nath and Bragg Diffractions	658
13.5	Coupled-Mode Analysis for Bragg Acousto-optic Wave Couplers	661
	Problems	664
	References	666
<b>Chapter 14.</b>	<b>Electroabsorption Modulators</b>	<b>669</b>
14.1	General Formulation for Optical Absorption Due to an Electron–Hole Pair	670
14.2	Franz–Keldysh Effect: Photon-Assisted Tunneling	673
14.3	Exciton Effect	677
14.4	Quantum Confined Stark Effect (QCSE)	683
14.5	Electroabsorption Modulator	691
14.6	Integrated Electroabsorption Modulator-Laser (EML)	693
14.7	Self-Electrooptic Effect Devices (SEEDs)	702
	Appendix 14A: Two-Particle Wave Function and the Effective Mass Equation	705
	Appendix 14B: Solution of the Electron–Hole Effective-Mass Equation with Excitonic Effects	709
	Problems	714
	References	714
<b>PART V</b>	<b>DETECTION OF LIGHT AND SOLAR CELLS</b>	<b>721</b>
<b>Chapter 15.</b>	<b>Photodetectors and Solar Cells</b>	<b>723</b>
15.1	Photoconductors	723
15.2	<i>p-n</i> Junction Photodiodes	734
15.3	<i>p-i-n</i> Photodiodes	740
15.4	Avalanche Photodiodes	744
15.5	Intersubband Quantum-Well Photodetectors	756
15.6	Solar Cells	761
	Problems	776
	References	778
<b>Appendix A.</b>	<b>Semiconductor Heterojunction Band Lineups in the Model–Solid Theory</b>	<b>787</b>
<b>Appendix B.</b>	<b>Optical Constants of GaAs and InP</b>	<b>797</b>

<b>Appendix C. Electronic Properties of Si, Ge, and a Few Binary, Ternary, and Quaternary Compounds</b>	<b>801</b>
<b>Appendix D. Parameters for InN, GaN, AlN, and Their Ternary Compounds</b>	<b>807</b>
<b>Index</b>	<b>811</b>

# Preface

Since the publication of the first edition, *Physics of Optoelectronic Devices*, by Wiley in 1995, significant advancements in the scientific field of optoelectronics, or photonics in general, have been made. The purpose of this new edition is to incorporate the new device concepts and to introduce novel photonic devices developed over the past years.

The new topics covered in this edition include a brief history on the invention of semiconductor lasers, the Lorentz dipole model and metal plasma, matrix optics, surface plasma waveguides, and optical ring resonators. Surface plasmonics and microring resonators have emerged as a new field of research for near-field imaging and biophotonics sensing applications. Therefore, we include them in the new edition.

On the generation of light, quantum dots have been researched in the past decade for applications to semiconductor lasers and nanophotonics applications. I include the theory of optical absorption in quantum dots and quantum wires, and their applications to semiconductor lasers. The sections on DFB lasers and VCSELs are revised with a more compact analysis with numerical examples. Novel microcavity and photonic crystal lasers, quantum-cascade lasers, and GaN blue-green lasers are exciting research subjects, and they are discussed within the context of advanced semiconductor lasers.

High-speed modulation of quantum-well and quantum-dot lasers, electrical and optical modulations, relative-intensity noise, and integrated electroabsorption modulator-laser (EML) play important roles in optical communications. They are presented in the section on the modulation of light.

Solar cells have played an important role in clean energy for the environment, and discussion of III–V  $p$ - $n$  junction based solar cells has been added.

## INTENDED AUDIENCE

The book is intended as a textbook for senior undergraduate and graduate students in the areas of optics and photonics. Chapters 5–8 and 13 on propagation of light and electrooptical modulators can be used independently for students in the optics and electromagnetics areas for undergraduate seniors. Chapters 2–4, 9–12, and 14–15 on semiconductor band structures, semiconductor lasers, electroabsorption modulators, photodetectors, and solar cells will be useful to graduate students as well as professionals in the photonics and optoelectronics community. This book will be useful for researchers and graduate students in physics, electrical engineering, mechanical engineering, and material science. The book covers strained quantum

wells and quantum dots, semiconductor band structures, and optoelectronic device physics. Most of the required formulations are shown in great detail. Selective experimental results are included.

## ACKNOWLEDGMENTS

I am indebted to many colleagues and students for their collaboration and technical discussions during the preparation of the manuscript. During the past years, I have had interactions with many colleagues. I am especially grateful to Professor Nick Holonyak, Jr., for his guidance, encouragement, and inspiration through coffee hours. I collaborate extensively with many colleagues and would like to thank them for their technical discussions, challenges, and contributions on many research ideas and projects: Professors Connie Chang-Hasnain, Paul D. Coleman, K. Y. Cheng, Russell Dupuis, Cun-Zheng Ning, S. H. Park, Hailing Wang, Weng Wang, Ming Wu, and Peidong Yang. I also benefited from technical discussions with Professors Yasuhiko Arakawa, Dieter Bimberg, Peter Blood, Yong-Hee Lee and Dr. Mitsuru Sugawara. I would like to thank my former and current students, postdocs, and visitors for their technical contributions to many publications in the field. Special thanks to Doyeol Ahn, Wei-chiao Fang, Matt Fisher, Alan Hsu, X. Jin, Tom Keating, Jungho Kim, Piotr Kondratko, Donghan Lee, Maytee Letteramb, Guobin Liu, Jeff Minch, and Jean-Francois Seurin for their recent contributions.

In preparation of the revised edition, I am indebted to Shu-Wei Chang for proofreading the entire manuscript. My group members, Guoen Chang, Adrian C. Y. Ni, T. R. Lin, Jian Li, Akira Matsudaira, Shin Mou, David Nielsen, and Adam Petschke, have contributed technically to the preparation of the figures and proofreading. I also thank Kelly C. Voyles for typing most of the chapters. I would like to express my gratitude to the students whose enthusiastic response and feedback help with my presentation of the concepts.

I am deeply indebted to my mother and brother for their unconditional support. I am grateful to my wife, Shu-Jung, for her love, dedication, and for inspiration from her poetic writing. Without her constant support, this work would have been impossible. I thank my children, Kendall, Kanglin, and Kangway, who have been a constant joy to our lives.

SHUN LIEN CHUANG

*May 2008*

*Urbana-Champaign, Illinois*

# Preface to the First Edition

This textbook is intended for graduate students and advanced undergraduate students in electrical engineering, physics, and material science. It also provides an overview of the theoretical background for professional researchers in optoelectronic industries and research organizations. This book deals with the fundamental principles in semiconductor electronics, physics, and electromagnetics, and then systematically presents practical optoelectronic devices including semiconductor lasers, optical waveguides, directional couplers, optical modulators, and photodetectors. Both bulk and quantum-well semiconductor devices are discussed. Rigorous derivations are presented and the author attempts to make the theories self-contained.

Research on optoelectronic devices has been advancing rapidly. To keep up with the progress in optoelectronic devices, it is important to grasp the fundamental physical principles. Only through a solid understanding of the fundamental physics are we able to develop new concepts and design novel devices with superior performances. The physics of optoelectronic devices is a broad field with interesting applications based on electromagnetics, semiconductor physics, and quantum mechanics.

I have developed this book for a course on optoelectronic devices which I have taught at the University of Illinois at Urbana-Champaign during the past ten years. Many of our students are stimulated by the practical applications of quantum mechanics in semiconductor optoelectronic devices because many quantum phenomena can be observed directly using artificial materials such as quantum-well heterostructures with absorption or emission wavelengths determined by the quantized energy levels.

## SCOPE

This book emphasizes the theory of semiconductor optoelectronic devices. Comparisons between theoretical and experimental results are also shown. The book starts with the fundamentals, including Maxwell's equations, the continuity equation, and the basic semiconductor equations of solid-state electronics. These equations are essential in learning semiconductor physics applied to optoelectronics. We then discuss the *propagation, generation, modulation, and detection of light*, which are the keys to understanding the physics behind the operation of optoelectronic devices. For example, knowledge of the generation and propagation of light is crucial for understanding how a semiconductor laser operates. The theory of gain coefficient of semiconductor lasers shows how light is amplified, and waveguide theory shows how light is confined to the waveguide in a laser cavity. An understanding of the modulation of light is useful in designing optical switches and modulators.

The absorption coefficient of bulk and quantum-well semiconductors demonstrates how light is detected and leads to a discussion on the operating principles of photodetectors.

## FEATURES

- Important topics such as semiconductor heterojunctions and band structure calculations near the band edges for both bulk and quantum-well semiconductors are presented. Both Kane's model assuming parabolic bands and Luttinger-Kohn's model with valence-band mixing effects in quantum wells are presented.
- Optical dielectric waveguide theory is discussed and applied to semiconductor lasers, directional couplers, and electrooptic modulators.
- Basic optical transitions, absorption, and gain are discussed with the time-dependent perturbation theory. The general theory for gain and absorption is then applied to studying interband and intersubband transitions in bulk and quantum-well semiconductors.
- Important semiconductor lasers such as double-heterostructure, stripe-geometry gain-guided semiconductor lasers, quantum-well lasers, distributed feedback lasers, coupled laser arrays, and surface-emitting lasers are treated in great detail.
- High-speed modulation of semiconductor lasers using both linear and nonlinear gains is investigated systematically. The analytical theory for the laser spectral linewidth enhancement factor is derived.
- New subjects such as the theories on the band structures of strained semiconductors and strained quantum-well lasers are investigated.
- The electroabsorptions, in bulk (Franz-Keldysh effects) and quantum-well semiconductors (quantum confined Stark effects), are discussed systematically including exciton effects. Both the bound and continuum states of excitons using the hydrogen atom model are discussed.
- Intersubband transitions in quantum wells, in addition to conventional interband absorptions for far-infrared photodetector applications, are presented.

## ACKNOWLEDGMENTS

After receiving a rigorous training in my Ph.D. work on electromagnetics at Massachusetts Institute of Technology, I became interested in semiconductor optoelectronics because of recent development in quantum-well devices with many applications of wave mechanics. I thank Professor J. A. Kong, my Ph.D. thesis adviser, and many of my professors for their inspirations and insight.

Because of the significant number of research results appearing in the literature, it is difficult to list all of the important contributions in the field. For a textbook, only

the fundamental principles are emphasized. I thank those colleagues who granted me permission to reproduce their figures. I apologize to all of my colleagues whose important contributions have not been cited. I am grateful to many colleagues and friends in the field, especially D. A. B. Miller, W. H. Knox, M. C. Nuss, A. F. J. Levi, J. O'Gorman, D. S. Chemla, and the late S. Schmitt-Rink, with whom I had many stimulating discussions on quantum-well physics during and after my sabbatical leave at AT&T Bell Laboratories. I would also like to thank many of my students who provided valuable comments, especially C. S. Chang and W. Fang, who proof-read the manuscript. I thank many of my research assistants, especially D. Ahn, C. Y. P. Chao, and S. P. Wu, for their interactions on research subjects related to this book. The support of my research on quantum-well optoelectronic devices by the Office of Naval Research during the past years is greatly appreciated. I am grateful to L. Beck for reading the whole manuscript and Kelly C. Voyles for typing many revisions of the manuscript in the past years. The constant support and encouragement of my wife, Shu-Jung, are deeply appreciated. Teaching and conducting research have been the stimulus for writing this book; it was an enjoyable learning experience.

SHUN LIEN CHUANG

*Illinois, March 1995*



# 1

## Introduction

Semiconductor photonic devices such as laser diodes, light-emitting diodes, optical waveguides, directional couplers, electrooptic modulators, and photodetectors have important applications in lightwave technology systems. To understand the physics and the operational characteristics of these photonic devices, we have to understand the fundamental principles. In this chapter, we review some of the basic concepts of semiconductor electronics, provide a brief history of the invention of semiconductor lasers and light-emitting diodes, review the general field of optoelectronics, then present the overview of this book.

### 1.1 BASIC CONCEPTS OF SEMICONDUCTOR BAND AND BONDING DIAGRAMS

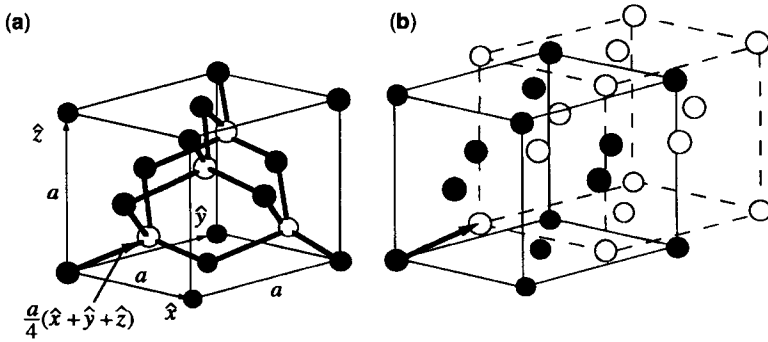
The basic idea is that for a semiconductor, such as GaAs or InP, many interesting optical properties occur near the band edges. For example, Table 1.1 shows part of the periodic table with many of the elements that are important for semiconductors [1], including group IV, III–V, and II–VI compounds. For a III–V compound semiconductor such as GaAs, the gallium (Ga) and arsenic (As) atoms form a zinc-blende structure, which consists of two interpenetrating face-centered-cubic lattices, one made of gallium atoms and the other made of arsenic atoms (Fig. 1.1). The Ga atom has an atomic number of 31, which has an [Ar]  $3d^{10}4s^24p^1$  configuration; that is, three valence electrons on the outermost shell (4s and 4p states). (Here [Ar] denotes the configuration of Ar, which has an atomic number of 18, and the 18 electrons are distributed as  $1s^22s^22p^63s^23p^6$ .)

The As atom has an atomic number of 33 with an [Ar]  $3d^{10}4s^24p^3$  configuration or five valence electrons in the outermost shell (4s and 4p states). For a simplified view, we show a planar bonding diagram [2, 3] in Fig. 1.2a, where each bond between two nearby atoms is indicated with two dots representing two *valence electrons*. These valence electrons are contributed by either Ga or As atoms. The bonding diagram shows that each atom such as Ga is connected to four nearby As atoms by four valence bonds or eight valence electrons. If we assume that none of the bonds is broken, then all of the electrons are in the valence band, and no free electrons are

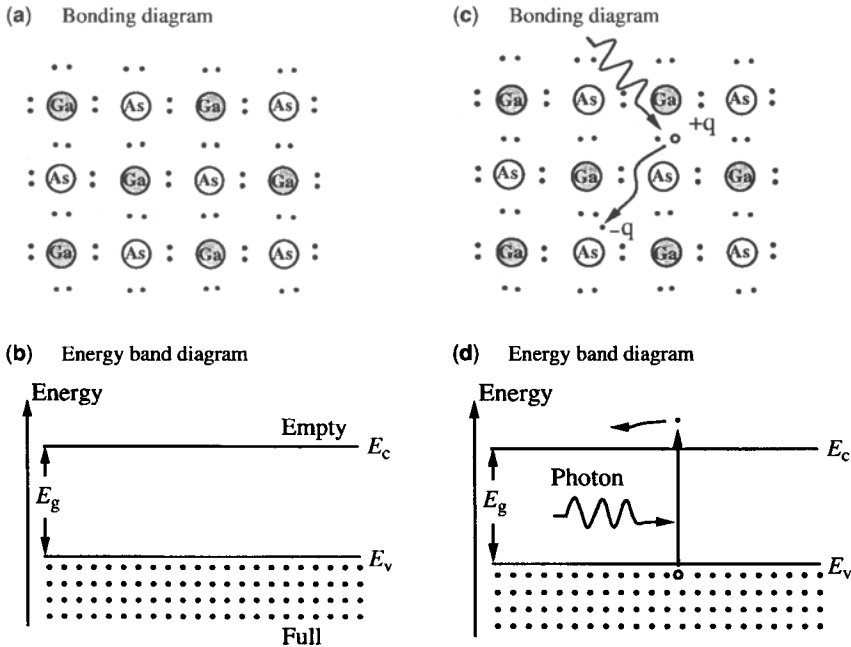
Table 1.1 Part of the Periodic Table Containing Group II – VI Elements

Group II		Group III		Group IV		Group V		Group VI	
A	B	A	B	A	B	A	B	A	B
4 Be $1s^2 2s^2$		5 B $1s^2 2s^2 2p^1$	6 C $1s^2 2s^2 2p^2$	7 N $1s^2 2s^2 2p^3$	8 O $1s^2 2s^2 2p^4$				
12 Mg [Ne] $3s^2$		13 Al [Ne] $3s^2 3p^1$	14 Si [Ne] $3s^2 3p^2$	15 P [Ne] $3s^2 3p^3$	16 S [Ne] $3s^2 3p^4$				
20 Ca [Ar] $4s^2$		21 Sc [Ar] $3d^1 4s^2$	22 Ti [Ar] $3d^2 4s^2$	23 V [Ar] $3d^3 4s^2$	24 Cr [Ar] $3d^5 4s^1$				
38 Sr [Kr] $5s^2$		39 Y [Kr] $4d^1 5s^2$	40 Zr [Kr] $4d^2 5s^2$	41 Nb [Kr] $4d^4 5s^1$	42 Mo [Kr] $4d^5 5s^1$				
56 Ba [Xe] $6s^2$		57 La [Xe] $4f^1 5d^1 6s^2$	58 Ce [Xe] $4f^1 5d^1 6s^2$	59 Pr [Xe] $4f^3 6s^2$	60 Nd [Xe] $4f^4 6s^2$				
		30 Zn [Ar] $3d^{10} 4s^2$	31 Ga [Ar] $3d^{10} 4s^2 4p^1$	32 Ge [Ar] $3d^{10} 4s^2 4p^2$	33 As [Ar] $3d^{10} 4s^2 4p^3$	34 Se [Ar] $3d^{10} 4s^2 4p^4$			
		48 Cd [Kr] $4d^{10} 5s^2$	49 In [Kr] $4d^{10} 5s^2 5p^1$	50 Sn [Kr] $4d^{10} 5s^2 5p^2$	51 Sb [Kr] $4d^{10} 5s^2 5p^3$	52 Te [Kr] $4d^{10} 5s^2 5p^4$			

Note: [Ne] =  $1s^2 2s^2 2p^6$ ; [Ar] = [Ne]  $3s^2 3p^6$ ; [Kr] = [Ar]  $3d^{10} 4s^2 4p^6$ ; [Xe] = [Kr]  $4d^{10} 5s^2 5p^6$ .



**Figure 1.1** (a) A zinc-blende structure such as those of GaAs and InP semiconductors. (b) The zinc-blende structure consists of two interpenetrating face-centered-cubic lattices separated by a constant vector  $(a/4)(\hat{x} + \hat{y} + \hat{z})$ , where  $a$  is the lattice constant of the semiconductor.



**Figure 1.2** (a) A planar bonding diagram for a GaAs lattice. Each bond consists of two valence electrons shared by a gallium and an arsenic atom. (b) The energy band diagram in real space shows the valence-band edge  $E_v$  below which all states are occupied and the conduction-band edge  $E_c$  above which all states are empty. The separation  $E_c - E_v$  is the band gap  $E_g$ . (c) A bonding diagram showing a broken bond due to the absorption of a photon with energy above the band gap. A free electron-hole pair is created. Note that the photogenerated electron is free to move around, and the hole is also free to hop around at different bonds between the Ga and As atoms. (d) The energy band diagram showing the energy levels of the electron and the hole.

in the conduction band. The energy band diagram as a function of position is shown in Fig. 1.2b, where  $E_c$  is the band edge of the conduction band and  $E_v$  is the band edge of the valence band.

When a photon with an optical energy  $h\nu$  above the band-gap energy  $E_g$  is incident on the semiconductor, optical absorption is significant. Here  $h$  is the Planck constant and  $\nu$  is the frequency of the photon,

$$h\nu = \frac{hc}{\lambda} = \frac{1.24}{\lambda} \text{ (eV)} \quad (1.1.1)$$

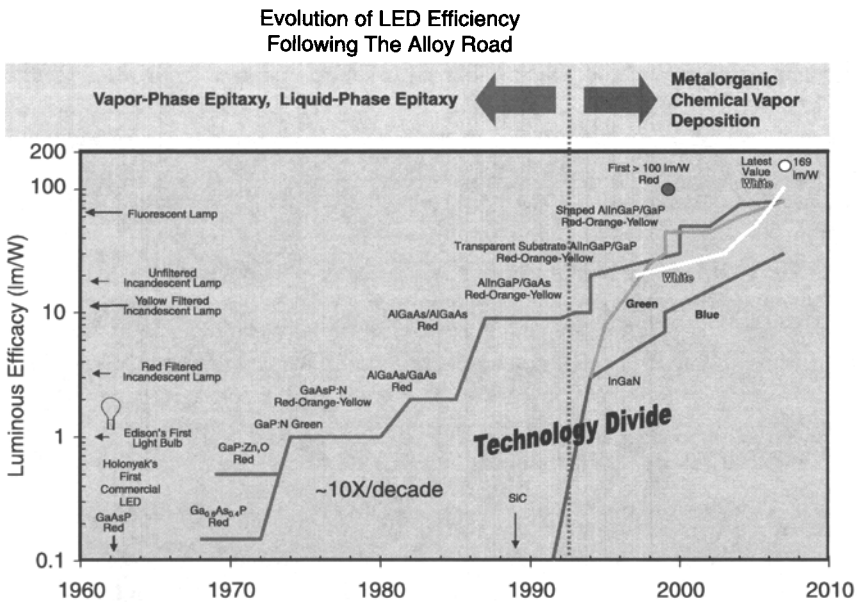
where  $c$  is the speed of light in free space, and  $\lambda$  is wavelength in micrometers ( $\mu\text{m}$ ). The absorption of a photon may break a valence bond and create an electron–hole pair, shown in Fig. 1.2c, where an empty position in the bond is represented by a hole. The same concept in the energy band diagram is illustrated in Fig. 1.2d, where the free electron propagating in the crystal is represented by a dot in the conduction band. It is equivalent to acquiring an energy larger than the band gap of the semiconductor, and the kinetic energy of the electron is that amount above the conduction-band edge. The reverse process can also occur if an electron in the conduction band recombines with a hole in the valence band; this excess energy may emerge as a photon, and the process is called spontaneous emission. In the presence of a photon propagating in the semiconductor with electrons in the conduction band and holes in the valence band, the photon may stimulate the downward transition of the electron from the conduction band to the valence band and emit another photon of the same wavelength and polarization, which is called a stimulated emission process. Above the conduction-band edge or below the valence-band edge, we have to know the energy versus momentum relation for the electrons or holes. These relations provide important information about the number of available states in the conduction band and in the valence band. By measuring the optical absorption spectrum as a function of the optical wavelength, we can map out the number of states per energy interval. This concept of joint density of states, which is discussed further in the following chapters, plays an important role in the optical absorption and gain processes in semiconductors.

## 1.2 THE INVENTION OF SEMICONDUCTOR LASERS

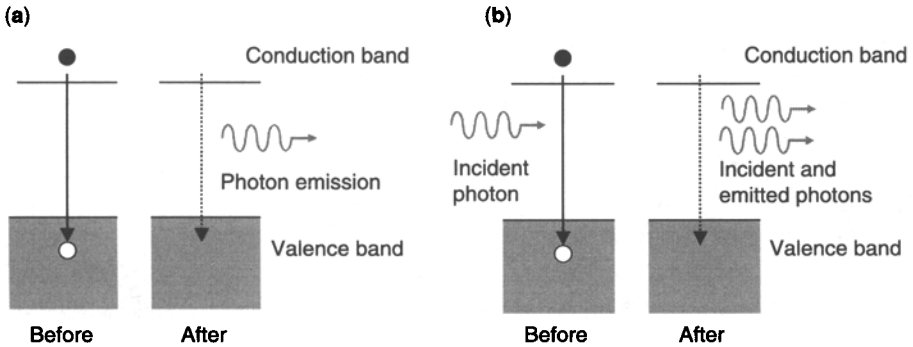
The first papers about the MASER (microwave amplification by stimulated emission of radiation) were published in early 1951 as a result of investigations carried out almost simultaneously by Charles Townes and co-workers at Columbia University in New York and by Nikolai Basov and Alexander Prokhorov at the Lebedev Institute in Moscow [4]. The experimental demonstration of the maser was realized in 1954 using ammonia gas at 23,870 MHz, which was utilized as a frequency standard for some years. The concept of LASER (light amplification by stimulated emission of radiation) was proposed during 1958 to 1960 (called optical maser initially) first by Arthur Schawlow and Charles Townes [5] and by other groups [6]. There was a 30-year patent war that ended with the award of a few laser patents to Gordon Gould [6], who was the first person to use the word *laser*. The first experimental demonstration was realized in 1960 by Theodore Maiman [7] who designed a three-level ruby laser pumped by

high-power flashes of intense light. It was then followed by the invention of helium–neon (HeNe) gas lasers by Ali Javan et al. [8] at Bell Laboratories in 1960.

At the Solid State Device Research Conference in July 1962, an MIT Lincoln Laboratory group and RCA Laboratories reported extremely high efficiency (85% to 100%) electroluminescence from GaAs diffused junction diodes. Semiconductor lasers were invented during September to October 1962 by four groups within 30 days [9–12] (see the review article by Dupuis in Ref. 13). They were led by Robert N. Hall of General Electric Research Development Center, Schenectady, New York; Nick Holonyak Jr. of General Electric, Syracuse, New York; Marshall I. Nathan of the IBM Research Laboratory, Yorktown Heights, New York; and Robert Rediker of the MIT Lincoln Laboratory, Lexington, Massachusetts. Among the four groups, only Holonyak’s laser diodes and light-emitting diodes (LEDs) were created from single-crystal GaAs<sub>x</sub>P<sub>1-x</sub> alloy material grown by vapor-phase transport and were the only devices emitting in the visible region. This work was also the beginning of band-gap engineering of ternary compound semiconductors beyond the binary compounds. The other three groups used zinc (Zn) diffused GaAs *p-n* junction emitting in the infrared. Figure 1.3 shows the evolution of visible-spectrum LEDs in terms of the electrical to optical power conversion (lumens/watt) since 1962 [14–16]. Over the past decades, remarkable progress in the performance of LEDs using compound semiconductors has been realized. Improvement of three orders of magnitude in power conversion efficiency has been achieved, hence the term *Alloy Road* (based on various compound semiconductors as opposed to single elements such as silicon



**Figure 1.3** The evolution of the electrical to optical power conversion of visible LEDs or the *Alloy Road* based on compound semiconductors. The vertical axis labels the performance (Lumens/Watt) of LEDs starting from Holonyak’s first commercial GaAsP LED. The performance of Edison’s first light bulb is also shown. (Reprinted with permission from [16] © 2008 IEEE.)



**Figure 1.4** The electron occupation in the conduction and valence bands of a semiconductor. (a) Spontaneous emission occurs when an electron in the conduction band recombines with a hole in the valence band. (b) Stimulated emission occurs when an incident photon stimulates the recombination of an electron–hole pair and generates another photon of the same energy (and polarization).

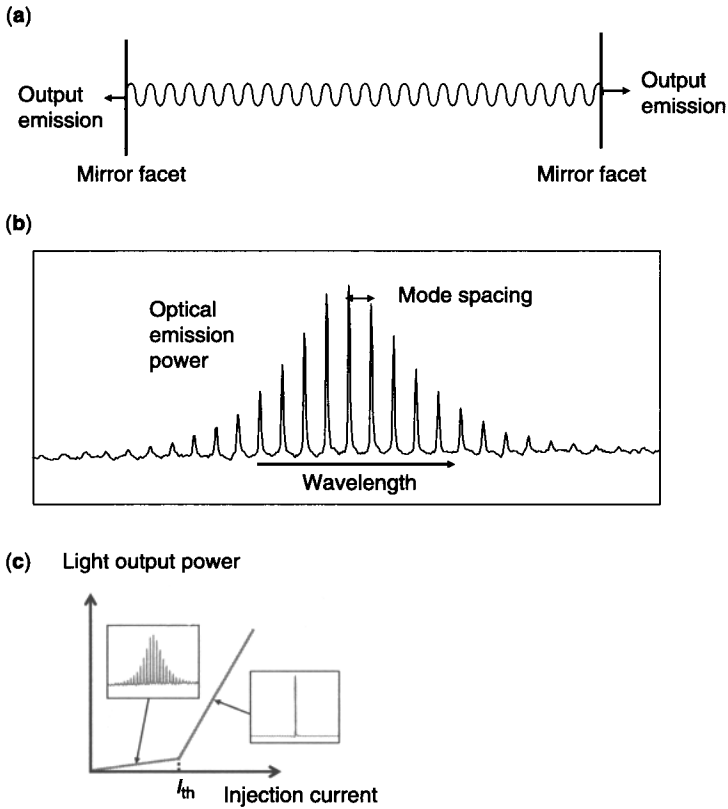
and germanium) shown in Fig. 1.3 was coined after the presentation of LumiLeds [14–16]. More recently, the realization of the blue and green LEDs based on InGaN and their power conversion started to take off in the early 1990s.

An electron in the conduction band can recombine with a hole (or empty state) in the valence band and emit a photon close to the band-gap energy—a process called *spontaneous emission* or more commonly called *radiative recombination* (Fig. 1.4a). When a photon is propagating in the semiconductor with electrons in the conduction band and holes in the valence band, a *stimulated emission* process can cause the number of photons to increase. Figure 1.4b shows the electron occupation before and after the stimulated emission process. The photons can also be absorbed by exciting electrons from the valence band to the conduction band, a process called *stimulated absorption*. However, if we are able to inject enough electrons and holes into the semiconductor to reach the so-called *population inversion condition*, which means that there are more downward than upward stimulated transitions, there will be a net gain of the photon number or optical intensity. Gain is not the only requirement for a laser. It requires a resonator, which can be a one-, two-, or three-dimensional structure. The most common one is the Fabry–Perot resonator formed by two parallel mirrors with a cavity length  $L$ . The light is reflected back and forth between the two mirrors, thus a standing wave pattern can be formed for certain resonant wavelengths (Fig. 1.5a). When the round-trip gain of the optical intensity is large enough to balance the loss due to waveguide absorption and mirror transmission, a threshold condition can be reached. It means that the optical field after the round-trip propagation reaches a resonance condition with a constructive phase and an amplitude of 1,

$$r_1 r_2 e^{i2kL + (G - \alpha)L} = 1 \quad (1.2.1)$$

where  $r_1$  and  $r_2$  are the reflection coefficients of the optical fields from the two end facets,  $k$  is the propagation constant,

$$k = 2\pi n / \lambda = 2\pi \nu n / c, \quad (1.2.2)$$



**Figure 1.5** (a) Standing wave in a Fabry–Perot cavity. (b) Amplified spontaneous emission (ASE) spectrum from a Fabry–Perot cavity. (c) The light output power of a laser diode as a function of the injection current. The inset shows the ASE spectrum below threshold and the lasing spectrum above threshold.  $I_{th}$  indicates the threshold current.

and  $n$  is the refractive index of the semiconductor.  $G$  is the modal gain coefficient of the guided optical mode in the semiconductor waveguide, and  $\alpha$  is the absorption coefficient. Equation (1.2.1) leads to the phase and magnitude conditions for lasing,

$$2kL = 2m\pi \tag{1.2.3}$$

$$G = \alpha + \frac{1}{2L} \ln\left(\frac{1}{R_1 R_2}\right) \tag{1.2.4}$$

where  $R_1 = |r_1|^2$  and  $R_2 = |r_2|^2$  are the power reflectivities. The phase condition (1.2.3) leads to the Fabry–Perot resonance spectrum

$$\nu_m = \frac{mc}{2nL} \quad m = \text{integer}. \tag{1.2.5}$$

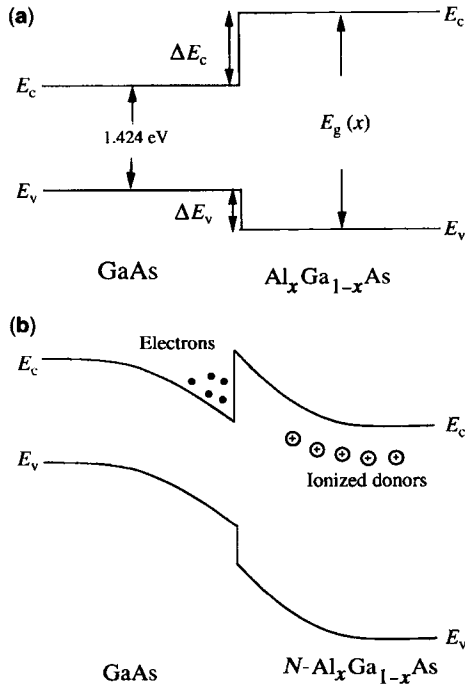
If we ignore the dispersion of the semiconductor (i.e., assuming that  $n$  is independent of the frequency), the mode spacing is given by  $\Delta\nu = c/(2nL)$ , which is inversely proportional to the cavity length and the refractive index.

When we inject enough electrons and holes into the semiconductor active region such that the gain of the propagation mode becomes significant, the emission of the photons gives the so-called amplified spontaneous emission spectrum (ASE), Fig. 1.5b. If the gain is large enough to balance the losses of the cavity, (1.2.4), the laser threshold can be reached. When we increase the gain by further increasing the injection current, laser action is expected to occur. Figure 1.5c shows the laser light output power as a function of the injection current. Below a threshold current value, the light output power is small and consists of the amplified spontaneous emission from Fabry–Perot modes. Above threshold, the lasing action occurs, and the optical power comes from the modes closest to the peak gain. The field of optoelectronics became possible with the success of semiconductor lasers using various heterojunctions, quantum wells, quantum wires, and quantum dots such that the optical gain can be enhanced without the energy spread of the carriers due to the improvement of the density of states in low-dimensional quantum structures.

### 1.3 THE FIELD OF OPTOELECTRONICS

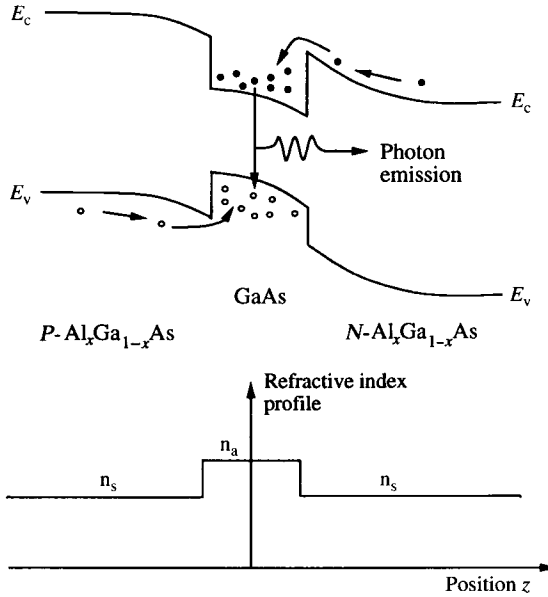
Semiconductor crystal growth techniques such as liquid-phase epitaxy (LPE), vapor-phase epitaxy (VPE), and chemical-vapor deposition (CVD) have been used to grow wafers for device applications. The recent progress in modern crystal growth techniques [17] such as molecular beam epitaxy (MBE) and metal–organic chemical vapor deposition (MOCVD) has demonstrated that it is possible to grow semiconductors of different atomic compositions on top of another semiconductor substrate with monolayer precision. This opens up extremely exciting possibilities of the so-called band-gap engineering. For example, aluminum arsenide (AlAs) has a similar lattice constant to that of gallium arsenide (GaAs). One can grow a few atomic layers of AlAs on top of a GaAs substrate, then grow alternate layers of GaAs and AlAs. One can also grow a ternary compound such as  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  (where the aluminum mole fraction  $x$  can be between 0 and 1) on a GaAs substrate and form a heterojunction, Fig. 1.6a. Interesting applications have been found using heterojunction structures. For example, when the wide band-gap  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  is doped by donors, the free electrons from the ionized donors tend to fall to the conduction band of the GaAs region because of the lower potential energy on that side, as shown by the band diagram in Fig. 1.6b. (This band bending is investigated in Chapter 2.) An applied field in a direction parallel to the junction interface will create conduction current. Because these electrons conduct in a channel on the GaAs region, which is undoped, the amount of impurity scattering can be reduced. Therefore, the electron mobility can be enhanced. Based on this concept, the high-electron-mobility transistor (HEMT) has been realized.

For optoelectronic device applications, heterojunction structures [18] play important roles. For example, when semiconductor lasers were invented, they had to be



**Figure 1.6** (a) A GaAs/Al<sub>x</sub>Ga<sub>1-x</sub>As heterojunction formed with different band gaps. The band edge discontinuities in the conduction band and the valence band are  $\Delta E_c = 0.67\Delta E_g$  and  $\Delta E_v = 0.33\Delta E_g$ , where  $\Delta E_g$  is the difference of the two band gaps. (b) With  $n$ -type doping in the wide gap Al<sub>x</sub>Ga<sub>1-x</sub>As region, the electrons ionized from the donors fall into the heterojunction surface layer on the GaAs side where the energy is smaller. An internal electric field pointing from the ionized (positive) donors in the Al<sub>x</sub>Ga<sub>1-x</sub>As region toward the electrons with negative charges creates band bending, which forms a triangular potential in the conduction band to confine the electrons.

cooled down to cryogenic temperature (77K), and the lasers could lase only in a pulsed mode. These lasers had large threshold current densities, which mean that a large amount of current has to be injected before the laser can start lasing. With the introduction of the heterojunction semiconductor lasers, the concept of carrier and photon confinements makes room temperature continuous wave (cw) operation possible, because the electrons and holes, once injected by the electrodes on both sides of the wide band-gap  $P$ - $N$  regions (Fig. 1.7), will be confined in the central GaAs region, where the band gap is smaller, resulting in a smaller potential energy for the electrons in the conduction band as well as a smaller potential energy for holes in the valence band. We note that the energy for the holes is measured downward, which is opposite to that of the electrons. For the photons, it turns out that the optical refractive index of the narrow band-gap material (GaAs) is larger than that of the wide band-gap material (Al<sub>x</sub>Ga<sub>1-x</sub>As). Therefore, the photons can be confined in the active region as well. This double confinement of both carriers and photons makes the stimulated emission process more efficient and leads to the room temperature operation of laser diodes.



**Figure 1.7** A double-heterojunction semiconductor laser structure, where the central GaAs region provides both the carrier confinement and optical confinement because of the conduction and valence band profiles and the refractive index profile. This double confinement enhances stimulated emissions and the optical modal gain.

The control of the mole fractions of different atoms also makes the band-gap engineering extremely exciting. For optical communication systems, it has been found that minimum attenuation [19] in the silica optical fibers occurs at  $1.30\ \mu\text{m}$  and  $1.55\ \mu\text{m}$  (Fig. 1.8a). The dispersion of light at  $1.30\ \mu\text{m}$  is actually zero (Fig. 1.8b). It is therefore natural to design sources such as light-emitting diodes and laser diodes, semiconductor modulators, and photodetectors operating at these desired wavelengths. In addition, many wavelengths, or the so-called optical channels for dense wavelength-division multiplexing (DWDM) applications, near  $1550\ \text{nm}$  with constant frequency spacing such as 50, 100, or 200 GHz can be used to take advantage of the broad 24 THz frequency bandwidth near the minimum attenuation. For example, by controlling the mole fraction of gallium and indium in an  $\text{In}_{1-x}\text{Ga}_x\text{As}$  material, a wide tunable range of band gap is possible because InAs has a 0.354 eV band gap and GaAs has a 1.424 eV band gap at room temperature. The lattice constant of the ternary alloy has a linear dependence on the mole fraction

$$a(A_xB_{1-x}C) = xa(AC) + (1-x)a(BC) \quad (1.3.1)$$

where  $a(AC)$  is the lattice constant of the binary compound  $AC$  and  $a(BC)$  is that of the compound  $BC$ . This linear interpolation formula works very well for the lattice constant, but not for the band gap. For the band-gap dependence, a quadratic