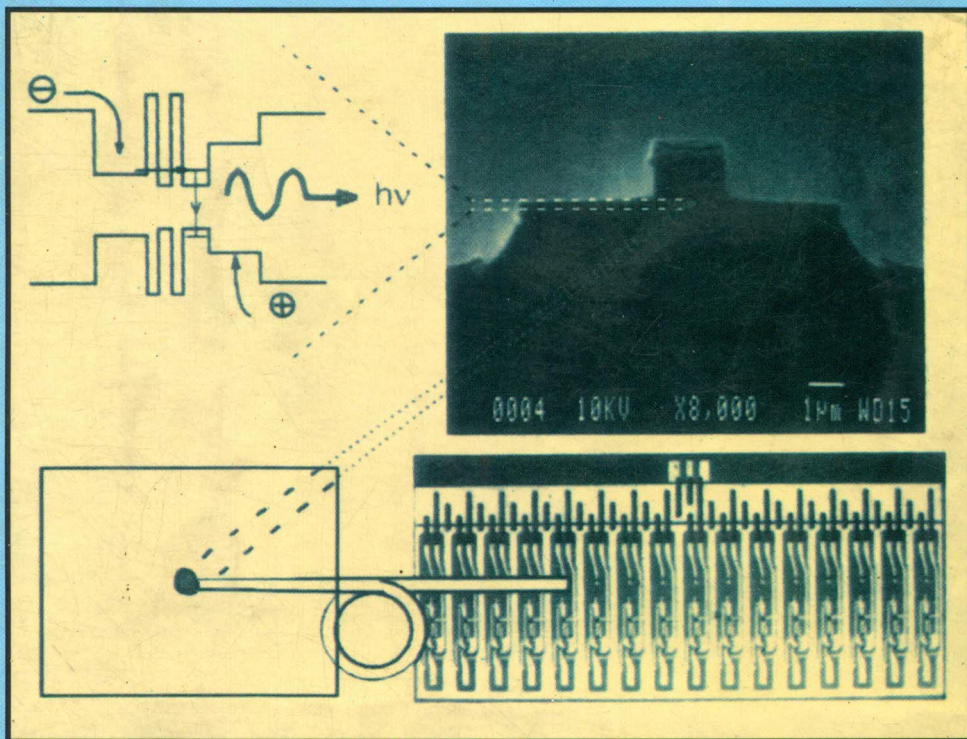


Semiconductor Optoelectronic Devices

Second Edition



PALLAB BHATTACHARYA

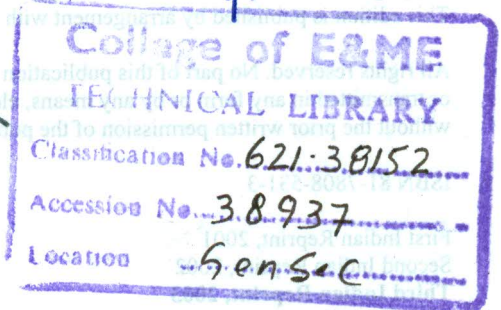


Semiconductor Optoelectronic Devices

Second Edition

PALLAB BHATTACHARYA

*Department of Electrical Engineering
and Computer Science
University of Michigan, Ann Arbor*



PEARSON
Education

621-38152
BHA
1997

Optoelectronic Devices

Second Edition

PALLAB BHATTACHARYA

The author and publisher of this book have used their best efforts in preparing this book. These efforts include the development, research, and testing of the theories and programs to determine their effectiveness. The author and publisher make no warranty of any kind, expressed or implied, with regard to these programs or the documentation contained in this book. The author and publisher shall not be liable in any event for incidental or consequential damages in connection with, or arising out of, the furnishing, performance, or use of these programs.

Copyright © 1997 by Pearson Education, Inc.

This edition is published by arrangement with Pearson Education, Inc.

All rights reserved. No part of this publication may be reproduced, stored in a database or retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, or otherwise, without the prior written permission of the publisher.

ISBN 81-7808-531-3

First Indian Reprint, 2001

Second Indian Reprint, 2002

Third Indian Reprint, 2003

This edition is manufactured in India and is authorized for sale only in India, Bangladesh, Pakistan, Nepal, Sri Lanka and the Maldives.

Published by Pearson Education (Singapore) Pte. Ltd., Indian Branch, 482 F.I.E. Patparganj, Delhi 110 092, India

Printed in India by Tan Prints (I) Pvt. Ltd.

Preface

SCOPE AND PURPOSE

Knowledge of the relation between light and electronics has existed since the dawn of human history. However, widespread use of the interaction of light with electronics became practical only with the development of the laser. The advent and use of optical fiber devices has occurred with the development of advanced optical fiber communication technology and the development of fiber optic fibers. Fiber optic devices convert light to electrical signals and solar cells and fiberoptic light transmitters. These devices, together with optical fibers and light modulators, have helped to usher us into the information age. Optoelectronics, which combines the properties of light with the capabilities of microelectronics, is an essential enabling technology for the information age. In fact, it is said that optoelectronics may be the most significant new technology since semiconductors. Diverse optical devices and circuits have abundantly and efficiently made their way into the marketplace. Television networks, laptop computers, remote control, photography, scientific instrumentation, compact discs, high definition television, flat-panel displays, laser surgery, and laser pointers are just a few examples. Stated differently, optoelectronics has helped in the collection, transmission, storage, and display of information in the information age. It is hoped that this text, dedicated to the enormous progress in the field, will serve two main purposes:

1. to formally introduce wide-level undergraduate and graduate students to optoelectronics, thereby helping them to make their studies and careers more comprehensive, and
2. to provide an accessible textbook, tutorial, a guide, and well-focused reference encyclopedial book for practicing engineers and physicists.

Preface

SCOPE AND PURPOSE

Knowledge of the relation between light and electricity has existed since the nineteenth century. However, widespread use of the interaction of light with electricity has become practical only within the last two decades. The advent and use of optoelectronic devices has occurred primarily due to the development of advanced semiconductor materials technology and the development of low-loss optical fibers. Optoelectronic devices convert light to electricity (detectors and solar cells) and electricity to light (emitters). These devices, together with optical fibers and light modulators, have helped to usher us into the information age. Optoelectronics, which combines the properties of light with the capabilities of microelectronics, is an essential enabling technology for the information age. In fact, it is said that optoelectronics may be the most significant new technology since semiconductors. Optoelectronic devices and circuits have unobtrusively and efficiently made their way into our daily lives. Telephone networks, laptop computers, remote controls, photography, imaging, bar code readers, compact discs, high-definition television, flat-panel displays, health care, and transportation are just a few examples. Stated differently, optoelectronics helps in the collection, transmission, storage, and display of information in the information age. It is hoped that this text, dedicated to the enormous progress in the field, will serve two main purposes:

1. to formally introduce senior-level undergraduate and graduate students to optoelectronics, thereby helping them to guide their studies and career developments; and
2. to provide, in an accessible textbook format, a good and well-focused reference/tutorial book for practicing engineers and physicists.

CHANGES IN THE SECOND EDITION

Even in the short time since the first edition was published, continued and rapid progress has been made in the field of optoelectronics. Vertical-cavity surface emitting lasers have near-zero threshold current, monolithically integrated photoreceivers now operate at bit rates higher than 20 Gbits/s, blue-emitting lasers using nitride-based heterostructures have been reported, true microcavity emitters are being made and tested, and lightwave networks operating at 10 Gbits/s or higher data rates are within reach. These rapid changes and the encouraging feedback received from students, fellow-scientists and reviewers of the first edition have motivated me to work on the second edition.

The present edition differs essentially from the first in the following respects.

Problems and Examples. The number of worked out examples and problems has been enhanced in every chapter to help the readers and instructors.

Additions in the Text. Two types of additions have been made in the present edition, to enhance readability and to enhance depth and breadth. Thus, in many instances explanations of materials and device phenomena have been expanded. At the same time new subjects have been added. Examples are nitrides and visible light emitters, a more detailed treatment of transient phenomena and linewidth of lasers, description of new types of modulators, more detailed treatment of distributed feedback lasers, surface-emitting lasers, avalanche and metal-semiconductor-metal photodiodes, photoreceivers and phototransistors, and description of new devices such as the quantum cascade laser and the tunneling injection laser.

Additional Appendices. A feature in the first edition that was viewed favorably was the use of Appendices as a vehicle for more rigorous treatment of selected subjects. This makes the text less intimidating to undergraduate students. Therefore, many of the additions mentioned previously have found their way into an expanded list of appendices in the present edition. There are 20 appendices in all.

New Chapter on Lightwave Networks. A new chapter on lightwave networks has been added to reflect the enormous progress in the field of fiber-optic communication and the use of optoelectronic devices for this application. The chapter begins with a brief description of optical fibers and describes components used in analog and digital transmission systems and wavelength division multiplexed networks.

Chapter Highlights. This feature has been added at the end of each chapter, not to serve as a table of contents, but to highlight new and attractive portions of the chapter.

Reading List. The list of reference texts has been updated and enhanced in almost every chapter.

List of Tables. This has been added in the beginning of the text.

PRESENTATION

The text has been developed at two levels to benefit both the seniors and graduate students. The book is intended to be self-sufficient and extensive reference work should not be necessary. A background of a first course in semiconductors is assumed.

The first four chapters lay the foundations for the optoelectronic devices. The first chapter describes compound semiconductor materials and their epitaxy. Much of the present-day device concepts would not be realized without sophisticated and matured epitaxial techniques. Semiconductor statistics and carrier transport properties are described in Chapter 2. The basic optical processes of absorption and recombination in bulk and quantum well structures are analyzed and described in Chapter 3. Here, detailed quantum mechanical calculations are excluded, since these are found in at least half-a-dozen texts. However, appropriate references are provided as footnotes. Chapter 4 describes junction theory, including metal-semiconductor junctions and heterojunctions. The case of high-level injection, which becomes important for laser operation, is emphasized in this chapter.

The devices themselves are described in Chapters 5–11 in the following order: light-emitting diodes, lasers, photodetectors, solar cells, and light-modulators. Lasers and photodetectors, which are perhaps the more important and common optoelectronic devices, are each described in two chapters. Optoelectronic integrated circuits (OEICs) are described in Chapter 12. Finally, the text is concluded in Chapter 13 with a review of lightwave networks, an emerging and important subject.

The principles of the devices and circuits are presented with appropriate analyses and derivations. Measurement techniques and recent experimental results are also included to give the reader a feel for real parameter values.

The organization of these chapters should provide the instructor the flexibility to present material to both undergraduate and graduate students. In discussing the different devices, I have introduced new concepts, within the scope of the text. For example, pseudomorphic materials, quantum wells, distributed-feedback, surface-emitting, visible and tunneling-based lasers, modulated barrier photodiodes, coherent and wavelength selective detection, quantum well modulation devices, and monolithically integrated transmitters and receivers are all described and analyzed in various levels of detail.

HOW TO USE THIS BOOK

This book is flexible and can be adapted to your local curriculum and course needs. An example of a one-term senior undergraduate course that could be taught from the book would cover Chapters 1, 2, and 4 as review; Chapters 3, 5, 6, part of 7, 8, and parts of 11 and 12 should be treated as essential; and Chapter 10 could be treated as optional. The rest of Chapters 7, 11, and 12, and Chapters 9 and 13 I consider advanced material that you can teach in a graduate level course or material that you can choose from selectively to tailor the course to your desired emphasis and objectives. Again, the appendices enhance the flexibility in the use of this text. For example, an undergradu-

ate course could omit the use of most of the appendices while graduate and research students would benefit from the rigorous derivations therein.

READING LIST AND PROBLEMS

Suggested texts for more extensive reading and key articles from journals and periodicals are listed at the end of each chapter and as footnotes. These will help the more inquisitive students to go beyond the confines of the text and course and to enhance their knowledge and understanding. Also included are a set of problems at the end of each chapter, in addition to worked-out examples. The purpose of these problems is twofold:

1. to enhance the understanding of the different devices and underlying concepts; and
2. to get a feel for practical values of different device and material parameters and their units.

UNITS

The rationalized MKS system of units has been mostly followed, with convenient changes. For example, cm is more often used as the unit of length, and the electron volt (eV) is used in place of joule (J) as the unit of energy. The cgs system is sometimes used to keep in line with common use.

ACKNOWLEDGMENTS

I gratefully acknowledge again all those who provided help and encouragement during the writing of the first edition and, in particular, Professors Ben Streetman, Jasprit Singh and Craig Casey. Special thanks are to my former and present doctoral students who have provided valuable inputs and criticisms and pointed out errors. The encouraging reviews of the first edition made by Drs. Niloy Dutta and Lily Pang and Professors Joe Campbell, Tina Stacy, Douglas Ross and Kurt Kosbar, which motivated the present project, are also gratefully acknowledged.

I would like to thank again my professional colleagues who have generously contributed data and photographs. They are J. Goldman (RIBER SA) and Drs. G. A. Antypas (Crystacomm Inc.), S. N. G. Chu (AT&T Bell Laboratories), I. Hayashi (Optoelectronics Technology Research Laboratory), J. L. Jewell (Photonics Research Incorporated), J. Loehr (Wright Laboratories, WPAFB), D. A. B. Miller (AT&T Bell Laboratories), D. Pooladdej (Laser Diode, Inc.), R. Sahai (Rockwell International), J. Singh (University of Michigan), S. Swirhun (Bandgap Technology Corporation), W. T. Tsang (AT&T Bell Laboratories), O. Wada (Fujitsu Limited), I. Weinberg (NASA, Lewis Research Center), and E. Woelk (AIXTRON GmbH).

Particular thanks are due to Dr. Jayanta Sarma for useful discussions on various por-

tions of the text and to Dr. Augusto Gutierrez-Aitken for critical reading of many additions to the text and for helping me with additional artwork. Thanks are also due to Izena Goulding and Amy Martin for help in word processing and to Prentice-Hall, Inc. for their effective cooperation and care in publishing this edition. Any amount of acknowledgement of my appreciation to you all will remain inadequate.

Ultimately, it is the encouragement, understanding, and support of my family which provided me the courage to embark on this project.

Pallab Bhattacharya
Ann Arbor, Michigan

1 ELEMENTAL AND COMPOUND SEMICONDUCTORS

1.1	Introduction	1
1.2	Bonding in Solids	4
1.3	Crystalline Nature of Solids	9
	1.3.1 Directional and Planar	13
	1.3.2 Reciprocal Lattice Vectors	16
1.4	Alloy Semiconductors	17
1.5	Lattice Mismatch and Pseudomorphous Material	21
1.6	Transition Metals and Choice of Materials	29
1.7	Crystal Growth	36
	1.7.1 Introduction	36
	1.7.2 Bulk Crystal Growth	38
	1.7.3 Epitaxial Material Growth	39
	1.7.4 Various Controlling Parameters of Quality	50
	1.7.5 Topping of Semiconductors	51
1.8	Device Processing	55
1.9	Course Highlights	57
	Problems	58
	Reading List	60

2 ELECTRONIC PROPERTIES OF SEMICONDUCTORS

2.1	Introduction	62
2.2	Carrier Effective Masses and Bandstructure	62

Contents

1 ELEMENTAL AND COMPOUND SEMICONDUCTORS

- 1.1 Introduction 2
- 1.2 Bonding in Solids 5
- 1.3 Crystalline Nature of Solids 9
 - 1.3.1 Directions and Planes, 13
 - 1.3.2 Reciprocal Lattice Vectors, 16
- 1.4 Alloy Semiconductors 17
- 1.5 Lattice-Mismatched and Pseudomorphic Materials 22
- 1.6 Transmission Media and Choice of Materials 30
- 1.7 Crystal Growth, 36
 - 1.7.1 Introduction, 36
 - 1.7.2 Bulk Crystal Growth, 36
 - 1.7.3 Epitaxial Material Growth, 38
 - 1.7.4 Factors Controlling Heterointerface Quality, 50
 - 1.7.5 Doping of Semiconductors, 51
- 1.8 Device Processing 55
- 1.9 Chapter Highlights 57
 - Problems 58
 - Reading List 60

2 ELECTRONIC PROPERTIES OF SEMICONDUCTORS

- 2.1 Introduction 62
- 2.2 Carrier Effective Masses and Bandstructure 62

2.3	Effect of Temperature and Pressure on Bandgap	67
2.4	Carrier Scattering Phenomena	70
2.5	Semiconductor Statistics	75
	2.5.1 Energy Distribution Functions,	75
	2.5.2 Density of States Function,	78
	2.5.3 Density of Carriers in Intrinsic and Extrinsic Semiconductors,	82
	2.5.4 Compensation in Semiconductors,	87
	2.5.5 Consequences of Heavy Doping: Bandtail States,	91
2.6	Conduction Processes in Semiconductors	94
2.7	Bulk and Surface Recombination Phenomena	102
	2.7.1 Introduction,	102
	2.7.2 Recombination-Generation via Defects or Levels in the Bandgap,	103
	2.7.3 Surface Recombination,	106
2.8	Chapter Highlights	108
	Problems	108
	Reading List	111

3 OPTICAL PROCESSES IN SEMICONDUCTORS

113

3.1	Electron-Hole Pair Formation and Recombination	114
	3.1.1 Radiative and Non-Radiative Recombination,	116
	3.1.2 Band-to-Band Recombination,	119
3.2	Absorption in Semiconductors	120
	3.2.1 Matrix Elements and Oscillator Strength for Band-to-Band Transitions,	120
	3.2.2 Indirect Intrinsic Transitions,	125
	3.2.3 Exciton Absorption,	127
	3.2.4 Donor-Acceptor and Impurity-Band Absorption,	128
	3.2.5 Low-Energy (Long-Wavelength) Absorption,	130
3.3	Effect of Electric Field on Absorption: Franz-Keldysh and Stark Effects	132
3.4	Absorption in Quantum Wells and the Quantum-Confined Stark Effect	134
3.5	The Kramers-Krönig Relations	138
3.6	Radiation in Semiconductors	140
	3.6.1 Relation between Absorption and Emission Spectra,	140
	3.6.2 Stokes Shift in Optical Transitions,	141
	3.6.3 Near-Bandgap Radiative Transitions,	142
3.7	Deep-Level Transitions	146
3.8	Auger Recombination	147
3.9	Luminescence from Quantum Wells	148

- 3.10 Measurement of Absorption and Luminescence Spectra **149**
- 3.11 Time-Resolved Photoluminescence **151**
- 3.12 Chapter Highlights **154**
- Problems **154**
- Reading List **156**

4 JUNCTION THEORY

158

- 4.1 Introduction **158**
- 4.2 P-N Junctions **158**
 - 4.2.1 *Junction Formation, 158*
 - 4.2.2 *Electrostatics of the p-n junction: Contact Potential and Space Charge, 164*
 - 4.2.3 *Current-Voltage Relationship, 172*
 - 4.2.4 *Quasi-Fermi Levels and High-Level Injection, 179*
 - 4.2.5 *Graded Junctions, 181*
 - 4.2.6 *AC Operation of Diodes: Diffusion Capacitance, 183*
 - 4.2.7 *Breakdown Phenomena in Junction Diodes, 184*
- 4.3 Schottky Barriers and Ohmic Contacts **187**
 - 4.3.1 *Introduction, 187*
 - 4.3.2 *Schottky Barriers, 187*
 - 4.3.3 *Ohmic Contacts, 192*
- 4.4 Semiconductor Heterojunctions **194**
 - 4.4.1 *Introduction, 194*
 - 4.4.2 *The Ideal Heterojunction, 195*
 - 4.4.3 *Current-Voltage Characteristics, 197*
 - 4.4.4 *Real Heterojunction Band Offsets, 198*
 - 4.4.5 *Application of Heterojunctions to Bipolar Transistors, 199*
 - 4.4.6 *Other Types of Heterojunction Band Lineups, 202*
- 4.5 Chapter Highlights **202**
- Problems **203**
- Reading List **205**

5 LIGHT EMITTING DIODES

206

- 5.1 Introduction **207**
- 5.2 The Electroluminescent Process **207**
- 5.3 Choice of LED Materials **209**
- 5.4 Device Configuration and Efficiency **211**
 - 5.4.1 *Injection Efficiency, 212*
 - 5.4.2 *Recombination Efficiency, 213*

	5.4.3	<i>Extraction Efficiency and External Conversion Efficiency</i> , 214	
	5.4.4	<i>Coupling Loss</i> , 218	
5.5		Light Output from LED 219	
5.6		LED Structures 222	
	5.6.1	<i>Heterojunction LED</i> , 222	
	5.6.2	<i>Burrus Surface-Emitting LED</i> , 223	
	5.6.3	<i>Guided Wave or Edge-Emitting LED</i> , 225	
	5.6.4	<i>Drive Circuitry</i> , 226	
5.7		Device Performance Characteristics 227	
	5.7.1	<i>Spectral Response</i> , 227	
	5.7.2	<i>Output Power-Time Characteristics</i> , 228	
	5.7.3	<i>Light(Power)-Current Characteristics</i> , 229	
	5.7.4	<i>Diode Current-Voltage Characteristics</i> , 229	
5.8		Frequency Response and Modulation Bandwidth 230	
5.9		Manufacturing Process and Applications 233	
5.10		LEDs for Display Applications 235	
5.11		Defects and Device Reliability 238	
5.12		Chapter Highlights 239	
		Problems 240	
		Reading List 241	
6		LASERS: OPERATING PRINCIPLES	242
6.1		Introduction 243	
6.2		Guided Waves 243	
	6.2.1	<i>Waveguide Modes</i> , 243	
	6.2.2	<i>Propagating Modes in a Symmetric Slab Waveguide</i> , 246	
	6.2.3	<i>Asymmetric and Three-Dimensional Waveguides</i> , 247	
	6.2.4	<i>Design of Laser Heterostructure: Calculation of the Cladding Layer Thickness</i> , 248	
6.3		Emission and Absorption of Radiation in a Two-Level Systems 249	
6.4		The Einstein Relations and Population Inversion 250	
6.5		Gain in a Two-Level Lasing Medium 253	
6.6		Lasing Condition and Gain in a Semiconductor 255	
6.7		Selective Amplification and Coherence—Need for Laser Cavity 259	
	6.7.1	<i>Threshold Condition for Lasing</i> , 260	
6.8		Lineshape Function and Line-Broadening Mechanisms 263	

- 6.9 Lasing Threshold Condition in a Two-Level System 265
- 6.10 Axial and Transverse Laser Modes 266
- 6.11 Application of Semiconductor Lasers 269
- 6.12 Chapter Highlights 269
- Problems 269
- Reading List 270

7 LASERS: STRUCTURES AND PROPERTIES

272

- 7.1 Junction Laser Operating Principles 273
- 7.2 Threshold Current 276
- 7.2.1 *Threshold Current Density of a Semiconductor Laser Treated as a Two-Level System, 276*
- 7.2.2 *Threshold Current Density from the Spontaneous Emission Rate, 277*
- 7.2.3 *Power Output, 282*
- 7.2.4 *Temperature Dependence of Threshold Current, 283*
- 7.3 Heterojunction Lasers 284
- 7.3.1 *Losses in Heterostructure Lasers, 290*
- 7.3.2 *Heterostructure Laser Materials, 290*
- 7.4 Distributed Feedback Lasers 292
- 7.4.1 *Introduction, 292*
- 7.4.2 *Coupled-Mode Theory, 292*
- 7.5 The Cleaved-Coupled-Cavity (C^3) Laser: A Technique for Obtaining Narrow Spectral Linewidth 298
- 7.6 Quantum Well Lasers 301
- 7.6.1 *Strained Quantum Well Lasers, 303*
- 7.7 Surface-Emitting Lasers 307
- 7.8 Rare-Earth Doped Lasers 309
- 7.9 Alternate Pumping Techniques 311
- 7.10 Device Fabrication 312
- 7.11 Measurement of Laser Characteristics 314
- 7.12 Laser Mounting and Fiber Coupling 315
- 7.13 Modulation of Lasers: Rate Equations 317
- 7.13.1 *Steady-State Solution or Static Characteristics, 319*
- 7.13.2 *Transient Phenomena and Frequency Response, 321*
- 7.14 Mode Locking of Semiconductor Lasers 331

7.15	Linewidth of Laser Modes	332
7.16	Anomalous Behavior and Device Reliability	334
7.17	Long-Wavelength Semiconductor Lasers	336
7.18	Tunneling Based Lasers	337
	7.18.1 Long-Wavelength Quantum Cascade Unipolar Laser,	337
	7.18.2 Tunneling Injection Laser,	338
7.19	Chapter Highlights	340
	Problems	340
	Reading List	343

8 PHOTODETECTORS

8.1	Introduction	345
8.2	Photoconductors	347
	8.2.1 DC Photoconductor,	351
	8.2.2 AC Photoconductor,	353
	8.2.3 Gain and Bandwidth,	353
	8.2.4 Noise in Photoconductors,	355
8.3	Junction Photodiodes	358
	8.3.1 Introduction,	358
	8.3.2 p-i-n (PIN) Photodiodes,	359
	8.3.3 Heterojunction Diodes,	371
8.4	Avalanche Photodiodes	373
	8.4.1 Introduction,	373
	8.4.2 Avalanche Multiplication: Ionization Threshold Energies,	374
	8.4.3 Multiplication and Ionization Coefficients in p-i-n and p-n Junction Diodes,	377
	8.4.4 Measurement of Multiplication Factors and Impact Ionization Coefficients,	381
	8.4.5 Noise Performance of Avalanche Photodiodes,	384
	8.4.6 Practical Avalanche Photodiodes,	386
	8.4.7 Superlattice Avalanche Photodiodes,	388
8.5	High-Speed Measurements	391
	8.5.1 Impulse Response Measurements,	391
	8.5.2 Optical Heterodyning,	391
	8.5.3 Electro-optic Measurement Technique,	392
	8.5.4 Fiber Coupling,	392
8.6	Comparison of Different Detectors	394
8.7	Chapter Highlights	396
	Problems	397
	Reading List	398

9	SPECIAL DETECTION SCHEMES	400
9.1	Introduction	401
9.2	Phototransistor	401
9.3	Modulated Barrier Photodiode	405
9.4	Metal-Semiconductor (Schottky Barrier) Photodiode	411
9.5	Metal-Semiconductor-Metal (MSM) Photodiode	412
9.6	Detectors for Long-Wavelength Operation	416
9.7	Wavelength Selective Detection	419
9.8	Coherent Detection	422
9.9	Microcavity Photodiodes	425
9.10	Chapter Highlights	427
	Problems	427
	Reading List	428
10	SOLAR CELLS	430
10.1	Introduction	430
10.2	Basic Principles: Current-Voltage Characteristics	431
10.3	Spectral Response	435
10.4	Heterojunction and Cascaded Solar Cells	437
10.5	Schottky Barrier Cells	441
10.6	Materials and Design Considerations	442
	10.6.1 <i>Materials Requirements</i> ,	442
	10.6.2 <i>Solar Cell Design</i> ,	442
	10.6.3 <i>p⁺-n-n⁺ versus n⁺-p-p⁺ Cells</i> ,	443
	10.6.4 <i>Dependence of Cell Performance on External Factors</i> ,	444
10.7	Chapter Highlights	444
	Problems	444
	Reading List	447
11	OPTOELECTRONIC MODULATION AND SWITCHING DEVICES	448
11.1	Introduction	449
11.2	Analog and Digital Modulation	451
11.3	Franz-Keldysh and Stark Effect Modulators	452

11.4	Quantum Well Electro-Absorption Modulators	452	
11.5	Electro-Optic Modulators	456	
	11.5.1	<i>Birefringence and the Electro-Optic Effect: Application to Phase Modulation</i>	456
	11.5.2	<i>Electro-Optic Amplitude Modulation</i>	460
	11.5.3	<i>The Quadratic Electro-Optic Effect: Quantum Well Modulators</i>	465
	11.5.4	<i>Modulation by Carrier Injection</i>	467
11.6	Optical Switching and Logic Devices	469	
	11.6.1	<i>Introduction</i>	469
	11.6.2	<i>Self-Electro-Optic Device</i>	469
	11.6.3	<i>The Bipolar Controller-Modulator</i>	472
	11.6.4	<i>Switching Speed and Energy</i>	478
11.7	Chapter Highlights	480	
	Problems	481	
	Reading List	481	
12	OPTOELECTRONIC INTEGRATED CIRCUITS		483
12.1	Introduction	484	
12.2	Need for Integration: Hybrid and Monolithic Integration	484	
12.3	Applications of Optoelectronic Integrated Circuits	487	
12.4	Materials and Processing for OEICs	489	
12.5	Integrated Transmitters and Receivers	491	
	12.5.1	<i>Front-End Photoreceivers</i>	491
	12.5.2	<i>OEIC Transmitters</i>	502
	12.5.3	<i>Complex Circuits and Arrays</i>	506
	12.5.4	<i>Optical Control of Microwave Oscillators</i>	508
12.6	Guided Wave Devices	509	
	12.6.1	<i>Waveguides and Couplers</i>	510
	12.6.2	<i>Active Guided Wave Devices</i>	514
12.7	Prospects for Optical Interconnects	516	
12.8	Chapter Highlights	519	
	Problems	519	
	Reading List	520	
13	LIGHTWAVE NETWORKS		522
13.1	Introduction	523	
13.2	Advantages of Optical Fiber Systems	523	

13.3 Fiber Types and Modes 525

13.4 Network Topologies and Configurations 527

13.5 Digital and Analog Transmission Systems 528

13.6 Techniques in Advanced Lightwave Networks 531

 13.6.1 Wavelength Division Multiplexing, 532

 13.6.2 Active and Passive Couplers, 534

 13.6.3 Regenerative and Non-Regenerative Amplifiers, 535

 13.6.4 Crosspoint Switches, 537

13.7 Operating Networks 539

13.8 Chapter Highlights 539

 Problems 540

 Reading List 540

LIST OF SYMBOLS 541

APPENDICES

1 IMPORTANT PROPERTIES OF COMMON SEMICONDUCTORS 548

2 DISPERSION RELATION OF A DIATOMIC LATTICE 550

3 THE FERMI INTEGRAL AND CARRIER CONCENTRATION IN DEGENERATE SEMICONDUCTORS 554

4 TRANSITION PROBABILITY OF AN ALLOWED DIRECT TRANSITION 556

5 THE KRAMERS-KRÖNIG RELATIONS 558

6 RADIATION DENSITY AND PHOTON DENSITY 560

7 PARAMETERS FOR UNIFORMLY DOPED ABRUPT GaAs JUNCTION AT 300°K 562

8 CONFINED MODES IN A SLAB WAVEGUIDE 564

9 MODE CUT-OFF CONDITIONS IN SYMMETRIC AND ASYMMETRIC PLANAR SLAB WAVEGUIDES 568

10 CALCULATION OF CLADDING LAYER THICKNESS OF HETEROSTRUCTURE LASER 570

11	OSCILLATION CONDITION AND THRESHOLD GAIN OF DISTRIBUTED FEEDBACK LASER	575
12	VERTICAL CAVITY SURFACE EMITTING LASER	578
13	LARGE-SIGNAL SOLUTION TO CARRIER AND PHOTON RATE EQUATIONS	585
14	CARRIER EXCESS NOISE FACTORS	586
15	OPTICAL GAIN OF A PHOTOTRANSISTOR	589
16	SIGNAL-TO-NOISE RATIO IN BALANCED DETECTION SYSTEM	592
17	ELECTROABSORPTION IN BIAXIALLY STRAINED QUANTUM WELLS	595
18	REFRACTIVE INDICES IN MULTILAYERED MATERIALS	597
19	DIGITAL RECEIVER SENSITIVITY	599
20	POWER FLOW IN DUAL-CHANNEL DIRECTIONAL COUPLER	602
	INDEX	604

List of Tables

- 1.1 COVALENT (TETRAHEDRAL) RADII
- 1.2 LATTICE CONSTANTS, NEAREST-NEIGHBOR DISTANCES AND COVALENT RADII OF ELEMENTAL AND COMPOUND SEMICONDUCTORS
- 1.3 ELECTRON EFFECTIVE MASSES IN $In_xGa_{1-x}As$ GROWN PSEUDOMORPHICALLY ON GaAs AND $In_{0.54+x}Ga_{0.47-x}As$ GROWN PSEUDOMORPHICALLY ON InP
- 1.4 OPTICAL COLORS AND THEIR WAVELENGTHS
- 1.5 COMPOSITIONAL DEPENDENCE OF THE ENERGY GAP OF TERNARY III-V SEMICONDUCTORS AT 300°K
- 1.6 PHYSICAL PARAMETERS FOR THE BINARY COMPOUNDS InAs, GaAs, AND AlAs USED TO ESTIMATE THE RATIO OF THEIR RELATIVE BOND STRENGTHS
- 2.1 ENERGY GAPS AND TRANSVERSE AND LONGITUDINAL ELECTRON EFFECTIVE MASSES FOR SOME IMPORTANT III-V BINARY COMPOUNDS
- 2.2 PARAMETERS FOR THE VARSHNI EQUATION
- 2.3 VALUES OF N_c , N_v AND n_i AT 300°K FOR A FEW SEMICONDUCTORS
- 3.1 DIELECTRIC CONSTANT AND REFRACTIVE INDEX IN SOME BINARY III-V COMPOUNDS
- 4.1 BANDGAP AND ELECTRON AFFINITY OF SOME IMPORTANT SEMICONDUCTORS

5.1 CHARACTERISTICS OF VISIBLE LIGHT-EMITTING DIODE

7.1 BAND STRUCTURE PARAMETERS OF $In_{1-x}Ga_xAs_yP_{1-y}$ LATTICE-MATCHED TO InP ($y = 2.16x$)

11.1 COMPARISON OF THE LINEAR ELECTRO-OPTIC COEFFICIENT OF $GaAs$ WITH OTHER CRYSTALS

11.2 THE TRUTH TABLE FOR THE MQW-HBT SWITCHING GATE AT DIFFERENT VOLTAGES

12.1 COMPARISON OF FRONT-END PHOTORECEIVER CIRCUITS

About the Author

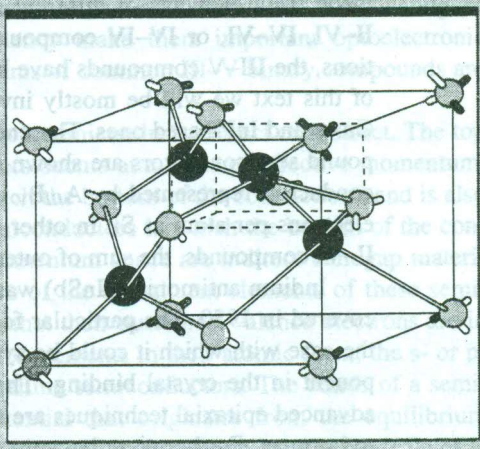
Elemental and Compound Semiconductors

PALLAB BHATTACHARYA is Professor of Electrical Engineering and Computer Science and Director of the Solid State Electronics Laboratory at the University of Michigan, Ann Arbor. His teaching and research interests include liquid-phase and molecular beam epitaxy of elemental and III-V compound semiconductors, materials characterization, electronic and optoelectronic devices and optoelectronic integrated circuits. He received the Ph.D. degree from the University of Sheffield, United Kingdom (1978) and was on the faculty of Oregon State University (1978–1983). Since 1983 he has been at the University of Michigan. He was Invited Professor at the Ecole Polytechnique Federale de Lausanne, Switzerland, during 1981–1982. He has published over 250 technical articles in archival journals. He received the Parker Rhodes Scholarship at the University of Sheffield, the L.L. Stewart Faculty Development Award at Oregon State University and the Research Excellence Award at the University of Michigan. He was elected Fellow of IEEE in 1988. He is Editor of *IEEE Transactions of Electron Devices* and has edited *Properties of Lattice-Matched and Strained InGaAs* (INSPEC, UK, 1993) and *Properties of III-V Quantum Wells and Superlattices* (INSPEC, UK, 1996). He has served on the Advisory Board of the Electrical and Communications Systems Division at the National Science Foundation. He has also served on several other committees and panels in academia, government, industry and technical conferences.

Elemental and Compound Semiconductors

Chapter Contents

- 1.1 Introduction
- 1.2 Bonding in Solids
- 1.3 Crystalline Nature of Solids
- 1.4 Alloy Semiconductors
- 1.5 Lattice-Mismatched and Pseudomorphic Materials
- 1.6 Transmission Media and Choice of Materials
- 1.7 Crystal Growth
- 1.8 Device Processing
- 1.9 Chapter Highlights



1.1 INTRODUCTION

Optoelectronics deals with the interaction of electronic processes with light and optical processes. Devices in which such interaction can suitably take place, usually accompanied by an energy conversion process (e.g., from electrical to optical, and vice versa), are called optoelectronic devices. Such devices are conveniently made with semiconductor optoelectronic devices and the properties of materials with which they can be made. Research and development of optoelectronic devices and optoelectronic integrated circuits have received a tremendous boost with the development of low-loss optical fibers for long distance communication. These devices and circuits now play an important role in our daily lives. The optoelectronics market is projected to grow at an annual rate of 9–10%.

Although the elemental semiconductors, and in particular Si, have been very useful for the development of microelectronics, they have some important drawbacks. The fundamental bandgap of these semiconductors is indirect. This implies that they emit light very poorly and their absorption coefficients are low. As a solar energy converter Si is technologically good, but because of its small energy gap the conversion efficiency is low. It became clear that Si, considered by many as a universal semiconductor material, cannot perform many important functions. For optoelectronic applications, in particular, it was natural then to turn to other materials. It turned out that compound semiconductor materials offered many of the desired properties and could be synthesized without much difficulty. Compound semiconductors, as the name suggests, are made from elements of different columns of the periodic table. Examples are III–V, II–VI, IV–VI, or IV–IV compounds. Historically, for optoelectronic device applications, the III–V compounds have been the first and most widely used. For the purpose of this text we will be mostly involved with III–V compounds, and in particular the GaAs and InP-based ones. The energy band diagrams of common elemental and compound semiconductors are shown in Fig. 1.1. It may be noted that a compound semiconductor, represented by $A_{III}B_V$ or $C_{IV}D_{VI}$, has the same average number of valence electrons per atom as Si. In other words Si has four valence electrons and in III–V or II–VI compounds, the sum of outer electrons is eight.

Indium antimonide (InSb) was the first III–V compound semiconductor to be discovered in 1950. The particular features of this compound that attracted interest were the ease with which it could be synthesized, the electron mobility, and the ionic component in the crystal binding. These properties are still of immense interest, and as advanced epitaxial techniques are being developed, the purity of the crystals continues to improve. Furthermore, because of its low bandgap, $\mathcal{E}_g = 0.17$ eV, InSb has become important for the development of far infrared detector technology. Two important events, the invention of the semiconductor laser and the discovery of the Gunn effect, turned the interest to other III–V compounds such as GaAs ($\mathcal{E}_g = 1.43$ eV) and InP ($\mathcal{E}_g = 1.35$ eV). The next in order of importance is GaP, which has its bandgap (2.1 eV) in the visible part of the spectrum and therefore became important for the development of the light-emitting diode (LED). It may be noted that the bandgap of GaP is indirect, but by certain doping techniques, which we shall learn about in Chapter 5, it is possible to improve the radiative efficiency. Compared to Si and Ge, GaAs

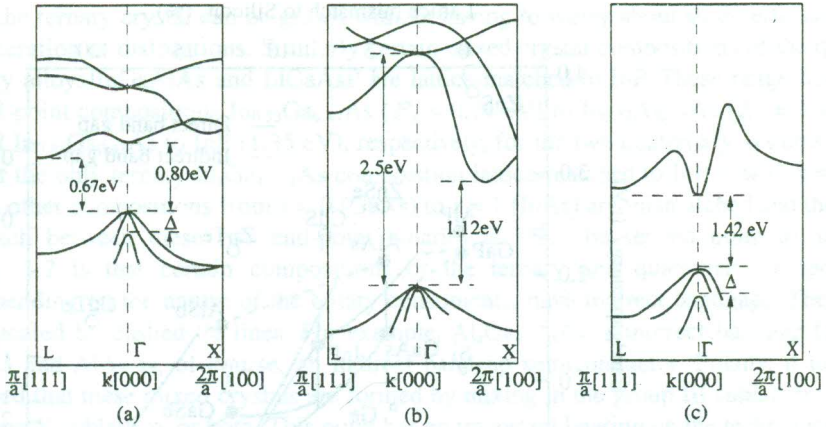


Figure 1.1 Diagrams showing the variations of electron energy with wave number (momentum) in (a) Ge, (b) Si, and (c) GaAs along the [100] and [111] directions in k space. Electrons are located near the minimum of the conduction band, whereas holes are located near the maximum of the valence band. The band structures of Ge and Si are examples of indirect-gap semiconductors, whereas that of GaAs represents a direct bandgap semiconductor. Δ is the spin-orbit splitting (from S. Wang, *Fundamentals of Semiconductor Theory and Device Physics*, Prentice Hall, Englewood Cliffs, NJ, 1989).

and InP have high electron mobilities and velocities, properties that are extremely important for the development of high-speed electronic devices. Their direct bandgaps and the consequent high radiative efficiency make them important optoelectronic materials. The bandgaps and lattice constants of common III-V binary compounds are depicted in Fig. 1.2.

It is instructive to find out what makes a semiconductor direct or indirect. The top of the valence band of most semiconductors occurs at a value of effective momentum, or k , equal to zero. Semiconductors in which the bottom of the conduction band is also at $k = 0$ are direct bandgap materials. Semiconductors in which the bottom of the conduction band occurs at other points in momentum space are indirect bandgap materials. It is evident from the atomic structure of the constituent elements of these semiconductors, described in the next section, that their outermost valence electrons are in s- or p-type orbitals. Although true only for elements in their atomic form, the s- or p-like character is also retained in the crystalline semiconductors. The bands of a semiconductor are a result of the crystal potential that originates from the equilibrium arrangement of atoms in the lattice. If the edge of the conduction band is made up of s-type states, the semiconductor is direct bandgap. If, on the other hand, the lowest conduction band edge is made up of p-type states, then the semiconductor is indirect bandgap.

An attractive feature of the binary compounds is that they can be combined or *alloyed* to form *ternary* or *quaternary* compounds, or *mixed crystals*. These compounds are made up of three or four group III and group V atoms and are indicated by the tie lines between the binary compounds in Fig. 1.2. Note that by choosing different binary compounds, it is possible to select different bandgaps, and therefore varying

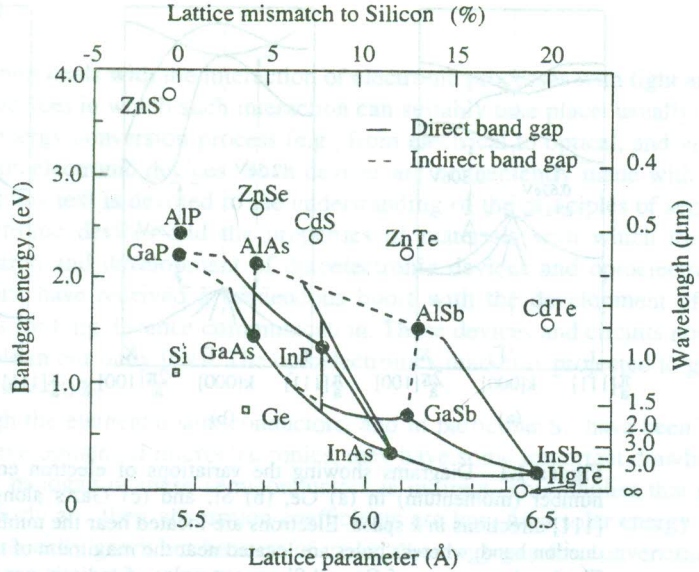


Figure 1.2 Energy bandgap versus lattice constant for common elemental and compound semiconductors. The tie lines joining the binaries represent ternary compositions. The dashed lines represent indirect bandgap material. The vertical dashed line passing through the point representing InP contains the bandgaps for the lattice-matched InGaAlAs and InGaAsP quaternary systems.

emission energies for light sources. However, by alloying it is possible to vary the bandgap *continuously* and monotonically, and together with it the bandstructure, electronic, and optical properties. The formation of ternary and quaternary compounds of varying bandgaps also enables the formation of heterojunctions, which have become essential for the design of high-performance electronic and optoelectronic devices. As an example, the bandgap of the ternary compound $\text{Al}_x\text{Ga}_{1-x}\text{As}$ ($0 \leq x \leq 1$) depends on the mole fraction x of AlAs in the solid solution and changes continuously from 1.43 eV (GaAs, $x = 0$) to 2.1 eV (AlAs, $x = 1$). As we shall see later, the bandstructure, electronic, and optical properties of the mixed crystal also change with change in alloy composition, and these are exploited in the design of electronic and optoelectronic devices. Among the common GaAs and InP-based ternary and quaternary compounds, the properties of $\text{Al}_x\text{Ga}_{1-x}\text{As}$ have been most thoroughly investigated. Other important ternary and quaternary compounds are $\text{GaAs}_{1-x}\text{P}_x$, $\text{In}_{1-x}\text{Ga}_x\text{P}$, $\text{In}_x\text{Ga}_y\text{Al}_{1-x-y}\text{As}$, and $\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}$. The last two are usually grown on InP substrates. The bandgaps and lattice constants of these compounds can be found from the tie lines in Fig. 1.2. The quaternary compounds mentioned above have emerged as being extremely important for optical communication, since their bandgaps correspond to the spectral window in which silica fibers have their lowest loss and dispersion. Several important observations may be made from Fig. 1.2. First, it may be noted that the lattice constants of GaAs (5.6532 Å) and AlAs (5.6611 Å) are almost identical. This implies that all the mixed crystal compositions of $\text{Al}_x\text{Ga}_{1-x}\text{As}$ can be grown *lattice-matched* on GaAs substrates. We shall soon see in Sec. 1.5 that this is very useful because any thickness

of the ternary crystal can be grown without having to worry about strain effects or the generation of dislocations. Similarly certain mixed crystal compositions of the quaternary alloys InGaAlAs and InGaAsP are lattice-matched to InP. These range from the end-point compositions $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ ($\mathcal{E}_g = 0.74$ eV) to $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ ($\mathcal{E}_g = 1.45$ eV) and $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ to InP (1.35 eV), respectively, for the two quaternary systems. Note that the only ternary $\text{In}_x\text{Ga}_{1-x}\text{As}$ composition lattice-matched to InP is with $x = 0.53$. All other compositions from $x = 0$ (GaAs) to $x = 1$ (InAs) are mismatched and the mismatch between these two end-point binaries is 7%. The second point to note in Fig. 1.2 is that certain compositions of the ternary and quaternary compounds, depending on the nature of the binary constituents, have indirect bandgaps. These are indicated by dashed tie lines. For example, $\text{Al}_x\text{Ga}_{1-x}\text{As}$ is indirect bandgap for $x \geq 0.43$ and AlAs is, of course, an indirect bandgap semiconductor. Finally, it may be noted that these mixed crystals are formed by mixing in the group III sublattice, or the group V sublattice, or both. This point has an important bearing on the techniques used to grow them.

Many physical parameters of ternary compounds are determined by the parameters of the constituent binaries and vary roughly linearly with composition. For example, the lattice constant, a , of $\text{In}_x\text{Ga}_{1-x}\text{As}$ is given by Vegard's law as

$$a_{\text{In}_x\text{Ga}_{1-x}\text{As}} = xa_{\text{InAs}} + (1-x)a_{\text{GaAs}} \quad (1.1)$$

Similarly, for a quaternary compound $\text{A}_1-x\text{B}_x\text{C}_y\text{D}_{1-y}$, a material parameter Q can be expressed as

$$Q(x,y) = \{x(1-x)[(1-y)T_{12}(x) + yT_{43}(x)] \\ + y(1-y)[(1-x)T_{14}(y) + xT_{23}(y)]\} \\ [x(1-x) + y(1-y)]^{-1} \quad (1.2)$$

where T_{ij} is the material parameter for the ternary alloy formed by binaries i and j . The relevant parameters of GaAs and $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ together with those for Si, for the purpose of comparison, are listed in Appendix 1.

1.2 BONDING IN SOLIDS

In the *solid state*, also referred to as *condensed matter*, the atoms forming the solid are held together by bonding forces. The atoms also maintain a finite, fixed distance from each other. If the array of atoms have long-range order or *periodicity*, the resulting solid is crystalline, and we will study the properties of crystals in the next section. The periodic array of atoms leads the way to the energy band models and conduction properties. However, before going into all that, we should understand the nature of the forces that hold the atoms together in their equilibrium positions. There are in general two types of forces, attractive and repulsive, which are both functions of the interatomic distance z . At large distances the attractive forces dominate, and therefore the atoms are drawn nearer to each other. At small interatomic distances the repulsive forces dominate, and the atoms are pushed further apart. In equilibrium the forces of attraction $F_A(z)$, and repulsion, $F_R(z)$, must balance to establish the equilibrium atomic spacing. In other words: