Photodetectors and Fiber Optics Edited by Hari Singh Nalwa



Photodetectors and Fiber Optics

This page intentionally left blank

Photodetectors and Fiber Optics

EDITED BY

Hari Singh Nalwa, M.Sc., Ph.D. Stanford Scientific Corporation Los Angeles, California, USA

Formerly at Hitachi Research Laboratory Hitachi Ltd., Ibaraki, Japan



A Harcourt Science and Technology Company

San Diego San Francisco New York Boston London Sydney Tokyo This book is printed on acid-free paper. ⊗

Copyright © 2001 by Academic Press

All rights reserved.

No part of this publication may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopy, recording, or any information storage and retrieval system, without permission in writing from the publisher.

Requests for permission to make copies of any part of the work should be mailed to: Permissions Department, Harcourt Inc., 6277 Sea Harbor Drive, Orlando, FL 32887-6777.

ACADEMIC PRESS A Harcourt Science and Technology Company 525 B Street, Suite 1900, San Diego, CA 92101-4495, USA http://www.academicpress.com

Academic Press Harcourt Place, 32 Jamestown Road, London NW1 7BY, UK http://www.academicpress.com

Library of Congress Catalog Card Number: 00-108485 International Standard Book Number: 0-12-513908-X

Printed in the United States of America 01 02 03 04 05 MB 9 8 7 6 5 4 3 2 1 For my closest friend, Krishi Pal Reghuvanshi This page intentionally left blank

CONTENTS

| Preface | | xiii | |
|---------|------------------|--|------|
| Ab | About the Editor | | |
| Со | ntributo | rs | xvii |
| 1 | Semi | conductor Photoconductors for Visible to | |
| | Far-I | nfrared Detection | |
| | N. M. | Haegel | |
| | 1 Inti | roduction | 2 |
| | 2 Me | chanisms of Photon Absorption | 6 |
| | 2.1 | Interaction with High-Energy Radiation | 9 |
| | 2.2 | Intrinsic Absorption | 11 |
| | 2.3 | Extrinsic Absorption Mechanisms | 15 |
| | 2.4 | Absorption in Quantum Wells and Superlattices | 22 |
| | 3 Inti | rinsic Photoconductors | 24 |
| | 3.1 | Figures of Merit | 27 |
| | 3.2 | Conventional Intrinsic Photoconductors | 33 |
| | 3.3 | Photoconductors for Ultrafast Optoelectronics | 38 |
| | 3.4 | Alternate Modes of Operation and Device Design | 40 |
| | 4 Ext | rinsic Photoconductors | 44 |
| | 4.1 | Operation of Extrinsic Photoconductors | 45 |
| | 4.2 | Figures of Merit | 52 |
| | 4.3 | Device Construction | 53 |
| | 4.4 | Extending the Wavelength Response | 54 |
| | 4.5 | Transient Behavior of Extrinsic Photoconductors | 62 |
| | 5 Blo | cked Impurity Band Detectors and the Solid-State | |
| | Pho | otomultiplier | 71 |
| | 5.1 | Solid-State Photomultiplier | 80 |

| | 6 | Qua | ntum-Well Infrared Photodetectors | 82 |
|---|---|--------------|---|-------|
| | 7 | Con | clusion | 91 |
| | Α | ckno | wledgments | 92 |
| | R | efere | nces | 93 |
| | | | | |
| 2 | R | eson | nant Cavity Enhanced Photodetectors | |
| | М | . S. Ü | inlü, G. Ulu, and M. Gökkavas | |
| | 1 | Intro | aduction | 08 |
| | 1 | 1 1 | Historical Perspective Prior to the 1000s | 00 |
| | | 1.1 | Organization of the Chapter | 100 |
| | 2 | The | oratical Formulation of Resonant Cavity Enhanced | 100 |
| | 2 | Dho | todetector Deremeters | 101 |
| | | P110 | Analytical Formulation of the Quantum Efficiency for Resonant | 101 |
| | | 2.1 | Analytical Formulation of the Quantum Efficiency for Resonant | 101 |
| | | 22 | Stonding Ways Effect | 101 |
| | | 2.2 | Standing wave Effect | 100 |
| | | 2.5 | Weyelength Selectivity of Research Covity Enhanced Photodetection | 112 |
| | | 2.4 | Angle Dependence of Quentum Efficiency | 110 |
| | | 2.5 | Nearly Unity Quantum Efficiency Decodetaction | 110 |
| | | 2.0 | Limitations of Analytical Formulation | 120 |
| | 2 | 2.7 Nixa | Limitations of Analytical Formulation | 122 |
| | 3 | 1NUII 2 1 | Beourgius Esemulation | 124 |
| | | 3.1 2.2 | Recursive Formulation | 120 |
| | 4 | 5.2 II:-1 | Scattering Matrix Method | 129 |
| | 4 | Higi | The speed Properties of Resonant Cavity Enhanced Photodiodes | 130 |
| | | 4.1 | Theoretical Considerations | 137 |
| | | 4.2 | High-Speed Capabilities of Resonant Cavity Enhanced Photodetectors | 143 |
| | | 4.5 | External Circultry and Packaging | 14/ |
| | - | 4.4 | Iransient Simulation of Resonant Cavity Enhanced Photodiodes | 148 |
| | 5 | Desi | ign Criteria for Resonant Cavity Enhanced Photodetectors | 151 |
| | | 5.1 | Evaluation of Various Resonant Cavity Enhanced Designs | 151 |
| | | 5.2 | Material Requirements for Resonant Cavity Enhanced Photodetection | 154 |
| | | 5.5 | Material System Combinations for Resonant Cavity Enhanced | 1.5.6 |
| | ~ | n | Photodetection | 156 |
| | 0 | Rev: | lew of Experimental Results | 161 |
| | | 0.1 | Characterization of Quantum Efficiency and Electrical Performance | 161 |
| | | 0.2 | Classification of Resonant Cavity Enhanced Photodetector Categories | 165 |
| | | 0.3 | Resonant Cavity Enhanced Photodetectors with High/Unity Efficiency | 166 |
| | | 0.4 | Weiselength Selective Research County Enhanced Photoetectors for Optical Communications | 170 |
| | | 0.3 | Polarization Sensing with Personant Cavity Enhanced Photodetectors | 1/8 |
| | | 0.0 67 | Resonant Cavity Enhanced Photodiadas Integrated with Light Provide | 185 |
| | | 6.8 | Advanced Designs _ Elat Spectral Despanse | 100 |
| | 7 | Con | clusions | 191 |
| | 1 | COU | CIUSIOIIS | 194 |

| Acknowledgments | 196 |
|-----------------|-----|
| References | 196 |

3 Silicon and GaAs as Far-Infrared Detector Material

| А. | G. U | . Perera | |
|----------------|----------------|---|-----|
| 1 | Intro | oduction | 204 |
| | 1.1 | Silicon Far-Infrared Detectors | 204 |
| | 1.2 | GaAs Far-Infrared Detectors | 206 |
| 2 | Far-J | Infrared Absorption | 207 |
| | 2.1 | Far-Infrared Absorption in GaAs | 207 |
| | 2.2 | Far-Infrared Absorption in Silicon | 210 |
| 3 | Hom | ojunction Interfacial Workfunction Internal Photoemission | |
| | Dete | ectors | 212 |
| | 3.1 | Type-I Homojunction Interfacial Workfunction Internal | |
| | | Photoemission Detectors: $N_a < N_c$ $(E_F > E_c^{n^+})$ | 214 |
| | 3.2 | Type-II Homojunction Interfacial Workfunction Internal | |
| | | Photoemission Detector: $N_c < N_a < N_0 (E_v^{p^+} > E_F > E_v^i)$ | 216 |
| | 3.3 | Performance Improvements in Homojunction Interfacial | |
| | | Workfunction Internal Photoemission Detectors | 225 |
| | 3.4 | Type-II Silicon Homojunction Interfacial Workfunction Internal | |
| | | Photoemission Detector | 230 |
| | 3.5 | Type-III Homojunction Internal Photoemission Detector: | |
| | | $N_a > N_0 \left(E_F < E_v^i \right)$ | 232 |
| 4 | Sum | mary | 233 |
| Acknowledgment | | | 233 |
| R | References 234 | | |
| | | | |

4 Bulk Semiconductors for Infrared Applications

| A. Burger, | JO. Ndap, | , K. Chatto | padhyay, | and S. | Morgan |
|------------|-----------|-------------|----------|--------|--------|
|------------|-----------|-------------|----------|--------|--------|

| 1 | Ove | rview | 239 |
|---|-----|--|-----|
| 2 | Mat | erial Preparation and Basic Characterization | 240 |
| | 2.1 | Materials for Infrared Detection | 240 |
| | 2.2 | Transition Metal-Doped II-VI Compounds for Tunable | |
| | | Midinfrared Lasers | 249 |
| | 2.3 | Electro-optic and Nonlinear Optic Materials | 256 |
| 3 | Mat | erial Properties Relevant for Infrared Devices | 269 |
| | 3.1 | Photorefractives | 269 |
| | 3.2 | Optical Limiters | 280 |
| | 3.3 | Solid-State Midinfrared Tunable Lasers | 282 |
| | 3.4 | Optical Parametric Oscillators (OPO) | 283 |
| | 3.5 | Infrared Optical Components | 289 |
| | | | |

| | 4 Con Refere | clusions ences | 291 293 |
|---|-----------------|--|------------|
| 5 | Photo A. Ban | detectors for Optical Fiber Communications | |
| | 1 Intr | oduction | 308 |
| | 2 Bas | ic Principles | 311 |
| | 3 <i>n</i> -i | <i>n</i> Photodetectors | 317 |
| | 3.1 | Introduction | 317 |
| | 3.2 | Vertically Illuminated <i>p-i-n</i> Photodiode Structure | 319 |
| | 3.3 | Edge-Illuminated Waveguide Photodiodes | 321 |
| | 3.4 | Resonance Cavity-Enhanced Photodiodes | 322 |
| | 3.5 | Effect of Packaging | 324 |
| | 3.6 | Reliability | 325 |
| | 4 Sch | ottky Barrier Photodetectors | 327 |
| | 5 Met | al-Semiconductor-Metal Photodetectors | 328 |
| | 5.1 | Introduction | 328 |
| | 5.2 | Metal-Semiconductor-Metal Photodiode Structure and Performance | 332 |
| | 6 Ava | lanche Photodiodes | 334 |
| | 6.1 | Introduction | 334 |
| | 6.2 | Separate Absorption Grading Charge Sheet and Multiplication APDs | 338 |
| | 6.3 | Superlattice APD | 343 |
| | 6.4 | Resonant Cavity Encapsulated APD | 349 |
| | 7 Si-H | Based Photodetectors | 351 |
| | 7.1 | InGaAs on Si-Based Photodetectors | 351 |
| | 7.2 | $Ge_{1-x}C_x/Si$ -Based Photodetectors | 354 |
| | 8 Opt | ical Receiver | 356 |
| | 8.1 | Introduction | 356 |
| | 8.2 | Hybrid Photoreceiver | 356 |
| | 8.3 | Monolithic Photoreceiver | 359 |
| | 9 Sun | nmary | 365 |
| | Ackno | owledgments | 365 |
| | Refere | ences | 365 |

6 Germanium Dioxide-Based Glasses as Advanced Optical Sensors Materials

| <i>A</i> . <i>A</i> . | Margaryan |
|-----------------------|-----------|
|-----------------------|-----------|

| 1 | Intro | oduction | 369 |
|---|--|--|-----|
| 2 | 2 Properties and Structure of Glass-Forming GeO ₂ | | 370 |
| | 2.1 | X-Ray and Neutron Scattering Studies of GeO ₂ | 370 |
| | 2.2 | Infrared Spectroscopy Studies | 372 |

| 23 | Electron Paramagnetic Resonance Studies | 277 |
|--------|---|-----|
| 2.5 | Optical Droporties | 200 |
| 2.4 | Optical Properties | 380 |
| 2.5 | Properties and Structure of Binary Germanate Glasses | 385 |
| 2.6 | Properties and Structure of Ternary Germanate Glasses | 415 |
| 2.7 | Pseudoternary Fluoride-Containing Germanate Systems | 438 |
| 2.8 | Germanium Dioxide Based Glasses in Applications | 453 |
| Refere | ences | 454 |
| | | |

7 High-Bandwidth Optical Networks and Communication

| M. J. Potasel |
|---------------|
|---------------|

| 1 | 1 Introduction | | | |
|---|------------------------|--|-----|--|
| 2 | 2 Networks | | | |
| | 2.1 | Local Area Networks | 466 | |
| | 2.2 | Metropolitan Area and Wide Area Networks | 466 | |
| | 2.3 | Internet Protocol | 467 | |
| | 2.4 | Network Layers | 468 | |
| 3 | Enal | bling Technologies and Transmission Systems | 469 | |
| | 3.1 Optical Amplifiers | | | |
| | 3.2 | Transmission Systems Design | 471 | |
| | 3.3 | Computer Aided Design | 474 | |
| 4 | Tran | smission | 474 | |
| | 4.1 | Linear Propagation | 474 | |
| | 4.2 | Single-Mode Dispersion and Dispersion Penalties | 475 | |
| | 4.3 | Nonlinear Propagation and the Nonlinear Schrödinger Equation | 476 | |
| | 4.4 | Wavelength-Division Multiplexing | 479 | |
| | 4.5 | Solitons | 481 | |
| | 4.6 | Soliton Optical Communications | 483 | |
| | 4.7 | Solitons and Polarization | 484 | |
| | 4.8 | Solitons and Amplification | 486 | |
| | 4.9 | Gordon-Haus Jitter and Timing Jitter Control | 487 | |
| | 4.10 | Dispersion Management and Dispersion-Managed Solitons | 488 | |
| | 4.11 | Wavelength-Division Multiplexing and Solitons | 490 | |
| | 4.12 | Systems Experiments | 493 | |
| | 4.13 | Femtosecond Propagation | 505 | |
| 5 | 5 Switching | | 511 | |
| | 5.1 | Switches in Communications | 511 | |
| | 5.2 | Soliton All-Optical Switching | 512 | |
| | 5.3 | Coupled Higher-Order Equations | 515 | |
| 6 | All-Optical Networks | | | |
| | 6.1 | Multihop Networks | 520 | |
| | 6.2 | Wavelength Routing Networks | 522 | |
| | 6.3 | Node Design | 523 | |
| | 6.4 | Crosstalk | 523 | |
| | | | | |

| | 6.5 | Traffic Patterns and Demands | 524 |
|-----------------|------|-----------------------------------|-----|
| | 6.6 | Routing and Wavelength Assignment | 524 |
| 7 | Free | e-Space Optical Propagation | 526 |
| | 7.1 | Self-Focusing | 526 |
| | 7.2 | Gigabit/sec Propagation | 526 |
| | 7.3 | Terabit/sec Propagation | 527 |
| 8 | Sun | nmary | 535 |
| Acknowledgments | | | 536 |
| References | | | 536 |
| | | | |

545

PREFACE

Photodetectors and Fiber Optics is an outgrowth of the recently published 10 volume set, Handbook of Advanced Electronic and Photonic Materials and Devices. The objective of this book is aimed to present highly coherent coverage of photodetectors and optical fibers. Semiconductor photoconductors for visible to far-infrared detection are covered by Nancy Haegel, while M. Selim Unlü, Gokhan Ulu, and Mutlu Gökkavas continue with their topic on resonant cavity enhanced photodetectors. A. G. Unil Perera discusses silicon and gallium arsenide (GaAs) based infrared detectors and Arnold Burger, Jean-Olivier Ndap, Kaushik Chattopadhyay, and Steve Morgan describe bulk semiconductors for infrared applications. Photodetectors have been extensively used for applications in optical fibers. The present boom in fiber optic technology illustrates how important photodetectors are and how they are correlated to fiber optics. A. Bandyopadhyay and M. Jamal Deen have provided an excellent overview on the importance and role of photodetectors for optical fiber communications. Germanium-dioxidebased glasses as optical sensors materials are described by Alfred Margaryan, and M. J. Potasek discusses high-bandwidth optical networks and communication.

This book covers a broad spectrum of photodetectors, including types of materials, their fabrication, physical properties, and industrial applications. Many industries around the world are engaged in developing fiber optic technology for the new millennium. The applications of photodetectors in fiber optics and the role of optical fibers in present communication technology have been discussed extensively. These are exciting areas of research that will play a crucial role in future communication technology. This reference should be a valuable resource to scientists and upper level graduate students working in solid state physics, optical engineering and photophysics, fiber optics, electrical and electronic engineering, materials science, data storage, information technology, and semiconductor industries.

Both editor and publisher are very grateful to the contributors of this volume for their outstanding work.

Hari Singh Nalwa Los Angeles, USA This page intentionally left blank

ABOUT THE EDITOR

Dr. H. S. Nalwa is the Managing Director of the Stanford Scientific Corporation in Los Angeles, California. Previously, he was Head of Department and R&D Manager at the Ciba Specialty Chemicals Corporation in Los Angeles (1999– 2000) and a staff scientist at the Hitachi Research Laboratory, Hitachi Ltd., Japan (1990–1999). He has authored over 150 scientific articles and 18 patents on electronic and photonic materials and devices.

He has published 13 books that include:

Thin Films Handbook, Vols. 1-5 (2001)

- Handbook of Surfaces and Interfaces of Materials, Vols. 1–5 (Academic Press, 2001)
- Advanced Functional Molecules and Polymers, Vols. 1–4 (Gordon & Breach, 2001)
- Supramolecular Photosensitive and Electroactive Materials (Academic Press, 2001)

Silicon-Based Materials and Devices (Academic Press, 2001)

- Handbook of Advanced Electronic and Photonic Materials and Devices, Vols. 1–10 (Academic Press, 2001)
- Handbook of Nanostructured Materials and Nanotechnology, Vols. 1–5 (Academic Press, 2000)
- Handbook of Low and High Dielectric Constant Materials and Their Applications, Vols. 1–2 (Academic Press, 1999)
- Handbook of Organic Conductive Molecules and Polymers, Vols. 1-4 (John Wiley & Sons, 1997)

Organic Electroluminescent Materials and Devices (Gordon & Breach, 1997) Nonlinear Optics of Organic Molecules and Polymers (CRC Press, 1997) Ferroelectric Polymers (Marcel Dekker, 1995) Handbook of Nanostructured Materials and Nanotechnology received the 1999 Award of Excellence from the Association of American Publishers. Dr. Nalwa serves on the editorial boards of Journal of Macromolecular Science-Physics, Applied Organometallic Chemistry (1993–1999), International Journal of Photoenergy, and Photonics Science News. He is the founder and Editor-in-Chief of the Journal of Porphyrins and Phthalocyanines. Dr. Nalwa has been cited in the Who's Who in Science and Engineering, Who's Who in America, and Who's Who in the World.

CONTRIBUTORS

Numbers in parentheses indicate the page on which the author's contribution begins.

- A. BANDYOPADHYAY (307), Maxim Integrated Products, Inc., Beaverton, Oregon 97005
- ARNOLD BURGER (239), Center for Photonic Materials and Devices, Department of Physics, Fisk University, Nashville, TN 37208
- **KAUSHIK CHATTOPADHYAY** (239), Center for Photonic Materials and Devices, Department of Physics, Fisk University, Nashville, TN 37208
- M. JAMAL DEEN (307), Department of Electrical and Computer Engineering Science, McMaster University, Hamilton, Ontario L8S 4K1, Canada
- MUTLU GÖKKAVAS (97), Department of Electrical and Computer Engineering, Boston University, Boston, MA 02215
- NANCY M. HAEGEL (1), Department of Physics, Fairfield University, Fairfield, CT 06430
- ALFRED A. MARGARYAN (369), Independent Consultant, Glendale, CA 91205
- STEVE MORGAN (239), Center for Photonic Materials and Devices, Department of Physics, Fisk University, Nashville, TN 37208

- JEAN-OLIVIER NDAP (239), Center for Photonic Materials and Devices, Department of Physics, Fisk University, Nashville, TN 37208
- A. G. UNIL PERERA (203), Department of Physics and Astronomy, Georgia State University, Atlanta, GA 30303
- M. J. POTASEK (459), Air Force Research Laboratory, HEDB, Brooks AFB, TX 78235-5102
- GOKHAN ULU (97), Department of Electrical and Computer Engineering, Boston University, Boston, MA 02215
- M. SELIM ÜNLÜ (97), Department of Electrical and Computer Engineering, Boston University, Boston, MA 02215

Semiconductor Photoconductors for Visible to Far-Infrared Detection

N. M. HAEGEL

Department of Physics, Fairfield University, Fairfield, CT 06430, USA

1. Introduction 2

2. Mechanisms of Photon Absorption 6

- 2.1. Interaction with High-Energy Radiation 9
- 2.2. Intrinsic Absorption 11
- 2.3. Extrinsic Absorption Mechanisms 15
- 2.4. Absorption in Quantum Wells and Superlattices 22

3. Intrinsic Photoconductors 24

- 3.1. Figures of Merit 27
- 3.2. Conventional Intrinsic Photoconductors 33
- 3.3. Photoconductors for Ultrafast Optoelectronics 38
- 3.4. Alternate Modes of Operation and

Device Design 40

- 4. Extrinsic Photoconductors 44
 - 4.1. Operation of Extrinsic Photoconductors 45
 - 4.2. Figures of Merit 52
 - 4.3. Device Construction 53
 - 4.4. Extending the Wavelength Response 54
 - 4.5. Transient Behavior of Extrinsic Photoconductors 62
- 5. Blocked Impurity Band Detectors and the Solid-State Photomultiplier 71
 - 5.1. Solid-State Photomultiplier 80
- 6. Quantum-Well Infrared Photodetectors 82
- 7. Conclusion 91

Acknowledgments 92

References 93

1. INTRODUCTION

The response of materials to light was a cornerstone of photography almost 200 years before an understanding of either solid state physics or the particle nature of light. From the first description of the "camera obscura" in a 1553 book entitled *Natural Magic* [1], the need to capture images was recognized. In the earliest cameras, the image was saved by tracing it on paper or ground glass. The subsequent development of photography required a way to "fix" an image by the interaction of light and matter. Over time, efforts to convert light into other signal forms that could be measured, manipulated, and stored would grow to encompass an amazing range of applications and devices.

In 1727, Johann Heinrich Schulze found that exposure to light of a calcium nitrate $(Ca(NO_3)_2)$ -silver carbonate (Ag_2CO_3) complex caused a color change to purple that was not replicated by exposure to heat. In documenting his discovery of photosensitive materials, Schulze wrote [2], "It was not long before the sun's rays, where they hit the glass through the cut-out parts of the paper, wrote each word or sentence on the chalk precipitate so exactly and distinctly that many who were curious about the experiment but ignorant of its nature took occasion to attribute the thing to some sort of trick." Studies of other materials with similar properties (AgBr, AgCl, and AgBrI) that would become the mainstays of photographic films soon followed.

Over a century later, in 1873, Willoughby Smith announced the discovery of *photoconductivity* in bars of the semimetal selenium. Photoconductivity, as opposed to photosensitivity, coupled optical and electrical effects. Writing in *Nature* [3], Smith reported that he began work on the resistance of bars of selenium while in search of higher resistance materials for the development of signaling devices for submarine cables. He was intrigued by the wide variations in resistivity reported by different operators when making measurements on the selenium and he began to investigate the cause of such wide resistance variations. Smith placed the bars inside a box with a slide cover and measured conductivity increases of $\sim 15-100\%$ when removing the cover of the box to expose his samples to light. Performing the same experiment with the samples immersed in water produced a similar result, indicating to Smith that exposure to light rather than heat was the source of the effect.

Although it took until the 1920s before a detailed, systematic study of photoconductivity was pursued, Smith's result did not go unnoticed. Less than a month later a fellow British scientist, Harry Napier Draper [4], wrote a Letter to the Editor stating, "It is of course impossible not to feel intense interest in the statement which Mr. Willoughby Smith makes. That I have been unable to obtain the same result has doubtless been due to my having worked under conditions different from those existing in Mr. Smith's experiments. My failure has not been one of degree, but has been absolute." This initial confusion in response to Smith's discovery was ultimately determined to be due to differences in the behavior of vitreous, as opposed to crystalline, selenium. It was an early indication of the importance that material properties would play over the years in the development of photoconductive devices.

Smith's basic result, of course, was ultimately corroborated. Today the photoconductivity of selenium plays a key role in the xerographic or copying process, which was first invented in 1938 [5]. A copying machine uses a xerographic drum (from the Greek *xeros* and *graphos*, meaning dry writing), which is a metal cylinder coated with a layer of photoconductive material. It makes use of the very property that initially bedeviled Smith. When parts of the drum are exposed to light, the selenium becomes conducting and loses an initial charge placed upon it. Dark areas retain the charge and the positively charged image remains on the selenium surface. The negatively charged toner is attracted to the positive regions and the image is finally transferred to paper. The initial photoconductor material, therefore, is still in use today, despite some concerns about its disposal and environmental effects.

Ionic materials and semimetals were the primary focus of the earliest studies of photosensitive and photoconductive materials. Today insulators and semimetals define the upper and lower limits for semiconductors, which now dominate the field of photoconductive devices. Semiconductors are generally defined to be materials with bandgaps ranging from 0 to 3.5 eV, though the high-energy limit between semiconductors and insulators is purely a matter of definition.

One can define insulators, such as ceramics, as materials in which ionic conductivity is the dominant conduction mechanism, as opposed to conduction by free charge (i.e., electrons and holes in semiconductors). However, it is also common to refer to a covalent elemental material such as diamond, with a bandgap of 5.5 eV, as an insulator, as its bandgap is so much greater than the 25 meV of thermal energy available at room temperature. In this case, an insulator is being defined as a material that conducts a minimal amount of current at a given temperature. In both types of materials, however, conduction in the absence of light is thermally activated, affecting either the mobility of ions in ionic materials or the generation of charge in semiconductors. The large bandgap limit for practical semiconductors is being consistently extended as a result of the growing interest in the electrical and optical properties of materials such as GaN, with a roomtemperature bandgap of 3.4 eV.

Traditional semiconductors encompass the purely covalent materials (Si and Ge) as well as mixed ionic-covalent solids such as gallium arsenide, indium antimonide, cadmium sulfide, lead telluride, and mercury cadmium telluride. It is interesting that photoconductivity was discovered in a semimetal, initially studied most extensively in wide bandgap materials of both covalent (diamond) and partially ionic (e.g., ZnS) character, and now applied across the spectrum from semimetal to insulator. The common feature is not the size of the bandgap of the material, but rather the response of the material to light—the interaction with photons to produce a conductivity change.

In addition to offering new means of collecting images, the photoconductive coupling of optical and electrical response also provided the mechanism that would become the basis of a wide range of optical detectors. Semiconductor photoconductivity, as an extension of photosensitivity, would allow for the manipulation and optimization of signals far beyond what could be achieved with film. In addition, photoconductivity became an important characterization tool for study of the semiconductor materials themselves.

Semiconductor materials are now the most common medium with which to detect photons over a wide range of the electromagnetic spectrum, from the submillimeter and far-infrared (FIR) to the highest energy gamma (γ) rays. Semiconductors serve as primary transducers between optical and electrical signals, allowing the subsequent amplification, averaging, and electronic storage of spectra and images. The use of semiconductor materials as radiation detectors far predates their use in now much more ubiquitous and famous electrical devices.

Optical detectors can be divided into three categories: 1) photon detectors (such as photoconductors and photodiodes) that form an electrical signal directly from the interaction with individual photons; 2) thermal detectors (such as bolometers and pyroelectric detectors), which respond to temperature changes of the material; and 3) coherent detectors (heterodyne mixers) that operate on the interaction of the electric field of the incident radiation with a local oscillator. Semiconductor materials are used in all three categories. A text by G. H. Rieke [6] entitled *Detection of Light* provides an excellent overview of all types of light detectors, from the ultraviolet to the submillimeter range.

Readers should be aware of a number of classic books on the topic of photoconductivity. While parts of them no longer represent a current understanding of or research priorities for the area of semiconductor photoconductors, they serve as important sources of the history and development of the field. In many cases, one finds that major work in a given area was done, only to be lost or neglected, as topics changed and old problems reasserted themselves in new form or in new materials. Perhaps the greatest change since the earliest studies has been the remarkable increase in the quality, both crystalline and chemical, of semiconductor materials now available, and the wealth of characterization tools that can be applied. Early work focused on polycrystalline, large bandgap materials. Today, single crystals are the norm and photoconductors, as already discussed, are fabricated across the bandgap spectrum.

The first major text, *Lichtelektrische Erscheinungen*, was published by B. Gudden [7] in 1928 and focused on work from Smith's initial discovery in selenium through the first extensive experiments with diamond and zinc sulfide that established photoconductivity as a quantum effect. Trevor Moss [8] followed in 1952 with *Photoconductivity in the Elements*, which contained a survey of photoconductivity in a range of nonmetallic elements. Richard Bube's 1960 text *Photoconductivity in Solids* was able to draw more heavily on the modern theory of solids that developed during the 1950s and 1960s and the major strides in high quality Si and Ge semiconductors that occurred after World War II [9]. Albert Rose, a major contributor to the photoconductivity literature, published *Concepts in Photoconductivity and Allied Problems* in 1963 and revised it in 1978 [10]. Marfaing reviewed the basic physics of photoconductivity in *Handbook of Semiconductors* in 1981 [11].

Recent books are less common, since much of the fundamental physics was well understood by the 1970s and emphasis in the field had shifted to new developments in device design. *Photoconductivity: Art, Science and Application*, by N. V. Joshi in 1990 [12], focuses on the physics of several aspects of photoconductivity, including transient behavior, band structure effects, and noise. His survey of photodetectors includes both photoconductive and photodiode devices. Over time, photoconductors have been increasingly supplanted for many applications by photodiodes and other more sophisticated devices for both collecting and processing charge.

This chapter will focus on semiconductor materials and devices used as photoconductors in the range from the visible to the far infrared. We will review the relevant semiconductor physics, survey the status of the most common types of photoconductors today, and describe recent advances in device design. As we will see, the line between conventional photoconductors and other device structures has blurred, as novel structures and hybrid devices are created. Emphasis will be placed upon the physics (photon absorption and carrier transport) and the materials that are important in modern photoconductors, rather than on device and performance specifications. This reflects both the author's interests as well as the fact that the latter topics are highly dependent on individual applications.

While the total amount of both historical and new research utilizing photoconductivity in the variety of different materials and device designs is overwhelming, certain types of photoconductors have become dominant in commercial and scientific application. This chapter will strive to help the reader appreciate what types of devices are most commonly used and why. The chapter will focus primarily on photoconductors, defined as photon detectors that depend upon conductivity changes in response to light to create a current or voltage modulation in a device. Although they may be operated with either constant voltage or constant current bias, photoconductors require the application of an external electric field to produce a current. They generally have two similar contacts and depend upon bulk changes in material properties.

A word of caution should be offered about the descriptions for wavelength ranges of response of various detectors. Much detector work has focused on the infrared part of the spectrum, due to interests in thermal imaging in defense and astronomy, as well as fiber-optic communication. Earth's atmosphere absorbs in parts of the infrared, while "windows" exist at wavelengths of 3–5 and 8–12 μ m that have allowed for use of infrared light for remote sensing. The community interested in these applications has developed terms for wavelength ranges that one often encounters in the literature. The most common of these refer to the 1–3 μ m range as the short wavelength infrared (SWIR), 3–5 μ m as the mid-infrared (MWIR), 8–12 μ m as the long wavelength infrared (LWIR), and 12 μ m as the very long infrared (VLWIR). For the astronomy community, however, which is another important user of infrared (IR) detectors, the wavelengths of interest extend to hundreds of microns, and a detector operating at 8 μ m would not necessarily be considered long wavelength. For this reason, we will attempt to avoid use of these generalized terms and give actual wavelength ranges as required.

The first requirement for any photoconductor is the absorption of a photon. The chapter will begin, therefore, with a general survey of the full range of photon absorption mechanisms in semiconductors. Photoconductors utilize only a fraction of these, but an understanding of the full range of photon-semiconductor interactions is important to understanding the distinction between photoconductors and the much wider family of semiconductor detectors for electromagnetic radiation to which they belong.

2. MECHANISMS OF PHOTON ABSORPTION

Figure 1.1 gives a schematic overview of the types of semiconductor detectors used to cover virtually the entire range of the electromagnetic spectrum. From the large volume Ge diodes used by the high-energy physics community for gamma ray (γ -ray) detection to the micron-scale semiconductor bolometers used by astrophysicists to measure the cosmic microwave background, semiconductor detectors span over ten orders of magnitude in photon energy. Photoconductors are used primarily in the middle part of this spectrum, from the ultraviolet and visible parts of the spectrum with ambient temperature intrinsic devices to wavelengths of ~200–300 µm with liquid helium-cooled extrinsic photoconductors.

The absorption of light in a material, neglecting for the moment reflection effects at front and back surfaces, is described by Lambert's law

$$I(\lambda) = I_o(\lambda)e^{-\alpha(\lambda)x}$$

where *I* is the transmitted light intensity, I_o is the initial light intensity, λ is the wavelength, *x* is the optical path length in the material and α is the linear absorption coefficient, the material parameter of interest. The linear absorption coefficient has units of inverse length, most commonly expressed as cm⁻¹. It is related to the extinction coefficient *k* (defined by $\varepsilon = (n + ik)^2$, where ε is the dielec-



FIGURE 1.1 Overview of semiconductor detectors for electromagnetic radiation.

tric constant and n and k are the index of refraction and extinction coefficient, respectively) as

$$\alpha = \frac{4\pi k}{\lambda}$$

so that a large value for the absorption coefficient indicates a strong interaction with the solid at a particular wavelength and a short penetration depth of the light into the material.

A photoconductor depends upon having an absorption process with sufficient α at the wavelength of interest to convert the light into an electrical signal. The ab-

sorption coefficient of a given semiconductor over the electromagnetic spectrum will depend both upon the semiconductor itself (intrinsic or host material properties) and the nature and concentration of impurity atoms and structural defects. Semiconductors exhibit a wide range of interactions with photons that can include photoelectric emission, band-to-band transitions, subband transitions as well as interactions with impurities, the lattice, or free carriers in the material.

A single semiconductor material, properly optimized, can provide state-of-theart detection capability over many orders of magnitude. Silicon, the materials basis of the electronics industry, is a key component for optical detectors as well. It is the basis of X-ray detectors, the widely used charge coupled device (CCD) and some extrinsic photoconductors for infrared detection, including the solid state photomultiplier (SSPM), with optical response to $\sim 40 \ \mu m$. Similarly, Ge is used for high-energy γ -ray detectors, photodiodes in the near-infrared, as well as photoconductors and bolometers that detect in the far-infrared and millimeter range. Gallium arsenide is used to produce ultrafast photoconductive switches at various laser wavelengths and is being developed both for γ -ray and far-infrared detectors. Similar examples could be cited in many other III-V and II-VI compounds to demonstrate the wide range of interactions between photons and semiconductors that make possible such versatility in the application of a single type of material. This range of fundamental photon interactions in combination with a high degree of material control is what gives semiconductors their dominant role as optical sensors.

To illustrate this point, consider a piece of high purity Ge, with a bandgap of 0.67 eV at 300 K and a net acceptor doping $(N_A - N_D)$ of $\sim 10^{10}$ cm⁻³. This material represents the state-of-the-art in high-purity crystal growth because Ge, with its moderate melting temperature (937°C) and favorable segregation coefficient for common electrically active impurities (e.g., P, As, Al), is the semiconductor that can be most easily purified. A residual doping level of 10^{10} cm⁻³ impurities in Ge translates to roughly one electrically active impurity atom in a trillion Ge atoms (i.e., $10^{10}/10^{22} \sim 1/10^{12}$). The achievable purities of other semiconductors, though not quite as extreme, are still impressive. Silicon can be purified to residual doping levels of $\sim 10^{12}$ cm⁻³ and GaAs to $\sim 10^{12}-10^{13}$ cm⁻³.

As with their electronic properties, it is the ability to have such a high degree of control of the starting material that allows one to then optimize a specific material for a given optical absorption mechanism. The material ultimately used for germanium high-energy detectors is quite different from that utilized for far-infrared photoconductors. In each case, however, the ability to control the concentration and types of dopant impurities to the levels previously described is what gives rise to optimized detector performance. In the next sections, we will survey the absorption mechanisms in semiconductors, beginning with very high-energy radiation and extending to the millimeter wave range.

2.1. INTERACTION WITH HIGH-ENERGY RADIATION

Figure 1.2 is a composite plot of the absorption coefficient for Ge and Si from the γ -ray region down to the fundamental absorption edge in the near infrared. Data have been compiled from several sources [13–15] in order to provide an overview of photon absorption over approximately eight orders of magnitude. A plot over this range of energies is dominated by intrinsic absorption, or absorption that is due to the Si electronic structure alone. Although different processes are dominant as the initial absorption mechanism over this range, the common result of the semiconductor-photon interaction is the production of free charge in the material.

The absorption of very high-energy radiation (e.g., γ and X-rays) is required in semiconductor detectors for a variety of scientific, astronomical, environmental, national security and medical applications [14]. Radiation detectors, as the higher energy detectors are commonly known, can detect electrons, protons, alpha particles and other ions, in addition to high-energy photons. They are often used not only to detect the presence of radiation but also to provide spectroscopy (i.e., measure the energy) for the incoming photon or particle. The range of energies is quite broad, ranging from soft X-rays to GeV-heavy ions.

In the interaction with high-energy radiation, three processes are initially dominant in semiconductors. All three convert photons into electrons or an electronpositron pair, which then produce the electron/hole pairs that create the electrical signal. These processes are: 1) the photoelectric effect (absorption of a photon to release an electron); 2) the Compton effect (scattering of a photon off an electron to produce a higher energy electron and a lower energy photon); and 3) pair production (creation of an electron-positron pair at energies in >1.02 MeV). Figure 1.3 shows these three processes schematically.



FIGURE 1.2 Linear absorption coefficient for Ge and Si as a function of photon energy.



FIGURE 1.3 Schematic illustration of the three primary mechanisms for high-energy photon absorption.

In practice, a γ -ray or X-ray spectrum in a detector will exhibit a combination of all three of the interaction processes described in Figure 1.3. The incoming energy is ultimately dissipated in the production of phonons and an ionization shower to produce electron-hole pairs. The probability for the photoelectric interaction of a photon and an electron is proportional to the atomic number Z of the detector material to the fifth power, $\alpha \sim Z^5$. This explains why higher Z materials, such as Ge, CdTe, CdZnTe, or HgI₂ are used for γ -ray applications. Silicon, with its excellent electronic and charge processing properties, has remained the dominant material for the X-ray region, where the absorption coefficient is higher. Detectors for energy dispersive X-ray (EDX) for chemical analysis on scanning electron microscopes are generally Si devices.

It is common to express the generation factor (the number of electron-hole pairs generated per incident electron or photon) as

$$G = E_b(1-\gamma)/E_i$$

where E_b is the electron or photon energy, γ is the fraction loss to backscattered electrons at the surface and E_i is the average energy required for the formation of an electron hole pair. For energies in the keV and higher range, the average ionization energy E_i can be related to the bandgap of the semiconductor E_g by

$$E_i = 2.8E_g + M$$

where M is a constant between 0 and 1 eV, depending on the material [16]. It is interesting to note that, for these energies, the dependence is linear with respect to the bandgap of the material and *independent of the beam energy and the type of radiation*. This is true throughout the X-ray and γ -ray regions and is due primarily to the nature of the phonon dissipation processes involved.

In many high-energy radiation detectors (e.g., in germanium and silicon detectors for spectroscopy), the charge that is generated is collected by the electric field in the depletion region of a reverse biased p-n junction. The high purity of the material allows for very large depletion widths (on the order of cm). This is