Silicon-Based Materials and Devices

Silicon-Based Materials and Devices

Volume 2

Properties and Devices

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

ACADEMIC PRESS
A Harcourt Science and Technology Company

San Diego San Francisco New York Boston
London Sydney Tokyo

This book is printed on acid-free paper. ♾

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: 00-108486

International Standard Book Number (Set): 0-12-513909-8
International Standard Book Number (Vol. 1): 0-12-513918-7
International Standard Book Number (Vol. 2): 0-12-513919-5

Printed in the United States of America
01 02 03 04 05 QW 9 8 7 6 5 4 3 2 1

To my brothers,

Jagmer Singh
and
Ranvir Singh Chaudhary

CONTENTS

Preface xi
About the Editor xiii
List of Contributors xv

Chapter 1. OPTICAL ABSORPTION, LUMINESCENCE, AND ESR SPECTRAL PROPERTIES OF POINT DEFECTS IN SILICA
M. Leone, S. Agnello, R. Boscaino, M. Cannas, and F. M. Gelardi

1. Introduction 2
2. Optical and ESR Activity of Oxygen-Deficient Centers in Silica 2
   2.1. Introduction 2
   2.2. Oxygen-Deficient Centers 3
   2.3. E′ Center: ESR and Optical Properties 4
   2.4. The Absorption Band B_2 and Related Emissions 4
   2.5. The Absorption Band E 6
   2.6. Summary 7
3. Optical and ESR Spectroscopy of Point Defects 7
   3.1. Introduction 7
   3.2. Electronic States of a Point Defect 8
   3.3. Optical Absorption Spectroscopy 9
   3.4. Luminescence Spectroscopy 12
   3.5. ESR Spectroscopy 13
4. Experimental Methods 15
   4.1. Introduction 15
   4.2. Samples and γ-radiation 15
   4.3. Experimental Techniques 16
5. Optical Activity in Natural Silica 19
   5.1. The 3.1 and 4.2 eV PL Bands Under UV Excitation 19
   5.2. Excitation of 3.1 eV and 4.2 eV PL Bands in Vacuum-UV Spectral Region 24
   5.3. Discussion 26
6. The Effects of γ Irradiation on the Optical and ESR Activity 26
   6.1. The Intrinsic and γ-Induced Optical Activity: A_I and A_R 26
   6.2. Relations between the 4.4 eV Emission and the OA Band E: A_T Activity 31
   6.3. Effects of the γ Irradiation on the Optical Activity B and Relation with ESR Structures 35
   6.4. γ Induced E′ Centers: ESR and Optical Activity 38
7. Effects of the Local Environment on the Optical Properties of Luminescent Centers 39
   7.1. Local Dynamic Properties 39
   7.2. The Effect of Conformational Disorder on the Photoluminescence Activity of Vitreous Systems 43
8. Conclusions 46
   8.1. Summary 46
   8.2. Future Aspects 48
   Acknowledgments 48
   References 48

Chapter 2. THE REFRACTIVE INDEX OF SILICA GLASS AND ITS DEPENDENCE ON PRESSURE, TEMPERATURE, AND THE WAVELENGTH OF THE INCIDENT LIGHT
C. Z. Tan and J. Arndt

1. Introduction . . . 51
2. Theories . . . 53
   2.1. Electric Potential Energy of the Incident Light and the Hamiltonian of the Induced Oscillators in Nonabsorbing Isotropic Dielectrics . . . 53
   2.2. The Mean Polarizability and Density of Glasses . . . 56
   2.3. Temperature Dependence of Refractive Index of Glassy SiO_2 in the Ultraviolet and Visible Regions . . . 60
3. Experiments . . . 63
   3.1. Optical Properties of Densified Silica Glasses . . . 63
   3.2. Determination of Refractive Index of Glassy SiO_2 for Infrared Wavelengths by IR Spectroscopy . . . 68
   3.3. Optical Phase Change on Reflection at v-SiO_2–Sn Interface . . . 72
   3.4. Optical Interference and Refractive Index of Silica in the Infrared Absorption Region . . . 74
   3.5. Temperature Dependence of Refractive Index of Glassy SiO_2 in the Infrared Wavelength Region . . . 77
   3.6. Temperature-Dependent Optical Depolarization in Glassy SiO_2 . . . 80
4. Implications . . . 82
   4.1. Faraday Effect in Glassy SiO_2 . . . 82
   4.2. Measurement of Piezoelectricity in Quartz and Electrostriction in SiO_2 Glass by Interferometric Method . . . 85
5. Summary . . . 89
   References . . . 90

Chapter 3. STRUCTURES AND PROPERTIES OF AMORPHOUS SILICON DIOXIDE—ISSUES ON THE RELIABILITY AND NOVEL APPLICATIONS
Hiroyuki Nishikawa

1. Introduction . . . 93
   1.1 Basic Properties of a-SiO_2 . . . 94
   1.2 Properties of a-SiO_2 . . . 96
2. Characterization Techniques of Defects in SiO_2 . . . 97
   2.1 Optical Characterization Techniques . . . 97
   2.2 ESR and Related Techniques . . . 100
   2.3 Computational Approaches . . . 102
3. Reliability Issues . . . 103
   3.1 Defects and Formation Reactions in a-SiO_2 . . . 103
   3.2 Optical Applications . . . 105
   3.3 Electronic Applications . . . 110
4. Novel Applications of a-SiO_2 . . . 113
   4.1 Fiber Gratings . . . 114
   4.2 Second Harmonic Generation (SHG) . . . 116
   4.3 Three-Dimensional (3D) Optical Memory . . . 116
   4.4 Silicon Nanostructures in SiO_2 . . . 117
5. Summary . . . 117
   Acknowledgment . . . 118
   References . . . 118

Chapter 4. POROUS SILICON MICROCAVITIES
Claudio Vinegoni, Massimo Cazzanelli, and L. Pavesi

1. Introduction . . . 124
2. Porous Silicon . . . 125
   2.1. Fabrication of Porous Silicon . . . 125
   2.2. Structure of Porous Silicon . . . 130

2.3. Chemical Properties of Porous Silicon 137
2.4. Optical Properties 141
2.5. Luminescence in Porous Silicon 143
3. Dielectric Multilayers 146
3.1. Thin Slab 147
3.2. Bragg Reflectors 148
3.3. Fabry-Perot Interference Filters 149
4. Semiconductor Microcavities 151
4.1. Weak Coupling Mode 152
4.2. Strong Coupling Mode 152
5. Porous Silicon Multilayers 153
5.1. Producing Porous Silicon Multilayers 155
5.2. Bragg Reflectors 158
5.3. Random Bragg Reflectors 159
5.4. Fabry-Perot Filters 161
5.5. Random Fabry-Perot Filters 162
6. Porous Silicon Microcavities 164
6.1. Physical Properties 164
6.2. Aging Effects in Porous Silicon Microcavities 167
6.3. Simulation of the Optical Properties of Porous Silicon Microcavities 168
6.4. Time-Resolved Spectroscopy in Porous Silicon Microcavities 169
6.5. Temperature Dependence of Porous Silicon Microcavities 175
6.6. Coupled Porous Silicon Microcavities 178
7. Applications of Porous Silicon Multilayers and Microcavities 182
7.1. Waveguides 182
7.2. Enhancement of Weak Absorption Signals 183
7.3. Optical Nonlinearities 183
7.4. Resonant Cavity Light-Emitting Diodes 183
7.5. Optical Sensor 185
7.6. Color-Sensitive Photodiodes 185
7.7. Metal–Porous Silicon Microcavities 186
8. Conclusions 187
Acknowledgments 188
References 188

Chapter 5. POLYCRYSTALLINE SILICON BASED THIN FILM TRANSISTORS FOR INTEGRATED ACTIVE-MATRIX LIQUID-CRYSTAL DISPLAYS
C. A. Dimitriadis

1. Introduction 183
2. Materials for Thin Film Transistors 194
2.1. Polycrystalline Silicon 194
2.2. Structural Properties 196
2.3. Electrical Properties 200
3. Polysilicon Thin Film Transistors 202
3.1. Grain Boundary Trapping States 203
3.2. Threshold Voltage 205
3.3. Field-Effect Mobility 208
3.4. Subthreshold Swing Voltage 209
3.5. Leakage Current 211
4. Reliability of Polysilicon TFTs 213
4.1. Reliability of Low-Temperature Polysilicon TFTs 213
4.2. Reliability of High-Temperature Polysilicon TFTs 216
5. Concluding Remarks and Future Trends 220
References 221

Chapter 6. LIGHT EMISSION IN SILICON
David J. Lockwood

1. Introduction . . . 225
2. Optoelectronics . . . 225
3. Optical Emission in Silicon . . . 226
4. Overcoming the Indirect Band Gap Limitations in Silicon . . . 227
   4.1. Brillouin Zone Folding in Atomic Layer Superlattices . . . 228
   4.2. Band Structure Engineering via Alloying . . . 229
   4.3. Luminescence via Impurity Centers . . . 230
   4.4. Silicon Nanostructures . . . 232
   4.5. Polymers and Molecules Containing Silicon . . . 240
   4.6. Hybrid Methods for Integrating Direct Gap Materials with Silicon . . . 241
5. Prospects For Silicon-Based Optoelectronic Devices . . . 242
   References . . . 243

Chapter 7. ERBIUM IN SILICON AND SILICON-GERMANIUM
J. H. Evans-Freeman and A. R. Peaker

1. Erbium in Silicon and Atomic Luminescence from Erbium . . . 247
   1.1. Historical Perspective . . . 247
   1.2. System Requirements . . . 248
   1.3. Erbium and Luminescence . . . 249
2. Incorporation of Erbium into Silicon and Silicon-Germanium . . . 250
   2.1. Solubility and Diffusivity . . . 250
   2.2. Incorporation by Diffusion and Epitaxy . . . 252
   2.3. Ion Implantation and Regrowth . . . 254
   2.4. Crystal Field Effects, Siting and Complexes . . . 257
   2.5. Erbium in Amorphous and in Porous Silicon . . . 259
3. Electrical Activity of Erbium in Si . . . 260
   3.1. Erbium as a Donor or Acceptor . . . 260
   3.2. Excitation of Erbium Atoms in a Silicon Host . . . 262
   3.3. Temperature Quenching of the Erbium Infra-f-Shell Luminescence . . . 265
   3.4. Luminescence Decay Mechanisms . . . 266
4. Silicon-Based LEDs and Proposed Laser Structures . . . 268
   4.1. Erbium-Doped Silicon LEDs . . . 268
   4.2. Erbium-Doped SiGe–Si Structures as LEDs . . . 270
   4.3. Proposed LASER Cavities . . . 271
   References . . . 272

Index . . . 275

PREFACE

Silicon-Based Materials and Devices is a follow-up to our recently published 10-volume set, *Handbook of Advanced Electronic and Photonic Materials and Devices*. It presents highly coherent coverage of silicon-based materials, namely, those that have been extensively used for applications in electronic and photonic technologies. This extensive reference provides broad coverage of silicon-based materials including different kinds of silicon-related materials, their processing, spectroscopic characterization, physical properties, and device applications. Fourteen chapters review state-of-the-art research on silicon-based materials and their applications to devices.

The details of amorphous silica are summarized by M. Tomozawa, whereas the structures and properties of amorphous silicon dioxide, which are related to the issues of reliability and novel applications, are discussed by H. Nishikawa. F. Giorgis and C. F. Pirri describe the growth, characterization, and physical properties of noncrystalline and nano-structured silicon-based alloys. Silicon carbide is very useful for tribological and structural applications because of its hardness, wide-temperature-range operation, and corrosion resistance. The structural, optical, and electrical properties of amorphous silicon carbide films are discussed by W. K. Choi, and in "Silicon Carbon Nitrides: A New Wideband Gap Material," L. C. Chen and coworkers focus on silicon carbide–related materials. M. Masi, C. Cavallotti, and S. Carra discuss the gas phase and surface kinetics of silicon chemical vapor deposition from silane and chlorosilane.

Three chapters focus on processing and physical properties of silicon; they include "Photonic and Magnetic Properties of Spark-Processed Silicon" by R. E. Hummel; "Wet-Chemical Conditioning of Silicon: Electronic Properties Correlated with the Surface Morphology" by H. Angermann, W. Henrion, and A. Röseler; and "Optical Absorption, Luminescence, and ESR Spectral Properties of Point Defects in Silica" by M. Leone, S. Agnello, R. Boscaino, M. Cannas, and F. M. Gelardi. The effect of pressure, temperature, and wavelength of the incident light on the refractive index of silica glasses is extensively discussed by C. Z. Tan and J. Arndt.

Besides many other applications, silicon is a key component of today's integrated circuit technology. For example, silicon dioxide has been used extensively as an interlayer dielectric material for microelectronic packaging devices, light-emitting diodes, transistors, optical fiber, endoscopy, and so forth. Four chapters focus on the applications of silicon and its related materials in electronic and photonic devices: "Porous Silicon Microcavities" by C. Vinegoni, M. Cazzanelli, and L. Pavesi; "Polycrystalline Silicon-based Thin Film Transistors for Integrated Active-Matrix Liquid-Crystal Displays" by C. A. Dimitriadis; "Light Emission in Silicon" by D. J. Lockwood; and "Erbium in Silicon and Silicon-Germanium" by A. R. Peaker and J. H. Evans-Freeman.

This book covers a broad spectrum of the silicon-based materials and their device applications. Many industries around the world are engaged in silicon-based technology for the new millennium. The applications of silicon and silicon-based materials in present microelectronics and communication technology have been extensively discussed. This reference should be a valuable resource to scientists, graduate and upper level graduate students working in solid state physics, materials science, chemistry, electrical and electronic engineering, optical engineering, microelectronics, data storage, information technology, and semiconductor industries.

Both the editor and the publisher are very grateful to the authors of this project for their outstanding contributions.

Hari Singh Nalwa
Los Angeles

ABOUT THE EDITOR

Dr. H. S. Nalwa is the Managing Director of the Stanford Scientific Corporation, Los Angeles, California. 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 more than 150 scientific articles and 18 patents on electronic and photonic materials and devices. He has edited the following books: *Ferroelectric Polymers* (Marcel Dekker, 1995), *Nonlinear Optics of Organic Molecules and Polymers* (CRC Press, 1997), *Organic Electroluminescent Materials and Devices* (Gordon & Breach, 1997), *Handbook of Organic Conductive Molecules and Polymers*, Vol. 1–4 (John Wiley & Sons, 1997), *Low and High Dielectric Constant Materials* Vol. 1–2 (Academic Press, 1999), *Handbook of Nanostructured Materials and Nanotechnology*, Vol. 1–5 (Academic Press, 1999), *Handbook of Advanced Electronic and Photonic Materials and Devices*, Vol. 1–10 (Academic Press, 2000), *Advanced Functional Molecules and Polymers*, Vol. 1–4 (Gordon & Breach, 2001), *Photodetectors and Fiber Optics* (Academic Press, 2001), *Supramolecular Photosensitive and Electroactive Materials* (Academic Press, 2001), *Nanostructured Materials and Nanotechnology* (Academic Press, 2001), *Handbook of Thin Film Materials*, Vol. 1–5 (Academic Press, 2001), and *Handbook of Surfaces and Interfaces of Materials*, Vol. 1–5 (Academic Press, 2001). The *Handbook of Nanostructured Materials and Nanotechnology* (Vol. 1–5) edited by him received the 1999 Award of Excellence from the Association of American Publishers.

Dr. Nalwa serves on the editorial board of the *Journal of Macromolecular Science-Physics, Applied Organometallic Chemistry* (1993–1999), *International Journal of Photoenergy*, and *Photonics Science News*. He was the founder and Editor-in-Chief of the *Journal of Porphyrins and Phthalocyanines* published by John Wiley & Sons (1997–2000). Dr. Nalwa is a member of the American Chemical Society (ACS), American Physical Society (APS), Materials Research Society (MRS), Electrochemical Society (ECS), and the American Association for the Advancement of Science (AAAS). Dr. Nalwa has been cited in the *Dictionary of International Biography, Who's Who in Science and Engineering, Who's Who in America*, and *Who's Who in the World*.

LIST OF CONTRIBUTORS

Numbers in parenthesis indicate the pages on which the author's contribution begins.

S. AGNELLO (1)
Istituto Nazionale di Fisica della Materia and Department of Physical and Astronomical Sciences, University of Palermo, Palermo, Italy

J. ARNDT (51)
Institut für Mineralogie, Freie Universität Berlin, Berlin, Germany

R. BOSCAINO (1)
Istituto Nazionale di Fisica della Materia and Department of Physical and Astronomical Sciences, University of Palermo, Palermo, Italy

M. CANNAS (1)
Istituto Nazionale di Fisica della Materia and Department of Physical and Astronomical Sciences, University of Palermo, Palermo, Italy

CLAUDIO VINEGONI (123)
Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA

DAVID J. LOCKWOOD (225)
Institute for Microstructural Sciences, National Research Council of Canada, Ottawa, Canada

C. A. DIMITRIADIS (193)
Aristotle University of Thessaloniki, Department of Physics, Thessaloniki, Greece

J. H. EVANS-FREEMAN (247)
Centre for Electronic Materials, Department of Electrical Engineering and Electronics, University of Manchester Institute of Science and Technology, Manchester, M60 1QD, UK

F.M. GELARDI (1)
Istituto Nazionale di Fisica della Materia and Department of Physical and Astronomical Sciences, University of Palermo, Palermo, Italy

HIROYUKI NISHIKAWA (93)
Department of Electrical Engineering, Tokyo Metropolitan Shibaura Institute of Technology, 3-9-1t Shibaura, Minato-Ku, Tokyo 108-8548, Japan

M. LEONE (1)
Istituto Nazionale di Fisica della Materia and Department of Physical and Astronomical Sciences, University of Palermo, Palermo, Italy

MASSIMO CAZZANELLI (123)
Department of Physics, Trinity College, Dublin, Ireland

L. PAVESI (123)
INFM and Dipartimento di Fisica, Università di Trento, Trento, Italy

A. R. PEAKER (247)
Center for Electronic Materials and Department of Electrical Engineering and Electronics, UMIST, Manchester, United Kingdom

C. Z. TAN (51)
Institut für Mineralogie, Freie Universität Berlin, Berlin, Germany