

ACADEMIC PRESS HANDBOOK SERIES

Handbook of Optical Constants of Solids

Edited by

EDWARD D. PALIK

Handbook of Optical Constants of Solids

Edited by

EDWARD D. PALIK

Naval Research Laboratory
Washington, D.C.

1985



ACADEMIC PRESS, INC.

(Harcourt Brace Jovanovich, Publishers)

Orlando San Diego New York London

Toronto Montreal Sydney Tokyo

COPYRIGHT © 1985, BY ACADEMIC PRESS, INC.
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.

ACADEMIC PRESS, INC.
Orlando, Florida 32887

United Kingdom Edition published by
ACADEMIC PRESS INC. (LONDON) LTD.
24-28 Oval Road, London NW1 7DX

Library of Congress Cataloging in Publication Data

Main entry under title:

Handbook of optical constants of solids.

1. Solids --Optical properties--Handbooks, manuals,
etc. I. Palik, Edward D.
QC176.8.06H36 1985 530.4'1 84-15870
ISBN 0-12-544420-6 (alk. paper)

PRINTED IN THE UNITED STATES OF AMERICA

85 86 87 88

9 8 7 6 5 4 3 2 1

Handbook of Optical Constants of Solids

Academic Press Handbook Series

EDWARD D. PALIK (ed.). Handbook of Optical Constants of Solids,
1985

In preparation

N. P. BANSAL AND R. H. DOREMUS. Handbook of Glass Properties

NORMAN G. EINSRUCH (ed.). VLSI Handbook

K. NARAHARI RAO (ed.). Handbook of Infrared Standards

AKIRA YAMAGUCHI. NMR Spectra and Data Handbook

Before using the tables and figures of the critiques in Part II of this handbook, the reader should refer to the editor's introduction to these materials (Chapter 1, pp. 6–7).

List of Contributors

Numbers in parentheses indicate the pages on which the authors' contributions begin.

- A. ADDAMIANO (597), Naval Research Laboratory, Washington, D.C. 20375
- D. E. ASPNES (89), Bell Communications Research, Inc., Murray Hill, New Jersey 07974
- G. BAUER (517, 535), Institut für Physik, Montanuniversität Leoben, A-8700 Leoben, Austria
- A. BORGHESI (445, 525), Dipartimento di Fisica "A. Volta" and Gruppo Nazionale di Struttura della Materia del CNR, Università di Pavia, Pavia, Italy
- W. J. CHOYKE (587), Westinghouse Research and Development Center, Pittsburgh, Pennsylvania 15235, and University of Pittsburgh, Pittsburgh, Pennsylvania 15260
- DAVID F. EDWARDS* (547, 665), University of California, Los Alamos National Laboratory, Los Alamos, New Mexico 87545
- J. E. ELDRIDGE (775), Department of Physics, University of British Columbia, Vancouver V6T 1W5, British Columbia, Canada
- O. J. GLEMBOCKI (503), Naval Research Laboratory, Washington, D.C. 20375
- G. GUIZZETTI (445, 525), Dipartimento di Fisica "A. Volta" and Gruppo Nazionale di Struttura della Materia del CNR, Università di Pavia, Pavia, Italy
- R. T. HOLM (479, 491), Naval Research Laboratory, Washington, D.C. 20375
- W. R. HUNTER† (69, 275, 675), Naval Research Laboratory, Washington, D.C. 20375
- MITIO INOKUTI (369), Argonne National Laboratory, Argonne, Illinois 60439
- B. JENSEN (169), Department of Physics, Boston University, Boston, Massachusetts 02215
- H. KRENN (517, 535), Institut für Physik, Montanuniversität Leoben, A-8700 Leoben, Austria

* Present address: Lawrence Livermore National Laboratory, Livermore, California 94550.

† Present address: Sachs/Freeman Associates, Inc., Bowie, Maryland 20715.

- DAVID W. LYNCH (189, 275), Department of Physics and Ames Laboratory, U.S. Department of Energy, Iowa State University, Ames, Iowa 50011
- SHASHANKA S. MITRA (213), Department of Electrical Engineering, University of Rhode Island, Kingston, Rhode Island 02881
- EDWARD D. PALIK (3, 409, 429, 479, 587, 597, 675, 695, 703, 775), Naval Research Laboratory, Washington, D.C. 20375
- H. R. PHILIPP (665, 719, 749, 765, 771), General Electric Research and Development Center, Schenectady, New York 12301
- H. PILLER (503, 571), Department of Physics and Astronomy, Louisiana State University, Baton Rouge, Louisiana 70803
- ROY F. POTTER (11, 465), Department of Physics and Astronomy, Western Washington University, Bellingham, Washington 98225
- M. W. RIBARSKY (795), School of Physics, Georgia Institute of Technology, Atlanta, Georgia 30332
- JOSEPH SHAMIR (113), Faculty of Electrical Engineering, Technion — Israel Institute of Technology, Haifa 32000, Israel
- E. SHILES* (369), Argonne National Laboratory, Argonne, Illinois 60439
- GEORGE J. SIMONIS (155), Electronics Research and Development Command, Harry Diamond Laboratories, Adelphi, Maryland 20783
- D. Y. SMITH (35, 369), Argonne National Laboratory, Argonne, Illinois 60439, and Max-Planck-Institut für Festkörperforschung, 7 Stuttgart 80, Federal Republic of Germany
- P. A. TEMPLE (135), Michelson Laboratory, Physics Division, Naval Weapons Center, China Lake, California 93555
- D. J. TREACY (623, 641), Physics Department, U.S. Naval Academy, Annapolis, Maryland 21402

* Present address: Gulf Research and Development Company, Houston, Texas 37048.

Preface

Those of us who do optical experiments have on many occasions needed the optical constants of a specific solid in a specific wavelength region. These numbers are often not readily available, and this situation requires a search in AIP, OSA, and CRC handbooks, as well as in reports never published in archival journals, or a visit to the library to sift through computer printouts of papers selected by key words. Then, once the papers are found, the spectral range presented is often narrow (not the one in which we are interested). I know of only two materials, namely, Si and NaCl, that have been treated in great detail (by H. H. Li), and these have served as models for the present work to some extent.

This handbook was roughed out by an *ad hoc* committee during the May 1980 meeting on the basic optical properties of materials at the National Bureau of Standards. Several colleagues, some of whom later became contributors to this volume, made up the committee, including David W. Lynch, H. E. Bennett, Roy F. Potter, M. Hass, and W. R. Hunter, as well as E. V. Cohen of Academic Press. The intent was to present as many materials as feasible over the widest possible spectral range with some discrimination, so that only a single set of numbers would be presented. Also, brief mention was to be made of the experimental technique, sample characterization, and accuracy and precision of the data (if available).

As completed, this handbook enlists the aid of 11 chapter contributors who summarize methods for the determination of the index of refraction n and the extinction coefficient k in various spectral regions (Chapters 1–9) and the absorption mechanisms in solids (Chapters 10 and 11). Significant time was spent on the film-on-a-substrate type of sample, which is so prevalent today in the areas of antireflection and reflection coatings, metals and insulators on semiconductors, multiple semiconductor layers, and deposited and epitaxial films on substrates in general. In addition, 21 contributors have read the published papers on the optical properties of 37 solids of scientific and technological interest and provided critiques. They have extracted from these papers what they feel is the best set of single values of n and k in the spectral range from x rays to millimeter waves and have produced detailed numerical tables and coarse graphs of these data. The original references are also provided should further detail be needed.

These data will be of interest to (1) those optical researchers who spend

their careers working with one material or a class of materials (metals, semiconductors, insulators), (2) those who are interested in optical properties in general, (3) those who are interested in the film on a substrate or multilayer thin films, and (4) those college professors who teach optics. For the teacher, the bird's-eye view of optical properties over the wide spectral range afforded by the graphs and data serves as a good introduction to understanding a wide variety of absorption and dispersion processes and, consequently, optical properties.

As editor, I have had the usual problems of getting results from 27 different scientists in a timely manner. I thank them for their efforts, from which I have learned a lot of optical physics. In addition, I thank Donna D. Strasburg and Dinah W. Smith for their secretarial help.

November 1984

EDWARD D. PALIK

Contents

List of Contributors	xv
Preface	xvii
Part I DETERMINATION OF OPTICAL CONSTANTS	
Chapter 1	Introductory Remarks 3
	EDWARD D. PALIK
	I. Introduction 3
	II. The Chapters 4
	III. The Critiques 5
	IV. The Tables 6
	V. The Figures of the Tables 7
	VI. General Remarks 8
	References 9
Chapter 2	Basic Parameters for Measuring Optical Properties 11
	ROY F. POTTER
	I. Introduction 11
	II. Intrinsic Material Parameters in Terms of Optical Constants 16
	III. Reflectance, Transmittance, and Absorptance of Layered Structures 18
	IV. The General Lamelliform — Phase Coherency Throughout 19
	V. The General Lamelliform — Phase Incoherency in Substrate 21
	VI. Summary 24
Appendix A.	Basic Formulas for Fresnel Coefficients 24
Appendix B.	General Formulas for the Case of a Parallel-Sided Slab 25
Appendix C.	Reflectance, R_{jk} at $j-k$ Interface 26
Appendix D.	Reflectance of Single Layer on Each Side of a Slab and Single Layer on Either Side of a Slab 26
Appendix E.	Critical Angle of Incidence 30
	Definition of Terms 33
	References 34
Chapter 3	Dispersion Theory, Sum Rules, and Their Application to the Analysis of Optical Data 35
	D. Y. SMITH
	I. Introduction 36
	II. Optical Sum Rules and Their Physical Interpretation 36
	vii

III.	Finite-Energy Sum Rules	45
IV.	Sum Rules for Reflection Spectroscopy	51
V.	Analysis of Optical Data and Sum-Rule Applications	55
VI.	Summary	64
	References	64
Chapter 4	Measurement of Optical Constants in the Vacuum Ultraviolet Spectral Region	69
	W. R. HUNTER	
I.	Introduction	69
II.	General Discussion of Reflectance Methods	70
III.	Reflectance Method for Two Media	85
	References	87
Chapter 5	The Accurate Determination of Optical Properties by Ellipsometry	89
	D. E. ASPNES	
I.	Reflection Techniques; Background and Overview	89
II.	Measurement Configurations	92
III.	Accurate Determination of Optical Properties: Overlayer Effects	96
IV.	Living with Overlayers	99
V.	Eliminating Overlayers	102
VI.	Bulk and Thin-Film Effects; Effective-Medium Theory	104
VII.	Conclusion	108
	References	110
Chapter 6	Interferometric Methods for the Determination of Thin-Film Parameters	113
	JOSEPH SHAMIR	
I.	Introduction	113
II.	Basic Principles	114
III.	Nonlaser Interferometers	117
IV.	Kösters-Prism Interferometers	123
V.	A Self-Calibrating Method	126
VI.	Surface Effects	131
VII.	Conclusions	132
	References	133
Chapter 7	Thin-Film Absorptance Measurements Using Laser Calorimetry	135
	P. A. TEMPLE	
I.	Introduction	135
II.	Single-Layer Films	138
III.	Wedged-Film Laser Calorimetry	139
IV.	Electric-Field Considerations in Laser Calorimetry	143
V.	Entrance versus Exit Surface Films	147

VI.	Experimental Determination of α_f , a_{af} , and a_{fs}	149
	References	153
Chapter 8	Complex Index of Refraction Measurements at Near-Millimeter Wavelengths	155
	GEORGE J. SIMONIS	
I.	Introduction	155
II.	Fourier Transform Spectroscopy	156
III.	Free-Space Resonant Cavity	161
IV.	Mach-Zehnder Interferometer	163
V.	Direct Birefringence Measurement	164
VI.	Overmoded Nonresonant Cavity	165
VII.	Crystal Quartz as Index Reference	165
VIII.	Conclusion	167
	References	167
Chapter 9	The Quantum Extension of the Drude-Zener Theory in Polar Semiconductors	169
	B. JENSEN	
I.	Introduction	169
II.	Quantum Theory of Free-Carrier Absorption	172
III.	Theoretical Results	174
IV.	Comparison with Experimental Data	176
	Appendix	187
	References	188
Chapter 10	Interband Absorption—Mechanisms and Interpretation	189
	DAVID W. LYNCH	
I.	Introduction	189
II.	One-Electron Model	190
III.	Electron-Hole Interaction, Excitons	198
IV.	Local Field Effects	203
V.	Examples	204
	References	210
	General References	211
Chapter 11	Optical Properties of Nonmetallic Solids for Photon Energies below the Fundamental Band Gap	213
	SHASHANKA S. MITRA	
I.	Introduction	213
II.	Infrared Dispersion by Polar Crystals	215
III.	Kramers-Kronig Dispersion Relations	227
IV.	Determination of Absorption Coefficient in the Intermediate Region	229
V.	Absorption Coefficient in the Transparent Regime	230
VI.	Multiphonon Absorption	232

VII.	Infrared Absorption by Defects and Disorders	254
VIII.	Infrared Dispersion by Plasmons	263
	References	267

Part II CRITIQUES

Subpart 1 Metals

	Comments on the Optical Constants of Metals and an Introduction to the Data for Several Metals	275
	DAVID W. LYNCH AND W. R. HUNTER	

I.	Introduction	275
II.	Anomalous Skin Effect	277
	References	279
III.	Copper (Cu)	280
	References	280
IV.	Gold (Au)	286
	References	287
V.	Iridium (Ir)	296
	References	296
VI.	Molybdenum (Mo)	303
	References	304
VII.	Nickel (Ni)	313
	References	314
VIII.	Osmium (Os)	324
	References	324
IX.	Platinum (Pt)	333
	References	334
X.	Rhodium (Rh)	342
	References	342
XI.	Silver (Ag)	350
	References	351
XII.	Tungsten (W)	357
	References	358

	The Optical Properties of Metallic Aluminum	369
	D. Y. SMITH, E. SHILES, AND MITIO INOKUTI	

I.	General Features	369
II.	Optical Measurements and Sample Conditions	372
III.	Tabulated Data	377
	References	383

Subpart 2 Semiconductors

	Cadmium Telluride (CdTe)	409
	EDWARD D. PALIK	
	References	413

Gallium Arsenide (GaAs)	429
EDWARD D. PALIK	
References	432
Gallium Phosphide (GaP)	445
A. BORGHESI AND G. GUIZZETTI	
References	449
Germanium (Ge)	465
ROY F. POTTER	
References	469
Indium Arsenide (InAs)	479
EDWARD D. PALIK AND R. T. HOLM	
References	481
Indium Antimonide (InSb)	491
R. T. HOLM	
References	494
Indium Phosphide (InP)	503
O. J. GLEMBOCKI AND H. PILLER	
References	506
Lead Selenide (PbSe)	517
G. BAUER AND H. KRENN	
References	518
Lead Sulfide (PbS)	525
G. GUIZZETTI AND A. BORGHESI	
References	528
Lead Telluride (PbTe)	535
G. BAUER AND H. KRENN	
References	538
Silicon (Si)	547
DAVID F. EDWARDS	
References	552

Silicon (Amorphous) (α-Si)	571
H. PILLER	
References	573
Silicon Carbide (SiC)	587
W. J. CHOYKE AND EDWARD D. PALIK	
References	589
Zinc Sulfide (ZnS)	597
EDWARD D. PALIK AND A. ADDAMIANO	
References	602
Subpart 3 Insulators	
Arsenic Selenide (As_2Se_3)	623
D. J. TREACY	
References	625
Arsenic Sulfide (As_2S_3)	641
D. J. TREACY	
References	644
Cubic Carbon (Diamond)	665
DAVID F. EDWARDS AND H. R. PHILIPP	
References	668
Lithium Fluoride (LiF)	675
EDWARD D. PALIK AND W. R. HUNTER	
References	678
Lithium Niobate (LiNbO_3)	695
EDWARD D. PALIK	
References	697
Potassium Chloride (KCl)	703
EDWARD D. PALIK	
References	706

Silicon Dioxide (SiO₂), Type α (Crystalline)	719
H. R. PHILIPP	
References	721
Silicon Dioxide (SiO₂) (Glass)	749
H. R. PHILIPP	
References	752
Silicon Monoxide (SiO) (Noncrystalline)	765
H. R. PHILIPP	
References	766
Silicon Nitride (Si₃N₄) (Noncrystalline)	771
H. R. PHILIPP	
References	772
Sodium Chloride (NaCl)	775
J. E. ELDRIDGE AND EDWARD D. PALIK	
References	779
Titanium Dioxide (TiO₂) (Rutile)	795
M. W. RIBARSKY	
References	798