
Springer Handbook of Condensed Matter and Materials Data

Springer Handbook provides a concise compilation of approved key information on methods of research, general principles, and functional relationships in physics and engineering. The world's leading experts in the fields of physics and engineering will be assigned by one or several renowned editors to write the chapters comprising each volume. The content is selected by these experts from Springer sources (books, journals, online content) and other systematic and approved recent publications of physical and technical information.

The volumes will be designed to be useful as readable desk reference book to give a fast and comprehensive overview and easy retrieval of essential reliable key information, including tables, graphs, and bibliographies. References to extensive sources are provided.

Springer Handbook

of Condensed Matter and Materials Data

W. Martienssen and H. Warlimont (Eds.)

With 1025 Figures and 914 Tables



Springer

Professor Werner Martienssen
Universität Frankfurt
Fachbereich 13, Physik
Robert-Mayer-Str. 2–4
60325 Frankfurt
Germany

Professor Hans Warlimont
IWF Dresden
Helmholzstr. 20
01069 Dresden
Germany

Library of Congress Control Number: 2004116537

ISBN 3-540-44376-2
Springer Berlin Heidelberg New York

This work is subject to copyright. All rights reserved, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilm or in any other way, and storage in data banks. Duplication of this publication or parts thereof is permitted only under the provisions of the German Copyright Law of September, 9, 1965, in its current version, and permission for use must always be obtained from Springer. Violations are liable for prosecution under the German Copyright Law.

Springer is a part of Springer Science+Business Media
springeronline.com

©Springer Berlin Heidelberg 2005
Printed in Germany

The use of designations, trademarks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

Product liability: The publisher cannot guarantee the accuracy of any information about dosage and application contained in this book. In every individual case the user must check such information by consulting the relevant literature.

Production and typesetting: LE-TeX GbR, Leipzig
Handbook coordinator: Dr. W. Skolaut, Heidelberg
Typography, layout and illustrations: schreiberVIS, Seeheim
Cover design: eStudio Calamar Steinen, Barcelona
Cover production: *design&production* GmbH, Heidelberg
Printing and binding: Stürtz AG, Würzburg

Printed on acid-free paper
SPIN 10678245 62/3141/ 5 4 3 2 1 0

Preface

The Springer Handbook of Condensed Matter and Materials Data is the realization of a new concept in reference literature, which combines introductory and explanatory texts with a compilation of selected data and functional relationships from the fields of solid-state physics and materials in a single volume. The data have been extracted from various specialized and more comprehensive data sources, in particular the Landolt-Börnstein data collection, as well as more recent publications. This Handbook is designed to be used as a desktop reference book for fast and easy finding of essential information and reliable key data. References to more extensive data sources are provided in each section. The main users of this new Handbook are envisaged to be students, scientists, engineers, and other knowledge-seeking persons interested and engaged in the fields of solid-state sciences and materials technologies.

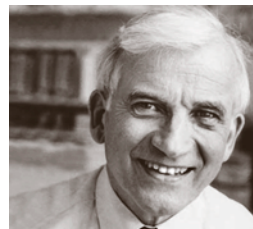
The editors have striven to find authors for the individual sections who were experienced in the full breadth of their subject field and ready to provide succinct accounts in the form of both descriptive text and representative data. It goes without saying that the sections represent the individual approaches of the authors to their subject and their understanding of this task. Accordingly, the sections vary somewhat in character. While some editorial influence was exercised, the flexibility that we have shown is deliberate. The editors are grateful to all of the authors for their readiness to provide a contribution, and to cooperate in delivering their manuscripts and by accepting essentially all alterations which the editors requested to achieve a reasonably coherent presentation.

An onerous task such as this could not have been completed without encouragement and support from the

publisher. Springer has entrusted us with this novel project, and Dr. Hubertus von Riedesel has been a persistent but patient reminder and promoter of our work throughout. Dr. Rainer Poerschke has accompanied and helped the editors constantly with his professional attitude and very personable style during the process of developing the concept, soliciting authors, and dealing with technical matters. In the later stages, Dr. Werner Skolaut became a relentless and hard-working member of our team with his painstaking contribution to technically editing the authors' manuscripts and linking the editors' work with the copy editing and production of the book.

We should also like to thank our families for having graciously tolerated the many hours we have spent in working on this publication.

We hope that the users of this Handbook, whose needs we have tried to anticipate, will find it helpful and informative. In view of the novelty of the approach and any possible inadvertent deficiencies which this first edition may contain, we shall be grateful for any criticisms and suggestions which could help to improve subsequent editions so that they will serve the expectations of the users even better and more completely.



Prof. Werner Martienssen



Prof. Hans Warlimont

September 2004
Frankfurt am Main, Dresden

Werner Martienssen,
Hans Warlimont

List of Authors

Wolf Assmus

Johann Wolfgang Goethe–University
Physics Department
Robert–Mayer–Str. 2 – 4
60054 Frankfurt am Main, Germany
e-mail: assmus@physik.uni-frankfurt.de

Stefan Brühne

Johann Wolfgang Goethe–University
Physics Department
Robert–Mayer–Str. 2 – 4
60054 Frankfurt am Main, Germany
e-mail: bruehne@physik.uni-frankfurt.de

Fabrice Charra

Commissariat à l'Énergie Atomique, Saclay
Département de Recherche sur l'État Condensé,
les Atomes et les Molécules
DRECAM–SPCSI, Centre d'Études de Saclay
91191 Gif-sur-Yvette, France
e-mail: fabrice.charra@cea.fr

Gianfranco Chiarotti

University of Rome "Tor Vergata"
Department of Physics
Via della Ricerca Scientifica 1
00133 Roma, Italy
e-mail: chiarotti@roma2.infn.it

Claus Fischer

Formerly Institute of Solid State and Materials
Research (IFW)
Georg–Schumann–Str. 20
01187 Dresden, Germany
e-mail: A_C.FischerDD@t-online.de

Günter Fuchs

Leibniz Institute for Solid State and Materials
Research (IFW) Dresden
Magnetism and Superconductivity in the Institute
of Metallic Materials
Helmholtzstraße 20
01171 Dresden, Germany
e-mail: fuchs@ifw-dresden.de

Frank Goodwin

International Lead Zinc Research Organization, Inc.
PO BOX 12036
Research Triangle Parc, NC 27709, USA
e-mail: fgoodwin@ilzro.org

Susana Gota–Goldmann

Commissariat à l'Énergie Atomique (CEA)
Direction de la Recherche Technologique (DRT)
Centre de Fontenay aux Roses BP 6
92265 Fontenay aux Roses Cédex, France
e-mail: susana.gota-goldmann@cea.fr

Sivaraman Guruswamy

University of Utah
Metallurgical Engineering
135 South 1460 East RM 412
Salt Lake City, UT 84112–0114, USA
e-mail: sguruswa@mines.utah.edu

Gagik G. Gurzadyan

Technical University of Munich
Institute for Physical and Theoretical Chemistry
Lichtenbergstrasse 4
85748 Garching, Germany
e-mail: gurzadyan@ch.tum.de

Hideki Harada

High Tech Association Ltd.
3730–30 Higashikaya, Fukaya, Saitama, Japan
e-mail: khhb16457@nifty.com

Bernhard Holzapfel

Leibniz Institute for Solid State and Materials
Research Dresden – Institute of Metallic Materials
Superconducting Materials
Helmholtzstr. 20
01069 Dresden, Germany
e-mail: B.Holzapfel@ifw-dresden.de

Karl U. Kainer

GKSS Research Center Geesthacht
Institute for Materials Research
Max-Planck-Str. 1
21502 Geesthacht, Germany
e-mail: karl.kainer@gkss.de

Catrin Kammer

METALL – Intl. Journal for Metallurgy
Kielsche Straße 43B
38642 Goslar, Germany
e-mail: Kammer@metall-news.com

Wolfram Knabl

Plansee AG
Technology Center
6600 Reutte, Austria
e-mail: wolfram.knabl@plansee.com

Alfred Koethe

Leibniz-Institut für Festkörper- und
Werkstoffforschung
Institut für Metallische Werkstoffe (retired)
Lessingstrasse 11
01099 Dresden, Germany
e-mail: alfred.koethe@web.de

Dieter Krause

Schott AG
Research and Technology-Development
PO BOX 2480
55014 Mainz, Germany
e-mail: dieter.krause@schott.com

Manfred D. Lechner

Universität Osnabrück
Institut für Chemie – Physikalische Chemie
Barbarastraße 7
46069 Osnabrück, Germany
e-mail: lechner@uni-osnabrueck.de

Gerhard Leichtfried

Plansee AG
Technology Center
6600 Reutte, Austria
e-mail: gerhard.leichtfried@plansee.com

Werner Martienssen

Universität Frankfurt/Main
Physikalisches Institut
Robert-Mayer-Strasse 2 – 4
60054 Frankfurt/Main, Germany
e-mail: Martienssen@Physik.uni-frankfurt.de

Toshio Mitsui

Osaka University
Nakasuji-Yamate, 3-6-24
665-0875 Takarazuka, Japan
e-mail: t-mitsui@jttk.zaq.ne.jp

Manfred Müller

Dresden University of Technology
Institute of Materials Science
Leubnitzer Straße 26
01069 Dresden, Germany
e-mail: m.mueller33@t-online.de

Sergei Pestov

Moscow State Academy of Fine Chemical
Technology
Department of Inorganic Chemistry
Vernadsky pr., 86
119571 Moscow, Russia
e-mail: pestovsm@yandex.ru

Günther Schlamp

Metallgesellschaft Ffm and Degussa
Demetron (retired)
Stettinerstr. 25
61449 Steinbach/Ts, Germany
e-mail:

Barbara Schüpp-Niewa

Leibniz-Institute for Solid State and Materials
Research Dresden
Institute for Metallic Materials
Helmholtzstraße 20
01069 Dresden, Germany
e-mail: b.schuepp@ifw-dresden.de

Roland Stickler

University of Vienna
Department of Chemistry
Währingerstr. 42
1090 Vienna, Austria
e-mail: roland.stickler@univie.ac.at

Pancho Tzankov

Max Born Institute for Nonlinear Optics
and Short Pulse Spectroscopy

Max-Born-Str. 2A

12489 Berlin, Germany

e-mail: *tzankov@mbi-berlin.de*

Volkmar Vill

University of Hamburg

Department of Chemistry,

Institute of Organic Chemistry

Martin-Luther-King-Platz 6

20146 Hamburg, Germany

e-mail: *vill@chemie.uni-hamburg.de*

Hans Warlimont

DSL Dresden Material-Innovation GmbH

Helmholtzstrasse 20

01069 Dresden, Germany

e-mail: *warlimont@ifw-dresden.de*

Contents

List of Abbreviations	XV
------------------------------------	-----------

Part 1 General Tables

1 The Fundamental Constants

<i>Werner Martienssen</i>	3
1.1 What are the Fundamental Constants and Who Takes Care of Them?	3
1.2 The CODATA Recommended Values of the Fundamental Constants	4
References.....	9

2 The International System of Units (SI), Physical Quantities, and Their Dimensions

<i>Werner Martienssen</i>	11
2.1 The International System of Units (SI)	11
2.2 Physical Quantities	12
2.3 The SI Base Units	13
2.4 The SI Derived Units	16
2.5 Decimal Multiples and Submultiples of SI Units	19
2.6 Units Outside the SI	20
2.7 Some Energy Equivalents	24
References.....	25

3 Rudiments of Crystallography

<i>Wolf Assmus, Stefan Brühne</i>	27
3.1 Crystalline Materials	28
3.2 Disorder	38
3.3 Amorphous Materials	39
3.4 Methods for Investigating Crystallographic Structure	39
References.....	41

Part 2 The Elements

1 The Elements

<i>Werner Martienssen</i>	45
1.1 Introduction	45
1.2 Description of Properties Tabulated	46
1.3 Sources	49
1.4 Tables of the Elements in Different Orders	49
1.5 Data	54
References.....	158

Part 3 Classes of Materials

1 Metals

<i>Frank Goodwin, Sivaraman Guruswamy, Karl U. Kainer, Catrin Kammer, Wolfram Knabl, Alfred Koethe, Gerhard Leichtfried, Günther Schlamp, Roland Stickler, Hans Warlimont</i>	161
1.1 Magnesium and Magnesium Alloys	162
1.2 Aluminium and Aluminium Alloys	171
1.3 Titanium and Titanium Alloys	206
1.4 Zirconium and Zirconium Alloys	217
1.5 Iron and Steels	221
1.6 Cobalt and Cobalt Alloys	272
1.7 Nickel and Nickel Alloys	279
1.8 Copper and Copper Alloys	296
1.9 Refractory Metals and Alloys	303
1.10 Noble Metals and Noble Metal Alloys	329
1.11 Lead and Lead Alloys	407
References	422

2 Ceramics

<i>Hans Warlimont</i>	431
2.1 Traditional Ceramics and Cements	432
2.2 Silicate Ceramics	433
2.3 Refractory Ceramics	437
2.4 Oxide Ceramics	437
2.5 Non-Oxide Ceramics	451
References	476

3 Polymers

<i>Manfred D. Lechner</i>	477
3.1 Structural Units of Polymers	480
3.2 Abbreviations	482
3.3 Tables and Figures	483
References	522

4 Glasses

<i>Dieter Krause</i>	523
4.1 Properties of Glasses – General Comments	526
4.2 Composition and Properties of Glasses	527
4.3 Flat Glass and Hollowware	528
4.4 Technical Specialty Glasses	530
4.5 Optical Glasses	543
4.6 Vitreous Silica	556
4.7 Glass-Ceramics	558
4.8 Glasses for Miscellaneous Applications	559
References	572

Part 4 Functional Materials

1 Semiconductors

<i>Werner Martienssen</i>	575
1.1 Group IV Semiconductors and IV–IV Compounds	578
1.2 III–V Compounds	604
1.3 II–VI Compounds	652
References	691

2 Superconductors

<i>Claus Fischer, Günter Fuchs, Bernhard Holzapfel, Barbara Schüpp-Niewa, Hans Warlimont</i>	695
2.1 Metallic Superconductors	696
2.2 Non–Metallic Superconductors	711
References	749

3 Magnetic Materials

<i>Hideki Harada, Manfred Müller, Hans Warlimont</i>	755
3.1 Basic Magnetic Properties	755
3.2 Soft Magnetic Alloys	758
3.3 Hard Magnetic Alloys	794
3.4 Magnetic Oxides	811
References	814

4 Dielectrics and Electrooptics

<i>Gagik G. Gurzadyan, Pancho Tzankov</i>	817
4.1 Dielectric Materials: Low–Frequency Properties	822
4.2 Optical Materials: High–Frequency Properties	824
4.3 Guidelines for Use of Tables	826
4.4 Tables of Numerical Data for Dielectrics and Electrooptics	828
References	890

5 Ferroelectrics and Antiferroelectrics

<i>Toshio Mitsui</i>	903
5.1 Definition of Ferroelectrics and Antiferroelectrics	903
5.2 Survey of Research on Ferroelectrics	904
5.3 Classification of Ferroelectrics	906
5.4 Physical Properties of 43 Representative Ferroelectrics	912
References	936

Part 5 Special Structures

1 Liquid Crystals

<i>Sergei Pestov, Volkmar Vill</i>	941
1.1 Liquid Crystalline State	941
1.2 Physical Properties of the Most Common Liquid Crystalline Substances	946

1.3	Physical Properties of Some Liquid Crystalline Mixtures	975
	References.....	977
2	The Physics of Solid Surfaces	
	<i>Gianfranco Chiarotti</i>	979
2.1	The Structure of Ideal Surfaces	979
2.2	Surface Reconstruction and Relaxation.....	986
2.3	Electronic Structure of Surfaces	996
2.4	Surface Phonons	1012
2.5	The Space Charge Layer at the Surface of a Semiconductor.....	1020
2.6	Most Frequently Used Acronyms	1026
	References.....	1029
3	Mesoscopic and Nanostructured Materials	
	<i>Fabrice Charra, Susana Gota-Goldmann</i>	1031
3.1	Introduction and Survey	1031
3.2	Electronic Structure and Spectroscopy.....	1035
3.3	Electromagnetic Confinement	1044
3.4	Magnetic Nanostructures	1048
3.5	Preparation Techniques	1063
	References.....	1066
	Acknowledgements	1073
	About the Authors	1075
	Detailed Contents	1081
	Subject Index	1091

List of Abbreviations

2D-BZ 2-dimensional Brillouin zone
2P-PES 2-photon photoemission spectroscopy

A

AES Auger electron spectroscopy
AFM atomic force microscope
AISI American Iron and Steel Institute
APS appearance potential spectroscopy
ARUPS angle-resolved ultraviolet photoemission spectroscopy
ARXPS angle-resolved X-ray photoemission spectroscopy
ASTM American Society for Testing and Materials
ATR attenuated total reflection

B

BBZ bulk Brillouin zone
BIPM Bureau International des Poids et Mesures
BZ Brillouin zone

C

CB conduction band
CBM conduction band minimum
CISS collision ion scattering spectroscopy
CITS current imaging tunneling spectroscopy
CMOS complementary metal–oxide–semiconductor
CODATA Committee on Data for Science and Technology
CVD chemical vapour deposition

D

DFB distributed-feedback
DFG difference frequency generation
DOS density of states
DSC differential scanning calorimetry
DTA differential thermal analysis

E

EB electron-beam melting
ECS electron capture spectroscopy
EELS electron-energy loss spectroscopy
ELEED elastic low-energy electron diffraction
ESD electron-stimulated desorption
EXAFS extended X-ray absorption fine structure

F

FEM field emission microscope/microscopy
FIM field ion microscope/microscopy

G

GMR giant magnetoresistance

H

HAS helium atom scattering
HATOF helium atom time-of-flight spectroscopy
HB Brinell hardness number
HEED high-energy electron diffraction
HEIS high-energy ion scattering/high-energy ion scattering spectroscopy
HK Knoop hardness
HOPG highly oriented pyrolytic graphite
HPDC high-pressure die casting
HR-EELS high-resolution electron energy loss spectroscopy
HR-LEED high-resolution LEED
HR-RHEED high-resolution RHEED
HREELS high-resolution electron energy loss spectroscopy
HRTEM high-resolution transition electron microscopy
HT high temperature
HTSC high-temperature superconductor
HV Vicker's Hardness

I

IACS International Annealed Copper Standard
IB ion bombardment
IBAD ion-beam-assisted deposition
ICISS impact ion scattering spectroscopy
ICSU International Council of the Scientific Unions
IPE inverse photoemission
IPES inverse photoemission spectroscopy
ISO International Organization for Standardization
ISS ion scattering spectroscopy
IUPAC International Union of Pure and Applied Chemistry

J

JDOS joint density of states

K		R	
KRIPES	K-resolved inverse photoelectron spectroscopy	RAS	reflectance anisotropy spectroscopy
L		RE	rare earth
LAPW	linearized augmented-plane-wave method	REM	reflection electron microscope/microscopy
LB	Langmuir–Blodgett	RHEED	reflection high-energy electron diffraction
LCM	liquid crystal material	RIE	reactive ion etching
LCP	liquid crystal polymer	RPA	random-phase approximation
LCs	liquid crystals	RT	room temperature
LDA	local-density approximation	RTP	room temperature and standard pressure
LDOS	local density of states	S	
LEED	low-energy electron diffraction	SAM	self-assembled monolayer
LEIS	low-energy ion scattering/low-energy ion scattering spectroscopy	SAM	scanning Auger microscope/microscopy
LPE	liquid phase epitaxy	SARS	scattering and recoiling ion spectroscopy
M		SAW	surface acoustic wave
MBE	molecular-beam epitaxy	SBZ	surface Brillouin zone
MD	molecular dynamics	SCLS	surface core level shift
MEED	medium-energy electron diffraction	SDR	surface differential reflectivity
MEIS	medium-energy ion scattering/medium-energy ion scattering spectroscopy	SEM	scanning electron microscope
MFM	magnetic force microscopy	SEXAFS	surface-sensitive EXAFS
ML	monolayer	SFG	sum frequency generation
MOCVD	metal-organic chemical vapor deposition	SH	second harmonic
MOKE	magneto-optical Kerr effect	SHG	second-harmonic generation
MOSFET	MOS field-effect transistor	SI	Système International d'Unités
MQW	multiple quantum well	SIMS	secondary-ion mass spectroscopy
N		SNR	signal-to-noise ratio
NICISS	neutral impact collision ion scattering spectroscopy	SPARPES	spin polarized angle-resolved photoemission spectroscopy
NIMs	National Institutes for Metrology	SPIPES	spin-polarized inverse photoemission spectroscopy
O		SPLEED	spin-polarized
OPO	optical parametric oscillation	SPV	surface photovoltage spectroscopy
P		SQUIDS	superconducting quantum interference devices
PDS	photothermal displacement spectroscopy	SS	surface state
PED	photoelectron diffraction	STM	scanning tunneling microscope/microscopy
PES	photoemission spectroscopy	STS	scanning tunneling spectroscopy
PLAP	pulsed laser atom probe	SXRD	surface X-ray diffraction
PLD	pulsed laser deposition	T	
PSZ	stabilized zirconia	TAFF	thermally activated flux flow
PZT	piezoelectric material	TEM	transmission electron microscope/microscopy
		TFT	thin-film transistor
		TMR	tunnel magnetoresistance
		TMT	thermomechanical treatment
		TOF	time of flight
		TOM	torsion oscillation magnetometry

TRS truncation rod scattering
TTT time-temperature-transformation

U

UHV ultra-high vacuum
UPS ultraviolet photoemission spectroscopy
UV ultraviolet

V

VBM valence band maximum
VLEED very low-energy electron diffraction

X

XPS X-ray photoemission spectroscopy