Springer Handbook of Electronic and Photonic Materials

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Springer Handbook of Electronic and Photonic Materials

Safa Kasap, Peter Capper (Eds.)

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Editors:
Safa Kasap
University of Saskatchewan
Department of Electrical Engineering
Saskatoon, SK, S7N 5A9
Canada

Peter Capper
SELEX Sensors and Airborne Systems Infrared Ltd.
Millbrook Industrial Estate
Southampton, Hampshire SO15 0EG
United Kingdom

Assistant Editor:
Cyril Koughia
University of Saskatchewan
Canada

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Foreword

Prof. Arthur Willoughby
Materials Research Group,
University of Southampton,
UK

The Editors, Authors, and Publisher are to be congratulated on this distinguished volume, which will be an invaluable source of information to all workers in the area of electronic and photonic materials. Having made contributions to earlier handbooks, I am well aware of the considerable, and sustained work that is necessary to produce a volume of this kind. This particular handbook, however, is distinguished by its breadth of coverage in the field, and the way in which it discusses the very latest developments. In such a rapidly moving field, this is a considerable challenge, and it has been met admirably.

Previous handbooks and encyclopaedia have tended to concentrate on semiconducting materials, for the understandable reason of their dominance in the electronics field, and the wide range of semiconducting materials and phenomena that must be covered. Few have been courageous enough to predict future trends, but in 1992 Mahajan and Kimerling attempted this in the Introduction to their Concise Encyclopaedia of Semiconducting Materials and Related Technologies (Pergamon), and foresaw future challenges in the areas of nanoelectronics, low dislocation-density III-V substrates, semi-insulating III-V substrates, patterned epitaxy of III-Vs, alternative dielectrics and contacts for silicon technology, and developments in ion-implantation and diffusion. To a greater or lesser extent, all of these have been proved to be true, but it illustrates how difficult it is to make such a prediction.

Not many people would have thought, a decade ago, that the III-nitrides would occupy an important position in this book. As high melting point materials, with the associated growth problems, they were not high on the list of favourites for light emitters at the blue end of the spectrum! The story is a fascinating one – at least as interesting as the solution to the problem of the short working life of early solid-state lasers at the red end of the spectrum. Optoelectronics and photonics, in general, have seen one of the most spectacular advances over the last decade, and this is fully reflected in the book, ranging from visible light emitters, to infra-red materials. The book covers a wide range of work in Part D, including III-V and II-VI optoelectronic materials and band-gap engineering, as well as photonic glasses, liquid crystals, organic photoconductors, and the new area of photonic crystals. The whole Part reflects materials for light generation, processing, transmission and detection – all the essential elements for using light instead of electrons.

In the Materials for Electronics part (Part C) the book charts the progress in silicon – overwhelmingly the dominant material for a whole range of electronic functions and circuitry – including new dielectrics and other issues associated with shrinking geometry of circuits and devices to produce ever higher packing densities. It also includes areas rarely covered in other books – thick films, high-temperature electronic materials, amorphous and microcrystalline materials. The existing developments that extend the life of silicon technology, including silicon/germanium alloys, appear too, and raise the question again as to whether the predicted timetable for the demise of silicon has again been declared too early!! Ferroelectrics – a class of materials used so effectively in conjunction with silicon – certainly deserve to be here.

The chapters in Part E (Novel Materials and Selected Applications), break new ground in a number of admirable ways. Most of us are aware of, and frequently use, information recording devices such as CDs, videos, DVDs etc., but few are aware of the materials, or principles, involved. This book describes magnetic information storage materials, as well as phase-change optical recording, keeping us fully up-to-date with recent developments. The chapters also include applications such as solar cells, sensors, photoconductors, and carbon nanotubes, on which such a huge volume of work is presently being pursued worldwide. Both ends of the spectrum from research to applications are represented in chapters on molecular electronics and packaging materials.

A particular strength of this book is that it ranges from the fundamental science (Part A) through growth and characterisation of the materials (Part B) to applications (Parts C–E). Virtually all the materials covered here have a wide range of applications, which is one of the reasons why this book is going to be so useful. As I indicated before, few of us will be successful in predicting the future direction and trends, occupying the high-ground in this field in the coming decade, but this book teaches us the basic principles of materials, and leaves it to us to adapt these to the needs of tomorrow. I commend it to you most warmly.

Preface

Other handbooks in various disciplines such as electrical engineering, electronics, biomedical engineering, materials science, etc. are currently available and well used by numerous students, instructors and professionals. Most libraries have these handbook sets and each contains numerous (at least 50) chapters that cover a wide spectrum of topics within each well-defined discipline. The subject and the level of coverage appeal to both undergraduate and postgraduate students and researchers as well as to practicing professionals. The advanced topics follow introductory topics and provide ample information that is useful to all, beginners and researchers, in the field. Every few years, a new edition is brought out to update the coverage and include new topics.

There has been no similar handbook in electronic and photonic materials, and the present Springer Handbook of Electronic and Photonic Materials (SHEPM) idea grew out of a need for a handbook that covers a wide spectrum of topics in materials that today's engineers, material scientists, physicists, and chemists need. Electronic and photonic materials is a truly interdisciplinary subject that encompasses a number of traditional disciplines such as materials science, electrical engineering, chemical engineering, mechanical engineering, physics and chemistry. It is not unusual to find a mechanical engineering faculty carrying out research on electronic packaging and electrical engineers carrying out characterization measurements on semiconductors. There are only a few established university departments in electronic or photonic materials. In general, electronic materials as a "discipline" appears as a research group or as an interdisciplinary activity within a "college". One could argue that, because of the very fact that it is such an interdisciplinary field, there is a greater need to have a handbook that covers not only fundamental topics but also advanced topics; hence the present handbook.

This handbook is a comprehensive treatise on electronic and photonic materials with each chapter written by experts in the field. The handbook is aimed at senior undergraduate and graduate students, researchers and professionals working in the area of electronic, optoelectronic and photonic materials. The chapters provide the necessary background and up-to-date knowledge in a wide range of topics. Each chapter has an introduction to the topic, many clear illustrations and numerous references. Clear explanations and illustrations make the handbook useful to all levels of researchers. All chapters are as self-contained as possible. There are both fundamental and advanced chapters to appeal to readers with different backgrounds. This is particularly important for this handbook since the subject matter is highly interdisciplinary. For example, there will be readers with a background (first degree) in chemical engineering and working on semiconductor processing who need to learn the fundamentals of semiconductors physics. Someone with a first degree in physics would need to quickly update himself on materials science concepts such as liquid phase epitaxy and so on. Difficult mathematics has been avoided and, whenever possible, the explanations have been given semiquantitatively. There is a "*Glossary of Defining Terms*" at the end of the handbook, which can serve to quickly find the definition of a term – a very necessary feature in an interdisciplinary handbook.

Dr. Peter Capper
Materials Team Leader,
SELEX Sensors and Airborne Systems,
Southampton, UK

Prof. Safa Kasap
Professor and Canada Research Chair,
Electrical Engineering Department,
University of Saskatchewan,
Canada

The editors are very grateful to all the authors for their excellent contributions and for their cooperation in delivering their manuscripts and in the various stages of production of this handbook. Sincere thanks go to Greg Franklin at Springer Boston for all his support and help throughout the long period of commissioning, acquiring the contributions and the production of the handbook. Dr. Werner Skolaut at Springer Heidelberg has very skillfully handled the myriad production issues involved in copy-editing, figure redrawing and proof preparation and correction and our sincere thanks go to him also for all his hard

work in making the handbook attractive to read. He is the most dedicated and efficient editor we have come across.

It is a pleasure to thank Professor Arthur Willoughby for his many helpful suggestions that made this a better handbook. His wealth of experience as editor of the Journal of Materials Science: Materials in Electronics played an important role not only in selecting chapters but also in finding the right authors.

Finally, the editors wish to thank all the members of our families (Marian, Samuel and Thomas; and Nicollette) for their support and particularly their endurance during the entire project.

Peter Capper and Safa Kasap
Editors

List of Authors

Martin Abkowitz
1198 Gatestone Circle
Webster, NY 14580, USA
e-mail: *mabkowitz@mailaps.org*,
abkowitz@chem.chem.rochester.edu

Sadao Adachi
Gunma University
Department of Electronic Engineering,
Faculty of Engineering
Kiryu-shi 376-8515
Gunma, Japan
e-mail: *adachi@el.gunma-u.ac.jp*

Alfred Adams
University of Surrey
Advanced Technology Institute
Guildford, Surrey, GU2 7XH,
Surrey, UK
e-mail: *alf.adams@surrey.ac.uk*

Guy J. Adriaenssens
University of Leuven
Laboratorium voor Halfgeleiderfysica
Celestijnenlaan 200D
B-3001 Leuven, Belgium
e-mail: *guy.adri@fys.kuleuven.ac.be*

Wilfried von Ammon
Siltronic AG
Research and Development
Johannes Hess Strasse 24
84489 Burghausen, Germany
e-mail: *wilfried.ammon@siltronic.com*

Peter Ashburn
University of Southampton
School of Electronics and Computer Science
Southampton, SO17 1BJ, UK
e-mail: *pa@ecs.soton.ac.uk*

Mark Auslender
Ben-Gurion University of the Negev Beer Sheva
Department of Electrical
and Computer Engineering
P.O.Box 653
Beer Sheva 84105, Israel
e-mail: *marka@ee.bgu.ac.il*

Darren M. Bagnall
University of Southampton
School of Electronics and Computer Science
Southampton, SO17 1BJ, UK
e-mail: *dmb@ecs.soton.ac.uk*

Ian M. Baker
SELEX Sensors and Airborne Systems Infrared Ltd.
Southampton, Hampshire SO15 0EG, UK
e-mail: *ian.m.baker@selex-sas.com*

Sergei Baranovskii
Philipps University Marburg
Department of Physics
Renthof 5
35032 Marburg, Germany
e-mail: *baranovs@staff.uni-marburg.de*

Mark Baxendale
Queen Mary, University of London
Department of Physics
Mile End Road
London, E1 4NS, UK
e-mail: *m.baxendale@qmul.ac.uk*

Mohammed L. Benkhedir
University of Leuven
Laboratorium voor Halfgeleiderfysica
Celestijnenlaan 200D
B-3001 Leuven, Belgium
e-mail: *MohammedLoufti.Benkhedir*
@fys.kuleuven.ac.be

Monica Brinza
University of Leuven
Laboratorium voor Halfgeleiderfysica
Celestijnenlaan 200D
B-3001 Leuven, Belgium
e-mail: *monica.brinza@fys.kuleuven.ac.be*

Paul D. Brown
University of Nottingham
School of Mechanical, Materials and
Manufacturing Engineering
University Park
Nottingham, NG7 2RD, UK
e-mail: *paul.brown@nottingham.ac.uk*

Mike Brozel
University of Glasgow
Department of Physics and Astronomy
Kelvin Building
Glasgow, G12 8QQ, UK
e-mail: *mikebrozel@beeb.net*

Lukasz Brzozowski
University of Toronto
Sunnybrook and Women's Research Institute,
Imaging Research/
Department of Medical Biophysics
Research Building, 2075 Bayview Avenue
Toronto, ON, M4N 3M5, Canada
e-mail: *lukbroz@sten.sunnybrook.utoronto.ca*

Peter Capper
SELEX Sensors and Airborne Systems Infrared Ltd.
Materials Team Leader
Millbrook Industrial Estate, PO Box 217
Southampton, Hampshire SO15 0EG, UK
e-mail: *pete.capper@selex-sas.com*

Larry Comstock
San Jose State University
6574 Crystal Springs Drive
San Jose, CA 95120, USA
e-mail: *Comstock@email.sjsu.edu*

Ray DeCorby
University of Alberta
Department of Electrical
and Computer Engineering
7th Floor, 9107-116 Street N.W.
Edmonton, Alberta T6G 2V4, Canada
e-mail: *rdecorby@trlabs.ca*

M. Jamal Deen
McMaster University
Department of Electrical
and Computer Engineering (CRL 226)
1280 Main Street West
Hamilton, ON L8S 4K1, Canada
e-mail: *jamal@mcmaster.ca*

Leonard Dissado
The University of Leicester
Department of Engineering
University Road
Leicester, LE1 7RH, UK
e-mail: *lad4@le.ac.uk*

David Dunmur
University of Southampton
School of Chemistry
Southampton, SO17 1BJ, UK
e-mail: *d.a.dunmur@soton.ac.uk*

Lester F. Eastman
Cornell University
Department of Electrical
and Computer Engineering
425 Phillips Hall
Ithaca, NY 14853, USA
e-mail: *lfe2@cornell.edu*

Andy Edgar
Victoria University
School of Chemical and Physical Sciences SCPS
Kelburn Parade/PO Box 600
Wellington, New Zealand
e-mail: *Andy.Edgar@vuw.ac.nz*

Brian E. Foutz
Cadence Design Systems
1701 North Street, Bldg 257-3
Endicott, NY 13760, USA
e-mail: *foutz@cadence.com*

Mark Fox
University of Sheffield
Department of Physics and Astronomy
Hicks Building, Hounsefield Road
Sheffield, S3 7RH, UK
e-mail: *mark.fox@shef.ac.uk*

Darrel Frear
RF and Power Packaging Technology Development,
Freescale Semiconductor
2100 East Elliot Road
Tempe, AZ 85284, USA
e-mail: *darrel.frear@freescale.com*

Milan Friesel
Chalmers University of Technology
Department of Physics
Fysikgränd 3
41296 Göteborg, Sweden
e-mail: *friesel@chalmers.se*

Jacek Gieraltowski
Université de Bretagne Occidentale
6 Avenue Le Gorgeu, BP: 809
29285 Brest Cedex, France
e-mail: *Jacek.Gieraltowski@univ-brest.fr*

Yinyan Gong
Columbia University
Department of Applied Physics
and Applied Mathematics
500 W. 120th St.
New York, NY 10027, USA
e-mail: *yg2002@columbia.edu*

Robert D. Gould†
Keele University
Thin Films Laboratory, Department of Physics,
School of Chemistry and Physics
Keele, Staffordshire ST5 5BG, UK

Shlomo Hava
Ben-Gurion University of the Negev Beer Sheva
Department of Electrical
and Computer Engineering
P.O. Box 653
Beer Sheva 84105, Israel
e-mail: *hava@ee.bgu.ac.il*

Colin Humphreys
University of Cambridge
Department of Materials Science and Metallurgy
Pembroke Street
Cambridge, CB2 3!Z, UK
e-mail: *colin.Humphreys@msm.cam.ac.uk*

Stuart Irvine
University of Wales, Bangor
Department of Chemistry
Gwynedd, LL57 2UW, UK
e-mail: *sjc.irvine@bangor.ac.uk*

Minoru Isshiki
Tohoku University
Institute of Multidisciplinary Research
for Advanced Materials
1-1, Katahira, 2 chome, Aobaku
Sendai, 980-8577, Japan
e-mail: *isshiki@tagen.tohoku.ac.jp*

Robert Johanson
University of Saskatchewan
Department of Electrical Engineering
57 Campus Drive
Saskatoon, SK S7N 5A9, Canada
e-mail: *johanson@engr.usask.ca*

Tim Joyce
University of Liverpool
Functional Materials Research Centre,
Department of Engineering
Brownlow Hill
Liverpool, L69 3BX, UK
e-mail: *t.joyce@liv.ac.uk*

M. Zahangir Kabir
Concordia University
Department of Electrical and Computer Engineering
Montreal, Quebec S7N5A9, Canada
e-mail: *kabir@encs.concordia.ca*

Safa Kasap
University of Saskatchewan
Department of Electrical Engineering
57 Campus Drive
Saskatoon, SK S7N 5A9, Canada
e-mail: *safa.kasap@usask.ca*

Alexander Kolobov
National Institute of Advanced Industrial Science and Technology
Center for Applied Near-Field Optics Research
1-1-1 Higashi, Tsukuba
Ibaraki, 305-8562, Japan
e-mail: *a.kolobov@aist.go.jp*

Cyril Koughia
University of Saskatchewan
Department of Electrical Engineering
57 Campus Drive
Saskatoon, SK S7N 5A9, Canada
e-mail: *kik486@mail.usask.ca*

Igor L. Kuskovsky
Queens College, City University of New York (CUNY)
Department of Physics
65-30 Kissena Blvd.
Flushing, NY 11367, USA
e-mail: *igor_kuskovsky@qc.edu*

Geoffrey Luckhurst
University of Southampton
School of Chemistry
Southampton, SO17 1BJ, UK
e-mail: *g.r.luckhurst@soton.ac.uk*

Akihisa Matsuda
Tokyo University of Science
Research Institute for Science and Technology
2641 Yamazaki, Noda-shi
Chiba, 278-8510, Japan
e-mail: *amatsuda@rs.noda.tus.ac.jp*, *a.matsuda@aist.go.jp*

Naomi Matsuura
Sunnybrook Health Sciences Centre
Department of Medical Biophysics, Imaging Research
2075 Bayview Avenue
Toronto, ON M4N 3M5, Canada
e-mail: *matsuura@sri.utoronto.ca*

Kazuo Morigaki
University of Tokyo
C-305, Wakabadai 2-12, Inagi
Tokyo, 206-0824, Japan
e-mail: *k.morigaki@yacht.ocn.ne.jp*

Hadis Morkoç
Virginia Commonwealth University
Department of Electrical and Computer Engineering
601 W. Main St., Box 843072
Richmond, VA 23284-3068, USA
e-mail: *hmorkoc@vcu.edu*

Winfried Mönch
Universität Duisburg-Essen
Lotharstraße 1
47048 Duisburg, Germany
e-mail: *w.moench@uni-duisburg.de*

Arokia Nathan
University of Waterloo
Department of Electrical and Computer Engineering
200 University Avenue W.
Waterloo, Ontario N2L 3G1, Canada
e-mail: *anathan@uwaterloo.ca*

Gertrude F. Neumark
Columbia University
Department of Applied Physics
and Applied Mathematics
500W 120th St., MC 4701
New York, NY 10027, USA
e-mail: *gfn1@columbia.edu*

Stephen K. O'Leary
University of Regina
Faculty of Engineering
3737 Wascana Parkway
Regina, SK S4S 0A2, Canada
e-mail: *stephen.oleary@uregina.ca*

Chisato Ogihara
Yamaguchi University
Department of Applied Science
2-16-1 Tokiwadai
Ube, 755-8611, Japan
e-mail: *ogihara@yamaguchi-u.ac.jp*

Fabien Pascal
Université Montpellier 2/CEM2-cc084
Centre d'Electronique
et de Microoptoélectronique de Montpellier
Place E. Bataillon
34095 Montpellier, France
e-mail: *pascal@cem2.univ-montp2.fr*

Michael Petty
University of Durham
Department School of Engineering
South Road
Durham, DH1 3LE, UK
e-mail: *m.c.petty@durham.ac.uk*

Asim Kumar Ray
Queen Mary, University of London
Department of Materials
Mile End Road
London, E1 4NS, UK
e-mail: *a.k.ray@qmul.ac.uk*

John Rowlands
University of Toronto
Department of Medical Biophysics
Sunnybrook and Women's College
Health Sciences Centre
S656-2075 Bayview Avenue
Toronto, ON M4N 3M5, Canada
e-mail: *john.rowlands@sri.utoronto.ca*

Oleg Rubel
Philipps University Marburg
Department of Physics
and Material Sciences Center
Renthof 5
35032 Marburg, Germany
e-mail: *oleg.rubel@physik.uni-marburg.de*

Harry Ruda
University of Toronto
Materials Science and Engineering,
Electrical and Computer Engineering
170 College Street
Toronto, M5S 3E4, Canada
e-mail: *ruda@ecf.utoronto.ca*

Edward Sargent
University of Toronto
Department of Electrical
and Computer Engineering
ECE, 10 King's College Road
Toronto, M5S 3G4, Canada
e-mail: *ted.sargent@utoronto.ca*

Peyman Servati
Ignis Innovation Inc.
55 Culpepper Dr.
Waterloo, Ontario N2L 5K8, Canada
e-mail: *pservati@uwaterloo.ca*

Derek Shaw
Hull University
Hull, HU6 7RX, UK
e-mail: *DerekShaw1@compuserve.com*

Fumio Shimura
Shizuoka Institute of Science and Technology
Department of Materials and Life Science
2200-2 Toyosawa
Fukuroi, Shizuoka 437-8555, Japan
e-mail: *shimura@ms.sist.ac.jp*

Michael Shur
Renssellaer Polytechnic Institute
Department of Electrical, Computer,
and Systems Engineering
CII 9017, RPI, 110 8th Street
Troy, NY 12180, USA
e-mail: *shurm@rpi.edu*

Jai Singh
Charles Darwin University
School of Engineering and Logistics,
Faculty of Technology, B-41
Ellengowan Drive
Darwin, NT 0909, Australia
e-mail: *jai.singh@cdu.edu.au*

Tim Smeeton
Sharp Laboratories of Europe
Edmund Halley Road, Oxford Science Park
Oxford, OX4 4GB, UK
e-mail: *tim.smeeton@sharp.co.uk*

Boris Straumal
Russian Academy of Sciences
Institute of Sold State Physics
Institutskii prospect 15
Chernogolovka, 142432, Russia
e-mail: *straumal@issp.ac.ru*

Stephen Sweeney
University of Surrey
Advanced Technology Institute
Guildford, Surrey GU2 7XH, UK
e-mail: *s.sweeney@surrey.ac.uk*

David Sykes
Loughborough Surface Analysis Ltd.
PO Box 5016, Unit FC, Holywell Park, Ashby Road
Loughborough, LE11 3WS, UK
e-mail: *d.e.sykes@lsaltd.co.uk*

Keiji Tanaka
Hokkaido University
Department of Applied Physics,
Graduate School of Engineering
Kita-ku, N13 W8
Sapporo, 060-8628, Japan
e-mail: *keiji@eng.hokudai.ac.jp*

Charbel Tannous
Université de Bretagne Occidentale
LMB, CNRS FRE 2697
6 Avenue Le Gorgeu, BP: 809
29285 Brest Cedex, France
e-mail: *tannous@univ-brest.fr*

Ali Teke
Balikesir University
Department of Physics, Faculty of Art and Science
Balikesir, 10100, Turkey
e-mail: *ateke@balikesir.edu.tr*

Junji Tominaga
National Institute of Advanced Industrial
Science and Technology, AIST
Center for Applied Near-Field Optics Research,
CAN-FOR
Tsukuba Central 4 1-1-1 Higashi
Tsukuba, 3.5-8562, Japan
e-mail: *j-tomonaga@aist.go.jp*

Dan Tonchev
University of Saskatchewan
Department of Electrical Engineering
57 Campus Drive
Saskatoon, SK S7N 5A9, Canada
e-mail: *dan.tonchev@usask.ca*

Harry L. Tuller
Massachusetts Institute of Technology
Department of Materials Science and Engineering,
Crystal Physics and Electroceramics Laboratory
77 Massachusetts Avenue
Cambridge, MA 02139, USA
e-mail: *tuller@mit.edu*

Qamar-ul Wahab
Linköping University
Department of Physics,
Chemistry, and Biology (IFM)
SE-581 83 Linköping, Sweden
e-mail: *quw@ifm.liu.se*

Robert M. Wallace
University of Texas at Dallas
Department of Electrical Engineering
M.S. EC 33, P.O.Box 830688
Richardson, TX 75083, USA
e-mail: *rmwallace@utdallas.edu*

Jifeng Wang
Tohoku University
Institute of Multidisciplinary Research
for Advanced Materials
1-1, Katahira, 2 Chome, Aobaku
Sendai, 980-8577, Japan
e-mail: *wang@tagen.tohoku.ac.jp*

David S. Weiss
NexPress Solutions, Inc.
2600 Manitou Road
Rochester, NY 14653-4180, USA
e-mail: *David_Weiss@Nexpress.com*

Rainer Wesche
Swiss Federal Institute of Technology
Centre de Recherches en Physique des Plasmas
CRPP (c/o Paul Scherrer Institute), WMHA/C31,
Villigen PS
Lausanne, CH-5232, Switzerland
e-mail: *rainer.wesche@psi.ch*

Roger Whatmore
Tyndall National Institute
Lee Maltings, Cork , Ireland
e-mail: *roger.whatmore@tyndall.ie*

Neil White
University of Southampton
School of Electronics and Computer Science
Mountbatten Building
Highfield, Southampton SO17 1BJ, UK
e-mail: *nmw@ecs.soton.ac.uk*

Magnus Willander
University of Gothenburg
Department of Physics
SE-412 96 Göteborg, Sweden
e-mail: *mwi@fy.chalmers.se*

Jan Willekens
University of Leuven
Laboratorium voor Halfgeleiderfysica
Celestijnenlaan 200D
B-3001 Leuven, Belgium
e-mail: *jan.willekens@kc.kuleuven.ac.be*

Contents

Part C Materials for Electronics

List of Abbreviations

2DEG	two-dimensional electron gas

A

AC	alternating current
ACCUFET	accumulation-mode MOSFET
ACRT	accelerated crucible rotation technique
AEM	analytical electron microscopes
AES	Auger electron spectroscopy
AFM	atomic force microscopy
ALD	atomic-layer deposition
ALE	atomic-layer epitaxy
AMA	active matrix array
AMFPI	active matrix flat-panel imaging
AMOLED	amorphous organic light-emitting diode
APD	avalanche photodiode

B

b.c.c.	body-centered cubic
BEEM	ballistic-electron-emission microscopy
BEP	beam effective pressure
BH	buried-heterostructure
BH	Brooks–Herring
BJT	bipolar junction transistor
BTEX	m-xylene
BZ	Brillouin zone

C

CAIBE	chemically assisted ion beam etching
CB	conduction band
CBE	chemical beam epitaxy
CBED	convergent beam electron diffraction
CC	constant current
CCD	charge-coupled device
CCZ	continuous-charging Czochralski
CFLPE	container-free liquid phase epitaxy
CKR	cross Kelvin resistor
CL	cathodoluminescence
CMOS	complementary metal-oxide-semiconductor
CNR	carrier-to-noise ratio
COP	crystal-originated particle
CP	charge pumping
CPM	constant-photocurrent method
CR	computed radiography
CR-DLTS	computed radiography deep level transient spectroscopy
CRA	cast recrystallize anneal
CTE	coefficient of thermal expansion
CTO	chromium(III) trioxalate
CuPc	copper phthalocyanine
CuTTBPc	tetra-tert-butyl phthalocyanine
CV	chemical vapor
CVD	chemical vapor deposition
CVT	chemical vapor transport
CZ	Czochralski
CZT	cadmium zinc telluride

D

DA	Drude approximation
DAG	direct alloy growth
DBP	dual-beam photoconductivity
DC	direct current
DCPBH	double-channel planar buried heterostructure
DET	diethyl telluride
DFB	distributed feedback
DH	double heterostructure
DIL	dual-in-line
DIPTe	diisopropyltellurium
DLC	diamond-like carbon
DLHJ	double-layer heterojunction
DLTS	deep level transient spectroscopy
DMCd	dimethyl cadmium
DMF	dimethylformamide
DMOSFET	double-diffused MOSFET
DMS	dilute magnetic semiconductors
DMSO	dimethylsulfoxide
DMZn	dimethylzinc
DOS	density of states
DQE	detective quantum efficiency
DSIMS	dynamic secondary ion mass spectrometry
DTBSe	ditertiarybutylselenide
DUT	device under test
DVD	digital versatile disk
DWDM	dense wavelength-division multiplexing
DXD	double-crystal X-ray diffraction

E

EBIC	electron beam induced conductivity
ED	electrodeposition
EDFA	erbium-doped fiber amplifier
EELS	electron energy loss spectroscopy
EFG	film-fed growth
EHP	electron–hole pairs
ELO	epitaxial lateral overgrowth
ELOG	epitaxial layer overgrowth
EM	electromagnetic
EMA	effective media approximation

ENDOR electron–nuclear double resonance
EPD etch pit density
EPR electron paramagnetic resonance
ESR electron spin resonance spectroscopy
EXAFS extended X-ray absorption fine structure

F

FCA free-carrier absorption
f.c.c. face-centered cubic
FET field effect transistor
FIB focused ion beam
FM Frank–van der Merwe
FPA focal plane arrays
FPD flow pattern defect
FTIR Fourier transform infrared
FWHM full-width at half-maximum
FZ floating zone

G

GDA generalized Drude approximation
GDMS glow discharge mass spectrometry
GDOES glow discharge optical emission spectroscopy
GF gradient freeze
GMR giant magnetoresistance
GOI gate oxide integrity
GRIN graded refractive index
GSMBE gas-source molecular beam epitaxy
GTO gate turn-off

H

HAADF high-angle annular dark field
HB horizontal Bridgman
HBT hetero-junction bipolar transistor
HDC horizontal directional solidification crystallization
HEMT high electron mobility transistor
HF high-frequency
HOD highly oriented diamond
HOLZ high-order Laue zone
HPc phthalocyanine
HPHT high-pressure high-temperature
HRXRD high-resolution X-ray diffraction
HTCVD high-temperature CVD
HVDC high-voltage DC
HWE hot-wall epitaxy

I

IC integrated circuit
ICTS isothermal capacitance transient spectroscopy
IDE interdigitated electrodes
IFIGS interface-induced gap states
IFTOF interrupted field time-of-flight
IGBT insulated gate bipolar transistor
IMP interdiffused multilayer process
IPEYS internal photoemission yield spectroscopy
IR infrared
ITO indium-tin-oxide

J

JBS junction barrier Schottky
JFET junction field-effect transistors
JO Judd–Ofelt

K

KCR Kelvin contact resistance
KKR Kramers–Kronig relation
KLN $K_3Li_2Nb_5O_{12}$
KTPO $KTiOPO_4$

L

LB Langmuir–Blodgett
LD laser diodes
LD lucky drift
LDD lightly doped drain
LEC liquid-encapsulated Czochralski
LED light-emitting diodes
LEIS low-energy ion scattering
LEL lower explosive limit
LF low-frequency
LLS laser light scattering
LMA law of mass action
LO longitudinal optical
LPE liquid phase epitaxy
LSTD laser light scattering tomography defect
LVM localized vibrational mode

M

MBE molecular beam epitaxy
MCCZ magnetic field applied continuous Czochralski
MCT mercury cadmium telluride
MCZ magnetic field applied Czochralski
MD molecular dynamics
MEED medium-energy electron diffraction
MEM micro-electromechanical systems
MESFET metal-semiconductor field-effect transistor
MFC mass flow controllers
MIGS metal-induced gap states
ML monolayer
MLHJ multilayer heterojunction
MOCVD metal-organic chemical vapor deposition
MODFET modulation-doped field effect transistor

MOMBE metalorganic molecular beam epitaxy
MOS metal/oxide/semiconductor
MOSFET metal/oxide/semiconductor field effect transistor
MOVPE metalorganic vapor phase epitaxy
MPc metallophthalocyanine
MPC modulated photoconductivity
MPCVD microwave plasma chemical deposition
MQW multiple quantum well
MR magnetoresistivity
MS metal–semiconductor
MSRD mean-square relative displacement
MTF modulation transfer function
MWIR medium-wavelength infrared

N

NDR negative differential resistance
NEA negative electron affinity
NeXT nonthermal energy exploration telescope
NMOS n-type-channel metal–oxide–semiconductor
NMP N-methylpyrrolidone
NMR nuclear magnetic resonance
NNH nearest-neighbor hopping
NSA naphthalene-1,5-disulfonic acid
NTC negative temperature coefficient
NTD neutron transmutation doping

O

OLED organic light-emitting diode
OSF oxidation-induced stacking fault
OSL optically stimulated luminescence
OZM overlap zone melting

P

PAE power added efficiency
PAni polyaniline
pBN pyrolytic boron nitride
Pc phthalocyanine
PC photoconductive
PCA principal component analysis
PCB printed circuit board
PDMA poly(methylmethacrylate)/poly(decyl methacrylate)
PDP plasma display panels
PDS photothermal deflection spectroscopy
PE polysilicon emitter
PE BJT polysilicon emitter bipolar junction transistor
PECVD plasma-enhanced chemical vapor deposition
PEN polyethylene naphthalate
PES photoemission spectroscopy
PET positron emission tomography
pHEMT pseudomorphic HEMT
PL photoluminescence
PM particulate matter
PMMA poly(methyl-methacrylate)
POT poly(*n*-octyl)thiophene
ppb parts per billion
ppm parts per million
PPS polyphenylsulfide
PPY polypyrrole
PQT-12 poly[5,5'-bis(3-alkyl-2-thienyl)-2,2'-bithiophene]
PRT platinum resistance thermometers
PSt polystyrene
PTC positive temperature coefficient
PTIS photothermal ionisation spectroscopy
PTS 1,1-dioxo-2-(4-methylphenyl)-6-phenyl-4-(dicyanomethylidene)thiopyran
PTV polythienylene vinylene
PV photovoltaic
PVD physical vapor transport
PVDF polyvinylidene fluoride
PVK polyvinylcarbazole
PVT physical vapor transport
PZT lead zirconate titanate

Q

QA quench anneal
QCL quantum cascade laser
QCSE quantum-confined Stark effect
QD quantum dot
QHE quantum Hall effect
QW quantum well

R

RAIRS reflection adsorption infrared spectroscopy
RBS Rutherford backscattering
RCLED resonant-cavity light-emitting diode
RDF radial distribution function
RDS reflection difference spectroscopy
RE rare earth
RENS resolution near-field structure
RF radio frequency
RG recombination–generation
RH relative humidity
RHEED reflection high-energy electron diffraction
RIE reactive-ion etching
RIU refractive index units
RTA rapid thermal annealing
RTD resistance temperature devices
RTS random telegraph signal

S

SA self-assembly
SAM self-assembled monolayers

SAW	surface acoustic wave
SAXS	small-angle X-ray scattering
SCH	separate confinement heterojunction
SCVT	seeded chemical vapor transport
SE	spontaneous emission
SEM	scanning electron microscope
SIMS	secondary ion mass spectrometry
SIPBH	semi-insulating planar buried heterostructure
SIT	static induction transistors
SK	Stranski–Krastanov
SNR	signal-to-noise ratio
SO	small outline
SOA	semiconductor optical amplifier
SOC	system-on-a-chip
SOFC	solid oxide fuel cells
SOI	silicon-on-insulator
SP	screen printing
SPECT	single-photon emission computed tomography
SPR	surface plasmon resonance
SPVT	seeded physical vapor transport
SQW	single quantum wells
SSIMS	static secondary ion mass spectrometry
SSPC	steady-state photoconductivity
SSR	solid-state recrystallisation
SSRM	scanning spreading resistance microscopy
STHM	sublimation traveling heater method
SVP	saturated vapor pressure
SWIR	short-wavelength infrared

T

TAB	tab automated bonding
TBA	tertiarybutylarsine
TBP	tertiarybutylphosphine
TCE	thermal coefficient of expansion
TCNQ	tetracyanoquinodimethane
TCR	temperature coefficient of resistance
TCRI	temperature coefficient of refractive index
TDCM	time-domain charge measurement
TE	transverse electric
TED	transient enhanced diffusion
TED	transmission electron diffraction
TEGa	triethylgallium
TEM	transmission electron microscope
TEN	triethylamine
TFT	thin-film transistors
THM	traveling heater method
TL	thermoluminescence
TLHJ	triple-layer graded heterojunction
TLM	transmission line measurement
TM	transverse magnetic
TMA	trimethyl-aluminum
TMG	trimethyl-gallium
TMI	trimethyl-indium
TMSb	trimethylantimony
TO	transverse optical
TOF	time of flight
ToFSIMS	time of flight SIMS
TPC	transient photoconductivity
TPV	thermophotovoltaic
TSC	thermally stimulated current
TSL	thermally stimulated luminescence

U

ULSI	ultra-large-scale integration
UMOSFET	U-shaped-trench MOSFET
UPS	uninterrupted power systems
UV	ultraviolet

V

VAP	valence-alternation pairs
VB	valence band
VCSEL	vertical-cavity surface-emitting laser
VCZ	vapor-pressure-controlled Czochralski
VD	vapor deposition
VFE	vector flow epitaxy
VFET	vacuum field-effect transistor
VGF	vertical gradient freeze
VIS	visible
VOC	volatile organic compounds
VPE	vapor phase epitaxy
VRH	variable-range hopping
VUVG	vertical unseeded vapor growth
VW	Volmer–Weber

W

WDX	wavelength dispersive X-ray
WXI	wide-band X-ray imager

X

XAFS	X-ray absorption fine-structure
XANES	X-ray absorption near-edge structure
XEBIT	X-ray-sensitive electron-beam image tube
XPS	X-ray photon spectroscopy
XRD	X-ray diffraction
XRSP	X-ray storage phosphor

Y

YSZ	yttrium-stabilized zirconia