
Springer Handbook of Electronic and Photonic Materials

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Springer Handbook of Electronic and Photonic Materials

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With CD-ROM, 930 Figures and 168 Tables



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Foreword

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



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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.

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



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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 Nicolette) for their support and particularly their endurance during the entire project.

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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 $\text{K}_3\text{Li}_2\text{Nb}_5\text{O}_{12}$
 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(<i>n</i> -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
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