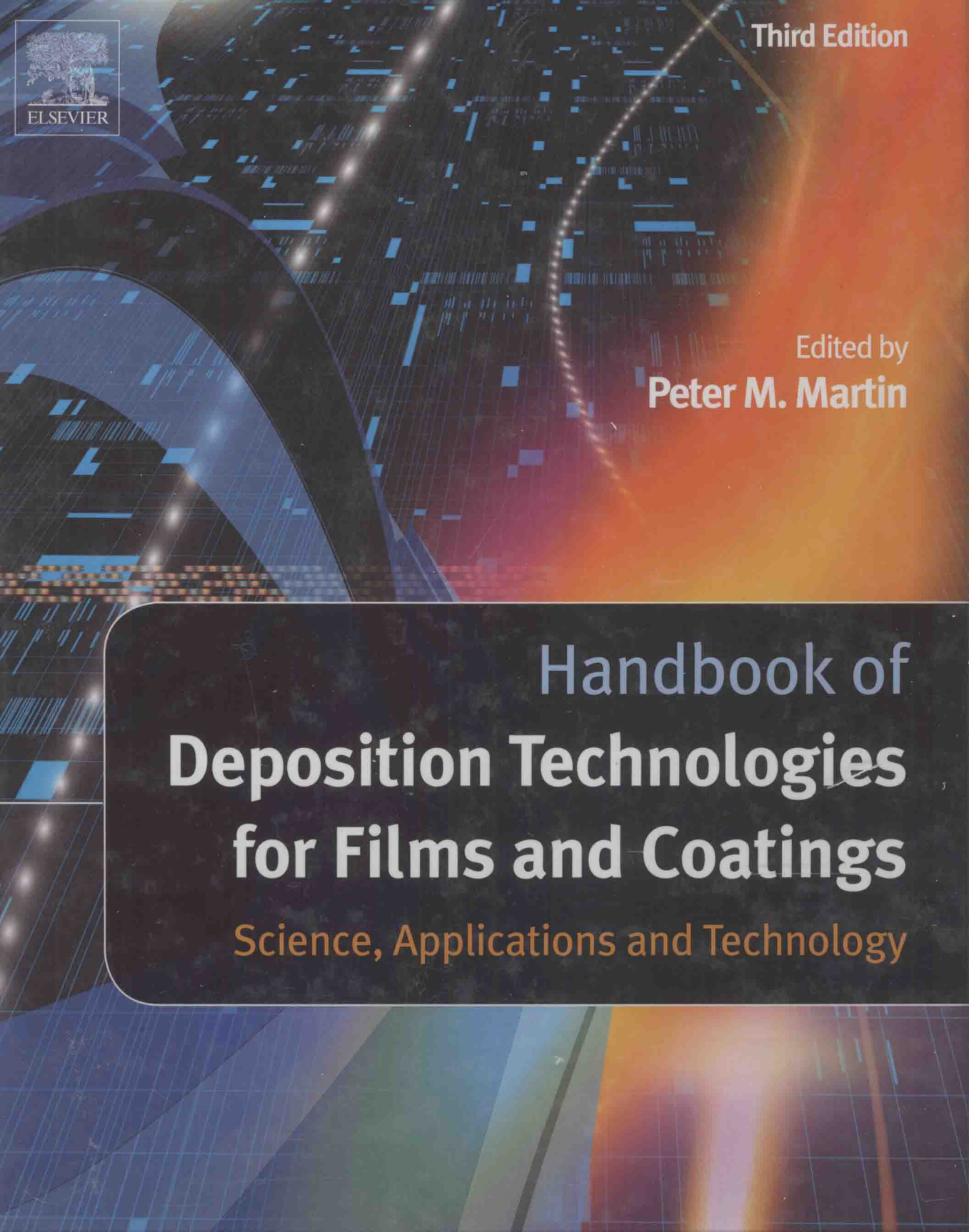
ELSEVIER
Third Edition
Edited by
Peter M. Martin
Handbook of
Deposition Technologies
for Films and Coatings
Science, Applications and Technology

# *Handbook of Deposition Technologies for Films and Coatings*

## Science, Applications and Technology

Edited by

Peter M. Martin



AMSTERDAM • BOSTON • HEIDELBERG • LONDON
NEW YORK • OXFORD • PARIS • SAN DIEGO
SAN FRANCISCO • SINGAPORE • SYDNEY • TOKYO

ELSEVIER

William Andrew is an imprint of Elsevier

William Andrew is an imprint of Elsevier
The Boulevard, Langford Lane, Kidlington, Oxford OX5 1GB, UK
30 Corporate Drive, Suite 400, Burlington, MA 01803, USA

First edition 2002
Second edition 2005



**British Library Cataloguing in Publication Data**
A catalogue record for this book is available from the British Library

**Library of Congress Cataloging-in-Publication Data**
A catalog record for this book is availabe from the Library of Congress

ISBN–13: 978-0-8155-2031-3

# *Handbook of Deposition Technologies for Films and Coatings*

Third Edition

## *Dedication*

*This volume is dedicated to Rointan Bunshah and my wife Ludmila. Rointan is the Editor of the first two handbooks and definitely one of the pioneers and leaders of thin film processes and technology. My wife Ludmila has been at my side through my entire career and Pacific Northwest National Laboratory and is an inspiration to me.*

# *Preface to the Third Edition*

The first two editions of this Handbook, edited by Ron Bunshaw, were immensely popular, are still used extensively and have become classics. The second edition was published in 1994, over fourteen years ago, and there is now a critical need for updating every chapter. To that end, the Third Edition of this Handbook has been entirely modified and encompasses virtually every aspect of thin film deposition technology. It is being brought out primarily to update how deposition technologies are keeping pace with the vast new developments in thin film structures and materials and applications. Advances in thin film deposition technology and characterization, and emerging technologies are addressed. This book complements other handbooks by presenting a broad range of thin film deposition and plasma technologies and characterization techniques written by international experts in the field. All chapters have been updated when necessary, some deleted, and new chapters on atomic layer deposition (ALD), cathodic arc deposition, sculpted thin films (GLAD), polymer thin films and atmospheric plasmas have been added. The major role of plasmas has also been expanded.

Thin film coating technology is advancing rapidly to keep pace with new applications in semiconductor, optical, tribological, display, decorative, solar, and medical technologies. Performance demands on virtually all types of thin film materials are continuously increasing. To meet these demands, thin film coatings and structures are becoming more sophisticated with engineered properties. Superlattices, nanotubes, nanolaminates, composites, chiral structures and diffusion barriers, to name a few, are now used routinely. Because of this, process and technology handbooks published even ten years ago are already out of date. Deposition processes and technologies are also changing rapidly to keep pace with advanced thin film materials and applications. Conventional deposition processes are being adapted in novel coating geometries to produce thin film structures with improved performance and properties not achievable by conventional methods. Additionally new deposition processes, such as high power pulsed plasma magnetron sputtering, are being developed to achieve new materials and physical properties. Thin films are now being engineered with electrical, optical, and mechanical properties not possible a decade ago. Characterization techniques are also improving.

In addition to the new subject areas, the following core subjects from the second edition have been addressed by new authors, while retaining many of the exceptional contributors from the

second edition: Evaporation, Physical Vapor Deposition (PVD), Ion Plating, Cathodic Arc Deposition (CAD), Plasma Enhanced Chemical Vapor Deposition (PECVD), Atmospheric Plasmas, Vacuum Polymer Deposition (VPD), Chemical Vapor Deposition (CVD), and Jet Vapor Deposition (JVD). The chapter on polymer coatings was added to include this very important family of materials, particularly in the area of gas and water barrier coatings for molecular electronic devices, thin film batteries and solar cells. Chapters on adhesion, structure of PVD deposits, tribological coatings, elemental and structural characterization, substrate cleaning, role of plasmas in deposition processes have all been completely revised. The chapter on Nucleation, Film Growth, and Microstructural Evolution has also been completely revised and is one of the most important subjects in this edition. The chapter on plasma assisted vapor deposition processes is eliminated since this material is redundant and covered in other chapters. Chapters on Deposition from Aqueous Solutions and Electrodeposition have also been eliminated because they are mature technologies with extensive publications and diminishing applications.

We hope that this edition will be just as or more useful to the multitude of disciplines represented by the technologists in this field and will remain germane for many years to come.

Peter M. Martin
Columbia Basin Thin Film Solutions LLC
Kennewick, Washington
September, 2009

# List of Abbreviations

| | |
|---|---|
| ABS | acrylonitrile butadiene styrene |
| ABS | arc bond sputtering |
| AEM | analytical electron microscopy |
| AES | Auger electron spectroscopy |
| AFM | atomic force microscopy |
| ALD | atomic layer deposition |
| APGD | atmospheric pressure glow discharge |
| APT | atom-probe tomography |
| AR | angle-resolved |
| AR | antireflective |
| ARE | activated reactive evaporation |
| ARXPS | angle resolved X-ray photoelectron spectroscopy |
| ASF | atomic sensitivity factor |
| ASH | atomic scale heating |
| ATR | attenuated total reflection |
| BARE | biased activated reactive evaporation |
| BE | binding energy |
| BF | bright field |
| CARS | coherent anti-Stokes Raman scattering |
| CCD | charge-coupled device |
| CCP | capacitively coupled plasma |
| CDC | carbide-derived carbon |
| Ch | chalcogen |
| CIGS | copper indium gallium diselenide |
| CIP | chemical ion plating |
| CIS | copper indium diselenide |
| CMA | coaxial cylindrical mirror analyzer |
| C:Me | metal-containing carbon |
| COF | coefficient of friction |
| CQ | collisional quenching |
| CSD | charge state distribution |
| CTEM | conventional transmission electron microscopy |
| CVD | chemical vapor deposition |
| DBD | dielectric barrier discharge |
| DC-MS | direct-current magnetron sputtering |
| DF | dark field |

| | |
|---|---|
| DFT | density functional theory |
| dHB | duMond–Hart–Bartels |
| DIET | desorption induced by electronic transitions |
| DLC | diamond-like carbon |
| DRAM | dynamic random access memory |
| DRS | direct recoiling spectroscopy |
| DRV | dimer row vacancy |
| DVD | directed vapor deposition |
| DVL | dimer vacancy line |
| EAG | Evans Analytical Group |
| EB | electron beam |
| EBSD | electron backscattering diffraction |
| EC | electrochromic |
| ECR | electron cyclotron resonance |
| ED | electron diffraction |
| EDTA | ethylene diamine tetraacetic acid |
| EDXS | energy-dispersive X-ray spectroscopy |
| EEDF | electron energy distribution function |
| EELS | electron energy-loss spectroscopy |
| EIS | electrochemical impedance spectroscopy |
| ELNES | energy loss near-edge structure |
| ELO | epitaxial lateral overgrowth |
| EM | effective medium |
| EMA | effective medium approximation |
| EMSL | Environmental Molecular Sciences Laboratory |
| ER | erosion resistance |
| ERDA | elastic recoil detection analysis |
| ERD-TOF | elastic recoil detection in the time-of-flight regime |
| ESCA | electron spectroscopy for chemical analysis |
| ESD | electron-stimulated desorption |
| ESZM | extended structure zone model |
| ETFE | ethylene-tetrafluoroethylene |
| EXAFS | X-ray absorption fine structure |
| EXELFS | extended electron energy loss fine structure |
| FCA | filtered cathodic arc |
| FCC | Federal Communications Commission |
| FHC | fused hollow cathode |
| FIB | focused ion beams |
| FTIR | Fourier transform infra-red spectroscopy |
| GB | grain boundary |
| GDMS | glow discharge mass spectrometry |

| | |
|---|---|
| GLAD | glancing angle (of incidence) deposition |
| GMR | giant magnetoresistance |
| GRIN | gradient-index |
| GRXRD | glancing-incidence X-ray diffraction |
| HA | hydroxyapatite |
| HAADF | high-angle annular dark field |
| HEIS | high-energy ion scattering |
| HEMT | high electron mobility transistor |
| H-HEAD | hybrid hollow electrode activated discharge |
| HIPIMS | high-power impulse magnetron sputtering |
| HMCTSZN | hexamethyl cyclotrisilazane |
| HMDSN | hexamethyl disilazane |
| HMDSO | hexamethyl disiloxane |
| HPPMS | high-power pulsed magnetron sputtering |
| HRPVD | high-rate physical vapor deposition |
| HRTEM | high-resolution transmission electron microscopy |
| HRXRD | high-resolution X-ray diffraction |
| IA | ion assist |
| IAD | ionization assisted deposition |
| IBAD | ion beam assisted deposition |
| IBED | ion beam enhanced deposition |
| IC | integrated circuit |
| IC | internal conversion |
| ICP | inductively coupled plasma |
| IEA | ion energy analyzer |
| IEDF | ion energy distribution function |
| IGC | inert gas condensation |
| IMFP | inelastic mean free path |
| IPA | isopropyl alcohol |
| IPVD | ionized physical vapor deposition |
| IR | infrared |
| ISC | intersystem crossing |
| ISE | ion-induced secondary electron |
| ISS | ion scattering spectroscopy |
| ITO | indium–tin oxide |
| ITU | International Telecommunications Union |
| IVD | ion vapor deposition |
| JVD | jet vapor deposition |
| KE | kinetic energy |
| KPZ | Kardar–Parisi–Zhang |
| LAFAD | large-area filtered arc deposition |

| | |
|---|---|
| LAIGC | laser-assisted inert gas condensation |
| LC | liquid crystal |
| LEED | low-energy electron diffraction |
| LEIS | low-energy ion scattering |
| LEL | lower explosive limit |
| LIF | laser induced fluorescence |
| LML | liquid multilayer |
| LPPD | low-pressure plasma deposition |
| LSCF | lanthanum strontium cobalt iron oxide |
| MBE | molecular beam epitaxy |
| MD | molecular dynamics |
| MDP | molecularly doped polymer |
| MEIS | medium-energy ion scattering |
| MEMS | microelectromechanical system |
| MF | mid-frequency |
| MF/DMS | mid-frequency/dual magnetron sputtering |
| MH | Mullins–Herring |
| MIM | metal–insulator–metal |
| ML | monolayer |
| MLD | molecular layer deposition |
| MNS | metal-nitride semiconductor |
| MOCVD | metal-organic chemical vapor deposition |
| MoDTC | molybdenum dialkyl dithiocarbamate |
| MS | magnetron sputtering |
| MS | mass spectrometry |
| MSRI | mass spectroscopy of recoiled ions |
| MW | microwave |
| nc | nanocomposite |
| NCD | nanocrystalline diamond |
| NIR | near infrared |
| NIST | National Institute of Standards and Technology |
| NPL | National Physical Laboratory |
| NRA | nuclear reaction analysis |
| NSOM | near-field scanning optical microscopy |
| OCP | open circuit potential |
| OES | optical emission spectroscopy |
| OIF | optical interference filter |
| OLED | organic light-emitting device |
| OTR | oxygen transmission rate |
| PACVD | plasma-assisted chemical vapor deposition |
| PC | polycarbonate |
| PC | photonic crystal |

| | |
|---|---|
| pc-D | polycrystalline diamond |
| PECVD | plasma-enhanced chemical vapor deposition |
| PET | polyethylene terephthalate |
| PICVD | plasma impulse chemical vapor deposition |
| PIIID | plasma immersion ion implantation deposition |
| PIXE | proton-induced X-ray emission |
| PLD | pulsed laser deposition |
| PLZT | lead lanthanum zirconate titanate |
| PML | polymer multilayer |
| PMMA | polymethyl methacrylate |
| PMS | plasma mass spectrometry |
| PPFC | plasma polymerized fluorocarbon |
| PPHC | plasma polymerized hydrocarbon |
| PPML | plasma polymer multilayer process |
| PPOS | plasma polymerized organosilicone |
| PTFE | polytetrafluoroethylene |
| PVD | physical vapor deposition |
| PZT | lead–zirconium–titanate |
| QA | QuinAcridone |
| QD | quantum dot |
| RBS | Rutherford backscattering spectrometry |
| RF | radio frequency |
| RHEED | reflection high-energy electron diffraction |
| RIE | reactive ion etching |
| RIP | reactive ion plating |
| RMS | Roughness Measurement System |
| RPE | reactive plasma etching |
| RS | Raman spectroscopy |
| RT | room temperature |
| RTSE | real-time spctroscopic ellipsometry |
| SAE | Society of Automotive Engineers |
| SAED | selected area electron diffraction |
| SBD | serial bideposition |
| SCF | supercritical fluid |
| SEG | selective epitaxial growth |
| SEM | scanning electron microscopy |
| SERS | surface-enhanced Raman spectroscopy |
| SIMS | secondary ion mass spectroscopy |
| S-K | Stranski–Krastanow |
| SPM | scanning probe microscopy |
| SS | stainless steel |
| SST | supersonic transport |

| | |
|---|---|
| STEM | scanning transmission electron microscopy |
| STF | sculptured thin film |
| STM | scanning tunneling microscopy |
| SZM | structure zone model |
| TACVD | thermally activated CVD |
| TCO | transparent conductive oxide |
| TCP | tricalcium phosphate |
| TE | transverse electric |
| TEG | triethyl gallium |
| TEM | transmission electron microscopy |
| TEOS | tetra ethoxysilane |
| TEOT | tetra ethoxy titanium |
| TFEL | thin film electroluminescent |
| TIPT | tetraisopropyltitanate |
| TLK | Terrace, Ledge, Kink |
| TM | transverse magnetic |
| TMA | trimethyl-aluminum |
| TMAA | trimethyl-amine alane |
| TMG | trimethyl gallium |
| TOF | time-of-flight |
| TPD | thermally programmed desorption |
| TPO | thermoplastic olefin |
| TRPL | time-resolved photoluminescence |
| UHV | ultrahigh vacuum |
| ULSI | ultra large scale integration |
| UV | ultraviolet |
| VASE | variable angle spectroscopic ellipsometry |
| VLSI | very large scale integration |
| VOC | volatile organic compound |
| VPD | vacuum polymer deposition |
| VPE | vapor phase epitaxy |
| VR | vibrational relaxation |
| VUV | vacuum ultraviolet |
| WVTR | water vapor transmission rate |
| XANES | X-ray absorption near-edge structure |
| XPS | X-ray photoelectron spectroscopy |
| XRD | X-ray diffraction |
| XRR | X-ray reflectivity |
| XTEM | cross-sectional transmission electron microscopy |
| YSZ | yttria-stabilized zirconia |
| ZDDP | zinc dialkyl dithiophosphate |

# Contents