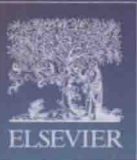


Second Edition



Donald M. Mattox

# Handbook of Physical Vapor Deposition (PVD) Processing

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Donald M. Mattox



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

William Andrew is an imprint of Elsevier

**W** William  
Andrew  
Applied Science Publishers

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 1998  
Second edition 2010

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#### **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 available from the Library of Congress

ISBN: 978-0-8155-2037-5

For information on all Elsevier publications visit  
our web site at [books.elsevier.com](http://books.elsevier.com)

Typeset by MPS Limited, a Macmillan Company, Chennai, India  
[www.macmillansolutions.com](http://www.macmillansolutions.com)

Printed and bound in The United States of America

10 11 12 13 14 15 10 9 8 7 6 5 4 3 2 1

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# ***Handbook of Physical Vapor Deposition (PVD) Processing***

**Second edition**

## ***Dedication***

### ***To my wife Vivienne***

*Without Vivienne's constant support, encouragement,  
and editorial assistance, this edition would not exist.*

## ***Preface to First Edition***

The motivation for writing this book is that there is no single source of information which covers all aspects of Physical Vapor Deposition (PVD) processing in a comprehensive manner. The properties of thin films deposited by PVD processes depend on a number of factors, and each must be considered when developing a reproducible process and obtaining a high product throughput and yield from the production line.

This book covers all aspects of Physical Vapor Deposition (PVD) process technology from the characterizing and preparing the substrate material, through deposition processing and film characterization, to post deposition processing. The emphasis of the book is on the aspects of the process flow that are critical to reproducible deposition of films that have the desired properties.

The book covers both neglected subjects such as film adhesion, substrate surface characterization, and the eternal processing environment, as well as widely discussed subjects such as vacuum technology, film properties, and the fundamentals of individual deposition processes. In this book the author relates these subjects to the practical issues that arise in PVD processing, such as contamination control and substrate property effects on film growth, which are often not discussed or even mentioned in the literature. By bringing these subjects together in one book, the author has made it possible for the reader to better understand the interrelationship between various aspects of the film deposition processing and the resulting film properties. The author draws upon his long experience with developing PVD processes, troubleshooting the processes in the manufacturing environment, and teaching short courses on PVD processing, to not only present the basics but to provide useful hints for avoiding problems, and solving problems when they arise. Some examples of actual problems and solutions (“war stories”) are provided as footnotes throughout the text. The organization of the text allows a reader who is already knowledgeable in the subject to scan through a section and find discussions that are of particular interest. The author has tried to make the subject index as useful as possible so that the reader can rapidly go to sections of particular interest. Extensive references allow the reader to pursue subjects in greater detail if desired.

An important aspect of the book is the useful reference material presented in the Appendices. A glossary of over 2500 terms and acronyms will be especially useful to those individuals that

are just entering the field and those who are not fully conversant with the English language. Many of the terms are colloquialisms that are used in the field of Surface Engineering.

The author realizes that covering this subject is a formidable task, particularly for one person, and that this effort is incomplete at best. He would like to elicit comments, corrections, and additions, which may be incorporated in a later edition of the book. In particular, he would like to elicit “war stories” of actual problems and solutions. Credit will be given for those that are used.

Donald M. Mattox  
Albuquerque, NM

## ***Preface to Second Edition***

The motivation and premise of the first edition is still applicable, but times have changed! Given a term (or an author) and any of the search engines, a vast amount of information is available to the reader on the Internet. In the second edition, I have taken particular care to have terms, synonyms, acronyms, antonyms, and related terms that can be searched for on the internet for more information. There have been some major changes in processing techniques in the last ten years, namely the introduction of HIPIMS and HIPIMS+, the increased use of chemical vapor precursors in reactive PVD processing, and the increased development of thick and nanolayered PVD coatings, particularly for tribological applications. The importance of gas/vapor flow and control in reactive PVD and PECVD processes has led to the addition of Chapter 4 on “The Sub-Atmospheric Processing Environment” and the change of the title of Chapter 3 from “The Low-Pressure Gas and Vacuum Processing Environment” to “The “Good” Vacuum (Low Pressure) Processing Environment.”

Donald M. Mattox  
Management Plus, Inc.  
Albuquerque, NM  
March 2010



## ***Acknowledgements***

The author would like to thank Sandia National Laboratories for supporting his work in PVD processing for many years. He would also like to thank the Society of Vacuum Coaters for permission to use many of the figures that were developed for the *Education Guides to Vacuum Coating Processing* (SVC Publications – 2009). These guides are one-page descriptions of various aspects of PVD processing written in order to “chunk” the information for easy learning.

Most of all, the author would like to thank his wife, Vivienne, for the encouragement and vast amount of help that have made this second edition possible.

# *Acronyms Used in Vacuum Coating and Surface Engineering*

## **A**

a ( $\alpha$ )	Amorphous (Example: a-Si), Optical adsorption coefficient ( $\text{cm}^{-1}$ )
A	Ampere
Å	Ångstrom
AAS	Atomic absorption spectroscopy
ABS	Acrylonitrile butadiene styrene; Alky-benzene-sulfonate detergent
ABST <sup>TM</sup>	Arc-bonded sputtering
ACGIH	American Conference of Governmental Industrial Hygienists
a-C	Amorphous carbon
a-C:H	Amorphous hydrogen-containing carbon (one form of diamond-like carbon)
AC	Alternating current
ACS	American Chemical Society
AEM	Analytical electron microscopy
AES	Auger electron spectroscopy
AESF	American Electroplaters and Surface Finishers
AF	Audio frequency
AFM	Atomic force microscope; Atomic force microscopy; Abrasive flow machining
AIMCAL	Association of Industrial Metallizers, Coaters and Laminators, Inc.
AIP	American Institute of Physics
ALD	Atomic layer deposition
AMLCD	Active-matrix liquid crystal display
AMR	Anisotropic magnetoresistive
amu	Atomic mass unit
ANSI	American National Standards Institute
AO	Atomic oxygen
APC	Adaptive process control
APCVD	Atmospheric pressure chemical vapor deposition

APGD	Atmospheric pressure glow discharge
APIMS	Atmospheric pressure ionization mass spectrometry
APP	Atmospheric pressure plasma
APS	American Physical Society
AR	Antireflective
ARAS	Antireflective/antistatic
ARC	Antireflective coating
ARE	Activated reactive evaporation
ARF	Argon fluoride
ARIP	Activated reactive ion plating
ARO	After receipt of order
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
ASIC	Application-specific integrated circuit
ASM	ASM International (previously American Society for Metals; now ASM International)
ASME	American Society of Mechanical Engineers
ASNT	American Society for Non-destructive Testing
ASQC	American Society for Quality Control
ASTM	American Society for Testing and Materials
atm	Atmosphere (usually standard atmosphere)
at%	Atomic per cent
AVEM	Association of Vacuum Equipment Manufacturers (more correctly known as AVEM International)
AVS	The society that used to be known as the American Vacuum Society

## **B**

B	Magnetic field (vector)
BAG	Bayard–Alpert gauge
BARE	Bias active reactive evaporation
BBAR	Broad band antireflection
bcc	Body-centered cubic (crystallography)
BOPP	Biaxially oriented polypropylene
bp	Boiling point
BP	Bandpass (filter)
BPSG	Borophosphosilicate glass
BRDF	Bidirectional reflectance distribution function (light)
BSC	Black sooty crap

## C

c	Velocity of light in a vacuum, crystalline
C	Capacitance; Degrees centigrade; Coulomb; ceiling
CAD	Computer-aided design
CAM	Computer-aided manufacturing
CAPVD	Cathodic arc physical vapor deposition
CAS	Chemical abstract service
CASING	Crosslinking by activated species of inert gas
CASS	Copper-accelerated acetic acid salt spray
cc	Cubic centimeter
CCAI	Chemical Coaters Association International
CCC	Chromate conversion coating
CCD	Charged-coupled device
CCW	Counterclockwise
cd	Candela
CD	Compact disc; Critical dimension; Cross direction
CDG	Capacitance diaphragm gauge
CDMS	Chlorodimethylsilane
CD-R	Compact disc-recordable
CE	<i>Conformité européenne</i>
CEVC	Completely enclosed vapor cleaner
CF <sup>TM</sup>	Conflat (vacuum flange)
CFC	Chlorofluorocarbon
CFC-111	Trichloroethane
CFC-113	Trichlorotrifluoroethane
cfm	Cubic feet per minute
cfs	Cubic feet per second
CGA	Compressed Gas Association
cgs	Centimeter–gram–second system of measurement
CIE	Commission International de l'Eclairage (International Commission on Illumination)
CIGS	Copper–indium–gallium–diselenide
CLA	Center line average
CLEO	Conference on Laser and Electro-Optics
cm	Centimeter
cmh	Cubic meters per hour
CMM	Converting machinery/materials
CMOS	Complementary metal oxide semiconductor
CMP	Chemical–mechanical polishing; Chemical–mechanical planarization

CN	Coordination number
CNDP	Cold neutron depth profile
COO (CoO)	Cost of ownership
CNT	Carbon nanotube
CPP	Cast polypropylene
CPWR	Coupled plasmon-waveguide resonance
CrP	Chromium-rich oxide passivation
CRT	Cathode ray tube
CSP	Concentrated solar power (solar thermal)
CTE	Coefficient of thermal expansion
CTMS	Chlorotrimethylsilane
C-V	Capacitance-voltage
CVD	Chemical vapor deposition
CW	Clockwise

## **D**

d	Day
dc	Direct current (preferable to DC)
D-CVD	Dielectric-chemical vapor deposition
DBD	Dielectric barrier discharge
DCS	Dichlorosilane
di-	2; Two
DI	Deionized
Diff	Diffusion pump
DIO	Deionized and -ozonated (water)
DIW	Deionized water
DLC	Diamond-like carbon
DLF	Diamond-like films
DMS	Dual magnetron sputtering
DMSO	Dimethyl sulfoxide
DOE	Department of Energy (US); Design of experiments
DOI (Doi)	Digital object identifier (intellectual property)
DOP	Diethyl phthalate
DOT	Department of Transportation
DOVID	Diffraction optically variable image device
DP	Diffusion pump
DRAM	Dynamic random access memory
DTIC	Defense Technical Information Center (US)

DVD	Directed vapor deposition
DUV	Deep ultraviolet
DWDM	Dense wavelength division multiplexing
dwt	Pennyweight

## E

E	Emissivity; Electric field (vector); Elastic modulus
e	Exponential
EB (eb)	Electron beam
e-beam	Electron beam
ECD	Electrochemical deposition
ECM	Electrochemical machining
ECR	Electron cyclotron resonance
ECS	Electrochemical Society
EDM	Electrodischarge machining
EDX	Energy-dispersive X-ray
EDTA	Ethylene diamine tetraacetic acid
EELS	Electron energy loss spectroscopy
EHC	Electrolytic hard chrome
IES	Electron impact emission spectroscopy
EL	Electroplated
ELD	Electroluminescent display (flat panel)
EM	Electromigration
emf	Electromotive force
EMI	Electromagnetic interference
EN	Electroless nickel
EPA	Environmental Protection Agency
epi	Epitaxial
EPMA	Electron probe X-ray microanalysis
ERA	Evaporative rate analysis
ERD	Elastic recoil detection
ES&H	Environmental Safety and Health
ESCA	Electron spectroscopy for chemical analysis
ESD	Electrostatic discharge
EU	European Union
EUV	Extreme ultraviolet
eV	electron volt

**F**

F	Farad; Free machining (steel)
FC	Fault classification
fcc	Face centered cubic
FD	Fault detection
FDD	Floppy disc drive
FEC	Field emission cathode
FED	Field emission display; Field emission diode
FE-SEM	Field emission-scanning electron microscopy
FET	Field effect transistor
FF	Fill factor
FIB	Focused ion beam
FIFO	First in first out
FIM	Field ion microscopy
FLIR	Forward-looking infrared (7.5 to 12 $\mu\text{m}$ )
FPC	Fixed process control; Flexible printed circuits
FPD	Flat panel display
fpm	Feet per minute
FTIR	Fourier transform infrared
FTO	Fluorine-doped tin oxide

**G**

g	Unit of gravitational acceleration; Gram
G	Giga (suffix for $10^9$ ); Unit of magnetic field strength (Gauss); Gallons; Unit of acceleration due to gravity
GANA	Glass Association of North America
GDMS	Glow discharge mass spectrometry
GDOES	Glow discharge optical emission spectroscopy
GFCI	Ground fault circuit interrupter
GLAD	Glancing angle deposition
GPM	Gallons per minute
gr	Grain
GWP	Global warming potential

**H**

h	Planck's constant; Hour; Hecto ( $10^2$ )
H	Henry (unit of inductance); Hardness

HAD	Hollow cathode-assisted deposition
HAP	Hazardous air pollutants
HAZ	Heat-affected zone; Hazardous (material)
HCD	Hollow cathode discharge
HCFC	Hydrochlorofluorocarbon
HCL	Hollow cathode lamp; Hydrochloric acid
hcp	Hexagonal close-packed
HDD	Hard disk drive
HDP-CVD	High density plasma chemical vapor deposition
HEED	High energy electron diffraction
HEPA	High efficiency particle air (see also ULPA)
HF	Hydrofluoric acid
HFCVD	Hot filament chemical vapor deposition
HFE	Hydrofluoroether
HIP	Hot isostatic processing
HIPIMS	High power impulse magnetron sputtering
HIPIMS+	Modulated pulse power (MPP) HIPIMS
HK	Knoop hardness
HLB	Hydrophilic–lipophilic balance
HMC	Hybrid micro circuit
HMCTSO	Hexamethylcyclotrisiloxane
HMDSO	Hexamethyldisiloxane
hPa	Hectopascals
HPPMS	High power pulse magnetron sputtering
HRI	High refractive index
HV	Vickers hardness
HVOF	High velocity oxygen fuel
HWOT	Half wave optical thickness
Hz	Hertz (cycles per second)

## I

i	Prefix used to indicate that the film was formed using beam-type film ion deposition. Examples: i-C; i-BN
IAD	Ion-assisted deposition
IARC	International Agency for Research on Cancer (establishes carcinogenicity of materials)
IBA	Ion beam analysis
IBAD	Ion beam-assisted deposition
IBAE	Ion beam-assisted etching



IBED	Ion beam-enhanced deposition
IBEST™	Ion beam surface treatment
IC	Integrated circuit
ICB	Ionized cluster beam (deposition)
ICP	Inductively coupled plasma
ICP-MS	Inductively coupled plasma mass spectrometer
ID	Internal diameter
IDLH	Immediately dangerous to life or health
IDM	Integrated device manufacturing
IEEE	Institute of Electrical and Electronic Engineers
IES	Institute of Environmental Sciences
IG	Ionization gauge
IGU	Insulated glass unit (double glazing)
ILD	Interlayer dielectric
IMD	Intermetal dielectric
IMEMS	Integrated microelectromechanical systems
$I_{oc}$	Open circuit current (solar cell)
IP	Intellectual property
IPA	Isopropyl alcohol
IPC	Institute for Interconnecting and Packaging Electronic Circuits; International patent classification
iPVD	Ionized physical vapor deposition
I-PVD	Ion-assisted physical vapor deposition
IR	Infrared
$I_{sc}$	Short circuit current (solar cell)
ISCST	International Society of Coating Science and Technology
ISHM	International Society for Hybrid Microelectronics
ISO	International Standards Organization
ISS	Ion scattering spectroscopy
IT	Information technology; Internet transactions
ITO	Indium–tin oxide alloy (90:10)
I-V	Current-voltage
IVD	Ion vapor deposition
IWFA	International Window Film Association

## J

J	Joule; Electric current (vector)
JVST	Journal of Vacuum Science and Technology