

PHYSICAL VAPOR DEPOSITION OF THIN FILMS

JOHN E. MAHAN

Colorado State University



A Wiley-Interscience Publication

JOHN WILEY & SONS, INC.

New York • Chichester • Weinheim • Brisbane • Singapore • Toronto

CONTENTS

PREFACE	xv
I Introduction to Physical Vapor Deposition	1
I.1 Physical Vapor Deposition Technologies and Their Basic Physical Science, 1	
Overview, 1	
Kinetic Theory, 5	
Adsorption and Condensation, 8	
High Vacuum, 12	
Sputtering Discharges, 14	
I.2 Summary of Principal Equations, 16	
I.3 Mathematical Symbols, Constants, and Their Units, 17	
Reference, 18	
II The Kinetic Theory of Gases	19
II.1 Statistics, 20	
The Boltzmann Distribution, 20	
Characteristic Particle Speeds, 22	
II.2 Collisions, 23	
Impingement Rate and Incident Flux Angular Distribution, 23	
The Ideal Gas Law, 26	
Mean Free Path, 27	

- II.3 Properties, 30
 - Heat Capacity; the Ideal Diatomic Gas, 30
 - Diffusivity, 31
 - Viscosity, 32
 - Thermal Conductivity, 34
- II.4 Gas Flow, 34
 - Flow Regimes, 34
 - Viscous Laminar Flow, 35
 - Molecular Flow, 36
 - Conductance, 37
- II.5 Units of Pressure and Amounts of Gas, 38
 - Units of Pressure, 38
 - Amounts of Gas, 39
- II.6 Summary of Principal Equations, 39
- II.7 Appendix, 40
 - Arrhenius Plots, 40
 - Some Definite Integrals, 41
 - Atomic Diameters of the Elements, 42
- II.8 Mathematical Symbols, Constants, and Their Units, 43
 - References, 44

III Adsorption and Condensation

45

- III.1 Adsorption of Gases, 47
 - Why Gases Adsorb, 47
 - Mean Residence Time, 49
 - Langmuir's Adsorption Isotherm, 49
 - Atomic Layer Epitaxy, 53
- III.2 Vapor Pressure, 57
 - The Thermally Activated Vapor Pressure, 57
 - Vapor Pressure Data for the Elements, 58
 - Vapor Pressures of Alloys and Compounds, 60
- III.3 Condensation of Vapors, 62
 - Condensation of Pure Elements, 62
 - Condensation of Compounds that Produce
 - a Stoichiometric Vapor, 64
 - Flash Evaporation of Compounds that Dissociate, 65
 - Steady-State Techniques for Alloy Films, 65
 - Coevaporation with the Three-Temperature Method, 67

	Reactive Evaporation and Sputtering, 70	
III.4	Summary of Principal Equations, 71	
III.5	Appendix: Thermodynamic Fundamentals, 72	
	The Thermodynamic Potentials and the First and Second Laws, 72	
	The Gibbs Free Energy: The Relevant Potential for Equilibria at Fixed Temperature and Pressure, 73	
	Standard Reaction and Formation Quantities, and the Equilibrium Constant, 74	
	Standard Thermochemical Data, 76	
III.6	Mathematical Symbols, Constants, and Their Units, 79	
	References, 80	
IV	Principles of High Vacuum	83
IV.1	Basic Vacuum Concepts, 84	
	Pumping Speed, 84	
	Throughput, 87	
	A Throughput Law, 88	
	Conductance, 93	
IV.2	Behavior of Real Vacuum Systems, 94	
	A More Realistic Vacuum System Model, 94	
	Desorption, Outgassing, and Permeation, 96	
IV.3	Operation Principles of Vacuum Pumps and Gauges, 99	
	How Seven Important Pumps Work, 99	
	Two Vacuum Gauges in Widespread Use: The Thermocouple and Ionization Gauges, 105	
IV.4	Summary of Principal Equations, 107	
IV.5	Appendix, 107	
	How to Draw and Analyze Vacuum Schematic Diagrams, 107	
	An Electrical Network Analogy, 108	
	A Survey of Past Definitions of Throughput, 111	
IV.6	Mathematical Symbols, Constants, and Their Units, 112	
	References, 112	
V	Evaporation Sources	115
V.1	The Effusion Cell and Nozzle-Jet Evaporation Sources, 117	
	The Ideal Effusion Cell, 117	
	The Cosine Law of Emission, 118	

- The Nonequilibrium Effusion Cell, 119
- The Near-Ideal Effusion Cell, 121
- The Open-Tube Effusion Cell, 123
- The Conical Effusion Cell, 124
- The Nozzle-Jet Source, 125
- V.2 Free Evaporation Sources, 127
 - Free Evaporation, 127
 - The Ideal Point Source Model, 129
 - How E-Gun Evaporators Work, 129
 - Beam Intensity of the E-Gun Evaporator, 131
- V.3 Pulsed Laser Deposition, 133
 - Laser-Induced Vaporization, 133
 - A Simple Heating Model, 135
 - Other Phenomena, 141
- V.4 Materials Aspects of Evaporation Sources, 143
 - Evaporation Temperatures of the Elements, 143
 - The Problem of Composition Change in the
Evaporation of Alloys, 144
 - Crucible Interactions, 146
- V.5 Summary of Principal Equations, 147
- V.6 Mathematical Symbols, Constants, and Their Units, 148
 - References, 149

VI Principles of Sputtering Discharges

153

- VI.1 Sputtering Arrangements, 155
 - DC Sputtering, 155
 - RF Sputtering, 156
 - The Magnetron, 157
 - Other Sputtering Arrangements, 158
- VI.2 A Practical Sputtering Plasma and its Current Densities
and Potentials, 159
 - A Practical Sputtering Plasma, 159
 - The Ideal Langmuir Probe, 161
 - An Experimental Langmuir Probe Characteristic, 165
 - The Enhanced Ion Current Density, 165
 - The Probe Sheath, 168
- VI.3 Gaseous Discharges for Sputtering, 170
 - A DC Discharge Model, 170

	The Cathode and Anode Sheaths, 174	
	The Sputtering Projectiles that Bombard the Cathode, 176	
	An RF Discharge Model, 178	
	The RF Sheaths, 182	
VI.4	Summary of Principal Equations, 183	
VI.5	Appendix, 184	
	The Voltage–Current Characteristic of a DC Discharge, 184	
	The Voltage–Current Characteristic of an RF Discharge, 189	
	The DC Glow, 190	
	The RF Glow, 193	
	Exceptions to the Above, 193	
VI.6	Mathematical Symbols, Constants, and Their Units, 195	
	References, 196	
VII	Sputtering	199
VII.1	General Characteristics and Background, 199	
	Definition of Sputtering, 199	
	The Mechanisms of Sputtering, 201	
	A Brief History of Sputtering Theory and Simulation, 203	
	Sources of Sputter Yield Data, 205	
VII.2	Trends in Sputter Yield Data, 206	
	Projectile Energy Dependence, 207	
	Dependence on Surface Binding Energy, 212	
	Dependence on Choice of Projectile, 214	
	Effect of Angle of Incidence, 214	
	Energy Distribution of Sputtered Particles, 219	
	Angular Distribution of Sputtered Particles, 220	
	Single-Crystal Targets, 222	
	Target Conditioning and Dose Effects, 222	
VII.3	Basic Concepts for Modeling, 223	
	The Surface Binding Energy, 223	
	Energy Transfer in Binary Elastic Collisions of Hard Spheres, 225	
	Threshold Energy for Sputtering at Normal Incidence, 227	
	Nuclear Energy Loss Theory, 229	
	Linear Cascade Theory, 232	

- VII.4 A Simplified Collisional Model for Sputter Yield, 238
 - A Yield Expression, 238
 - Predictions, 241
 - Summary, 244
- VII.5 An Ideal Sputter Deposition Source, 245
 - The Cosine Law of Emission, 245
 - The Beam Intensity of a Sputtering Source, 247
 - Combined Internal Flux Spectra for the Simplified Collisional Model, 248
 - Combined External Spectra Assuming the Spherical Surface Binding Model, 248
 - Combined External Spectra Assuming the Planar Surface Binding Model, 249
- VII.6 Summary of Principal Equations Not Found in the Sample Calculation of Yield, 250
- VII.7 Appendixes, 251
 - Appendix A: The Empirical Yield Formula of Matsunami et al. [1984], 251
 - Appendix B: A Summary of Target Parameters, 252
 - Appendix C: Some Collisional Sputtering Theories, 256
 - Appendix D: A Sample Calculation of Yield with the Simplified Collisional Model, 258
- VII.8 Mathematical Symbols, Constants, and Their Units, 259
 - References, 260

VIII Film Deposition

265

- VIII.1 Incident Flux and Film Deposition Rate, 267
 - The Incident Flux at the Substrate, 267
 - Film Deposition Rate, 269
 - Associated Substrate Heating Mechanisms, 272
- VIII.2 Film Thickness Profiles of the Ideal Small Source, 277
 - Three Fundamental Receiving Surfaces, 277
 - The Moving-Shutter Technique, 278
- VIII.3 Thermalization and Ionization of the Sputtered Beam, 281
 - The Thermalization Distance, 283

	Reduction of the Incident Flux, 283
	Ionized Physical Vapor Deposition, 286
VIII.4	Deposition with Substrate Rotation and with Ideal Large Sources, 289
	Off-Axis Substrate Rotation, 290
	A Large Disk Source with a Planar Substrate, 291
	A Large Ring Source, 293
VIII.5	Deposition Monitors, 295
	The Quartz Crystal Microbalance, 295
	True Flux Sensors, 298
VIII.6	Summary of Principal Equations, 300
VIII.7	Appendix: Some Definite Integrals, 300
VIII.8	Mathematical Symbols, Constants, and Their Units, 301
	References, 302