HANDBOOK OF VACUUM SCIENCE AND TECHNOLOGY

Edited by

Dorothy M. Hoffman
(deceased)

Bawa Singh

David M. Sarnoff Research Center
Princeton, New Jersey

John H. Thomas, III

3M Research Laboratories
St. Paul, Minnesota

ACADEMIC PRESS

San Diego London Boston
New York Sydney Tokyo Toronto

Contents

Preface xvii

List of Contributors xxi

Part 1 Fundamentals of Vacuum Technology and Surface Physics 1

1.1 Vacuum Nomenclature and Definitions 3
1.1.1 Basic Definition 3
1.1.2 Pressure Regions of Vacuum 3
1.2 Gas Properties 8
1.2.1 Description of Vacuum as a Low-Pressure Gas 8
1.2.2 Characteristics of a Gas — Basic Definitions 8
1.2.3 Gas Laws 9
1.3 Molecular Processes and Kinetic Theory 11
1.3.1 General Description 11
1.3.2 Molecular Motion 12
1.3.3 Kinetic Theory Derivation of the Gas Laws 14
1.3.4 Pressure 15
1.3.5 Molecular Mean Free Path 17
1.3.6 Number of Impacts with the Chamber Wall 19
1.3.7 Time to Form a Monolayer 20
1.3.8 Thermal Transpiration 20
1.3.9 Coefficient of Thermal Conductivity 21
1.3.10 Coefficient of Diffusion 21
1.4 Throughput, Pumping Speed, Evacuation Rate, Outgassing Rate, and Leak Rate 22
1.5 Gas Flow 25
1.5.1 Nature of Gas Flow 25
1.5.2 Turbulent Flow 27

1.5.3 Viscous, Streamline, or Laminar Flow 28
1.5.4 Molecular Flow 29
1.5.5 Flow Relationships 29
1.6 Conductance 32
1.6.1 Conductance 32
1.6.2 Conductances in Parallel 33
1.6.3 Conductances in Series 33
1.7 Flow Calculations 35
1.7.1 Equations for Viscous Flow 35
1.7.2 Equations for Molecular Flow 37
1.7.3 Knudsen's Formulation 37
1.7.4 Clausing Factors 38
1.8 Surface Physics and Its Relation to Vacuum Science 40
1.8.1 Physical Adsorption or "Adsorption" 40
1.8.2 Chemisorption 42
1.8.3 Sticking Coefficient 43
1.8.4 Surface Area 44
1.8.5 Surface Adsorption Isotherms 45
1.8.6 Capillary Action 47
1.8.7 Condensation 48
1.8.8 Desorption Phenomena 49
1.8.9 Thermal Desorption 50
1.8.10 Photoactivation 52
1.8.11 Ultrasonic Desorption 53
1.8.12 Electron- and Ion-Stimulated Desorption 53
1.8.13 Gas Release from Surfaces 54
References 55

Part 2 Creation of Vacuum 57

2.1 Technology of Vacuum Pumps — An Overview 59
2.1.1 Vacuum Pump Function Basics 59
2.1.2 Gas Transport: Throughput 61
2.1.3 Performance Parameters 62
2.1.4 Pumping Speed 64
2.1.5 Pumpdown Time 65
2.1.6 Ultimate Pressure 69
2.1.7 Forevacuum and High-Vacuum Pumping 71
2.1.8 Pump System Relationships 73
2.1.9 Crossover from Rough to High-Vacuum Pumps 78
2.1.10 Pumping System Design 79
References 83

2.2 Diaphragm Pumps ... 84
2.2.1 Introduction: Basics and Operating Principle ... 84
2.2.2 State-of-the-Art Design and Manufacturing ... 87
2.2.3 Performance and Technical Data ... 91
2.2.4 Modular Concept for Specific Application Setups: Standalone Operation ... 92
2.2.5 Diaphragm Pumps as Backing and Auxiliary Pumps in Vacuum Systems ... 93
References ... 96
2.3 Vacuum Blowers ... 97
2.3.1 Introduction ... 97
2.3.2 Equipment Description ... 97
2.3.3 Blower Operating Principle ... 100
2.3.4 Blower Pumping Efficiency ... 101
2.3.5 Blower Pumping Speed Calculations ... 103
2.3.6 Power Requirements ... 104
2.3.7 Temperature Considerations ... 106
2.3.8 Flow and Compression Ratio Control Mechanisms ... 108
2.3.9 Liquid-Sealed Blowers ... 112
2.3.10 Selected System Arrangements ... 112
2.4 Vacuum Jet Pumps (Diffusion Pumps) ... 116
2.4.1 Basic Pumping Mechanism ... 117
2.4.2 Pumping Speed ... 122
2.4.3 Throughput ... 127
2.4.4 Tolerable Forepressure ... 128
2.4.5 Ultimate Pressure ... 132
2.4.6 Backstreaming ... 137
2.4.7 Other Performance Aspects ... 144
References ... 148
2.5 Cryogenic Pumps ... 149
2.5.1 Introduction ... 149
2.5.2 Cryopump Basics ... 156
2.5.3 Advanced Control Systems ... 167
2.5.4 Cryopump Process Applications ... 173
2.5.5 Cryogenic Pumps Specifically for Water Vapor ... 177
2.5.6 Comparison of Cryopumps to Other Types of Pumps ... 179
2.5.7 Future Developments ... 181
References ... 181
2.6 Turbomolecular Pumps ... 183
2.6.1 Turbomolecular Pumps (TMP) ... 183
2.6.2 Molecular Drag Pumps (MDP) ... 195
2.6.3 Combination of Pumps (TMP + MDP) ... 197

2.6.4 Evaluation of Combinations of Backing Pumps and TMPs, Etc.. 200
2.6.5 The Use of TMP in Applications: Specific Effects and Demands 208
2.6.6 Avoiding Operational Mistakes 211
References 212
2.7 Pumps for Ultra-High Vacuum Applications 214
2.7.1 System Design for Ultra-High Vacuum. 215
2.7.2 The Selection of Pumps for Ultra-High Vacuum Applications. 216
2.7.3 Sputter-Ion Pumps 220
2.7.4 Getter Pumps 242
References 252

Part 3 Vacuum Measurements 255

3.1 The Measurement of Low Pressures 257
3.1.1 Overview 258
3.1.2 Direct Reading Gauges 260
3.1.3 Indirect Reading Gauges 265
3.1.4 Calibration of Vacuum Gauges 286
References 288
3.2 Mass Analysis and Partial Pressure Measurements. 290
3.2.1 Overview and Applications 290
3.2.2 Inlet Systems 300
3.2.3 Ion Generation and Ion Sources. 303
3.2.4 Ion Separation Analyzers. 308
3.2.5 Detection of Ions 323
References 326
3.3 Practical Aspects of Vacuum System Mass Spectrometers. 335
3.3.1 Historical Insight 335
3.3.2 Expected Gases in a Vacuum System 336
3.3.3 The Ion Generation Process. 340
3.3.4 Techniques for Analysis. 351
3.3.5 Calibration of Vacuum System Mass Spectrometers. . . . 364
3.3.6 Some Applications. 370
References 374
3.4 Mass Flow Measurement and Control. 376
3.4.1 General Principles of Mass Flow Measurement 376
3.4.2 Overview of Thermal Mass Flow Controller Technology 378
3.4.3 Performance Characteristics 382
3.4.4 Troubleshooting. 386
References 387

Part 4 Systems Design and Components 389

4.1 Selection Considerations for Vacuum Valves 391
4.1.1 Introduction 391
4.1.2 Valves for Shutoff 391
4.1.3 Valves for Control 397
4.1.4 Valve Construction. 398
4.1.5 Specialty Valves 404
4.1.6 Installation Considerations for Vacuum Valves 407
References 408
4.2 Flange and Component Systems 409
4.2.1 Introduction 409
4.2.2 Selecting a Flange System 410
4.2.3 Common Flange Systems 410
4.2.4 Components with Flanges Attached 425
Trademarks 430
References 432
4.3 Magnetic-Fluid-Sealed Rotary Motion Feedthroughs 433
4.3.1 Basic Sealing Principle 433
4.3.2 Application Factors 434
4.3.3 Impact of Feedthrough on Process 436
4.3.4 Impact of Process on Feedthrough 437
4.3.5 Materials Considerations 438
4.3.6 Application Examples 440
4.3.7 Comparison to Other Types of Feedthroughs 442
4.4 Viewports 444
4.4.1 Materials 444
4.4.2 Mounting Systems and Precautions 445
4.5 Construction Materials 446
4.5.1 Properties Defining Material Performance 446
4.5.2 Vacuum Chamber Materials 451
4.5.3 Special-Purpose Materials 455
References 462
4.6 Demountable Seals for Flanges and Valves 463
4.6.1 Sealing Overview: Polymer and Metal Seals 463
4.6.2 The Elastomeric and Nonelastomeric Polymers Used in Vacuum Sealing 464
4.6.3 Metal Seals 474
References 482
4.7 Outgassing of Materials 484
4.7.1 Relationships Among System Pressure, Pumping Speed, and Outgassing 484

4.7.2 Initial Pumpdown from Atmospheric Pressure 494
4.7.3 Pressure Vs. Time During Outgassing 495
4.7.4 The Outgassing Rate of Elastomers and Plastics 497
4.7.5 The Outgassing Rate of Metals and Ceramics 501
4.7.6 The Outgassing Rate of Preconditioned Vacuum Systems After Short Exposure to the Atmosphere 504
4.7.7 Methods of Decreasing the Outgassing Rate 506
4.7.8 Measurement of the Outgassing Rate of Materials 507
References 508
4.8 Aluminum-Based Vacuum Systems 509
4.8.1 Outgassing 509
4.8.2 Demountable Seals 512
4.8.3 Cleaning and Surface Finishing 518
4.8.4 Mechanical Considerations 520
4.8.5 Thermal Conductivity and Emissivity 536
4.8.6 Corrosion 538
4.8.7 Welding Aluminum for Vacuum Applications 541
References 548
4.9 Preparation and Cleaning of Vacuum Surfaces 553
4.9.1 Surface Modification 554
4.9.2 External Cleaning 567
4.9.3 Assembly, Handling, and Storage 587
4.9.4 *In Situ* Cleaning 591
4.9.5 Documentation 599
4.9.6 Conclusion 601
Trade Names 601
References 601

Part 5 Vacuum Applications 607

5.1 High-Vacuum-Based Processes: Sputtering 609
5.1.1 Sputtering and Deposition 611
5.1.2 Sputter Deposition Technologies 612
5.1.3 Magnetron Applications 624
5.1.4 Future Directions in Sputtering 626
References 627
5.2 Plasma Etching 628
5.2.1 Introduction 628
5.2.2 Review of Plasma Concepts Applicable to Etching Reactors 628
5.2.3 Basic Plasma Etching Requirements 633
5.2.4 Plasma Diagnostics 641
5.2.5 Basic Plasma Etch Reactors 643

5.2.6 Advanced Plasma Etch Reactors 649
5.2.7 New Trends 665
References 667
5.3 Ion Beam Technology 672
5.3.1 Introduction 672
5.3.2 Ion Beam Etching 678
5.3.3 Ion Beam Sputter Deposition 683
5.3.4 Ion-Beam-Assisted Deposition 687
5.3.5 Ion Beam Direct Deposition 689
5.3.6 Conclusion 690
References 691
5.4 Pulsed Laser Deposition 694
5.4.1 Introduction 694
5.4.2 Pulsed Laser Deposition System 695
5.4.3 The Ablation Mechanism 698
5.4.4 Advantages and Limitations 700
5.4.5 Materials Survey 705
5.4.6 Future Outlook 708
References 708
5.5 Plasma-Enhanced Chemical Vapor Deposition 711
5.5.1 Introduction 711
5.5.2 Equipment and Other Practical Considerations 717
5.5.3 Process Scaleup 723
5.5.4 Conclusion 727
References 728
5.6 Common Analytical Methods for Surface and Thin Film 731
5.6.1 Introduction 731
5.6.2 The Electron Spectroscopies 732
5.6.3 Methods Based on Ion Bombardment 745
5.6.4 UHV Generation and System Considerations for Surface Analysis 755
References 757

Part 6 Large-Scale Vacuum-Based Processes 759

6.1 Roll-to-Roll Vacuum Coating 761
6.1.1 Overview of Roll-to-Roll Vacuum Coating 761
6.1.2 Typical Products 764
6.1.3 Materials and Deposition Processes Commonly Used in Roll-to-Roll Coating 765
6.1.4 Vacuum Systems for Roll-to-Roll Coating Applications. 775
6.1.5 Substrates (Webs) 779
6.1.6 Process Control 783

6.1.7 Specific Problems Exhibited by Coatings 784
References 787
6.2 The Development of Ultra-High-Vacuum Technology for Particle Accelerators and Magnetic Fusion Devices 789
6.2.1 Introduction 789
6.2.2 Storage Rings and the Need for UHV 790
6.2.3 UHV for Early Storage Rings 793
6.2.4 Storage Ring Vacuum Vessel and Pumping System Developments.............................. 796
6.2.5 Cold-Bore Machines 798
6.2.6 Superconducting RF Accelerators 800
6.2.7 The Next-Generation Big Accelerator?............. 801
6.2.8 The Magnetic Fusion Road Map 801
6.2.9 The Early History of Magnetic Fusion 803
6.2.10 Model C: The First UHV Fusion Device............. 804
6.2.11 The Russian Revolution in Fusion: Tokamaks 805
6.2.12 Plasma Impurities and Vacuum Technology 806
6.2.13 Toward the Breakeven Demonstrations.............. 808
6.2.14 The Next Step in Fusion 810
Acknowledgments 810
References 812