Contents

1 Some Fundamental Aspects of Plasma-Assisted Etching
J.W. Coburn 1

1.1 Introduction 1
1.2 The Evolution of Plasma Etching Equipment 4
1.2.1 The "Barrel" Systems 4
1.2.2 Planar and Cylindrical Diode Systems 5
1.2.3 Planar Triode Systems 8
1.2.4 Dual Frequency Planar Triode Systems 9
1.2.5 Inductively Coupled Plasmas, Wave Generated Plasmas, etc. 9
1.3 The Role of Ions in Reactive Ion Etching 12
1.3.1 Ion-Assisted Gas-Surface Chemistry and the Resulting Etching Anisotropy 12
1.3.2 Mechanistic Aspects of Ion-Assisted Gas-Surface Chemistry 15
1.3.3 Other Factors That Influence Etching Anisotropy 18
1.4 The Influence of the Reactor Walls and Other Surfaces 22
1.4.1 The Etching Process 22
1.4.2 Polymer Deposition 24
1.4.3 Surface-Catalyzed Atom–Atom Recombination 25
1.5 Ion Beam-Based Methods 27
1.6 Summary 31
References 31

2 Plasma Fundamentals for Materials Processing
J.E. Stevens 33

2.1 Introduction 33
2.2 Single Particle Motion 36
2.3 Collision Processes 38
2.4 Velocity Distributions 43
2.5 Sheaths 45
2.6 Plasma Transport 51
2.7 Dielectric Properties 55
2.8 Plasma Sources for Thin Films Processing 57
2.8.1 Capacitive Sources 58

2.8.2 High Density Sources 59
2.8.3 Inductive Sources 60
2.8.4 ECR Sources 61
2.8.5 Helicon Sources 62
2.8.6 Wave Sources 63
2.8.7 Downstream Sources 63
References 65

3 Plasma Modeling
E. Meeks and P. Ho 69

3.1 Introduction 69
3.2 Historical Perspective 70
3.3 Plasma Modeling Issues 71
3.3.1 Well Mixed Reactor Models and Applications (0-D) 73
3.3.2 One-Dimensional Models and Applications 76
3.3.3 Two-Dimensional Models and Applications 79
3.3.4 Three-Dimensional Models and Applications 83
3.3.5 2-D and 3-D Profile Evolution Models and Applications 84
3.4 Chemical Reaction Mechanisms 84
3.4.1 Gas-Phase Kinetic and Transport Processes 86
3.4.2 Surface Chemistry 92
3.4.3 Reaction Mechanism Validation, Tuning, and Reduction 96
3.4.4 Sample Reaction Mechanism 98
3.5 Examples of Application of Plasma Modeling to Design or Optimization 103
3.5.1 Optimization of Plasma Cleaning Process to Reduce Reactor Emissions 103
3.5.2 Optimization of Chemical Downstream Etch Process Conditions 107
3.5.3 Reactor Design: Scaling-Up from 200 to 300 mm Wafers 111
3.5.4 Mapping Pressure Gradients in Reactor Pump Port and Inlet Regions 114
3.6 Future Directions of Plasma Modeling 114
References 117

4 Plasma Reactor Modeling
M. Meyyappan 123

4.1 Introduction 123
4.2 Reactor Scale Model 124
4.2.1 A Review of Various Approaches 124
4.2.2 Global Model 125
4.2.3 Continuum Reactor Model 127
4.2.4 Hybrid Model 134
4.3 Feature Level Modeling 137

4.4 Database Needs . . . 141
4.5 Concluding Remarks . . . 141
References . . . 143

5 Overview of Plasma Diagnostic Techniques
G.A. Hebner, P.A. Miller, and J.R. Woodworth . . . 145

5.1 Introduction . . . 145
5.2 Plasma Electrical Characterization . . . 146
5.2.1 Electrical Diagnostics . . . 146
5.2.2 Microwave Diagnostic Techniques . . . 167
5.2.3 Ion-Energy Analyzers . . . 171
5.3 Optical Diagnostic Techniques . . . 177
5.3.1 Optical Emission . . . 177
5.3.2 Optical Absorption Techniques . . . 185
5.3.3 Laser-Induced Fluorescence . . . 190
5.3.4 Negative Ion Photodetachment . . . 197
5.3.5 Optogalvanic Spectroscopy . . . 198
5.3.6 Thomson Scattering . . . 199
References . . . 200

6 Mass Spectrometric Characterization of Plasma Etching Processes
C.R. Eddy, Jr. . . . 205

6.1 Introduction . . . 205
6.2 Application to Fundamental Studies . . . 208
6.2.1 Silicon/Fluorine . . . 209
6.2.2 Silicon/Chlorine . . . 210
6.2.3 Gallium Arsenide/Chlorine . . . 211
6.3 Application in Etch Processing Reactors . . . 212
6.3.1 General Description of Experiments . . . 212
6.3.2 IV–IV Semiconductors . . . 212
6.3.3 III–V Semiconductors . . . 219
6.3.4 II–VI Semiconductors . . . 232
6.3.5 Metals and Perovskites . . . 239
6.3.6 Issues in Application and Interpretation . . . 244
6.4 Summary and Future Directions . . . 248
References . . . 254

7 Fundamentals of Plasma Process-Induced Charging and Damage
K.P. Giapis . . . 257

7.1 Introduction . . . 257
7.2 The Origin of Pattern-Dependent Charging . . . 260
7.2.1 Differences in Ion and Electron Angular Distributions . . . 260

7.2.2 Charging as a Result of Current Imbalance 263
7.2.3 Electron Shading Effects 264
7.3 The Notching Effect 268
7.3.1 Observations and Mechanisms 268
7.3.2 Phenomena that Influence Notching 270
7.3.3 Results from Self-Consistent Charging Simulations 275
7.3.4 Validation 279
7.4 Other Profile Effects Influenced by Charging 282
7.4.1 Reactive Ion Etching Lag 282
7.4.2 Microtrenching 285
7.5 Gate Oxide Degradation 290
7.5.1 The Driving Force for Current Injection 290
7.5.2 Tunneling Current Transients 292
7.5.3 The Influence of Electron and Ion Temperature 295
7.6 Charging Reduction Methodology 300
7.7 Concluding Remarks 303
7.7.1 Historical Perspective 303
7.7.2 Will Charging Problems Persist? 304
References 305

8 Surface Damage Induced by Dry Etching
S.W. Pang 309

8.1 Introduction 309
8.2 Surface Damage in Si 309
8.2.1 Changes in Electrical Characteristics due to Dry Etching . 310
8.2.2 Defects Evaluated by Surface Analysis 315
8.2.3 Modeling of Etch-Induced Damage 319
8.3 Surface Damage in III–V Semiconductors 325
8.3.1 Damage Dependence on Etch Conditions 326
8.3.2 Effects of Etch Time and Materials on Defect Generation . 335
8.3.3 Changes in Electrical and Optical Characteristics 338
8.4 Damage Removal 344
8.4.1 Wet Etching, Dry Etching, Thermal Annealing, and Two-Step Etching 344
8.4.2 Passivation by Low-Energy Reactive Species 353
8.5 Summary 357
References 357

9 Photomask Etching
D.J. Resnick 361

9.1 Introduction 361
9.2 Optical Lithography 364
9.2.1 Photomask Basics 364
9.2.2 Chrome Photomasks 364

9.2.3 MoSi Photomasks . . . 372
9.2.4 Phase Shift Mask Technology . . . 379
9.3 X-Ray Lithography . . . 383
9.3.1 X-Ray Lithography Basics . . . 383
9.3.2 Gold Absorber-Based Masks . . . 385
9.3.3 Refractory Masks . . . 388
9.3.4 Amorphous Refractory-Based Masks . . . 389
9.3.5 Thermal Characteristics of a Mask Etch Process . . . 395
9.3.6 Hard Mask Materials . . . 400
9.4 SCALPEL . . . 402
9.4.1 SCALPEL Basics . . . 402
9.4.2 SCALPEL Mask Blank Processing . . . 404
9.4.3 SCALPEL Mask Pattern Transfer . . . 405
9.5 EUVL . . . 407
9.5.1 EUVL Basics . . . 407
9.5.2 EUVL Masks . . . 408
9.5.3 EUV Mask Pattern Transfer . . . 409
9.6 Ion Projection Lithography . . . 411
9.6.1 Ion Projection Lithography Basics . . . 411
9.6.2 IPL Masks . . . 411
9.6.3 IPL Mask Pattern Transfer . . . 413
9.7 IPL Mask Distortion Issues . . . 414
9.8 Conclusion . . . 415
References . . . 416

10 Bulk Si Micromachining for Integrated Microsystems and MEMS Processing
R.J. Shul and J.G. Fleming . . . 419

10.1 Introduction . . . 419
10.2 Etch Technologies . . . 421
10.2.1 Wet Chemical Etching . . . 421
10.2.2 Plasma Etching . . . 421
10.2.3 Reactive Ion Etching . . . 423
10.2.4 High-Density Plasma Etching . . . 424
10.2.5 Deep Reactive Ion Etching . . . 425
10.3 ECR Results . . . 426
10.3.1 ECR Experimental . . . 427
10.3.2 ECR Process Parameters . . . 427
10.3.3 ECR Process Applications . . . 433
10.4 DRIE Results . . . 439
10.4.1 DRIE versus ICP Etch Comparison . . . 439
10.4.2 Etch Rates and Selectivity to Masking Materials . . . 441
10.4.3 Aspect Ratio Dependent Etching (ARDE) in DRIE . . . 445
10.4.4 Etch Selectivities . . . 446

10.5 DRIE Applications 448
10.5.1 Chemical Sensing Devices 448
10.5.2 Advanced Packaging 453
10.5.3 SOI DRIE Etching 455
10.6 Conclusions 457
References 457

11 Plasma Processing of III-V Materials
C. Youtsey and I. Adesida 459

11.1 Introduction 459
11.2 Dry Etching Techniques 459
11.2.1 Ion Beam Etching 459
11.2.2 Reactive Ion Etching 462
11.2.3 High-Density Plasma Reactive Ion Etching 464
11.3 Masking Materials and Methods 466
11.4 Dry Etching Chemistries 469
11.5 Dry Etching of GaAs and Related Materials 474
11.6 Dry Etching of InP and Related Materials 477
11.7 Dry Etching of GaN and Related Materials 483
11.8 Selective Dry Etching of III-V Materials 490
11.8.1 GaAs on AlGaAs 490
11.8.2 InGaAs on InAlAs 492
11.8.3 GaN on AlGaN 493
11.9 Conclusion 494
References 496

12 Ion Beam Etching of Compound Semiconductors
G.A. Vawter 507

12.1 Introduction 507
12.2 Definitions 507
12.2.1 Ion Beam Etching 507
12.2.2 Reactive Ion Beam Etching 508
12.2.3 Chemically Assisted Ion Beam Etching 508
12.2.4 Sputter Yield 510
12.3 Ion Sources 510
12.4 Historic Development 512
12.5 Grid Design, Beam Uniformity, and Divergence 513
12.6 Brief Overview of Etching Kinetics and Chemistry 515
12.7 Surface Quality and Etch Masking 518
12.8 RIBE Etch Technology 522
12.8.1 RIBE of GaAs and AlGaAs 522
12.8.2 RIBE of InP 526
12.8.3 RIBE of InGaAsP and InP 528
12.8.4 RIBE of AlGaInP, GaInP and AlGaInAs 528

12.8.5 RIBE of (Al,Ga)Sb, (In,Ga)Sb and InAsSb 529
12.8.6 RIBE of GaP and GaN 530
12.8.7 RIBE of ZnSe and ZnS 530
12.9 CAIBE Etch Technology 530
12.9.1 CAIBE of GaAs 531
12.9.2 CAIBE of AlGaAs 532
12.9.3 CAIBE of InP and InGaAsP 533
12.9.4 CAIBE of AlGaInP and AlGaInAs 534
12.9.5 CAIBE of (Al,Ga)Sb and InSb 535
12.9.6 CAIBE of (Al,Ga)N 535
12.10 Endpoint Detection 535
12.11 Damage 538
References 539

13 Dry Etching of InP Vias
S. Thomas III and J.J. Brown 549

13.1 Introduction 549
13.2 Past Difficulties in Obtaining High Rate Etching for InP 553
13.2.1 High Bias CH_4-based Etching of InP 553
13.2.2 Elevated Temperature Cl-based Etching of InP 554
13.3 High Density Plasma Sources for High InP Etch Rate 554
13.3.1 Reduced Bias CH_4-Based ECR Etching of InP 555
13.3.2 Addition of Cl to CH_4-Based ECR Etching of InP 556
13.3.3 Low Temperature Cl-Based Etching 556
13.4 Measurement of Plasma Heating for InP Etching 557
13.4.1 Wafer Heating During High-Density Plasma Etching 557
13.4.2 Impact of Plasma Heating for InP Etching 560
13.4.3 Effects of Chamber Pressure and Wafer Temperature on Etch Rate 563
13.5 Application to Via Hole Etching 564
13.5.1 Etch Mask and Etch Characteristics 565
13.5.2 Etching Slot Vias Using a Photoresist Mask 567
13.5.3 OES for Endpoint 569
13.6 Summary 570
References 571

14 Device Damage During Low Temperature High-Density Plasma Chemical Vapor Deposition
J. Lee and F. Ren 575

14.1 Introduction 575
14.2 Experimental 576
14.3 Results and Discussion 579
14.4 Summary and Conclusions 601
References 602

15 Dry Etching of Magnetic Materials
K.B. Jung, H. Cho, and S.J. Pearton 607

15.1 Introduction 607
15.2 Ion Milling 608
15.3 Cl_2-Based ICP Etching of NiFe and Related Materials 609
15.4 Copper Dry Etching in Cl_2/Ar 620
15.5 CO/NH_3 Etching of Magnetic Materials 628
15.6 ECR and ICP Etching of NiMnSb 635
15.7 Dry Etching of $LaCaMnO_X$ and SmCo 640
15.8 Summary and Conclusions 644
References 644

Subject Index 649