CONTENTS

Foreword xix
Contributing Authors xxiii

1 Why CMP?
Yuzhuo Li 1

1.1 Introduction, 1
1.2 Preparation of Planar Surface, 2
  1.2.1 Multilevel Metallization and the Need for Planarization, 2
  1.2.2 Degrees of Planarization, 4
  1.2.3 Methods of Planarization, 5
  1.2.4 Chemical and Mechanical Planarization of Dielectric Films, 7
  1.2.5 Preparation of Planar Thin Films for Non-IC Applications Using CMP, 8
1.3 Formation of Functional Microstructures, 9
  1.3.1 RC Delay and New Interconnect Materials, 9
  1.3.2 Damascene and Dual Damascene, 12
  1.3.3 Tungsten CMP, 15
  1.3.4 STI, 16
1.4 CMP to Correct Defects, 19
1.5 Advantages and Disadvantages of CMP, 20
1.6 Conclusion, 21
# Contents

## 2 Current and Future Challenges in CMP Materials

*Mansour Moinpour*

2.1 Introduction, 25  
2.2 Historic Prospective and Future Trends, 27  
2.3 CMP Material Characterization, 32   
  2.3.1 Thermal Effects, 33  
  2.3.2 Slurry Rheology Studies, 35  
  2.3.3 Slurry–Pad Interactions, 38  
  2.3.4 Pad Groove Effects, 42  
  2.3.5 Pad–Wafer Contact and Slurry Transport: Dual Emission Laser Induced Fluorescence, 43  
  2.3.6 Dynamic Nuclear Magnetic Resonance, 45  
  2.3.7 CMP Slurry Stability and Correlation with Defectivity, 49  
2.4 Conclusions, 51

## 3 Processing Tools for Manufacturing

*Manabu Tsujimura*

3.1 CMP Operation and Characteristics, 57  
3.2 Description of the CMP Process, 59  
3.3 Overview of Polishers, 60   
  3.3.1 CMP System, 60  
  3.3.2 Brief History of CMP Systems, 61  
  3.3.3 Diversity in CMP Tools, 62  
  3.3.4 Polisher, 62  
  3.3.5 Cleaning Module in a Dry-in/Dry-out System, 64  
3.4 Carriers and Dressers, 65  
  3.4.1 Functions of Carriers and Dressers, 65  
  3.4.2 Carrier, 65  
  3.4.3 Profile Control by Carriers, 68  
  3.4.4 Dressers, 69  
3.5 *In Situ* and *Ex Situ* Metrologies, 72  
  3.5.1 Application, 72  
  3.5.2 Representative Monitors, 72  
  3.5.3 Other Applications for the Monitors, 75  
  3.5.4 Communication, 75  
3.6 Conclusions, 78

## 4 Tribometrology of CMP Process

*Norm Gitis and Raghu Mudhivarthi*

4.1 Introduction, 81  
4.2 Tribometrology of CMP, 82
4.3 Factors Influencing the Tribology During CMP, 85
   4.3.1 Process Parameters During CMP, 85
   4.3.2 Polishing Pad Characteristics, 88
   4.3.3 Slurry Characteristics, 90
   4.3.4 Water Contour Characteristics, 92
4.4 Optimizing Pad Conditioning Process, 92
   4.4.1 PadProbe™, 92
   4.4.2 Effect of Temperature, 100
4.5 Conditioner Design, 102
4.6 CMP Consumable Testing, 105
   4.6.1 Slurry Testing, 105
   4.6.2 Pad Testing, 108
   4.6.3 Retaining Rings, 110
4.7 Defect Analysis, 113
   4.7.1 Coefficient of Friction and Acoustic Emission Signal, 113
   4.7.2 Advanced Signal Processing, 114
4.8 Summary, 117

5 Pads for IC CMP

Changxue Wang, Ed Paul, Toshihiro Kobayashi and Yuzhuo Li

5.1 Introduction, 123
5.2 Physical Properties of CMP Pads and Their Effects on Polishing Performance, 124
   5.2.1 Pad Types, 124
   5.2.2 Pad Microstructures and Macrostructures, 125
   5.2.3 Polyurethane Pad Properties and Control, 127
      5.2.3.1 Hardness, Young’s Modulus, and Strength, 127
      5.2.3.2 Pad Porosity/Density, 128
      5.2.3.3 Pad Thickness, 128
      5.2.3.4 Pad Stiffness/Stacked Pads, 129
      5.2.3.5 Pad Grooves, 129
   5.2.4 Effects of Pad Property on Polishing Performance, 129
      5.2.4.1 Pad Roughness Effects, 130
      5.2.4.2 Pad Porosity/Density Effects, 131
      5.2.4.3 Pad Hardness, Young’s Modulus, Stiffness, and Thickness Effects, 136
      5.2.4.4 Pad Groove Effects, 138
5.3 Chemical Properties of CMP Pads and Their Effects on Polishing Performances, 140
   5.3.1 Polyurethane Pad Components, 140
   5.3.2 Polyurethane Property Control by Chemical Components, 140
   5.3.3 Chemical Effects on Polishing Performance, 141
CONTENTS

5.4 Pad Conditioning and Its Effect on CMP Performance, 142
5.5 Modeling of Pad Effects on Polishing Performance, 145
  5.5.1 Review of Modeling of Pad Effects on Polishing Performance, 145
  5.5.2 Modeling of Pad Effects on Polishing Performance, 148
    5.5.2.1 Pads and Pressure, 148
    5.5.2.2 Pads and Abrasives, 150
    5.5.2.3 Pads, Dishing, and Erosion, 154
5.6 Novel Designs of CMP Pads, 159
  5.6.1 Particle-Containing Pads, 159
  5.6.2 Surface-Treated Pads, 162
  5.6.3 Reactive Pad, 164

6 Modeling
Leonard Borucki and Ara Philipossian

  6.1 Introduction, 171
  6.2 A Two-Step Chemical Mechanical Material Removal Model, 172
  6.3 Pad Surfaces and Pad Surface Contact Modeling, 175
  6.4 Reaction Temperature, 178
  6.5 A Polishing Example, 185
  6.6 Topography Planarization, 189

7 Key Chemical Components in Metal CMP Slurries
Krishnayya Cheemalapati, Jason Keleher and Yuzhuo Li

  7.1 Introduction, 201
  7.2 Oxidizers, 202
    7.2.1 Nitric Acid, 202
    7.2.2 Hydrogen Peroxide, 203
    7.2.3 Ferric Nitrate, 210
    7.2.4 Potassium Permanganate, Dichromates, and Iodate, 212
  7.3 Chelating Agents, 214
    7.3.1 Ammonia, 215
    7.3.2 Amino Acids, 216
    7.3.3 Organic Acids, 217
    7.3.4 Thermodynamic Consideration and Quantitative Description, 218
  7.4 Surfactants, 219
    7.4.1 Structures and Physical Properties of Surfactants, 219
    7.4.2 Dispersion of Particles, 221
    7.4.3 Surface Modification of Wafer Surface, 222
7.5 Abrasive Particles, 225
  7.5.1 Hardness, 225
  7.5.2 Bulk Particle Density, 227
  7.5.3 Particle Crystallinity and Shapes, 227
  7.5.4 Particle Size and Oversized Particle Count, 228
  7.5.5 Particle Preparation, 230
  7.5.6 Surface Properties, 231
7.6 Particle Surface Modification, 233
7.7 Soft Particles, 234
7.8 Case Study: Organic Particles as Abrasives in Cu CMP, 235
  7.8.1 Particle Characterization, 235
  7.8.2 Material Removal Rate and Selectivity, 235
  7.8.3 Step Height Reduction Efficiency and Overpolishing Window, 239
  7.8.4 Summary on the Organic Particles, 239
7.9 Conclusions, 239

8 Corrosion Inhibitor for Cu CMP Slurry
Suresh Kumar Govindaswamy and Yuzhuo Li

  8.1 Thermodynamic Considerations of Copper Surface, 250
  8.2 Types of Passivating Films on Copper Surface Under Oxdizing Conditions, 252
  8.3 Effect of pH on BTA in Glycine-Hydrogen Peroxide Based Cu CMP Slurry, 257
  8.4 Evaluation of Potential BTA Alternatives for Acidic Cu CMP Slurry, 259
  8.5 Electrochemical Polarization Study of Corrosion Inhibitors in Cu CMP Slurry, 263
  8.6 Hydrophobicity of the Surface Passivation Film, 265
  8.7 Competitive Surface Adsorption Behavior of Corrosion Inhibitors, 266
  8.8 Summary, 270

9 Tungsten CMP Applications
Jeff Visser

  9.1 Introduction, 277
  9.2 Basic Tungsten Application, Requirements, and Process, 278
    9.2.1 Basic Applications of Tungsten CMP, 278
    9.2.2 Basic W CMP Requirements and Procedures, 281
9.3 W CMP Defects, 282
9.4 Various W CMP Processing Options, 285
  9.4.1 Basic Considerations, 285
  9.4.2 Barrier Polishing, 289
  9.4.3 Oxide Buffing, 289
  9.4.4 Post-W CMP Cleaning, 290
9.5 Overall Tungsten Process (Various Processing Design Options and Suggestions), 290
  9.5.1 W CMP Process Controls, 290
  9.5.2 Platen Temperature Control, 291
  9.5.3 Slurry Selectivity, 292
9.6 Conclusions, 292

10 Electrochemistry in ECMP  
Jinshan (Jason) Huo

10.1 Introduction, 295
10.2 Physical and Chemical Processes in Electrochemical Planarization, 297
  10.2.1 Electrode/Electrolyte Interface, 297
  10.2.2 Electrochemical Reaction, 298
  10.2.3 Mass Transport, 299
  10.2.4 Anodic Polarization Curve and Conditions for Electrochemical Planarization, 300
10.3 Mechanisms and Limitation of Electrochemical Planarization, 304
  10.3.1 Ohmic Leveling, 304
  10.3.2 Diffusion Leveling, 305
  10.3.3 Migration Leveling, 307
10.4 In Situ Analysis of Anodic/Passivation Films, 309
  10.4.1 Impedance Measurement, 309
  10.4.2 Electrochemical Impedance Spectroscopy, 310
  10.4.3 Ellipsometry, 311
10.5 Modified Electrochemical Polishing Approaches, 312

11 Planarization Technologies Involving Electrochemical Reactions  
Laertis Economikos

11.1 Introduction, 319
11.2 CMP, 321
11.3 ECP, 322
11.4 ECMP, 326
11.5 Full Sequence Electrochemical–Mechanical Planarization, 334
11.6 Conclusions, 340
12 Shallow Trench Isolation Chemical Mechanical Planarization 345
Yordan Stefanov and Udo Schwalke

12.1 Introduction, 345
12.2 LOCOS to STI, 346
12.3 Shallow Trench Isolation, 349
12.4 The Planarization Step in Detail, 351
12.5 Optimization Techniques, 358
  12.5.1 Dummy Active Area Insertion, 359
  12.5.2 Patterned Oxide Etch Back, 359
  12.5.3 Nitride Overcoat, 360
  12.5.4 EXTIGATE, 361
  12.5.5 Selective Oxide Deposition, 363
  12.5.6 Polysilicon-Filled Trenches, 363
12.6 Outlook, 364

13 Consumables for Advanced Shallow Trench Isolation (STI) 369
Craig D. Burkhard

13.1 Introduction, 369
13.2 Representative Testing Wafers for STI Process and Consumable Evaluations, 371
13.3 Effects of Abrasive Types on STI Slurry Performance, 373
13.4 Effects of Chemical Additives to Oxide: Nitride Selectivity, 379
13.5 Effect of Slurry pH, 385
13.6 Effect of Abrasive Particle Size on Removal Rate and Defectivity, 388
13.7 Conclusion, 395

14 Fabrication of Microdevices Using CMP 401
Gerfried Zwicker

14.1 Introduction, 401
14.2 Microfabrication Processes, 402
14.3 Microfabrication Products, 403
14.4 CMP Requirements in Comparison with IC Fabrication, 404
14.5 Examples of CMP Applications for Microfabrication, 412
  14.5.1 Case Study I: Integrated Pressure Sensor, 416
  14.5.2 Case Study II: Poly-Si Surface Micromachining and Angular Rate Sensor, 417
  14.5.3 Case Study III: Infrared Digital Micromirror Array, 422
  14.5.4 More Representative Applications, 425
14.6 Outlook, 426
15 Three-Dimensional (3D) Integration

J. Jay McMahon, Jian-Qiang Lu and Ronald J. Gutmann

15.1 Overview of 3D Technology, 431
15.2 Factors Motivating Research in 3D, 432
  15.2.1 Small Form Factor, 432
  15.2.2 Heterogeneous Integration, 433
  15.2.3 Performance Enhancement, 434
15.3 Approaches to 3D, 435
  15.3.1 Singulated Die 3D, 435
  15.3.2 Wafer-Level 3D, 436
    15.3.2.1 Wafer-Level 3D Using Oxide–Oxide Bonding, 436
    15.3.2.2 Wafer-Level 3D Using Copper–Copper Bonding, 438
    15.3.2.3 Wafer-Level 3D Using Adhesive Bonding, 439
    15.3.2.4 3D Integration Using Redistribution Layer Bonding, 440
    15.3.2.5 Summary of Wafer Level 3D Approaches, 440
15.4 Wafer-Level 3D Unit Processes, 442
  15.4.1 Wafer-to-Wafer Alignment, 442
  15.4.2 Wafer-to-Wafer Bonding, 444
    15.4.2.1 Oxide–Oxide and Silicon–Oxide Wafer Bondings, 444
    15.4.2.2 Copper–Copper Wafer Bonding, 444
    15.4.2.3 Polymer Adhesive Wafer Bonding, 446
  15.4.3 Wafer Thinning for 3D, 447
    15.4.3.1 Timed Removal Thinning Approaches, 448
    15.4.3.2 Thinning to Either an Etch or Polish Stop, 448
  15.4.4 Through-Silicon Vias, 449
15.5 Planarity Issues in 3D Integration, 450
  15.5.1 CMP Planarity Capabilities, 451
    15.5.1.1 Nano- and Microscale Planarization, 451
    15.5.1.2 Wafer-Scale Planarity, 451
  15.5.2 Planarity Issues for Various 3D Approaches, 452
    15.5.2.1 CMP for Via-Last Approach to 3D Using Oxide-to-Oxide Bonding, 452
    15.5.2.2 CMP for Via-Last Approach to 3D Using Polymer Adhesive Bonding, 454
    15.5.2.3 CMP for Via-First Approach to 3D Using Copper-to-Copper Bonding, 455
    15.5.2.4 CMP for Via-First 3D Using Redistribution Layer Bonding, 455
15.6 Conclusions, 456
16 Post-CMP Cleaning

Jin-Goo Park, Ahmed A. Busnaina and Yi-Koan Hong

16.1 Introduction, 467
16.2 Types of Post-CMP Cleaning Processes, 468
  16.2.1 Wet Bath Type Cleaning, 468
  16.2.2 Single Wafer Cleanings, 469
    16.2.2.1 Immersion-Type Single-Wafer Post-CMP Cleaning System, 469
    16.2.2.2 Single-Wafer Spin Cleaner, 469
    16.2.2.3 Brush Cleaning, 473
    16.2.2.4 Drying, 475
16.3 Post-CMP Cleaning Chemistry, 477
  16.3.1 Conventional Wet Cleanings, 477
  16.3.2 Chemicals Used in Post-CMP Cleaning and their Roles, 478
    16.3.2.1 NH\textsubscript{4}OH, 478
    16.3.2.2 HF, 478
    16.3.2.3 Organic Acids, 479
    16.3.2.4 Surfactants, 479
16.4 Post-CMP Cleaning According to Applications, 480
  16.4.1 Post-Oxide CMP Cleaning, 480
  16.4.2 Post-W CMP Cleaning, 481
  16.4.3 Post-STI CMP Cleaning, 481
  16.4.4 Post-Poly-Si CMP Cleaning, 482
  16.4.5 Post-Cu/Low-k CMP Surface Cleaning, 484
    16.4.5.1 Corrosion, 486
    16.4.5.2 Organic Residue, 487
    16.4.5.3 Low-k Materials, 489
    16.4.5.4 Effect of Other Additives on Cleaning, 491
16.5 Adhesion Force, Friction Force, and Defects During Cu CMP, 492
  16.5.1 Adhesion Force of Silica and Alumina on Cu, 493
  16.5.2 Friction Force in Cu CMP Process, 494
  16.5.3 Removal Rates of Cu Surface in Cu CMP, 494
  16.5.4 Surface Quality of Cu After Cu CMP Process, 496
  16.5.5 Correlation Among Friction, Adhesion Force, Removal Rate, and Surface Quality in Cu CMP, 498
16.6 Case Study: Megasonic Post-CMP Cleaning of Thermal Oxide Wafers, 499
  16.6.1 Experimental Procedure, 499
  16.6.2 The Effect of Megasonic Input Power, 500
  16.6.3 The Effect of Temperature, 503
  16.6.4 The Effect of Etching on Cleaning, 503
16.7 Summary, 505
17 Defects Observed on the Wafer After the CMP Process

Paul Lefevre

17.1 Introduction, 511

17.2 Defects After Oxide CMP, 512
   17.2.1 Introduction, 512
   17.2.2 Scratches, 513
   17.2.3 Color Variation—Oxide Thickness Variation, 516
   17.2.4 Slurry Residues and Organic Residues, 518
   17.2.5 Other Particles, 519
   17.2.6 Crystal Formation, 519
   17.2.7 Traces Elements, 519
   17.2.8 Radioactive Contamination, 519
   17.2.9 Defects Existing Before Oxide CMP, 520
   17.2.10 Source of Defect-Causing Large Particles, 520

17.3 Defects After Polysilicon CMP, 520
   17.3.1 Introduction, 520
   17.3.2 Scratches, 521
   17.3.3 Polysilicon Residues, 521
   17.3.4 Particles, 522
   17.3.5 Residues, 522
   17.3.6 Trace Elements, 522
   17.3.7 Polysilicon Pitting and Voids, 523
   17.3.8 Discoloration at the Edge of the Structure
        or Edge of the Arrays, 523
   17.3.9 Defects Existing Before and Revealed After
        Polysilicon CMP, 523
   17.3.10 Influence of Processing Temperature, 524

17.4 Defects After Tungsten CMP, 524
   17.4.1 Introduction, 524
   17.4.2 Corrosion, Pitting, and Void, 524
   17.4.3 Tungsten Recess and Rough Tungsten Surface, 525
   17.4.4 Scratches, 528
   17.4.5 Discoloration—Edge Overerosion (EOE), 529
   17.4.6 Tungsten and Metal Liner Residues, 530
   17.4.7 Particles, Slurry Residues, and Trace Metal, 531
   17.4.8 Delamination, 531
   17.4.9 Preexisting Defects Revealed After
        Tungsten CMP, 531

17.5 Defects After Copper CMP, 532
   17.5.1 Introduction and Summary on Copper
        CMP Defects, 532
   17.5.2 Copper Corrosion, 533
   17.5.3 Copper Pitting, 535
   17.5.4 Trenching at the Copper Line Edge, 537
17.5.5 Rough Copper and Copper Recess, 539
17.5.6 Discoloration—Metals Thickness Variations and/or Dielectric Thickness Variation, 540
17.5.7 Copper Electromigration, 542
17.5.8 Scratches, 544
17.5.9 Metal Residues, 544
17.5.10 Particles, Residues, and Trace Metals, 547
17.5.11 Delamination, 548
17.6 Defect Observation and Characterization Techniques, 551
17.6.1 Optical Microscope, 551
17.6.2 Scanning Electron Microscope, 552
17.6.3 Energy Dispersive X-Ray Spectroscopy (EDX), 552
17.6.4 Scanning Auger Microscope (SAM), 553
17.6.5 Atomic Force Microscopy, 553
17.7 Ensemble Defect Detection and Inspection Techniques, 554
17.7.1 Optical Scan of Flat Film Blanket Wafers, 554
17.7.2 Optical Scan of Patterned Wafers, 554
17.7.3 Defect Classification, 555
17.8 Consideration for the Future, 555

18 CMP Slurry Metrology, Distribution, and Filtration 563
Rakesh K. Singh

18.1 Introduction, 564
18.2 CMP Slurry Metrology and Characterization, 567
18.2.1 Slurry Health Monitoring and Control, 568
18.2.2 CMP Slurry Blend Control, 569
  18.2.2.1 Two-Component Blend Control, 570
  18.2.2.2 Three-Component Blend Control, 572
18.2.3 CMP Slurry Characterization, 573
18.2.4 Summary, 576
18.3 CMP Slurry Blending and Distribution, 577
18.3.1 Slurry Delivery Technologies, 578
18.3.2 Continuous (On-Demand) Slurry Dispense and Metrology, 578
18.3.3 Slurry Turnovers in Fab Distribution, 580
18.3.4 Slurry Abrasive Settling and Dispersion, 580
  18.3.4.1 Slurry Settling Rate Quantification, 580
  18.3.4.2 Settling Behavior of Different Abrasive CMP Slurries, 581
  18.3.4.3 Required Minimum Flow Velocity for CMP Slurries, 584
18.3.5 Summary, 585
18.4 CMP Slurry Filtration, 586
  18.4.1 Slurry Filtration Methodology, 587
18.4.2 Filter Design Consideration, 588
18.4.3 Slurry Filter Characterization, 591
18.4.4 CMP Process and Consumable Trends and Challenges, 592
18.4.5 Slurry Filtration-Case Studies, 595
  18.4.5.1 Silica Dispersion Single-Pass High-Retention Filtration, 595
  18.4.5.2 Silica Slurry POU and Recirculation, 596
  18.4.5.3 Silica, Ceria, and Alumina Slurry Tighter Filtration, 599
  18.4.5.4 Polystyrene Latex (PSL) Bead Solution Filtration, 602
18.4.6 Summary, 602
18.5 Pump Handling Effects on CMP Slurry Filtration—Case Studies, 603
  18.5.1 Pump Technologies and Applications, 604
  18.5.2 Pump Shearing Effects on Slurry Abrasives, 605
  18.5.3 Pump Handling and Filtration Data, 606
  18.5.4 Test Cases, 607
  18.5.5 Summary, 620

19 The Facilities Side of CMP

John H. Rydzewski

19.1 Introduction, 627
19.2 Characterization of the CMP Waste Stream, 628
19.3 Materials of Compatibility, 629
19.4 Collection System Methodologies, 631
19.5 Treatment System Components, 632
  19.5.1 Collection Tank and pH Adjustment, 632
  19.5.2 Oxidizer Removal, 633
  19.5.3 Organics Removal, 635
  19.5.4 Treatment of Suspended Solids, 635
  19.5.5 Removal of Trace Metals, 638
19.6 Integration of Components—Putting It All Together, 644
  19.6.1 Solids Treatment Before Metals Removal, 644
  19.6.2 Solids Treatment After Metals Removal, 645
  19.6.3 No Solids Removal, 646
19.7 Conclusions, 647

20 CMP—The Next Fifteen Years

Joseph M. Steigerwald

20.1 The Past 15 Years, 651
20.2 Challenges to Silicon IC Manufacturing, 655
20.3 New CMP Processes, 661
   20.3.1 The Two-Year Development Cycle, 661
   20.3.2 Finfet Transistors, 664
   20.3.3 High-k Gate Oxides, 665
   20.3.4 Other Examples, 670
20.4 CMP Challenges, 673
   20.4.1 Development Time of New CMP Materials, 673
   20.4.2 CMP Defect Reduction, 675
   20.4.3 CMP Process Control, 677
      20.4.3.1 CMP Film Thickness Control, 678
      20.4.3.2 Process Control Systems, Consumables Material
            Control, and Excursion Prevention, 680
   20.4.4 Cost of CMP, 683
20.5 Summary, 683

21 Utilitarian Information for CMP Scientists and Engineers 687
   Yongqing Lan and Yuzhuo Li

   21.1 Physical and Chemical Properties of Abrasive Particles, 687
   21.2 Physical and Chemical Properties on Oxidizers, 690
   21.3 Physical and Chemical Properties on Relevant Surfactants, 690
      21.3.1 Classification of Surfactants, 690
      21.3.2 Critical Micellar Concentration, 692
      21.3.3 Ternary Phase Diagrams Involving Surfactants, 693
   21.4 Relevant Pourbaix Diagram, 696
   21.5 Commonly Used Buffering Systems, 703
   21.6 Useful Web Sites, 704

Index 725