



S E C O N D E D I T I O N

MEMS

AND MICROSYSTEMS

DESIGN, MANUFACTURE, AND NANOSCALE ENGINEERING

Tai-Ran Hsu

CONTENTS

PREFACE	xvii
PREFACE TO THE FIRST EDITION	xix
SUGGESTIONS TO INSTRUCTORS	xxiii
1 OVERVIEW OF MEMS AND MICROSYSTEMS	1
1.1 MEMS and Microsystems / 1	
1.2 Typical MEMS and Microsystems Products / 7	
1.2.1 Microgears / 7	
1.2.2 Micromotors / 7	
1.2.3 Microturbines / 7	
1.2.4 Micro-Optical Components / 7	
1.3 Evolution of Microfabrication / 10	
1.4 <i>Microsystems and Microelectronics</i> / 11	
1.5 Multidisciplinary Nature of Microsystems Design and Manufacture / 13	
1.6 Microsystems and Miniaturization / 15	
1.7 Application of Microsystems in Automotive Industry / 21	
1.7.1 Safety / 22	
1.7.2 Engine and Power Trains / 24	
1.7.3 Comfort and Convenience / 24	
1.7.4 Vehicle Diagnostics and Health Monitoring / 24	
1.7.5 Future Automotive Applications / 26	
1.8 Application of Microsystems in Other Industries / 27	

- 1.8.1 Application in Health Care Industry / 27
- 1.8.2 Application in Aerospace Industry / 28
- 1.8.3 Application in Industrial Products / 29
- 1.8.4 Application in Consumer Products / 29
- 1.8.5 Application in Telecommunications / 30
- 1.9 Markets for Microsystems / 30
- Problems / 32

2 WORKING PRINCIPLES OF MICROSYSTEMS

35

- 2.1 Introduction / 35
- 2.2 Microsensors / 35
 - 2.2.1 Acoustic Wave Sensors / 36
 - 2.2.2 Biomedical and Biosensors / 37
 - 2.2.3 Chemical Sensors / 40
 - 2.2.4 Optical Sensors / 42
 - 2.2.5 Pressure Sensors / 44
 - 2.2.6 Thermal Sensors / 50
- 2.3 Microactuation / 53
 - 2.3.1 Actuation Using Thermal Forces / 53
 - 2.3.2 Actuation Using Shape Memory Alloys / 54
 - 2.3.3 Actuation Using Piezoelectric Effect / 54
 - 2.3.4 Actuation Using Electrostatic Forces / 55
- 2.4 MEMS with Microactuators / 59
 - 2.4.1 Microgrippers / 59
 - 2.4.2 Miniature Microphones / 61
 - 2.4.3 Micromotors / 64
- 2.5 Microactuators with Mechanical Inertia / 66
 - 2.5.1 Microaccelerometers / 66
 - 2.5.2 Microgyroscopes / 70
- 2.6 Microfluidics / 72
 - 2.6.1 Microvalves / 74
 - 2.6.2 Micropumps / 75
 - 2.6.3 Micro-Heat Pipes / 75
- Problems / 77

3 ENGINEERING SCIENCE FOR MICROSYSTEMS DESIGN AND FABRICATION

83

- 3.1 Introduction / 83
- 3.2 Atomic Structure of Matter / 83

- 3.3 Ions and Ionization / 86
- 3.4 Molecular Theory of Matter and Intermolecular Forces / 87
- 3.5 Doping of Semiconductors / 89
- 3.6 *Diffusion Process* / 92
- 3.7 Plasma Physics / 99
- 3.8 Electrochemistry / 100
 - 3.8.1 Electrolysis / 101
 - 3.8.2 Electrohydrodynamics / 102
- Problems / 105

4 ENGINEERING MECHANICS FOR MICROSYSTEMS DESIGN

109

- 4.1 Introduction / 109
- 4.2 Static Bending of Thin Plates / 110
 - 4.2.1 *Bending of Circular Plates with Edge Fixed* / 112
 - 4.2.2 Bending of Rectangular Plates with All Edges Fixed / 114
 - 4.2.3 Bending of Square Plates with Edges Fixed / 116
- 4.3 Mechanical Vibration / 119
 - 4.3.1 General Formulation / 119
 - 4.3.2 Resonant Vibration / 123
 - 4.3.3 Microaccelerometers / 125
 - 4.3.4 Design Theory of Accelerometers / 126
 - 4.3.5 Damping Coefficients / 134
 - 4.3.6 Resonant Microsensors / 144
- 4.4 Thermomechanics / 150
 - 4.4.1 Thermal Effects on Mechanical Strength of Materials / 150
 - 4.4.2 Creep Deformation / 150
 - 4.4.3 Thermal Stresses / 152
- 4.5 Fracture Mechanics / 165
 - 4.5.1 Stress Intensity Factors / 166
 - 4.5.2 Fracture Toughness / 167
 - 4.5.3 Interfacial Fracture Mechanics / 169
- 4.6 Thin-Film Mechanics / 172
- 4.7 Overview of Finite Element Stress Analysis / 173
 - 4.7.1 The Principle / 173
 - 4.7.2 Engineering Applications / 175
 - 4.7.3 Input Information to FEA / 175

- 4.7.4 Output from FEA / 175
- 4.7.5 Graphical Output / 176
- 4.7.6 General Remarks / 176
- Problems / 178

5 THERMOFLUID ENGINEERING AND MICROSYSTEMS DESIGN

183

- 5.1 Introduction / 183
- 5.2 Overview of Basics of Fluid Mechanics at Macro- and Mesoscales / 184
 - 5.2.1 Viscosity of Fluids / 184
 - 5.2.2 Streamlines and Stream Tubes / 186
 - 5.2.3 Control Volumes and Control Surfaces / 187
 - 5.2.4 Flow Patterns and Reynolds Number / 187
- 5.3 Basic Equations in Continuum Fluid Dynamics / 187
 - 5.3.1 *Continuity Equation* / 187
 - 5.3.2 Momentum Equation / 190
 - 5.3.3 Equation of Motion / 192
- 5.4 Laminar Fluid Flow in Circular Conduits / 195
- 5.5 Computational Fluid Dynamics / 198
- 5.6 Incompressible Fluid Flow in Microconduits / 199
 - 5.6.1 Surface Tension / 199
 - 5.6.2 Capillary Effect / 201
 - 5.6.3 Micropumping / 203
- 5.7 Overview of Heat Conduction in Solids / 204
 - 5.7.1 General Principle of Heat Conduction / 204
 - 5.7.2 Fourier Law of Heat Conduction / 205
 - 5.7.3 Heat Conduction Equation / 207
 - 5.7.4 Newton's Cooling Law / 208
 - 5.7.5 Solid-Fluid Interaction / 209
 - 5.7.6 Boundary Conditions / 210
- 5.8 Heat Conduction in Multilayered Thin Films / 215
- 5.9 Heat Conduction in Solids at Submicrometer Scale / 220
 - Problems / 221

6 SCALING LAWS IN MINIATURIZATION

227

- 6.1 Introduction to Scaling / 227
- 6.2 Scaling in Geometry / 228

- 6.3 Scaling in Rigid-Body Dynamics / 230
 - 6.3.1 Scaling in Dynamic Forces / 230
 - 6.3.2 Trimmer Force Scaling Vector / 231
- 6.4 Scaling in Electrostatic Forces / 233
- 6.5 Scaling of Electromagnetic Forces / 235
- 6.6 Scaling in Electricity / 237
- 6.7 Scaling in Fluid Mechanics / 238
- 6.8 Scaling in Heat Transfer / 242
 - 6.8.1 Scaling in Heat Conduction / 242
 - 6.8.2 Scaling in Heat Convection / 243
- Problems / 244

7 MATERIALS FOR MEMS AND MICROSYSTEMS

245

- 7.1 Introduction / 245
- 7.2 Substrates and Wafers / 245
- 7.3 Active Substrate Materials / 247
- 7.4 Silicon as Substrate Material / 247
 - 7.4.1 Ideal Substrate for MEMS / 247
 - 7.4.2 Single-Crystal Silicon and Wafers / 248
 - 7.4.3 Crystal Structure / 250
 - 7.4.4 Miller Indices / 253
 - 7.4.5 Mechanical Properties of Silicon / 256
- 7.5 Silicon Compounds / 258
 - 7.5.1 Silicon Dioxide / 258
 - 7.5.2 Silicon Carbide / 259
 - 7.5.3 Silicon Nitride / 259
 - 7.5.4 Polycrystalline Silicon / 260
- 7.6 Silicon Piezoresistors / 261
- 7.7 Gallium Arsenide / 266
- 7.8 Quartz / 267
- 7.9 Piezoelectric Crystals / 268
- 7.10 Polymers / 274
 - 7.10.1 Polymers as Industrial Materials / 274
 - 7.10.2 Polymers for MEMS and Microsystems / 275
 - 7.10.3 Conductive Polymers / 275
 - 7.10.4 Langmuir–Blodgett Film / 277
 - 7.10.5 SU-8 Photoresists / 278
- 7.11 Packaging Materials / 280
- Problems / 281

- 8.1 Introduction / 285
- 8.2 Photolithography / 285
 - 8.2.1 Overview / 286
 - 8.2.2 Photoresists and Application / 286
 - 8.2.3 Light Sources / 288
 - 8.2.4 Photoresist Development / 289
 - 8.2.5 Photoresist Removal and Postbaking / 289
- 8.3 Ion Implantation / 289
- 8.4 Diffusion / 292
- 8.5 Oxidation / 295
 - 8.5.1 Thermal Oxidation / 295
 - 8.5.2 Silicon Dioxide / 296
 - 8.5.3 Thermal Oxidation Rates / 296
 - 8.5.4 Oxide Thickness by Color / 300
- 8.6 *Chemical Vapor Deposition* / 301
 - 8.6.1 Working Principle of CVD / 301
 - 8.6.2 Chemical Reactions in CVD / 302
 - 8.6.3 Rate of Deposition / 303
 - 8.6.4 Enhanced CVD / 310
- 8.7 Physical Vapor Deposition: Sputtering / 312
- 8.8 Deposition by Epitaxy / 313
- 8.9 Etching / 315
 - 8.9.1 Chemical Etching / 316
 - 8.9.2 Plasma Etching / 317
- 8.10 Summary of Microfabrication / 317
 - Problems / 318

- 9.1 Introduction / 323
- 9.2 Bulk Micromanufacturing / 324
 - 9.2.1 Overview of Etching / 324
 - 9.2.2 Isotropic and Anisotropic Etching / 325
 - 9.2.3 Wet Etchants / 326
 - 9.2.4 Etch Stop / 328
 - 9.2.5 Dry Etching / 329
 - 9.2.6 Comparison of Wet versus Dry Etching / 333
- 9.3 Surface Micromachining / 333
 - 9.3.1 Description / 333

- 9.3.2 Process / 335
- 9.3.3 Mechanical Problems Associated with Surface Micromachining / 336
- 9.4 LIGA Process / 338
 - 9.4.1 Description / 339
 - 9.4.2 Materials for Substrates and Photoresists / 340
 - 9.4.3 Electroplating / 341
 - 9.4.4 SLIGA Process / 342
- 9.5 Summary of Micromanufacturing / 343
 - 9.5.1 Bulk Micromanufacturing / 343
 - 9.5.2 Surface Micromachining / 343
 - 9.5.3 LIGA Process / 343
- Problems / 344

10 MICROSYSTEMS DESIGN

349

- 10.1 Introduction / 349
- 10.2 Design Considerations / 350
 - 10.2.1 Design Constraints / 351
 - 10.2.2 Selection of Materials / 352
 - 10.2.3 Selection of Manufacturing Processes / 354
 - 10.2.4 Selection of Signal Transduction / 355
 - 10.2.5 Electromechanical System / 358
 - 10.2.6 Packaging / 358
- 10.3 Process Design / 358
 - 10.3.1 Photolithography / 359
 - 10.3.2 Thin-Film Fabrications / 360
 - 10.3.3 Geometry Shaping / 362
- 10.4 Mechanical Design / 362
 - 10.4.1 Geometry of MEMS Components / 362
 - 10.4.2 Thermomechanical Loading / 362
 - 10.4.3 Thermomechanical Stress Analysis / 363
 - 10.4.4 Dynamic Analysis / 364
 - 10.4.5 Interfacial Fracture Analysis / 369
- 10.5 Mechanical Design Using Finite Element Method / 369
 - 10.5.1 Finite Element Formulation / 370
 - 10.5.2 Simulation of Microfabrication Processes / 375
- 10.6 Design of Silicon Die of a Micropressure Sensor / 378
- 10.7 Design of Microfluidic Network Systems / 382
 - 10.7.1 Fluid Resistance in Microchannels / 383

- 10.7.2 Capillary Electrophoresis Network Systems / 386
- 10.7.3 Mathematical Modeling of Capillary Electrophoresis Network Systems / 388
- 10.7.4 Design Case: Capillary Electrophoresis Network System / 389
- 10.7.5 Capillary Electrophoresis in Curved Channels / 392
- 10.7.6 Issues in Design of CE Processes / 394
- 10.8 Computer-Aided Design / 395
 - 10.8.1 Why CAD? / 395
 - 10.8.2 What Is in a CAD Package for Microsystems? / 395
 - 10.8.3 How to Choose a CAD Package / 398
 - 10.8.4 Design Case Using CAD / 398
- Problems / 402

11 ASSEMBLY, PACKAGING, AND TESTING OF MICROSYSTEMS 407

- 11.1 Introduction / 407
- 11.2 Overview of Microassembly / 409
- 11.3 High Costs of Microassembly / 410
- 11.4 Microassembly Processes / 411
- 11.5 Major Technical Problems in Microassembly / 413
 - 11.5.1 Tolerances in Microassembly / 414
 - 11.5.2 Tools and Fixtures / 417
 - 11.5.3 Contact Problems in Microassembly Tools / 417
- 11.6 Microassembly Work Cells / 419
- 11.7 Challenging Issues in Microassembly / 421
- 11.8 Overview of Microsystems Packaging / 422
- 11.9 General Considerations in Packaging Design / 424
- 11.10 Three Levels of Microsystems Packaging / 424
 - 11.10.1 Die-Level Packaging / 424
 - 11.10.2 Device-Level Packaging / 425
 - 11.10.3 System-Level Packaging / 427
- 11.11 Interfaces in Microsystems Packaging / 427
- 11.12 Essential Packaging Technologies / 428
- 11.13 Die Preparation / 429
- 11.14 Surface Bonding / 429
 - 11.14.1 Adhesives / 430
 - 11.14.2 Eutectic Bonding / 431
 - 11.14.3 Anodic Bonding / 432
 - 11.14.4 Silicon Fusion Bonding / 434
 - 11.14.5 Overview of Surface Bonding Techniques / 434

- 11.14.6 Silicon-on-Insulator: Special Surface Bonding Techniques / 435
- 11.15 Wire Bonding / 437
- 11.16 Sealing and Encapsulation / 439
 - 11.16.1 Integrated Encapsulation Processes / 440
 - 11.16.2 Sealing by Wafer Bonding / 441
 - 11.16.3 Vacuum Sealing and Encapsulation / 442
- 11.17 Three-Dimensional Packaging / 443
- 11.18 Selection of Packaging Materials / 444
- 11.19 Signal Mapping and Transduction / 447
 - 11.19.1 Typical Electrical Signals in Microsystems / 447
 - 11.19.2 Measurement of Resistance / 447
 - 11.19.3 Signal Mapping and Transduction in Pressure Sensors / 448
 - 11.19.4 Capacitance Measurements / 450
- 11.20 Design Case on Pressure Sensor Packaging / 451
- 11.21 Reliability in MEMS Packaging / 455
- 11.22 Testing for Reliability / 456
 - Problems / 458

12 INTRODUCTION TO NANOSCALE ENGINEERING

465

- 12.1 Introduction / 465
- 12.2 Micro- and Nanoscale Technologies / 467
- 12.3 General Principle of Nanofabrication / 468
- 12.4 Nanoproducts / 471
- 12.5 Application of Nanoproducts / 474
- 12.6 Quantum Physics / 478
- 12.7 Molecular Dynamics / 479
- 12.8 Fluid Flow in Submicrometer- and Nanoscales / 482
 - 12.8.1 Rarefied Gas / 482
 - 12.8.2 Knudsen and Mach Numbers / 482
 - 12.8.3 Modeling of Micro- and Nanoscale Gas Flow / 483
- 12.9 Heat Conduction at Nanoscale / 486
 - 12.9.1 Heat Transmission at Submicrometer- and Nanoscale / 486
 - 12.9.2 Thermal Conductivity of Thin Films / 489
 - 12.9.3 Heat Conduction Equation for Thin Films / 490
- 12.10 Measurement of Thermal Conductivity / 491
- 12.11 Challenges in Nanoscale Engineering / 497
 - 12.11.1 Nanopatterning in Nanofabrication / 498
 - 12.11.2 Nanoassembly / 500

12.11.3	New Materials for Nanoelectromechanical Systems (NEMS) / 500
12.11.4	Analytical Modeling / 501
12.11.5	Testing / 502
12.12	Social Impacts of Nanoscale Engineering / 502
	Problems / 503

REFERENCES	509
APPENDIX 1 RECOMMENDED UNITS FOR THERMOPHYSICAL QUANTITIES	523
APPENDIX 2 CONVERSION OF UNITS	525
INDEX	527