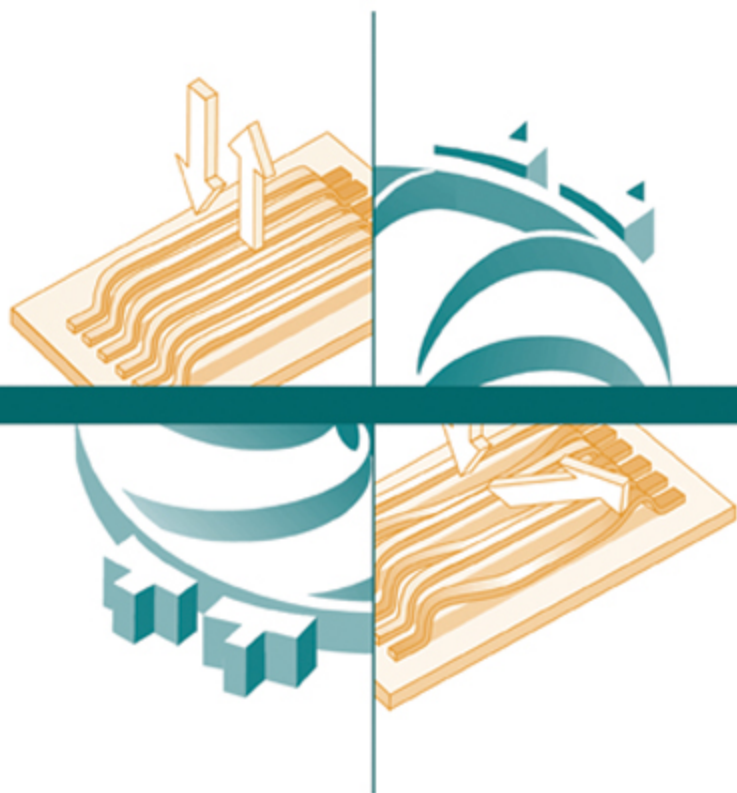


M E M S

MICROELECTROMECHANICAL SYSTEMS SERIES

An Introduction to Microelectromechanical Systems Engineering

SECOND EDITION



**NADIM MALUF
KIRT WILLIAMS**

Contents

Foreword	<i>xiii</i>
Preface	<i>xv</i>
Preface to First Edition	<i>xix</i>
CHAPTER 1	
MEMS: A Technology from Lilliput	1
The Promise of Technology	1
What Are MEMS—or MST?	2
What Is Micromachining?	3
Applications and Markets	4
To MEMS or Not To MEMS?	7
Standards	8
The Psychological Barrier	8
Journals, Conferences, and Web Sites	9
List of Journals and Magazines	9
List of Conferences and Meetings	10
Summary	11
References	11
Selected Bibliography	12
CHAPTER 2	
Materials for MEMS	13
Silicon-Compatible Material System	13
Silicon	13
Silicon Oxide and Nitride	19
Thin Metal Films	20
Polymers	21
Other Materials and Substrates	21
Glass and Fused Quartz Substrates	21
Silicon Carbide and Diamond	22
Gallium Arsenide and Other Group III-V Compound Semiconductors	22
Polymers	23
Shape-Memory Alloys	23
Important Material Properties and Physical Effects	24

Piezoresistivity	24
Piezoelectricity	26
Thermoelectricity	29
Summary	31
References	31
Selected Bibliography	32
CHAPTER 3	
Processes for Micromachining	33
Basic Process Tools	34
Epitaxy	34
Oxidation	35
Sputter Deposition	35
Evaporation	36
Chemical-Vapor Deposition	37
Spin-On Methods	40
Lithography	40
Etching	44
Advanced Process Tools	55
Anodic Bonding	55
Silicon Direct Bonding	56
Grinding, Polishing, and Chemical-Mechanical Polishing	57
Sol-Gel Deposition Methods	58
Electroplating and Molding	58
Supercritical Drying	60
Self-Assembled Monolayers	61
SU-8 Photosensitive Epoxy	61
Photosensitive Glass	62
EFAB	62
Nonlithographic Microfabrication Technologies	63
Ultraprecision Mechanical Machining	64
Laser Machining	64
Electrodischarge Machining	65
Screen Printing	65
Microcontact Printing/Soft Lithography	66
Nanoimprint Lithography	67
Hot Embossing	67
Ultrasonic Machining	68
Combining the Tools—Examples of Commercial Processes	68
Polysilicon Surface Micromachining	69
Combining Silicon Fusion Bonding with Reactive Ion Etching	71
DRIE of SOI Wafers	71
Single Crystal Reactive Etching and Metallization	72
Summary	74
References	75
Selected Bibliography	77

CHAPTER 4

MEM Structures and Systems in Industrial and Automotive Applications	79
General Design Methodology	79
Techniques for Sensing and Actuation	81
Common Sensing Methods	81
Common Actuation Methods	82
Passive Micromachined Mechanical Structures	85
Fluid Nozzles	85
Hinge Mechanisms	88
Sensors and Analysis Systems	89
Pressure Sensors	89
High-Temperature Pressure Sensors	93
Mass Flow Sensors	94
Acceleration Sensors	96
Angular Rate Sensors and Gyroscopes	104
Carbon Monoxide Gas Sensor	114
Actuators and Actuated Microsystems	116
Thermal Inkjet Heads	116
Micromachined Valves	119
Micropumps	126
Summary	128
References	129
Selected Bibliography	131

CHAPTER 5

MEM Structures and Systems in Photonic Applications	133
Imaging and Displays	133
Infrared Radiation Imager	133
Projection Display with the Digital Micromirror Device™	135
Grating Light Valve™ Display	139
Fiber-Optic Communication Devices	141
Tunable Lasers	142
Wavelength Locker	151
Digital $M \times N$ Optical Switch	154
Beam-Steering Micromirror for Photonic Switches and Cross Connects	156
Achromatic Variable Optical Attenuation	161
Summary	165
References	165
Selected Bibliography	167

CHAPTER 6

MEMS Applications in Life Sciences	169
Microfluidics for Biological Applications	169
Pumping in Microfluidic Systems	170
Mixing in Microfluidics	171
DNA Analysis	172

The Structure of DNA	172
PCR	174
PCR on a Chip	174
Electrophoresis on a Chip	176
DNA Hybridization Arrays	180
Microelectrode Arrays	182
DNA Addressing with Microelectrodes	183
Cell Cultures over Microelectrodes	185
Summary	185
References	186
Selected Bibliography	187
CHAPTER 7	
MEM Structures and Systems in RF Applications	189
Signal Integrity in RF MEMS	189
Passive Electrical Components: Capacitors and Inductors	190
Quality Factor and Parasitics in Passive Components	190
Surface-Micromachined Variable Capacitors	192
Bulk-Micromachined Variable Capacitors	195
Micromachined Inductors	197
Microelectromechanical Resonators	200
Comb-Drive Resonators	201
Beam Resonators	203
Coupled-Resonator Bandpass Filters	206
Film Bulk Acoustic Resonators	208
Microelectromechanical Switches	211
Membrane Shunt Switch	213
Cantilever Series Switch	213
Summary	214
References	214
Selected Bibliography	216
CHAPTER 8	
Packaging and Reliability Considerations for MEMS	217
Key Design and Packaging Considerations	218
Wafer or Wafer-Stack Thickness	219
Wafer Dicing Concerns	219
Thermal Management	220
Stress Isolation	221
Protective Coatings and Media Isolation	222
Hermetic Packaging	223
Calibration and Compensation	224
Die-Attach Processes	225
Wiring and Interconnects	227
Electrical Interconnects	227
Microfluidic Interconnects	231
Optical Interconnects	232

Types of Packaging Solutions	233
Ceramic Packaging	233
Metal Packaging	237
Molded Plastic Packaging	240
Quality Control, Reliability, and Failure Analysis	243
Quality Control and Reliability Standards	244
Statistical Methods in Reliability	246
Accelerated Life Modeling	248
Major Failure Modes	249
A Reliability Case Study: The DMD	254
Summary	256
References	257
Selected Bibliography	259
Glossary	261
About the Authors	271
Index	273