

Contents

1. Introduction	1
2. MEMS	5
2.1 Miniaturisation and Systems	5
2.2 Examples for MEMS.....	6
2.2.1 Bubble Jet	7
2.2.2 Actuators.....	9
2.2.3 Micropumps.....	10
2.3 Small and Large: Scaling	13
2.3.1 Electromagnetic Forces.....	13
2.3.2 Coulomb Friction.....	16
2.3.3 Mechanical Strength	16
2.3.4 Dynamic Properties.....	17
2.4 Available Fabrication Technology	20
2.4.1 Technologies Based on Lithography	20
2.4.1.1 Silicon Micromachining	21
2.4.1.2 LIGA.....	22
2.4.2 Miniaturisation of Conventional Technologies	23
3. Introduction into Silicon Micromachining	24
3.1 Photolithography	24
3.2 Thin Film Deposition and Doping	25
3.2.1 Silicon Dioxide	26
3.2.2 Chemical Vapour Deposition.....	27
3.2.3 Evaporation.....	29
3.2.4 Sputterdeposition	31
3.2.5 Doping	31
3.3 Wet Chemical Etching	32
3.3.1 Isotropic Etching.....	32
3.3.2 Anisotropic Etching.....	34
3.3.3 Etch Stop.....	36
3.4 Waferbonding.....	40
3.4.1 Anodic Bonding.....	41
3.4.2 Silicon Fusion Bonding	43

3.5	Plasma Etching	45
3.5.1	Plasma	45
3.5.2	Anisotropic Plasma Etching Modes.....	47
3.5.3	Configurations	48
3.5.4	Black Silicon Method	53
3.6	Surface Micromachining	55
3.6.1	Thin Film Stress.....	56
3.6.2	Sticking	57
4.	Mechanics of Membranes and Beams	59
4.1	Dynamics of the Mass Spring System.....	59
4.2	Strings.....	63
4.3	Beams	65
4.3.1	Stress and Strain	65
4.3.2	Bending Energy	66
4.3.3	Radius of Curvature	67
4.3.4	Lagrange Function of a Flexible Beam.....	70
4.3.5	Differential Equation for Beams.....	70
4.3.6	Boundary Conditions for Beams.....	72
4.3.7	Examples.....	73
4.3.8	Mechanical Stability	75
4.3.9	Transversal Vibration of Beams	77
4.4	Diaphragms and Membranes.....	80
4.4.1	Circular Diaphragms.....	80
4.4.2	Square Membranes	82
	Appendix 4.1: Buckling of Bridges.....	84
5.	Principles of Measuring Mechanical Quantities:	
	Transduction of Deformation	85
5.1	Metal Strain Gauges	85
5.2	Semiconductor Strain Gauges	86
5.2.1	Piezoresistive Effect in Single Crystalline Silicon	87
5.2.2	Piezoresistive Effect in Polysilicon Thin Films.....	88
5.2.3	Transduction from Deformation to Resistance	89
5.3	Capacitive Transducers	90
5.3.1	Electromechanics	90
5.3.2	Diaphragm Pressure Sensors	94
6.	Force and Pressure Sensors.....	97
6.1	Force Sensors	98
6.1.1	Load Cells.....	101
6.2	Pressure Sensors	106
6.2.1	Piezoresistive Pressure Sensors	107
6.2.2	Capacitive Pressure Sensors	112
6.2.3	Force Compensation Pressure Sensors	119

6.2.4	Resonant Pressure Sensors.....	121
6.2.5	Miniature Microphones.....	126
6.2.6	Tactile Imaging Arrays.....	130
7.	Acceleration and Angular Rate Sensors.....	132
7.1	Acceleration Sensors.....	133
7.1.1	Introduction.....	133
7.1.2	Bulk Micromachined Accelerometers.....	134
7.1.3	Surface Micromachined Accelerometers.....	138
7.1.4	Force Feedback.....	143
7.2	Angular Rate Sensors.....	145
8.	Flow sensors.....	153
8.1	The Laminar Boundary Layer.....	153
8.1.1	The Navier-Stokes Equations.....	153
8.1.2	Heat Transport.....	157
8.1.3	Hydrodynamic Boundary Layer.....	158
8.1.4	Thermal Boundary Layer.....	163
8.1.5	Skin Friction and Heat Transfer.....	166
8.2	Heat Transport in the Limit of Very Small Reynolds Numbers.....	168
8.3	Thermal Flow Sensors.....	173
8.3.1	Anemometer Type Flow Sensors.....	174
8.3.2	Two-Wire Anemometers.....	181
8.3.3	Calorimetric Type Flow Sensors.....	183
8.3.4	Sound Intensity Sensors - The Microflow.....	188
8.3.5	Time of Flight Sensors.....	194
8.4	Skin Friction Sensors.....	195
8.5	“Dry Fluid Flow” Sensors.....	200
8.6	“Wet Fluid Flow” Sensors.....	205
9.	Resonant Sensors.....	209
9.1	Basic Principles and Physics.....	209
9.1.1	Introduction.....	209
9.1.2	The Differential Equation of a Prismatic Microbridge.....	211
9.1.3	Solving the Homogeneous, Undamped Problem using Laplace Transforms.....	212
9.1.4	Solving the Inhomogeneous Problem by Modal Analysis.....	215
9.1.5	Response to Axial Loads.....	217
9.1.6	Quality Factor.....	219
9.1.7	Nonlinear Large-Amplitude Effects.....	220
9.2	Excitation and Detection Mechanisms.....	222
9.2.1	Electrostatic Excitation and Capacitive Detection.....	223
9.2.2	Magnetic Excitation and Detection.....	223
9.2.3	Piezoelectric Excitation and Detection.....	223
9.2.4	Electrothermal Excitation and Piezoresistive Detection.....	224
9.2.5	Optothermal Excitation and Optical Detection.....	224

9.2.6 Dielectric Excitation and Detection	225
9.3 Examples and Applications	225
10. Electronic Interfacing	229
10.1 Piezoresistive Sensors	230
10.1.1 Wheatstone Bridge Configurations.....	230
10.1.2 Amplification of the Bridge Output Voltage	233
10.1.3 Noise and Offset	235
10.1.4 Feedback Control Loops.....	236
10.1.5 Interfacing with Digital Systems	237
10.1.5.1 Analog-to-Digital Conversion	237
10.1.5.2 Voltage to Frequency Converters	240
10.2 Capacitive Sensors	240
10.2.1 Impedance Bridges	241
10.2.2 Capacitance Controlled Oscillators	245
10.3 Resonant Sensors.....	248
10.3.1 Frequency Dependent Behavior of Resonant Sensors	248
10.3.2 Realizing an Oscillator.....	249
10.3.3 One-Port Versus Two-Port Resonators	251
10.3.4 Oscillator Based on One-Port Electrostatically Driven Beam Resonator	251
10.3.5 Oscillator Based on Two-Port Electrodynamically Driven H-shaped Resonator.....	257
11. Packaging	259
11.1 Packaging Techniques.....	260
11.1.1 Standard Packages	260
11.1.2 Chip Mounting Methods.....	262
11.1.2 Wafer Level Packaging.....	263
11.1.3 Interconnection Techniques.....	265
11.1.4 Multichip Modules.....	267
11.1.5 Encapsulation Processes	269
11.2 Stress Reduction	269
11.3 Pressure Sensors	270
11.4 Inertial Sensors.....	272
11.5 Thermal Flow Sensors.....	272
References	274
Index	291