

Smart Material Systems and MEMS: Design and Development Methodologies

Vijay K. Varadan

University of Arkansas, USA

K. J. Vinoy

Indian Institute of Science, Bangalore, India

S. Gopalakrishnan

Indian Institute of Science, Bangalore, India



John Wiley & Sons, Ltd

Contents

Preface

xi

About the Authors

xiii

PART 1: FUNDAMENTALS	1
1 Introduction to Smart Systems	3
1.1 Components of a smart system	3
1.1.1 ‘Smartness’	6
1.1.2 Sensors, actuators, transducers	7
1.1.3 Micro electromechanical systems (MEMS)	7
1.1.4 Control algorithms	9
1.1.5 Modeling approaches	10
1.1.6 Effects of scaling	10
1.1.7 Optimization schemes	10
1.2 Evolution of smart materials and structures	11
1.3 Application areas for smart systems	13
1.4 Organization of the book	13
References	15
2 Processing of Smart Materials	17
2.1 Introduction	17
2.2 Semiconductors and their processing	17
2.2.1 Silicon crystal growth from the melt	19
2.2.2 Epitaxial growth of semiconductors	20
2.3 Metals and metallization techniques	21
2.4 Ceramics	22
2.4.1 Bulk ceramics	22
2.4.2 Thick films	23
2.4.3 Thin films	25
2.5 Silicon micromachining techniques	26
2.6 Polymers and their synthesis	26
2.6.1 Classification of polymers	27
2.6.2 Methods of polymerization	28
2.7 UV radiation curing of polymers	31
2.7.1 Relationship between wavelength and radiation energy	31
2.7.2 Mechanisms of UV curing	32
2.7.3 Basic kinetics of photopolymerization	33

2.8 Deposition techniques for polymer thin films	35
2.9 Properties and synthesis of carbon nanotubes	35
References	40
PART 2: DESIGN PRINCIPLES	43
3 Sensors for Smart Systems	45
3.1 Introduction	45
3.2 Conductometric sensors	45
3.3 Capacitive sensors	46
3.4 Piezoelectric sensors	48
3.5 Magnetostrictive sensors	48
3.6 Piezoresistive sensors	50
3.7 Optical sensors	51
3.8 Resonant sensors	53
3.9 Semiconductor-based sensors	53
3.10 Acoustic sensors	57
3.11 Polymeric sensors	58
3.12 Carbon nanotube sensors	59
References	61
4 Actuators for Smart Systems	63
4.1 Introduction	63
4.2 Electrostatic transducers	64
4.3 Electromagnetic transducers	68
4.4 Electrodynamic transducers	70
4.5 Piezoelectric transducers	73
4.6 Electrostrictive transducers	74
4.7 Magnetostrictive transducers	78
4.8 Electrothermal actuators	80
4.9 Comparison of actuation schemes	82
References	83
5 Design Examples for Sensors and Actuators	85
5.1 Introduction	85
5.2 Piezoelectric sensors	85
5.3 MEMS IDT-based accelerometers	88
5.4 Fiber-optic gyroscopes	92
5.5 Piezoresistive pressure sensors	94
5.6 SAW-based wireless strain sensors	96
5.7 SAW-based chemical sensors	97
5.8 Microfluidic systems	100
References	102
PART 3: MODELING TECHNIQUES	103
6 Introductory Concepts in Modeling	105
6.1 Introduction to the theory of elasticity	105
6.1.1 Description of motion	105
6.1.2 Strain	107

6.1.3 Strain–displacement relationship	109
6.1.4 Governing equations of motion	113
6.1.5 Constitutive relations	114
6.1.6 Solution procedures in the linear theory of elasticity	117
6.1.7 Plane problems in elasticity	119
6.2 Theory of laminated composites	120
6.2.1 Introduction	120
6.2.2 Micromechanical analysis of a lamina	121
6.2.3 Stress–strain relations for a lamina	123
6.2.4 Analysis of a laminate	126
6.3 Introduction to wave propagation in structures	128
6.3.1 Fourier analysis	129
6.3.2 Wave characteristics in 1-D waveguides	134
References	144
7 Introduction to the Finite Element Method	145
7.1 Introduction	145
7.2 Variational principles	147
7.2.1 Work and complimentary work	147
7.2.2 Strain energy, complimentary strain energy and kinetic energy	148
7.2.3 Weighted residual technique	149
7.3 Energy functionals and variational operator	151
7.3.1 Variational symbol	153
7.4 Weak form of the governing differential equation	153
7.5 Some basic energy theorems	154
7.5.1 Concept of virtual work	154
7.5.2 Principle of virtual work (PVW)	154
7.5.3 Principle of minimum potential energy (PMPE)	155
7.5.4 Rayleigh–Ritz method	156
7.5.5 Hamilton’s principle (HP)	156
7.6 Finite element method	158
7.6.1 Shape functions	159
7.6.2 Derivation of the finite element equation	162
7.6.3 Isoparametric formulation and numerical integration	164
7.6.4 Numerical integration and Gauss quadrature	167
7.6.5 Mass and damping matrix formulation	168
7.7 Computational aspects in the finite element method	171
7.7.1 Factors governing the speed of the FE solution	172
7.7.2 Equation solution in static analysis	173
7.7.3 Equation solution in dynamic analysis	174
7.8 Superconvergent finite element formulation	178
7.8.1 Superconvergent deep rod finite element	179
7.9 Spectral finite element formulation	182
References	184
8 Modeling of Smart Sensors and Actuators	187
8.1 Introduction	187
8.2 Finite element modeling of a 3-D composite laminate with embedded piezoelectric sensors and actuators	189
8.2.1 Constitutive model	189
8.2.2 Finite element modeling	191

8.2.3 2-D Isoparametric plane stress smart composite finite element	192
8.2.4 Numerical example	194
8.3 Superconvergent smart thin-walled box beam element	196
8.3.1 Governing equation for a thin-walled smart composite beam	196
8.3.2 Finite element formulation	199
8.3.3 Formulation of consistent mass matrix	201
8.3.4 Numerical experiments	202
8.4 Modeling of magnetostrictive sensors and actuators	204
8.4.1 Constitutive model for a magnetostrictive material (Terfenol-D)	204
8.4.2 Finite element modeling of composite structures with embedded magnetostrictive patches	205
8.4.3 Numerical examples	209
8.4.4 Modeling of piezo fibre composite (PFC) sensors/actuators	212
8.5 Modeling of micro electromechanical systems	215
8.5.1 Analytical model for capacitive thin-film sensors	216
8.5.2 Numerical example	218
8.6 Modeling of carbon nanotubes (CNTs)	219
8.6.1 Spectral finite element modeling of an MWCNT	222
References	229
 9 Active Control Techniques	231
9.1 Introduction	231
9.2 Mathematical models for control theory	232
9.2.1 Transfer function	232
9.2.2 State-space modeling	234
9.3 Stability of control system	237
9.4 Design concepts and methodology	239
9.4.1 PD, PI and PID controllers	239
9.4.2 Eigenstructure assignment technique	240
9.5 Modal order reduction	241
9.5.1 Review of available modal order reduction techniques	242
9.6 Active control of vibration and waves due to broadband excitation	246
9.6.1 Available strategies for vibration and wave control	247
9.6.2 Active spectral finite element model (ASEM) for broadband wave control	248
References	253
 PART 4: FABRICATION METHODS AND APPLICATIONS	255
 10 Silicon Fabrication Techniques for MEMS	257
10.1 Introduction	257
10.2 Fabrication processes for silicon MEMS	257
10.2.1 Lithography	257
10.2.2 Resists and mask formation	258
10.2.3 Lift-off technique	259
10.2.4 Etching techniques	260
10.2.5 Wafer bonding for MEMS	261
10.3 Deposition techniques for thin films in MEMS	263
10.3.1 Metallization techniques	264
10.3.2 Thermal oxidation for silicon dioxide	265
10.3.3 CVD of dielectrics	266

10.3.4 Polysilicon film deposition	268
10.3.5 Deposition of ceramic thin films	268
10.4 Bulk micromachining for silicon-based MEMS	268
10.4.1 Wet etching for bulk micromachining	269
10.4.2 Etch-stop techniques	269
10.4.3 Dry etching for micromachining	271
10.5 Silicon surface micromachining	271
10.5.1 Material systems in sacrificial layer technology	273
10.6 Processing by both bulk and surface micromachining	274
10.7 LIGA process	274
References	278
11 Polymeric MEMS Fabrication Techniques	281
11.1 Introduction	281
11.2 Microstereolithography	282
11.2.1 Overview of stereolithography	282
11.2.2 Introduction to microstereolithography	284
11.2.3 MSL by scanning methods	285
11.2.4 Projection-type methods of MSL	287
11.3 Micromolding of polymeric 3-D structures	289
11.3.1 Micro-injection molding	290
11.3.2 Micro-photomolding	291
11.3.3 Micro hot-embossing	291
11.3.4 Micro transfer-molding	291
11.3.5 Micromolding in capillaries (MIMIC)	292
11.4 Incorporation of metals and ceramics by polymeric processes	293
11.4.1 Burnout and sintering	293
11.4.2 Jet molding	293
11.4.3 Fabrication of ceramic structures with MSL	294
11.4.4 Powder injection molding	295
11.4.5 Fabrication of metallic 3-D microstructures	296
11.4.6 Metal-polymer microstructures	300
11.5 Combined silicon and polymer structures	300
11.5.1 Architecture combination by MSL	300
11.5.2 MSL integrated with thick-film lithography	301
11.5.3 AMANDA process	301
References	302
12 Integration and Packaging of Smart Microsystems	307
12.1 Integration of MEMS and microelectronics	307
12.1.1 CMOS first process	307
12.1.2 MEMS first process	307
12.1.3 Intermediate process	308
12.1.4 Multichip module	308
12.2 MEMS packaging	310
12.2.1 Objectives in packaging	311
12.2.2 Special issues in MEMS packaging	313
12.2.3 Types of MEMS packages	314
12.3 Packaging techniques	315
12.3.1 Flip-chip assembly	315
12.3.2 Ball-grid array	316

12.3.3 Embedded overlay	316
12.3.4 Wafer-level packaging	317
12.4 Reliability and key failure mechanisms	319
12.5 Issues in packaging of microsystems	321
References	322
 13 Fabrication Examples of Smart Microsystems	 325
13.1 Introduction	325
13.2 PVDF transducers	325
13.2.1 PVDF-based transducer for structural health monitoring	325
13.2.2 PVDF film for a hydrophone	328
13.3 SAW accelerometer	332
13.4 Chemical and biosensors	336
13.4.1 SAW-based smart tongue	337
13.4.2 CNT-based glucose sensor	339
13.5 Polymeric fabrication of a microfluidic system	342
References	344
 14 Structural Health Monitoring Applications	 347
14.1 Introduction	347
14.2 Structural health monitoring of composite wing-type structures using magnetostrictive sensors/actuators	349
14.2.1 Experimental study of a through-width delaminated beam specimen	350
14.2.2 Three-dimensional finite element modeling and analysis	352
14.2.3 Composite beam with single smart patch	353
14.2.4 Composite beam with two smart patches	355
14.2.5 Two-dimensional wing-type plate structure	357
14.3 Assesment of damage severity and health monitoring using PZT sensors/actuators	358
14.4 Actuation of DCB specimen under Mode-II dynamic loading	364
14.5 Wireless MEMS-IDT microsensors for health monitoring of structures and systems	365
14.5.1 Description of technology	367
14.5.2 Wireless-telemetry systems	368
References	374
 15 Vibration and Noise-Control Applications	 377
15.1 Introduction	377
15.2 Active vibration control in a thin-walled box beam	377
15.2.1 Test article and experimental set-up	378
15.2.2 DSP-based vibration controller card	378
15.2.3 Closed-loop feedback vibration control using a PI controller	380
15.2.4 Multi-modal control of vibration in a box beam using eigenstructure assignment	383
15.3 Active noise control of structure-borne vibration and noise in a helicopter cabin	385
15.3.1 Active strut system	387
15.3.2 Numerical simulations	387
References	394
 Index	 397