Table of contents

- Preface (p. xi)
- About the Authors (p. xiii)
- Part 1 Fundamentals (p. 1)
- 1 Introduction to Smart Systems (p. 3)
- 1.1 Components of a smart system (p. 3)
- **1.1 1 'Smartness'** (p. 6)
- 1.1.2 Sensors, actuators, transducers (p. 7)
- 1.1.3 Micro electromechanical systems (MEMS) (p. 7)
- 1.1.4 Control algorithms (p. 9)
- 1.1.5 Modeling approaches (p. 10)
- **1.1.6 Effects of scaling** (p. 10)
- 1.1.7 Optimization schemes (p. 10)
- 1.2 Evolution of smart materials and structures (p. 11)
- 1.3 Application areas for smart systems (p. 13)
- 1.4 Organization of the book (p. 13)
- **References** (p. 15)
- 2 Processing of Smart Materials (p. 17)
- **2.1 Introduction** (p. 17)
- 2.2 Semiconductors and their processing (p. 17)
- 2.2.1 Silicon crystal growth from the melt (p. 19)
- 2.2.2 Epitaxial growth of semiconductors (p. 20)
- 2.3 Metals and metallization techniques (p. 21)
- **2.4 Ceramics** (p. 22)
- **2.4.1 Bulk ceramics** (p. 22)
- **2.4.2 Thick films** (p. 23)
- **2.4.3 Thin films** (p. 25)
- 2.5 Silicon micromachining techniques (p. 26)
- **2.6 Polymers and their synthesis** (p. 26)
- 2.6.1 Classification of polymers (p. 27)
- **2.6.2 Methods of polymerization** (p. 28)
- **2.7 UV radiation curing of polymers** (p. 31)
- 2.7.1 Relationship between wavelength and radiation energy (p. 31)
- 2.7.2 Mechanisms of UV curing (p. 32)
- 2.7.3 Basic kinetics of photopolymerization (p. 33)
- 2.8 Deposition techniques for polymer thin films (p. 35)
- 2.9 Properties and synthesis of carbon nanotubes (p. 35)
- **References** (p. 40)
- Part 2 Design Principles (p. 43)
- 3 Sensors for Smart Systems (p. 45)
- **3.1 Introduction** (p. 45)
- 3.2 Conductometric sensors (p. 45)
- 3.3 Capacitive sensors (p. 46)
- 3.4 Piezoelectric sensors (p. 48)
- 3.5 Magnetostrictive sensors (p. 48)

- 3.6 Piezoresistive sensors (p. 50)
- **3.7 Optical sensors** (p. 51)
- 3.8 Resonant sensors (p. 53)
- 3.9 Semiconductor-based sensors (p. 53)
- **3.10 Acoustic sensors** (p. 57)
- **3.11 Polymeric sensors** (p. 58)
- 3.12 Carbon nanotube sensors (p. 59)
- References (p. 61)
- 4 Actuators for Smart Systems (p. 63)
- **4.1 Introduction** (p. 63)
- **4.2 Electrostatic transducers** (p. 64)
- 4.3 Electromagnetic transducers (p. 68)
- **4.4 Electrodynamic transducers** (p. 70)
- 4.5 Piezoelectric transducers (p. 73)
- 4.6 Electrostrictive transducers (p. 74)
- **4.7 Magnetostrictive transducers** (p. 78)
- 4.8 Electrothermal actuators (p. 80)
- **4.9 Comparison of actuation schemes** (p. 82)
- References (p. 83)
- 5 Design Examples for Sensors and Actuators (p. 85)
- **5.1 Introduction** (p. 85)
- **5.2 Piezoelectric sensors** (p. 85)
- 5.3 MEMS IDT-based accelerometers (p. 88)
- 5.4 Fiber-optic gyroscopes (p. 92)
- **5.5 Piezoresistive pressure sensors** (p. 94)
- **5.6 SAW-based wireless strain sensors** (p. 96)
- **5.7 SAW-based chemical sensors** (p. 97)
- 5.8 Microfluidic systems (p. 100)
- **References** (p. 102)
- Part 3 Modeling Techniques (p. 103)
- 6 Introductory Concepts in Modeling (p. 105)
- **6.1 Introduction to the theory of elasticity** (p. 105)
- **6.1.1 Description of motion** (p. 105)
- **6.1.2 Strain** (p. 107)
- **6.1.3 Strain-displacement relationship** (p. 109)
- **6.1.4 Governing equations of motion** (p. 113)
- **6.1.5 Constitutive relations** (p. 114)
- 6.1.6 Solution procedures in the linear theory of elasticity (p. 117)
- **6.1.7 Plane problems in elasticity** (p. 119)
- 6.2 Theory of laminated composites (p. 120)
- **6.2.1 Introduction** (p. 120)
- 6.2.2 Micromechanical analysis of a lamina (p. 121)
- **6.2.3 Stress-strain relations for a lamina** (p. 123)
- **6.2.4 Analysis of a laminate** (p. 126)
- 6.3 Introduction to wave propagation in structures (p. 128)
- **6.3.1 Fourier analysis** (p. 129)

- 6.3.2 Wave characteristics in 1-D waveguides (p. 134)
- **References** (p. 144)
- 7 Introduction to the Finite Element Method (p. 145)
- **7.1 Introduction** (p. 145)
- 7.2 Variational principles (p. 147)
- 7.2.1 Work and complimentary work (p. 147)
- 7.2.2 Strain energy, complimentary strain energy and kinetic energy (p. 148)
- **7.2.3 Weighted residual technique** (p. 149)
- 7.3 Energy functionals and variational operator (p. 151)
- **7.3.1 Variational symbol** (p. 153)
- 7.4 Weak form of the governing differential equation (p. 153)
- **7.5 Some basic energy theorems** (p. 154)
- **7.5.1 Concept of virtual work** (p. 154)
- 7.5.2 Principle of virtual work (PVW) (p. 154)
- 7.5.3 Principle of minimum potential energy (PMPE) (p. 155)
- **7.5.4 Rayleigh-Ritz method** (p. 156)
- **7.5.5 Hamilton's principle (HP)** (p. 156)
- **7.6 Finite element method** (p. 158)
- **7.6.1 Shape functions** (p. 159)
- 7.6.2 Derivation of the finite element equation (p. 162)
- 7.6.3 Isoparametric formulation and numerical integration (p. 164)
- 7.6.4 Numerical integration and Gauss quadrature (p. 167)
- 7.6.5 Mass and damping matrix formulation (p. 168)
- 7.7 Computational aspects in the finite element method (p. 171)
- 7.7.1 Factors governing the speed of the FE solution (p. 172)
- 7.7.2 Equation solution in static analysis (p. 173)
- 7.7.3 Equation solution in dynamic analysis (p. 174)
- 7.8 Superconvergent finite element formulation (p. 178)
- 7.8.1 Superconvergent deep rod finite element (p. 179)
- 7.9 Spectral finite element formulation (p. 182)
- **References** (p. 184)
- 8 Modeling of Smart Sensors and Actuators (p. 187)
- **8.1 Introduction** (p. 187)
- 8.2 Finite element modeling of a 3-D composite laminate with embedded piezoelectric sensors and actuators (p. 189)
- **8.2.1 Constitutive model** (p. 189)
- 8.2.2 Finite element modeling (p. 191)
- 8.2.3 2-D Isoparametric plane stress smart composite finite element (p. 192)
- **8.2.4 Numerical example** (p. 194)
- 8.3 Superconvergent smart thin-walled box beam element (p. 196)
- 8.3.1 Governing equation for a thin-walled smart composite beam (p. 196)
- **8.3.2 Finite element formulation** (p. 199)
- 8.3.3 Formulation of consistent mass matrix (p. 201)
- 8.3.4 Numerical experiments (p. 202)
- 8.4 Modeling of magnetostrictive sensors and actuators (p. 204)
- 8.4.1 Constitutive model for a magnetostrictive material (Tefenol-D) (p. 204)

- 8.4.2 Finite element modeling of composite structures with embedded magnetostrictive patches (p. 205)
- **8.4.3 Numerical examples** (p. 209)
- 8.4.4 Modeling of piezo fibre composite (PFC) sensors/actuators (p. 212)
- 8.5 Modeling of micro electromechanical systems (p. 215)
- 8.5.1 Analytical model for capacitive thin-film sensors (p. 216)
- **8.5.2 Numerical example** (p. 218)
- 8.6 Modeling of carbon nanotubes (CNTs) (p. 219)
- 8.6.1 Spectral finite element modeling of an MWCNT (p. 222)
- **References** (p. 229)
- 9 Active Control Techniques (p. 231)
- **9.1 Introduction** (p. 231)
- 9.2 Mathematical models for control theory (p. 232)
- **9.2.1 Transfer function** (p. 232)
- **9.2.2 State-space modeling** (p. 234)
- 9.3 Stability of control system (p. 237)
- **9.4 Design concepts and methodology** (p. 239)
- **9.4.1 PD, PI and PID controllers** (p. 239)
- 9.4.2 Eigenstructure assignment technique (p. 240)
- **9.5 Modal order reduction** (p. 241)
- 9.5.1 Review of available modal order reduction techniques (p. 242)
- 9.6 Active control of vibration and waves due to broadband excitation (p. 246)
- 9.6.1 Available strategies for vibration and wave control (p. 247)
- 9.6.2 Active spectral finite element model (ASEM) for broadband wave control (p. 248)
- **References** (p. 253)
- Part 4 Fabrication Methods and Applications (p. 255)
- 10 Silicon Fabrication Techniques for MEMS (p. 257)
- **10.1 Introduction** (p. 257)
- 10.2 Fabrication processes for silicon MEMS (p. 257)
- **10.2.1 Lithography** (p. 257)
- 10.2.2 Resists and mask formation (p. 258)
- **10.2.3 Lift-off technique** (p. 259)
- **10.2.4 Etching techniques** (p. 260)
- **10.2.5 Wafer bonding for MEMS** (p. 261)
- 10.3 Deposition techniques for thin films in MEMS (p. 263)
- **10.3.1 Metallization techniques** (p. 264)
- 10.3.2 Thermal oxidation for silicon dioxide (p. 265)
- **10.3.3 CVD of dielectrics** (p. 266)
- 10.3.4 Polysilicon film deposition (p. 268)
- 10.3.5 Deposition of ceramic thin films (p. 268)
- 10.4 Bulk micromachining for silicon-based MEMS (p. 268)
- 10.4.1 Wet etching for bulk micromachining (p. 269)
- **10.4.2 Etch-stop techniques** (p. 269)
- 10.4.3 Dry etching for micromachining (p. 271)

- 10.5 Silicon surface micromachining (p. 271)
- 10.5.1 Material systems in sacrificial layer technology (p. 273)
- 10.6 Processing by both bulk and surface micromachining (p. 274)
- **10.7 LIGA process** (p. 274)
- **References** (p. 278)
- 11 Polymeric MEMS Fabrication Techniques (p. 281)
- **11.1 Introduction** (p. 281)
- 11.2 Microstereolithography (p. 282)
- 11.2.1 Overview of stereolithography (p. 282)
- 11.2.2 Introduction to microstereolithography (p. 284)
- **11.2.3 MSL by scanning methods** (p. 285)
- 11.2.4 Projection-type methods of MSL (p. 287)
- 11.3 Micromolding of polymeric 3-D structures (p. 289)
- 11.3.1 Micro-injection molding (p. 290)
- **11.3.2 Micro-photomolding** (p. 291)
- 11.3.3 Micro hot-embossing (p. 291)
- **11.3.4 Micro transfer-molding** (p. 291)
- 11.3.5 Micromolding in capillaries (MIMIC) (p. 292)
- 11.4 Incorporation of metals and ceramics by polymeric processes (p. 293)
- **11.4.1 Burnout and sintering** (p. 293)
- 11.4.2 Jet molding (p. 293)
- 11.4.3 Fabrication of ceramic structures with MSL (p. 294)
- 11.4.4 Powder injection molding (p. 295)
- 11.4.5 Fabrication of metallic 3-D microstructures (p. 296)
- 11.4.6 Metal-polymer microstructures (p. 300)
- 11.5 Combined silicon and polymer structures (p. 300)
- 11.5.1 Architecture combination by MSL (p. 300)
- 11.5.2 MSL integrated with thick-film lithography (p. 301)
- **11.5.3 AMANDA process** (p. 301)
- **References** (p. 302)
- 12 Integration and Packaging of Smart Microsystems (p. 307)
- 12.1 Integration of MEMS and microelectronics (p. 307)
- **12.1.1 CMOS first process** (p. 307)
- **12.1.2 MEMS first process** (p. 307)
- **12.1.3 Intermediate process** (p. 308)
- **12.1.4 Multichip module** (p. 308)
- **12.2 MEMS packaging** (p. 310)
- 12.2.1 Objectives in packaging (p. 311)
- 12.2.2 Special issues in MEMS packaging (p. 313)
- **12.2.3 Types of MEMS packages** (p. 314)
- **12.3 Packaging techniques** (p. 315)
- **12.3.1 Flip-chip assembly** (p. 315)
- **12.3.2 Ball-grid array** (p. 316)
- **12.3.3 Embedded overlay** (p. 316)
- **12.3.4 Wafer-level packaging** (p. 317)
- 12.4 Reliability and key failure mechanisms (p. 319)

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