


*Materials Degradation and Failures Series*



# **Materials and Failures in MEMS and NEMS**

Edited by **Atul Tiwari and Baldev Raj**

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Edited by

**Atul Tiwari and Baldev Raj**



**WILEY**

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# Materials and Failures in MEMS and NEMS

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**Materials Degradation and Failure Series**

Studies and investigations on materials failure are critical aspects of science and engineering. The failure analysis of existing materials and the development of new materials demands in-depth understanding of the concepts and principles involved in the deterioration of materials

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## Preface

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Manufacturing, diagnosis and treatment of biospecies, agriculture, energy and infrastructure, governance, security, etc., need sensors and devices based on well-grounded concepts, engineering and technology. Miniaturization demands new materials, designs and fabrication technologies. The decrease in the size and volume of devices has necessitated the incorporation of a high level of fabrication technologies. There is a priority need to address failures in micro- and nanodevices.

The invention of Microelectromechanical Systems (MEMS) and Nanoelectromechanical Systems (NEMS) fabrication technologies has revolutionized the science and engineering industry. It is estimated that market prospects for MEMS and NEMS will increase rapidly to reach \$200 billion in 2025. The key to the success of MEMS and NEMS will be the development of technologies that can integrate multiple devices with electronics on a single chip. Among the technologies available so far, the fabrication of MEMS and/or NEMS has been predominately achieved by etching the polysilicon material. Novel materials and technologies are being explored to overcome the challenges in fabrication or manufacturing processes. In order to meet the ever-increasing demands of MEMS and NEMS, enormous amounts of research, applications and innovations have been explored and exploited. Most of the relevant information originating from such efforts is being treated as confidential or privileged, which seeds extensive barriers to the research, development and aspirational demands of these technologies.

This book includes chapters written by eminent experts in the area of MEMS and NEMS. The opening chapter of this book reviews various C-MEMS fabrication technologies involving patterning of polymeric precursors of carbon such as epoxy photoresists and sol-gel polymers, followed by pyrolysis to generate glassy or semicrystalline carbon. Another chapter discusses the origins of fault in such devices, related mathematical models and utilization of filters in fault diagnosis. Also, the authors have illustrated the structure of a multiple-model adaptive estimator and its application in fault diagnosis simulation. Another chapter provides an overview of the design of MEMS heat exchangers such as heat sinks, heat pipes and two-fluid heat exchangers. The formation of porous silicon devices by electrochemical etching of silicon and the control over the porosity and pore size are discussed in a separate chapter. The use of such porous silicon devices as biosensors is thoroughly investigated by these contributors. Further, a chapter provides an overview on MEMS and NEMS switches using Si-to-Si contact. An interesting chapter discusses the design challenges during fabrication and failure analysis of cMUT devices. Investigators have compared the device fabrication by surface micromachining and wafer bonding techniques. Moreover, failure analysis of cMUT using various materials characterization techniques and their importance for successful device fabrication are also investigated.

A successive chapter investigates an effective approach to solve inverse problems in MEMS and NEMS. This chapter describes inverse problems in micro- and nanomechanical resonators and also the stiction test of MEMS and NEMS. Further, there is a chapter in the book dedicated to the control of ohmic RF-MEMS switches operating under different actuation modes, such as single pulse, tailored pulse, and tailored-pulse optimization methods, based on Taguchi's technique of resistive damping; and the hybrid actuation mode, which is a combination of the tailored pulse, the resistive damping, and Taguchi's optimization technique. Additional challenges involved in design methodologies, and available simulation packages to model and simulate MEMS devices are explored in a separate chapter. To develop MEMS devices and to understand the inception of fabrication defects, researchers have explored fabrication techniques such as surface micromachining and bonding silicon to glass. The use of different characterization techniques, such as visual, electrical and mechanical, for inspecting the defects in these devices has also been demonstrated. An independent chapter systematically investigates the buckling behavior of a typical micron-scale constantan-wire/polymer-substrate structure under electrical loading. Another crucial chapter discusses many important aspects of microcantilever sensors such as operation principles, fabrication of silicon and polymer microcantilevers, mechanical and electrical characterization, readout principles, applications of microcantilever sensors for vapor-phase chemical or gas detection, biosensing and agriculture applications; and nanogenerators for energy harvesting. A chapter in the book elaborates the inherent challenges encountered in CMOS-MEMS along with the possibility of integration at board and chip levels. This chapter also lists various circuit architectures being used in capacitance detection along with a detailed comparison on their merits and demerits. The final chapter proposes a mathematical model to determine strategies for preventive replacement and inspection for MEMS that are subject to multiple dependent competing failure processes as a result of degradation and/or shock loads.

We are confident that this book will constitute a large knowledge bank for students, research scholars and engineers who are involved in the research, development and deployment of advanced MEMS and NEMS for a wide variety of applications. To the best of the editors' knowledge, such a book that addresses the developments and failures in these advanced devices has not yet been available to readers. Comprehensive expertise is mapped out and discussed in this book to advance the knowledge bank of readers in order to enable precise control over dimensional stability, quality, reliability, productivity and life cycle management of MEMS and NEMS.

The editors look forward to constructive suggestions and feedback for improving the next edition of this book on this important, relatively young subject of increasing importance and relevance.

Wishing you a purposeful and wonderful reading experience.

Atul Tiwari, PhD  
Baldev Raj, PhD  
August 4, 2015

# Contents

<b>1</b>	<b>Carbon as a MEMS Material</b>	<b>1</b>
	<i>Amritha Rammohan and Ashutosh Sharma</i>	
1.1	Introduction	1
1.2	Structure and Properties of Glassy Carbon	3
1.3	Fabrication of C-MEMS Structures	4
1.3.1	Mechanism and Features of the Pyrolysis Process	4
1.3.2	Lithographic Processes for the Fabrication of C-MEMS Structures	6
1.3.3	Soft Lithographic Techniques	11
1.3.4	Self-Assembly and Bottom-Up Processes for the Fabrication of C-MEMS Structures	13
1.4	Integration of C-MEMS Structures with Other Materials	15
1.5	Conclusion	18
	References	18
<b>2</b>	<b>Intelligent Model-Based Fault Diagnosis of MEMS</b>	<b>21</b>
	<i>Afshin Izadian</i>	
2.1	Introduction	21
2.1.1	MEMS Structure and Origins of Fault	22
2.1.1.1	Material Growth Effects	22
2.1.1.2	Lithography and Its Effects	23
2.1.1.3	Effect of Etching Process on Parameters of MEMS	25
2.1.1.4	Effect of Stress, Stress Gradients, Wearing, and Stiction on Deposited Films	26
2.1.1.5	Electrostatic Force	27
2.2	Model-Based Fault Diagnosis	29
2.2.1	Fault and Failure Definitions	30
2.2.2	System Behavior	30
2.2.3	Fault and Model Uncertainty	31
2.2.4	Faulty System Modes and Conditions	31
2.2.5	Fault Diagnosis	31
2.2.6	MEMS Mathematical Model	33
2.2.6.1	Mass Calculations	34
2.2.6.2	Spring Constant Calculations	34
2.2.6.3	Damping Coefficient	35
2.2.6.4	Model of MEMS	36



2.2.6.5	Multiple-Model Estimation Approach	37
2.2.6.6	Multiple Models as Signature Faults	38
2.2.6.7	Kalman Filters	39
2.2.7	Adaptive Estimation	39
2.2.8	Simulation and Experimental Results	41
2.2.9	Experimental Results and Discussion	44
2.2.9.1	Displacement Measurement Technique	44
2.3	Self-Tuning Estimation	49
2.3.1	Estimator Structure	49
2.3.2	Fault Diagnosis Application in MEMS: Simulation and Experiment	50
2.3.2.1	Experimental Results	52
2.3.2.2	Adaptive Self-Tuning Fault Diagnosis	54
2.3.2.3	Discussion	58
	References	59
<b>3</b>	<b>MEMS Heat Exchangers</b>	<b>63</b>
	<i>B. Mathew and L. Weiss</i>	
3.1	Introduction	63
3.2	Fundamentals of Thermodynamics, Fluid Mechanics, and Heat Transfer	67
3.2.1	Thermodynamics	67
3.2.2	Fluid Mechanics	70
3.2.3	Heat Transfer	78
3.2.3.1	Conduction	78
3.2.3.2	Convection	79
3.2.3.3	Thermal Resistance	84
3.3	MEMS Heat Sinks	86
3.4	MEMS Heat Pipes	92
3.6	Need for Microscale Internal Flow Passages	113
	Nomenclature	115
	Greek Alphabets	116
	Subscripts	116
	References	117
<b>4</b>	<b>Application of Porous Silicon in MEMS and Sensors Technology</b>	<b>121</b>
	<i>L. Sujatha, Chirasree Roy Chaudhuri and Enakshi Bhattacharya</i>	
4.1	Introduction	121
4.1.1	Properties of Porous Silicon for MEMS Applications	122
4.1.2	Review of PS for MEMS Applications	122
4.1.3	Formation of PS	123
4.1.3.1	Porous Silicon Formation Setup	123
4.1.3.2	Formation Parameters	124
4.1.3.3	PS Formation Chemistry	124
4.1.3.4	Measurement of Porosity and Thickness of PS Layer	125
4.1.3.5	I-V Characteristics	126

4.1.4	Classification of PS	127
4.1.4.1	Micro PS	127
4.1.4.2	Macro PS	128
4.1.4.3	Meso PS	129
4.1.5	Effect of Formation Parameters on Porosity and Thickness	130
4.1.6	PS Drying Mechanisms	130
4.1.7	Effect of PS Formation on Stiction in MEMS	130
4.2	Porous Silicon in Biosensors	131
4.2.1	PS Cantilever-Based Resonant Frequency Detection	131
4.2.1.1	Antibody–Antigen Binding Detection	132
4.2.1.2	Triglyceride Detection	133
4.2.2	PS-Based Impedance Detection	138
4.2.2.1	Bacteria Detection	138
4.2.2.2	Food Toxin Detection	141
4.2.2.3	DNA Detection	145
4.2.3	PS-Based EISCAP Structure for Capacitive Detection	148
4.2.3.1	Triglyceride Detection	149
4.2.3.2	Penicillin Detection	151
4.2.4	PS-Based Other Electrochemical Biosensors	151
4.2.4.1	Glucose Detection	151
4.2.4.2	DNA Detection	152
4.2.4.3	Bacteria Detection	152
4.2.4.4	IgG Detection	153
4.2.4.5	Other Analytes	153
4.2.5	Reliability	154
4.3	Porous Silicon for Pressure Sensors	155
4.3.1	Pressure Sensor with Silicon/PS Composite Membrane	156
4.3.1.1	Fabrication of Pressure Sensor with Composite Membrane	157
4.3.1.2	Performance of Si/PS Composite Membrane Pressure Sensor	158
4.3.1.3	Temperature and Humidity Effects on Packaged Si/PS Composite Membrane Pressure Sensor	159
4.3.2	Pressure Sensors with Piezoresistive Effect of PS	160
4.3.2.1	Fabrication of the Device	161
4.3.2.2	Experimental Results	162
4.3.2.3	Estimation of Piezoresistive Coefficient	163
4.4	Conclusion	165
	References	165
5	<b>MEMS/NEMS Switches with Silicon to Silicon (Si-to-Si) Contact Interface</b>	<b>173</b>
	<i>Chengkuo Lee, Bo Woon Soon and You Qian</i>	
5.1	Introduction	173
5.1.1	Why Silicon?	174
5.1.2	Electrostatic Switch	174

5.2	Bi-Stable CMOS Front End Silicon Nanofin (SiNF) Switch for Non-volatile Memory Based On Van Der Waals Force	175
5.2.1	Operational SiNF NEMS Switch with Bi-Stable States	176
5.2.2	Van Der Waals Operation and Critical Length	176
5.2.3	Fabrication Process	178
5.2.4	Electrical Characteristics of NEMS Switch Non-volatile Memory	181
5.2.4.1	Non-volatile Memory Array Application	183
5.3	Vertically Actuated U-Shape Nanowire NEMS Switch	184
5.3.1	Dual-Silicon-Nanowires-Based U-Shape NEMS Switch	184
5.3.2	U-Shape Nanowire Fabrication	185
5.3.3	Low-Voltage Operation	185
5.4	A Vacuum Encapsulated Si-to-Si MEMS Switch for Rugged Electronics	187
5.4.1	Three Terminal On-Off with Vacuum Encapsulated Switch	187
5.4.2	Vacuum Encapsulated Si-to-Si Switch	191
5.4.3	Reliability of a Vacuum Encapsulated Si-to-Si Switch	193
5.5	Summary	197
	References	197
<b>6</b>	<b>On the Design, Fabrication, and Characterization of cMUT Devices</b>	<b>201</b>
	<i>J. Jayapandian, K. Prabakar, C.S. Sundar and Baldev Raj</i>	
6.1	Introduction	201
6.2	cMUT Design and Finite Element Modeling Simulation	203
6.3	cMUT Fabrication and Characterization	205
6.3.1	Surface Micromachining Method	205
6.3.2	Wafer Bonding Method	205
6.3.2.1	Dynamic Characterization Using Laser Doppler Vibrometer	208
6.3.2.2	Capacitance Measurement	209
6.3.2.3	Surface Profile and Morphology of cMUT Membrane	209
6.3.2.4	SEM and EDS Analysis	209
6.3.3	Wafer Bonding Method with Isolation Trenches	211
6.3.3.1	Dynamic Characterization Using Nano Vibration Analyzer	212
6.3.3.2	Static Characterization and CV Measurements	214
6.4	Summary and Conclusions	216
	Acknowledgments	217
	References	217
<b>7</b>	<b>Inverse Problems in the MEMS/NEMS Applications</b>	<b>219</b>
	<i>Yin Zhang</i>	
7.1	Introduction	219
7.2	Inverse Problems in the Micro/Nanomechanical Resonators	222
7.2.1	Determining the Mass and Position of Adsorbate by Using the Shifts of Resonant Frequencies	222
7.2.2	Determining the Adsorption-Induced Surface Stress and Mass by Measuring the Shifts of Resonant Frequencies	224

7.2.3	Determining the Surface Elasticity and Surface Stress by Measuring the Shifts of Resonant Frequencies	227
7.2.4	Determining the Stiffness and Mass of Biochemical Adsorbates by a Resonator Sensor	230
7.3	Inverse Problems in the MEMS Stiction Test	231
	Acknowledgment	234
	References	234
<b>8</b>	<b>Ohmic RF-MEMS Control</b>	<b>239</b>
	<i>M. Spasos and R. Nilavalan</i>	
8.1	Introduction	239
8.1.1	Voltage Drive Control Under Single Pulse	240
8.1.2	Voltage Drive Control Under Tailored Pulse	241
8.1.3	Voltage Drive Control Under Optimized-Tailored Pulse	245
8.1.3.1	Pull-Down Phase	246
8.1.3.2	Release Phase	246
8.2	Charge Drive Control (Resistive Damping)	251
8.3	Hybrid Drive Control	255
8.4	Control Under High-Pressure Gas Damping	258
8.5	Comparison between Different Control Modes	258
	References	260
<b>9</b>	<b>Dynamics of MEMS Devices</b>	<b>263</b>
	<i>Vamsy Godthi, K. Jayaprakash Reddy and Rudra Pratap</i>	
9.1	Introduction	263
9.1.1	Resonant Devices	264
9.1.2	Non-resonant Devices	265
9.2	Modeling and Simulation	266
9.2.1	Design Parameters	266
9.2.2	Multi-physics	268
9.2.3	Simulation Tools	270
9.2.4	Process Flow Simulation	272
9.3	Fabrication Methods	273
9.3.1	Surface Micromachining	273
9.3.1.1	Issues	274
9.3.2	Bonding	275
9.3.2.1	Issues	275
9.4	Characterization	276
9.4.1	Visual	277
9.4.2	Electrical	277
9.4.3	Mechanical	279
9.5	Device Failures	280
9.5.1	Frequency Shifts	280
9.5.2	Wrong Modes	281
9.5.3	Structural Integrity	282
9.5.4	Reliability Failure	282
	Acknowledgments	283
	References	283

<b>10</b>	<b>Buckling Behaviors and Interfacial Toughness of a Micron-Scale Composite Structure with a Metal Wire on a Flexible Substrate</b>	<b>285</b>
	<i>Qinghua Wang, Huimin Xie and Yanjie Li</i>	
10.1	Introduction	285
10.2	Buckling Behaviors of Constantan Wire under Electrical Loading	289
10.2.1	Sample and Experiments	290
10.2.1.1	Sample Preparation and Characterization	290
10.2.1.2	Electrical Loading Experiments	291
10.2.1.3	Electrical–Mechanical Loading Experiments	293
10.2.1.4	Temperature Variation under Electrical Loading	293
10.2.2	Buckling Morphologies and Characteristics of Constantan Wire	294
10.2.2.1	Buckling Morphologies under Electrical Loading	294
10.2.2.2	Effects of the Electric Current Form and Current Density	295
10.2.2.3	Buckling Morphologies under Electrical–Mechanical Loading	297
10.2.3	Buckling Mechanism Analysis of Constantan Wire	299
10.2.4	Critical Buckling Analysis of Constantan Wire	300
10.2.5	Post-Buckling Analysis of Constantan Wire	301
10.2.5.1	Derivation of Residual Stress Calculation Formula	301
10.2.5.2	Calculation of Residual Stress in Constantan Wire	303
10.3	Interfacial Toughness between Constantan Wire and Polymer Substrate	305
10.3.1	Interfacial Toughness Formula for Rigid Film and Flexible Substrate	305
10.3.2	Interfacial Toughness Measurement and Discussions	306
10.3.2.1	Measurement of the Interfacial Toughness	306
10.3.2.2	Discussions	308
10.3.3	Applicable Condition of the Electricity-Induced Buckling Method	309
10.4	Buckling Behaviors of Polymer Substrate Restricted by Constantan Wire	310
10.4.1	Sample and Experiments	310
10.4.1.1	Sample Preparation and Characterization	310
10.4.1.2	Experiments	310
10.4.1.3	Sample Temperature Variations during Experiments	311
10.4.2	Micron-Scale Buckling Mode of the Polymer Substrate	312
10.4.2.1	Orthogonal Wave Buckling	312
10.4.2.2	Oblique Wave Buckling and Crumpled Wave Buckling	315
10.4.2.3	Occurrence Conditions of Micron-Scale Buckling Modes	316
10.4.3	Micron and Submicron Cross-Scale Buckling Modes	317
10.4.4	The Buckling Mechanism Analysis of the Polymer Substrate	319
10.4.4.1	Formation Mechanisms of Micron-Scale Wave Buckling Modes	319
10.4.4.2	Formation Mechanisms of Submicron-Scale Wrinkles	320
10.5	Conclusions	321
	Acknowledgments	322
	References	322

<b>11</b>	<b>Microcantilever-Based Nano-Electro-Mechanical Sensor Systems: Characterization, Instrumentation, and Applications</b>	<b>325</b>
	<i>Sheetal Patil and V. Ramgopal Rao</i>	
11.1	Introduction	325
11.1.1	General Definitions and Concepts	325
11.2	Operation Principle and Fundamental Models	327
11.3	Microcantilever Sensor Fabrication	330
11.3.1	Si Microcantilevers	331
11.3.2	Bulk Micromachining	331
11.3.3	Polymer Microcantilevers	333
11.3.4	Surface Micromachining	333
11.3.5	Microcantilevers with Integrated Functionality	334
11.4	Mechanical and Electrical Characterization of Microcantilevers	335
11.4.1	Nano-Indentation Techniques	335
11.4.2	Surface and Resonant Frequency Measurements	337
11.4.3	Electrical Characterization	338
11.4.4	Noise and Reliability Characterizations	338
11.5	Readout Principles	339
11.5.1	Integrated Optical Readout	340
11.5.2	Piezo-Resistive Readout	341
11.5.3	Piezoelectric Readout	343
11.5.4	Capacitance Readout	344
11.6	Application of Microcantilever Sensors	344
11.6.1	Vapor Phase/Gas/Chemical Detection	344
11.6.2	Biosensors	346
11.6.3	Agriculture Applications	347
11.7	Energy Harvesting for Sensor Networks	349
11.7.1	Low-Frequency Vibration Energy Harvesting	349
11.7.2	Microwave Energy Harvesting	351
11.7.3	Photo-Voltaic and Thermal Energy Harvesting	351
11.8	Conclusion	351
	References	352
<b>12</b>	<b>CMOS MEMS Integration</b>	<b>361</b>
	<i>Thejas and Navakanta Bhat</i>	
12.1	Introduction	361
12.2	State-of-the-Art inertial Sensor	362
12.2.1	Hybrid Integration-Based Sensors	364
12.2.2	Monolithic Integration-Based Sensors and Actuators	366
12.3	Capacitance Sensing Techniques	366
12.4	Capacitance Sensing Architectures	367
12.5	Continuous Time Voltage Sensing Circuit	368
12.6	CMOS ASIC Design	371
12.7	Test Results of CMOS–MEMS Integration	377
12.8	Electrical Reliability Issues	378
	References	380

<b>13 Solving Quality and Reliability Optimization Problems for MEMS with Degradation Data</b>	<b>381</b>
<i>Yash Lundia, Kunal Jain, Mamanduru Vamsee Krishna, Manoj Kumar Tiwari and Baldev Raj</i>	
Abbreviations	381
13.1 Introduction	382
13.2 Notations and Assumptions	384
13.2.1 Notations	384
13.2.2 Assumptions	385
13.3 Reliability Model	385
13.3.1 Wear Degradation due to Burn-In Procedure	386
13.3.2 Non-destructive Evaluation	387
13.3.3 Replacement and Failure Cost	388
13.3.3.1 Catastrophic Failures as a Result of Random Shocks	389
13.3.3.2 Soft Failures as a Result of Shocks and Degradation	390
13.3.4 Optimization Model	393
13.3.5 Solution Methodology—Algorithm Description	394
13.4 Numerical Example	395
13.5 Conclusions	397
References	397

# Carbon as a MEMS Material

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## Abstract

Carbon has become a popular material in microelectromechanical (MEMS) applications because of its versatile electrochemical and mechanical properties, as well as the numerous precursor materials and facile fabrication methods available. This review details various C-MEMS fabrication technologies, most of which involve the patterning of polymeric precursors of carbon such as epoxy photoresists and sol-gel polymers followed by their pyrolysis to create glassy or semicrystalline carbon pattern replicas. The structure and properties of glassy carbon, as well as the pyrolysis process and concurrent shrinkage, are also discussed in detail, as these directly affect the applicability of the carbon structures and devices. The integration of carbon structures in MEMS devices by means of surface modification and the incorporation of additives and fillers such as carbon nanotubes and carbon nanofibers to enhance the functional properties are also discussed.

**Keywords:** Carbon, C-MEMS, pyrolysis, volumetric shrinkage, MEMS integration, lithography

## 1.1 Introduction

Carbon is one of the most versatile materials in the periodic table. Due to its ability to form  $sp$ ,  $sp^2$ , and  $sp^3$  hybridized covalent bonds with various elements including itself, carbon-based compounds and materials are amongst the most adaptable materials available to us. The ability of carbon to form bonds with itself is manifested in the form of many allotropes of carbon including fullerenes, nanotubes, graphite, graphene, and diamond. Even within these allotropes, despite being all made of carbon, the properties such as electrical conductivity, hardness, and strength vary widely with allotrope due to different microstructures in terms of crystallite size, long-range order, anisotropy, *etc.* [1]. Amorphous or glassy carbon, in particular, has a wide window of electrochemical stability as well as high thermal conductivity and excellent biocompatibility, warranting its use in various electrochemical and biological applications [2]. Diamond-like carbon or DLC, another form of carbon, has superior tribological properties and wear

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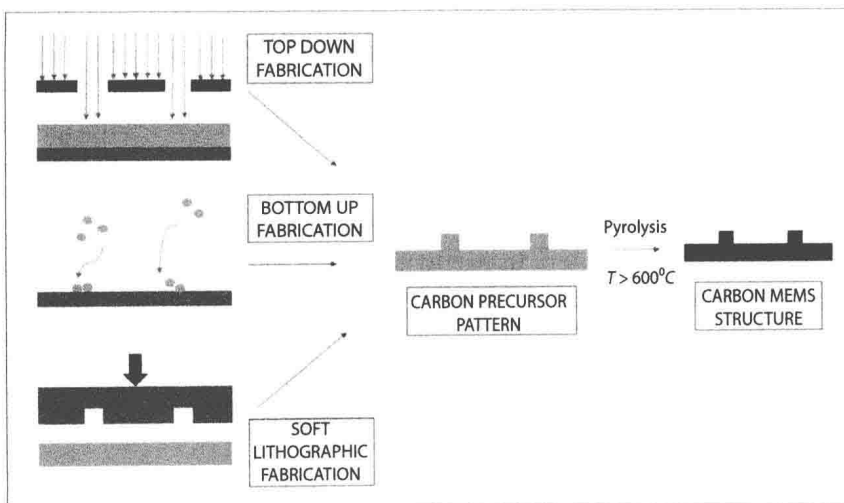
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resistance, and anisotropic carbon materials such as nanotubes and nanofibers can be leveraged for their unique and anisotropic electromechanical properties as well [2–4].

When this versatility in functional properties is combined with appropriate micro/nanofabrication techniques, carbon structures become highly viable as elements in micro and nano electromechanical systems (MEMS/NEMS). In order to create micro- and nanosized electromechanical structures such as actuators and microsensors from carbon, appropriate robust and facile micro/nanofabrication techniques have to be adopted. The methods to pattern carbon and its precursors into MEMS structures are divided, like other microfabrication techniques, into top-down and bottom-up techniques. Top-down techniques are subtractive processes such as reactive ion etching (RIE) and lithographic patterning with photons, electrons, or ions. Bottom-up or additive processes include sputtering, evaporation, and chemical vapor deposition (CVD) [5]. While top-down techniques create deterministic patterns with good shape and size control, bottom-up techniques result in increased functionality and have greater capability for three-dimensional (3D) patterns. Self-assembled structures that are formed with very little external guidance or direction also fall in the latter category of bottom-up techniques. Apart from strictly top-down and bottom-up techniques, many fabrication techniques include a combination of these two. For example, hierarchical structures can be achieved by top-down patterning of large-scale structures and bottom-up patterning of smaller, 3D features. Soft lithographic techniques such as micromolding and nanoimprinting are often considered a third classification of microfabrication techniques and have also been used successfully in the patterning of C-MEMS (Carbon MEMS) structures [6].

One process that facilitates the fabrication of amorphous or glassy carbon microstructures involves the pyrolysis of carbon-containing precursor molecules (usually polymers) that have been prefabricated into requisite micro/nanostructures (Figure 1.1). Pyrolysis or carbonization is the method of heating carbon-containing precursors to temperatures upward of 600 °C in an inert atmosphere such as nitrogen



**Figure 1.1** Fabrication of Carbon MEMS structures using top-down, bottom-up and soft lithographic techniques.