*Materials Degradation and Failures Series*

# Materials and Failures in MEMS and NEMS

Edited by **Atul Tiwari and Baldev Raj**

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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 The *Material's Degradation and Failure* series encourages the publication of titles that are centered on understanding the failure in materials. Topics treating the kinetics and mechanism of degradation of materials is of particular interest. Similarly, characterization techniques that record macroscopic (e.g., tensile testing), microscopic (e.g., *in-situ* observation) and nanoscopic (e.g., nanoindentation) damages in materials will be of interest. Modeling studies that cover failure in materials will also be included in this series.

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# Preface

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 elec¬trochemical 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 fab¬rication 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 vari¬ous materials characterization techniques and their importance for successful device fabrica¬tion 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 tech¬nique 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<br>Baldev Raj, PhD<br>August 4, 2015

# Contents

# 1

# Carbon as a MEMS Material

**Amritha Rammohan* and Ashutosh Sharma**

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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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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

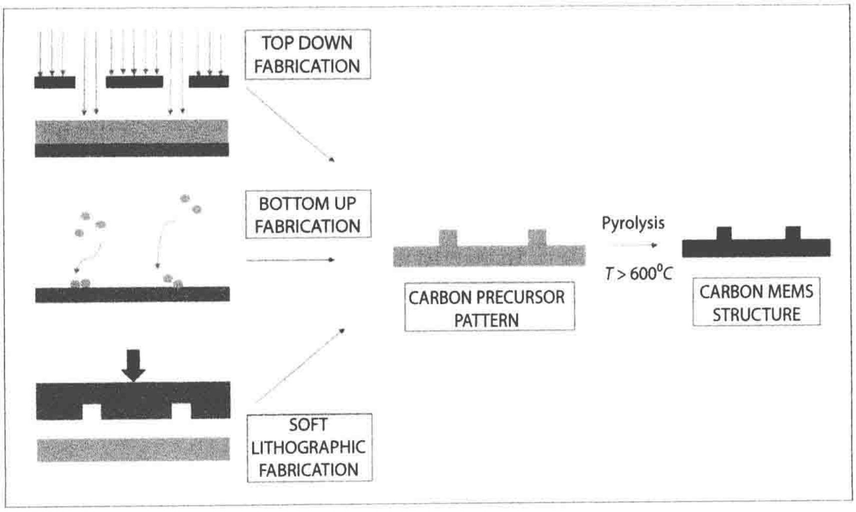


**Figure 1.1** Fabrication of Carbon MEMS structures using top-down, bottom-up and soft lithographic techniques.