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微机电系统基础

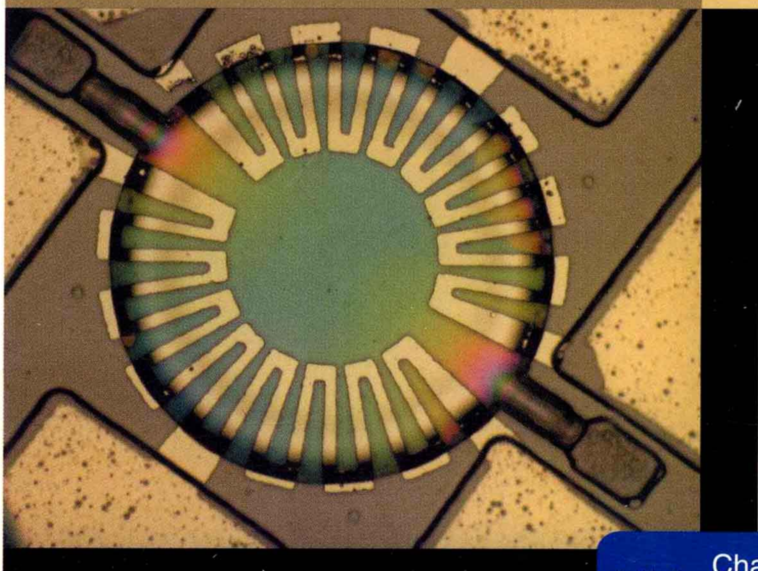
（英文版·第2版）

Foundations of

MEMS

Second Edition

CHANG LIU



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Preface

Five years have passed since the first edition of this book was published. Over the five years, the world has witnessed a technological revolution headlined by an array of exciting consumer and industrial products such as the Nintendo Wii, Apple iPod/iPad, sensor-rich smart phones, phones with cameras, new operating systems for mobile phones and apps, e-books, WiFi, voice-over-IP calls, social networking, 3D animated movies, and cloud computing, to name the major ones that affect everyday living. These new entries were practically nonexistent in the main stream when the first edition of this book was published in 2005. World news in 2010 is dominated by such themes as alternative energy, scarcity of resources, manufacturing outsourcing, budget and credit crisis, economic growth in some parts of the world, and reforms in financial management, health care, and education.

This book has been warmly welcomed since its first edition. It is adapted in over 50 universities world wide, and has been translated into three international editions (simplified Chinese, traditional Chinese, and Korean). In preparing for the second edition, I am very encouraged by feedback from editors, students, and teachers who use this book. The objectives of the second edition are the following:

1. To strengthen the book's discussion about MEMS design, processing, and materials.
2. To update course materials by including new insights and new developments. Many changes have happened in the MEMS field. New ideas, new capabilities, and new case studies of product successes are available today. This book reflects these new trends in development.
3. To enrich this book by providing new homework problems, updated examples, figures, etc.
4. To correct known mistakes.
5. To provide an enduring infrastructure to support teaching activities and MEMS education to a broader audience.

Readers will find the following major update features:

New contents, concepts, and insight. The MEMS field has changed dramatically in the past five years. This book captures new contents (generated in academia and industry), new concepts (e.g., packaging and integration), and insights. This should provide more value for the reader.

New homework problems. New homework problems have been added to facilitate teaching and student learning. Homework solutions can be provided to teachers upon request.

Added analytical examples for design and process selection. This new edition provides teachers with new materials to discuss design and process analytically.

New beginner-friendly materials for teaching processes. Beginning students may be amazed by the array of processing-related information. A number of new tables are provided to make it easier for students to climb the learning curve. These tables (in the appendix section) provide first-time students a simplified summary of the most commonly encountered materials and etching methods. An easy-to-understand table summarizing their interactions is also provided.

Deeper case studies added to challenge the readers understanding about the subject. The overall structural of the book is maintained. A new chapter (Chapter 15) is added, dealing with in-depth case discussion of successful MEMS products in the market place. I believe these commercialized MEMS devices, conceived for and tested in the real-life business world, are good examples to illustrate principles of design, fabrication, and integration. A discussion of most essential fabrication technology is added in Chapter 2. The discussion is meant to provide essential and qualitative review of processing methods. Other changes can be found in various chapters, especially Chapters 1, 2, and 12.

A new dedicated companion Web site for teachers and students. The Web site is a permanent home to the book and will serve the readers of this book in the new era of internet and online communication. On this Web site, a reader can find supplemental chapters, supplemental teaching materials, links to resources pertaining to the MEMS field, and errata. Teachers will find teaching aid materials such as PowerPoint files, figures, homework solutions, etc. The Web site serves a number of important purposes. It is originally driven by the desire to not make this book too large while still maintain its ability to satisfy a varied audience. It will help the user community in a way that is more enduring than a single print.

The Web site dedicated to this book is www.memscentral.com.

Student and instructor resources for the International Edition are available at www.pearsoninternationaleditions.com/liu

Chapter line-up and flow is streamlined. The chapter on optical MEMS is now moved to the Web site as a supplement. This and other chapters dealing with specialty topics (such as RF MEMS, BioMEMS) will be hosted in the Web site so that I can keep the book small and still satisfy the needs of teachers who wish to discuss about these exciting areas in class. Moving the chapters to the Web site also makes it possible to update frequently.

May the MEMS field continue to grow! I hope you enjoy reading and using this book.

CHANG LIU
Evanston, IL
September 2010

A Note to Instructors

This section is intended to communicate with instructors who use this book to teach a body of students at undergraduate or graduate school levels. It summarizes my thoughts on selection and ordering of materials. I hope it helps instructors fully utilize this book and teach the subject of MEMS effectively.

Materials in this book are presented in a way to facilitate the teaching of MEMS to beginners and to an interdisciplinary body of readers. During the writing process, I strove to maintain a balanced approach.

First and foremost, this book balances the needs of readers and students from a variety of backgrounds. This book is written for an interdisciplinary body of readers and is meant to intellectually satisfy and challenge every student in a classroom, no matter what his or her background is. Two extreme feelings of students and readers—*boredom* when a familiar subject is repeated in detail and *frustration* when an unfamiliar subject is not covered sufficiently—should be avoided at all times. To minimize the initial learning curve, only the most vital vocabulary and the most frequently used concepts are introduced.

Secondly, this book presents balanced discussions about design, fabrication, and materials, the three pillars of the MEMS knowledge base. Modular case studies are carefully selected to exemplify the intersection of design, materials, and fabrication methods. An instructor may select alternative cases to append to the existing collection.

Third, this book balances practicality and fundamentals. Fundamental concepts are explained and exemplified through text, examples, and homework assignments. Practical and advanced topics related to materials, design, and fabrication are discussed in paragraph-length mini reviews—which are detailed but with their length kept to a minimum to avoid distracting readers' attention. I hope this will encourage and facilitate students and instructors who may wish to follow reference leads and explore topics beyond classroom discussions. For the reader's benefit, the references cited in this book are primarily from archival journals and magazines, and therefore, are easily accessible.

This book attempts to provide a logical build-up of knowledge as it progresses from chapter to chapter. A number of important topics, such as mechanical design and fabrication, are discussed in several passes. In terms of design concept, an instructor can lead students through three steps: (1) learn basic concepts; (2) observe how they are used in real cases; (3) learn to apply the design methods to homework problems or practical applications. In terms of fabrication, three steps can be followed as well: (1) observe how processes work in examples and critically analyze processes discussed in the case studies; (2) build detailed knowledge base of processes in a systematic framework; (3) synthesize processes in homework problems and for various applications.

Chapters are presented in a modular fashion. Readers and instructors may follow different routes depending on background and interest. For example, one may choose to review in-depth information about microfabrication (Chapters 10 and 11) before covering transduction principles (Chapters 4 through 9).

A challenge I faced when writing this book was how to integrate a rich body of existing work with many points of innovation without making the book cluttered and focus-less. In other words, a student should feel the excitement of innovation without being diverted from a sense of focus. The contents of this book are organized in the following way to achieve this aim. In the first twelve chapters, I shall review a number of representative applications (cases), with the selection being *consistent* throughout the chapters to provide a basis for comparison. When a chapter deals mainly with a transduction principle for sensing, I discuss *inertia* sensors (including acceleration sensors and/or gyros), *pressure* sensors (including acoustic sensors), *flow* sensors, and *tactile* sensors, in that order, along with examples—if good examples are available. These four sensor topics have been carefully chosen out of many possible applications of MEMS. Inertia and pressure sensors are well-established applications of MEMS. Many good research articles are available, with comprehensive coverage of integrated mechanics and electronics. Flow sensors generally involve different physical transduction principles, designs, and characterization methods than inertia and pressure sensors. Tactile sensors must offer robustness better than the three other sensor types and, therefore, will necessitate discussions of unique materials, designs, and fabrication issues. When a chapter deals with a transduction principle that is mainly used for actuation, I discuss one case of an actuator with small displacements (linear or angular) and another case of an actuator with large displacements, in that order, along with examples—if proper examples are available.

I believe the best way to learn a subject is through examples and guided practices. This book offers a large selection of examples and problems for students.

Homework problems cover not only design and the use of equations. Many aspects of MEMS, including the selection of materials and processes, are beyond the description of mathematical formula. Many homework problems are designed to challenge a student to think critically about a fabrication process, to review literature, and to explore various aspects of MEMS, either individually or in small cooperative groups.

There are four types of homework exercises—design, review, fabrication, and challenges. A *design* type problem helps a student gain familiarity with formulae and concepts for designing and synthesizing MEMS elements. A *review* type problem requires a student to search for information outside of the textbook to gain wider and deeper understanding of a topic. A *fabrication* type problem challenges a student to think critically about various aspects of a fabrication process. For example, a student may be required to develop and demonstrate true understanding of a process by illustrating it down to fine details, or by devising and evaluating alternative approaches. A *challenge* type problem stimulates the competitive edge within students. It provides students with opportunities to think at an integrative level by considering many aspects, including physics, design, fabrication and materials. A challenge type problem may be a competitive, research-level question without existing answers, at least at the time of this writing.

Success in science and technology takes more than technical expertise in a narrow area. To successfully conduct MEMS research and product development requires knowledge, skills, insight, and resources that no single person can amass alone. Teaming and collaboration is essential for executing a project or building a career. Many homework problems in this textbook are team based—they encourage student to work together in interdisciplinary teams. I believe that teamwork at this stage will enhance their learning experiences through social and technical interactions with other fellow students and prepare them for their success in future careers.

I hope you will enjoy this book.

Notational Conventions

Author's note: The design of a MEMS device involves multiple domains of engineering and physics. Symbols and notations have evolved independently in these domains and may overlap with one another. For example, the symbol J corresponds to current density in electrical engineering and torsional moment of inertia in mechanical engineering. The symbol ε often means permitivity to electrical engineers and mechanical strain to mechanical engineers. In this book, *a symbol may represent several different variables.* The exact correlation depends on the specific circumstance of use. I chose against inventing a notation system with no overlap. A lineage of use to different fields is purposefully maintained.

a	acceleration
α	volumetric expansion coefficient
α_r	temperature coefficient of resistance (TCR)
α_s	Seebeck coefficient of a single material
B	magnetic field density
β	linear expansion coefficient
C	concentration
C_{ij}	elements of the stiffness matrix
c	damping coefficient
c_r	critical damping coefficient
c_{th}	heat capacity
c	magnetic susceptibility
D	diffusivity
D	electric displacement
d_{ij}	elements of piezoelectric coefficient matrix
γ	shear strain
E_g	bandgap
E	Modulus of elasticity, Young's modulus
E	Electric field
ε	permitivity, relative permitivity, dielectric constant
ε	radiative emissivity
F	force
f_r	resonant frequency
G	shear modulus of elasticity
G	gauge factor
H	magnetic field intensity
h	Planck constant
h	convective heat transfer coefficient
I	current
I	moment of inertia
J	current density
J	torsional moment of inertia
k	force constant
k	Boltzmann constant
κ	thermal conductivity
L	length or characteristic length
M	moment or torque
m	mass
μ	mobility of charge carriers
μ	magnetic permeability
μ	dynamic viscosity
m_n^*	effective mass of electrons
M_p^*	effective mass of holes
n	concentration of electrons
ν	Poisson's ratio
ν	kinematic viscosity
N_d	concentration of donor atoms
N_d^+	concentration of ionized donor atoms
N_a	concentration of acceptor atoms
N_a^-	concentration ionized acceptor atoms
n_o	concentration of electrons under equilibrium
n_i	concentration of electrons in intrinsic material
p	concentration of holes
p_o	concentration of holes under equilibrium
p_i	concentration of holes in intrinsic material
π_{ij}	component of the piezoresistance tensor
q	electric charge
q''	thermal conduction rate
R	resistance
Re	Reynolds number
r	radius of curvature
R_{th}	thermal resistance
ρ	resistivity
ρ_s	sheet resistivity
ρ_{th}	thermal resistivity
sh	specific heat
S_{ij}	elements of the compliant matrix
s	strain
s_i	elements of the strain tensor matrix
σ	electrical conductivity
σ	normal stress
σ	Stefan-Boltzmann constant
τ	torsion stress, shear stress
τ	fluid shear stress
T	moment or torque
T	temperature
T_i	elements of the stress tensor matrix
U	stored electrical energy
u	distance of undercut
V	voltage
V_p	pull in voltage
ω	frequency
ω_n	resonant frequency
ζ	damping ratio

Contents

CHAPTER 1

Introduction

1.0 PREVIEW

This chapter will present a broad overview of the MEMS field, along with basic vocabularies and concepts necessary for ensuing discussions on topics including design, fabrication, materials, and applications of MEMS.

In Section 1.1, a reader will have an opportunity to learn about the history of the MEMS field as well as future promises of MEMS. An understanding of the timing and circumstances under which MEMS technology was initiated will help a reader appreciate many characteristics of the technology. Such intrinsic characteristics are summarized in Section 1.2.

A large portion of MEMS applications involves sensors and actuators, collectively known as transducers. (The remaining MEMS applications involve passive microstructures that are not actively addressed or controlled.) In Section 1.3, a reader will be exposed to a broad range of concepts and practices of energy and signal transduction. A reader will learn what the most important performance metrics are when developing sensors and actuators.

I will discuss fundamental microfabrication methods for MEMS in Chapter 2.

1.1 THE HISTORY OF MEMS DEVELOPMENT

1.1.1 From the Beginning to 1990

The integrated circuit (IC) technology is the starting point for discussing the history of MEMS. The transistor, an electronics switching device invented in 1947 at the AT&T Bell Laboratories, unleashed a revolution in communication and computing. In 1971, the then state-of-the-art Intel 4004 chip consisted of only 2250 transistors. Intel 286 and Pentium III processors, unveiled in 1982 and 1999, had 120,000 and 24 million transistors, respectively. IC technology developed with a level of fierceness rarely matched in other fields. The density of transistor integration has increased by two-fold every 12 to 18 months, following the Moore's Law [1] after an observation made by Gordon Moore, one of the cofounders of the Intel Corporation. This is a remarkable feat of ingenuity and determination because, at several points in the past several decades, there were deep concerns that the trend predicted—and in some sense, *mandated*—in the Moore's Law would not continue but run into limits imposed by fundamental physics or engineering capabilities at the time. Engineers in the semiconductor industry prevailed over many seemingly impossible technical barriers to keep the Moore's Law going.

The *microfabrication* technology is the engine behind functional integration and miniaturization of electronics. Between the early 1960s to the middle of 1980s, the fabrication technology of integrated circuits rapidly matured after decades of research following the invention of the first semiconductor transistor [2]. Many scientific and engineering feats we take for granted today will not be here without the tremendous pace of progress in the area of *microfabrication* and *miniaturization*. The list includes the exponentially growing use of computers and the Internet, portable electronics, cellular telephony, digital photography (capturing, storing, transferring, and displaying), flat panel displays, plasma televisions, disk memory, solid-slide drives, bioinformatics (e.g., sequencing the entire human genome with 3 billion base pairs) [3], rapid DNA sequence identification [4], the discovery of new materials and drugs [5], and digital warfare.

The field of MEMS evolved from the integrated circuit industry. The germination of the MEMS field covers two decades (from the mid 1960s to 1980s), when sparse activities were carried out. For example, anisotropic silicon etching was discovered to sculpture three-dimensional features into otherwise planar silicon substrates [6]. Crucial elements of micro sensors, including piezoresistivity of single crystalline silicon and polycrystalline silicon, were discovered, studied, and optimized since 1954 [7–9]. In 1967, Harvey Nathanson at Westinghouse introduced a new type of transistor and resonator called the resonant gate transistor (RGT) [10]. Unlike conventional transistors, the gate electrode of the RGT was not fixed to the gate oxide but was movable with respect to the substrate, with the distance between the gate and the substrate controlled by electrostatic attractive forces. The RGT was perhaps the earliest demonstration of micro electrostatic actuators. At this stage, the name of the field had yet to be coined. However, both bulk micromachining and surface micromachining technologies were rapidly maturing [11–13]. Several pioneering researchers in academic and industrial laboratories [14] began to use the integrated circuit processing technology to make micro *mechanical* devices, including cantilevers, membranes, channels, and nozzles.

Several early companies took advantage of piezoresistive transducer effects of silicon to satisfy the needs of the automotive industry (e.g., manifold absolute pressure sensors and automotive crash sensors) and the medical industry (e.g., low-cost disposable blood pressure sensors). In the 1970s, Kurt Petersen at the IBM research laboratory, along with other colleagues, developed diaphragm-type silicon micromachined pressure sensors. Very thin silicon diaphragms with embedded piezoresistive sensors were made using silicon bulk micromachining. The diaphragm deforms under differential pressures, inducing mechanical stress that was picked up by the piezoresistors. The thin diaphragm allowed greater deformation under a given pressure differential, hence achieving greater sensitivity compared with conventional membrane-type pressure sensors. New etching technologies were used to guarantee uniformity and realize high yield. The sensors could be micromachined in batch, thereby reducing the costs of individual units to satisfy the needs of the medical industry. More details about the design and fabrication of this pressure sensor can be found in Chapter 15.