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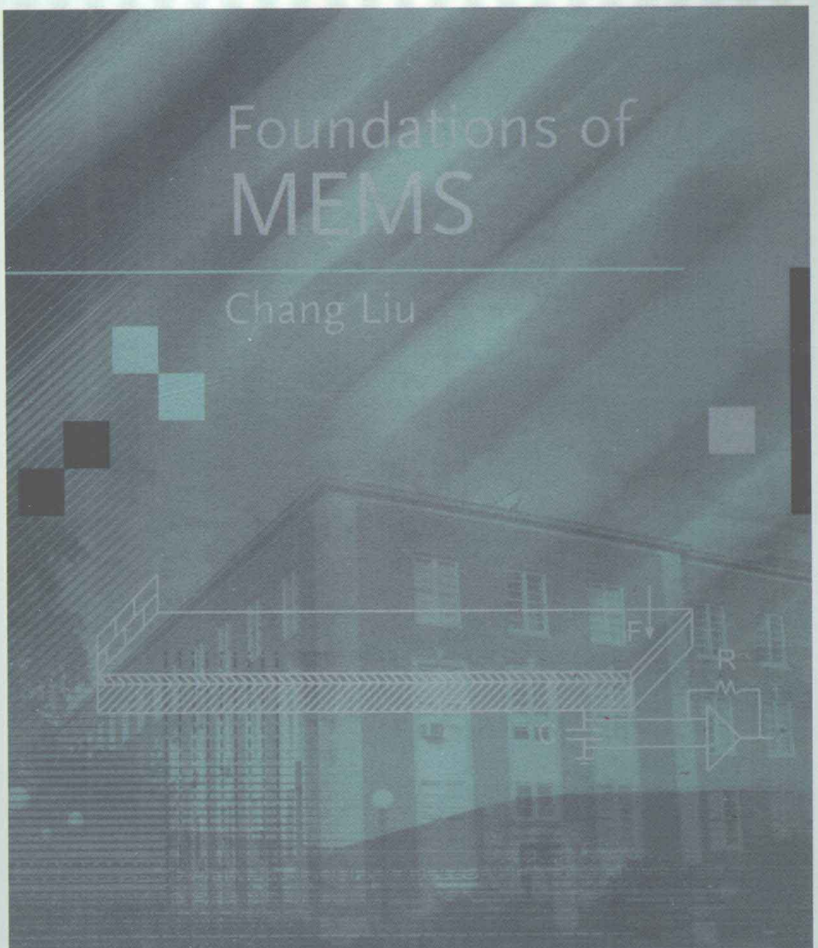

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Foundations of MEMS

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藏书章

（美） Chang Liu 著
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Preface

Welcome to the world of microelectromechanical systems (MEMS), an emerging research field and industry characterized by the integration of electrical and mechanical engineering, miniaturization, integrative fabrication methods, diverse application reaches, rapid pace of innovation, and vast opportunities for ingenuity. MEMS technology branched off from the integrated circuit industry, from which it inherited semiconductor materials, microfabrication technologies and equipment, and facility infrastructure. The field now sits at a confluent point of many disciplines including electrical engineering, mechanical engineering, material sciences, micro- and nanofabrication, life sciences, chemical engineering, and civil and environmental engineering, to name a few.

A student in the MEMS area is faced with unique challenges.

First, MEMS devices embody concepts from both electrical and mechanical engineering domains. A successful MEMS device cannot be developed without considering both aspects in concert. A reader who has received training in a traditional engineering curriculum must be conversant with the concepts and practices of unfamiliar fields. For example, an electrical engineering student who is trained in the semiconductor device area needs to calculate mechanical bending and stresses. A mechanical engineering student, on the other hand, needs to absorb the basic knowledge about solid-state materials and devices, as well as companion fabrication technologies.

Second, MEMS devices employ microfabrication technology, which is a fast evolving discipline with basic principles unfamiliar to many students and practicing engineers. Even readers with electrical engineering backgrounds are not necessarily familiar with microfabrication technology for integrated circuits. However, a MEMS device cannot be successfully designed and developed without considering *how it will be made later.* The electromechanical design of a sensor or actuator must be made with full cognizance of the opportunities and limitations of microfabrication technology—past, present, and future. At this relatively early stage of MEMS development, design, fabrication, materials, and performances intersect.

Third, the application of MEMS encompasses many fields beyond traditional electrical and mechanical engineering. This presents exciting new opportunities for a student and practitioner of MEMS to become involved in diverse application domains, such as bioengineering, chemistry, nanotechnology, optical engineering, power and energy, and wireless communication, to name a few. The reader must realize that a successful MEMS research project can hardly create the desired impact without developing insight and a grasp of domain-specific knowledge.

Fourth, the performance of a MEMS device is not the only factor that determines its chance of market acceptance. A MEMS device and system must provide combined cost and performance advantages over incumbent and/or competitive technologies if it is to survive and thrive in the real world. No matter how intriguing the miniaturization technology is, a sense of economic and societal reality must never be lost in the excitement of technology creation. The cost (of development and ownership) and the functions of MEMS devices must be carefully considered and optimized in a vast space of possible materials, designs, and fabrication technologies.

Needless to say, a MEMS practitioner must amass a broad knowledge base of materials, designs, manufacturing methods, and industrial trends in order to identify the right problems *and* find the right solutions.

With these challenges in mind, this book is designed to guide the reader in building critical knowledge about the field in a systematic and time-efficient way. The contents and the sequence of the discussions have been fine-tuned as a result of my experience teaching a MEMS course at the University of Illinois at Urbana–Champaign for the past seven years (1997–2003). The students who attended the classes were from both electrical and mechanical engineering departments.

There are four primary objectives of this textbook:

1. Gain critical cross-disciplinary knowledge about designing electromechanical transducers, including sensors and actuators. As a result, the reader should be able to analyze the key performance aspects of simple electromechanical devices and understand the options and challenges associated with a particular design task;
2. Attain a solid background in the area of microfabrication, to the extent that a reader without a prior background in MEMS will be able to critically judge a fabrication process and synthesize a new one for future applications;
3. Become experienced with commonly practiced designs and fabrication processes of MEMS through studies of classical and concurrent cases; and
4. Obtain the analytical and practical know-how to evaluate many intersecting points—design, fabrication, performance, robustness, and cost, among others—involved in successfully developing integrated MEMS devices.

The three main pillars of knowledge for a MEMS engineer are *design, fabrication*, and *materials*. In this book, I will address them in an ascending and widening spiral, with more details and interactions as the book progresses. For example, in Chapters 1 and 2, the reader will be exposed to a general discussion of transduction principles and microfabrication methods. Chapter 3 will discuss the basic electrical and mechanical engineering terms *most commonly* encountered in the everyday practice of MEMS. Chapters 4 through 9 review the various sensing and actuation methods and their uses. More detailed discussions about the device fabrication techniques will be embedded in case studies. In Chapters 10 through 11, a comprehensive treatment of the two most important classes of microfabrication techniques (bulk micromachining and surface micromachining) is presented. Chapter 12 discusses MEMS fabrication techniques related to the polymer materials family.

The final four chapters collectively give the reader an opportunity to integrate various facets of knowledge and to learn about pragmatic methodologies. In Chapters 13 through 15, several major branch areas of MEMS applications are selected for case studies. Various technologies for realizing similar application goals are presented, so that the reader will be able to evaluate the different sets of designs, materials, and technologies. In Chapter 16, I discuss practical issues pertaining to process integration and project management.

I would like to thank my students—past and present—in my *Introduction to MEMS* classes. Their feedback was critical to the layout of this book. I would also like to thank the following research associates and colleagues at Illinois for their encouragement and assistance during the production of this book: David Bullen, James Carroll, Jack Chen, Jonathan Engel, Zhifang Fan, Prof. Yonggang Huang, Prof. David Payne, Kee Ryu, Kashan Shaikh, Edgar Goluch, Loren

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Finally, I would like to thank the Head and Associate Head of the ECE Department, Prof. Richard Blahut and Prof. Narayan Rao respectively, for their encouragement and support of this project.

CHANG LIU
Urbana, IL

A Note to Instructors

This section is intended to assist instructors who use this book to teach a body of students at the undergraduate or graduate school levels. It summarizes my thoughts on the 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 to facilitate the teaching of MEMS to beginners and to an interdisciplinary body of readers. During the writing process, I tried 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 the classroom, regardless of his or her background. 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, which are the three pillars of the MEMS knowledge base. Modular case studies were 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. These are exhaustive, but their length is kept to a minimum to avoid distracting the attention of the reader. 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; therefore, they 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 concepts, an instructor can lead students through three steps: (1) learning basic concepts; (2) observing how they are used in real cases; and (3) learning to apply the design methods to homework problems or real applications. In terms of fabrication, three steps can be followed as well: (1) observing how processes work in examples and critically analyzing processes discussed in the case studies; (2) building a detailed knowledge base of processes in a systematic framework; and (3) synthesizing processes in homework problems and for various applications.

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

A challenge I faced while teaching and 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 losing the focus on learning. In other words, the student should feel the excitement of innovation without being diverted from a sense of focus. The contents of this book are carefully organized to achieve this aim. In the first 12 chapters, I review a number of representative applications (cases) with a *consistent* selection 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. 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; many include comprehensive coverage of integrated mechanics and electronics. Flow sensors are unlike inertia and pressure sensors; they generally involve different physical transduction principles, designs, and characterization methods. Tactile sensors must offer a robustness that is better than the three other sensor types; therefore, it 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 will discuss one case of an actuator with small displacement (linear or angular) and another case of an actuator with large displacement, in that order, and if proper examples are available.

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

Homework problems cover not only the design and the use of equations. Many aspects of MEMS, including the selection of materials and processes, are beyond the description of a 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* problem helps the student gain familiarity with formulae and concepts for designing and synthesizing MEMS elements. A *review* problem requires the student to search for information outside of the textbook to gain a wider and deeper understanding of a topic. A *fabrication* problem challenges the student to think critically about various aspects of a fabrication process. For example, the student may be required to develop and demonstrate a true understanding of a process by illustrating it in detail or by devising and evaluating alternative approaches. A *challenge* 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 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. Teamwork and collaboration are essential for executing a project or building a career. There are a significant number of homework problems throughout this textbook that encourage students to work together in interdisciplinary teams. I believe that teamwork, at this stage, will enhance learning experiences through social and technical interactions with other students and prepare them for success in their future careers.

I hope you will enjoy this book.

About the Author

Chang Liu received M.S. and Ph.D. degrees from the California Institute of Technology in 1991 and 1995, respectively. His dissertation was entitled "The Micromachined Sensors and Actuators for Fluid Mechanics Applications." In January 1996, he joined the Microelectronics Laboratory of the University of Illinois as a postdoctoral researcher. In January 1997, he became an assistant professor with a major appointment in the Electrical and Computer Engineering Department and a joint appointment in the Mechanical and Industrial Engineering Department. In 2003, he was promoted to the rank of Associate Professor with tenure.

Dr. Liu has had 14 years of research experience in the MEMS area and has published 120 technical papers in journals and refereed conference proceedings. He teaches undergraduate and graduate courses covering broad-ranging topics including MEMS, solid-state electronics, electromechanics, and heat transfer. He won a campus Incomplete List of Teachers Ranked as Excellent honor in 2001 for developing and teaching the MEMS class, which was a precursor to this book. He received the National Science Foundation's CAREER award in 1998 for his research proposal that focused on developing artificial haircells using MEMS technology. He is currently a Subject Editor of the *IEEE/ASME Journal of MEMS* (sponsored jointly by the ASME) and an Associate Editor of the *IEEE Sensors Journal*. His work has been cited in popular media. Dr. Liu is the co-founder of Integrated Micro Devices (IMD) Corporation (Champaign, IL) and a member of the scientific advisory board of NanoInk Corporation (Chicago, IL). In 2004, he won the University of Illinois College of Engineering Xerox Award for Faculty Research. In the same year, he was elected as a Faculty Associate at the Center for Advanced Studies at the University of Illinois to pursue research in large-format integrated sensors.

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 permittivity 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_{th}	heat capacity
χ	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	permittivity, relative permittivity, 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's 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 of 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

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