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EQA

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

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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.

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

To My Family—Lu, Sophia, Alina, and Our Parents

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).

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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.

About the Author

Chang Liu received his M.S. and Ph.D. degrees from the California Institute of Technology in 1991 and 1995, respectively. His Ph.D. thesis was titled *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 major appointment in the Electrical and Computer Engineering Department and joint appointment in the Mechanical and Industrial Engineering Department. In 2003, he was promoted to the rank of Associate Professor with tenure. In 2007, Chang Liu joined Northwestern University (Evanston, Illinois) as a full professor of engineering. He established the MedX Laboratory to conduct advanced engineering research for medicine and health care.

Dr. Liu has 20 years of research experience in the MEMS area and has published 200 technical papers in journals and refereed conference proceedings. He teaches undergraduate and graduate courses covering broad-ranging topics, including MEMS, solid-state electronics, electromechanics, sensor technology, circuits, dynamics, and heat transfer. He won a campus "Incomplete list of teachers ranked as excellent" honor in 2001 for developing and teaching the MEMS class, a precursor to this book. He received the National Science Foundation's CAREER award in 1998 for his research proposal of developing artificial haircells using MEMS technology. He is currently a Subject Editor of the IEEE/ASME *Journal of MEMS*, and was an Associate Editor of the IEEE *Sensors Journal*. His work has been cited in popular media. Dr. Liu is a cofounder of Integrated Micro Devices (IMD) Corporation 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 a Faculty Associate at the Center for Advanced Studies at the University of Illinois, to pursue research in large-format integrated sensors. He is a Fellow of the IEEE, the world's largest professional association for the advancement of technology.