MOEMS

Micro-Opto-Electro-Mechanical Systems

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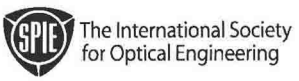

About the cover: Shown is Lucent's surface-machined two-axis tilting micromirror with Texas Instruments' DMD pixels both in the background and wrapping around the spine. Thanks to both TI and Lucent for granting permission to use these images.

This book is dedicated to my wife, Fariba.
Thank you for your encouragement and loving support.
Without you, this achievement would not have been possible.
The book is also dedicated to my four children:
Sheedeh, Shoaleh, Michael, and Cherissa.

FOREWORD

In the "good old days" of the early 1980s, before the name "MEMS" was used to describe the various types of microfabricated devices that have a primary functionality other than electronic, there was a sense among the pioneers that what later came to be called "MEMS" was a single field, with a common core technology, a cadre of investigators, and a sense that anyone in the field could and would work on any of the many applications which this technology could impact.

At the 1995 International Conference of Solid-State Sensors and Actuators (Transducers '95) held in Stockholm, one of those pioneers, Dr. Kurt Petersen, noted that a major change was taking place. No longer could MEMS be considered "a field." MEMS had become "an enabling technology" with such widespread applications that individual disciplines were adopting MEMS and setting up new conferences and journals that focused on the needs of each discipline. Historically, MEMS had grown out of the efforts of primarily electrical and microelectronic engineers (although the MEMS acronym itself was proposed in the mid-1980s by the mechanical engineering robotics group at the University of Utah). As MEMS migrated from being a field to becoming an enabling technology, specialists from the many disciplines that were adopting MEMS changed the nature of the discourse. By bringing the knowledge base of these diverse disciplines into contact with MEMS technology, wholly new sets of applications and opportunities were identified and became the subject of an innovative and highly creative effort. The fact that real products that addressed real markets could be manufactured at competitive prices provided opportunities for bold leaders to invest in, and create, new lines of business based on paradigm-shifting device designs. This was not confined to the large, established companies. Where promising markets could be identified, venture capitalists invested in many start-up companies (with all the associated hyperbole that accompanies such high-risk activities). While the reality has been that some of this venture investment resulted in disappointment (not because of the technology but rather because of the market readiness for some of the newest concepts), some of the venture investment has led to high-profile buyouts and to new publicly traded companies with real product lines based, in some fashion, on MEMS technology.

Optics is one of these disciplines. The adoption of MEMS technology by optical practitioners has been so complete that a new acronym "MOEMS" has been invented and is now widely used. With experienced optics people now thinking about MOEMS, the scope of effort has spread across a diversity of product areas (sensors, optical communication devices, scanners, displays) and brought with it the need to address real product needs such as alignment aids, lens

arrays, and hermetic wafer-scale packages. MEMS remains, however, as the enabling technology, and many of the concepts and fabrication technologies that were originally developed for pressure sensors or accelerometers have turned up in a variety of optical device applications. This is right and proper. Enabling technologies enable.

However, enabling technologies do not define the scope of their ultimate application. Rather, that is done by the practitioners, with thinking that has now gone well beyond the elementary idea of an actuator moving a shutter or mirror. The wave nature of light offers many opportunities to exploit interference and diffraction, and the marriage of MEMS to active optical devices offers the opportunity to build electromechanically tuned lasers.

This volume, commendably assembled by Ed Motamedi, one of the pioneers in the MOEMS field, addresses the full scope of the overlap of electromechanics, microfabrication, and optics. Some of the chapters use the case-study method, drawing on successful practical examples as teaching tools. Others are structured more as survey articles, with almost encyclopedic collection of relevant work. The book is thoroughly referenced and provides the reader with cited pathways for following up on the many examples presented here. A good measure of a book like this is to ask, "If you know everything in this book, do you know something important and useful?" The answer here is clearly, "yes."

Stephen D. Senturia
Professor of Electrical Engineering, Emeritus
Massachusetts Institute of Technology
September, 2004

PREFACE

The integration of micro-optics and micro-electro-mechanical systems (MEMS) has created a new class of microsystems, termed micro-opto-electro-mechanical systems (MOEMS) that are capable of unprecedented levels of performance and functionality. Born from the relatively new fields of micro-optics and MEMS, MOEMS are proving to be an attractive solution to a range of optical problems requiring high functionality, high performance, and low cost. In this early stage of MOEMS, the majority of devices demonstrated are miniaturized versions of macroscopic systems, leveraging the low-cost manufacturing technologies of integrated circuits. In the near future, it is expected that entirely new classes of microsystems will emerge that do not have a macroscopic counterpart and are fully enabled by MOEMS. It could be argued that the future development of high-density optical switch matrixes is an example of this trend.

The purpose of this book is to introduce this exciting and fast-moving field to graduate students, scientists, and engineers by providing a foundation of both micro-optics and MEMS to enable future research in the field of MOEMS. This book is not intended to be a summary of leading-edge research results, although state-of-the-art devices are used as examples throughout the text and chapter problems. The intent is to cover the topics in sufficient detail as to provide researchers with the foundation to proceed in the design, fabrication, and analysis of state-of-the-art MOEMS.

The book begins with a short history of integrated circuits and the development of micromachining. Then, the reader is given an overview of MEMS and micro-optics and the potential for merging the two fields. Following the introduction, the book is divided into four distinct parts. The first part of this book provides the necessary foundation in MEMS technology covering micromachining (Chapter 2) and micro-optics (Chapter 3). The second part of the book describes microfabricated sensors and actuators (Chapter 4), which hold promise for use in MOEMS, and micro-optical components and testing (Chapter 5), which serve as the building blocks of integrated microsystems. The third part of the book describes several major application areas for MOEMS from the perspective of device design and fabrication as well as systems integration. Since the list of applications for MOEMS is growing on a daily basis, we have focused on four major areas: fiber-optics (Chapter 6), optical scanning (Chapter 7), display and imaging (Chapter 8), and

adaptive optics (Chapter 9). Finally, in the last part of the book we discuss the recent advances in MOEMS CAD and simulation (Chapter 10), in major packaging issues (Chapter 11), and in material properties (Chapter 12).

M. E. Motamedi
January 2005

ACKNOWLEDGMENTS

Over the past decade, I have worked extensively in micro-optics, MEMS, and MOEMS, developing and teaching several short courses in the area. The necessity of publishing a book in this field soon became obvious, and I set out to write a reference book as an introduction to MOEMS, familiarizing readers with the potential of merging optical technology and MEMS. As MOEMS matured and many other branches of optics and MEMS were combined, I found that one person's knowledge cannot cover the entire field. Instead, I decided to form a team of experts to prepare a book to the highest standards.

Thanks to the worldwide web, my search for authors was a success. Our team has twenty three members: twelve from academia, seven from industry, and four from government and national labs. Had I been alone in this endeavor, I might have never been successful. Together, we formed a powerful and proactive team to create a comprehensive, authoritative guide to the most advanced technology of MOEMS. The book is a practical reference book, interdisciplinary in nature, and is for all undergraduate and graduate students in engineering.

First, I wish to acknowledge all contributors. A short biography of each author is listed at the end of the book. It was a great pleasure to work with this team to dynamically improve the book in response to readers' feedback.

The book was critically peer reviewed by several individuals. I would like to acknowledge them and express my gratitude for their comments, suggestions, and advice, which wholly improved the contents of this book. Special thanks goes to Dr. Steve Senturia who honored us with a Foreword, and to Dr. Doug Sparks for his comments regarding the commercial and manufacturing aspects of the book.

A large number of people have helped me to keep abreast of the latest technology and some encouraged me in the production of this book, either personally or professionally. I am indebted to these people. Some are my dear colleagues who worked with me at Rockwell during the 1980s for the development of CMOS MEMS monolithic accelerometers, and others were my colleagues during the 1990s for the development of micro-optics, eventually leading me to the field of MOEMS. For the development of CMOS MEMS, these people are Dr. Gus Andrews, Mr. Jack Uppal, Mr. Peter Hagon, and Dr. Eugene Whitcom; for the development of MOEMS, they are Dr. Monte Khoshnevisan, Dr. Bill Gunning, Dr. Bill Southwell, Dr. Haluk Sankur, Dr. Gus Andrews, Dr. Bill Tennant, Dr. Hank Marcy, Dr. Jeff DeNatali, Mr. Sangtae Park, Mr. Jeff Moranski, Mr. Bob Anderson, Mr. Mike Ugalde, Dr. Arthur Chiou, and Dr. Ian MacMichael.

I am also indebted to those outside of Rockwell: Dr. George Laskar from General Dynamics for his help of high-Gs MEMS environmental testing; Prof. Richard Muller and Prof. Richard White from UC Berkeley for their help in the development of microaccelerometers; Dr. Wilfred Veldkamp, Dr. Bob Knowlden, Dr. Margaret Stern, Dr. Garry Swanson, Dr. Michael Farn, and Mr. Bill Delaney of Lincoln Labs for their help in the development of micro-optics; Prof. Jan Smits from Boston University for the development of bimorph actuators; Prof. Chang-Jin Kim and Prof. Ming Wu from UCLA for their help in development of MOEMS devices and packaging; Dr. Larry Hornbeck for his input in DMD description; Dr. Kevin Chau from Analog Devices for his input in AD airbag-package chip description; and Dr. Arno Hoogerwerf and Dr. Francis Cardot from CSEM, Nuechâtel, Switzerland for their assistance in the development of manufacturable MOEMS.

I am especially indebted to a few special people who have played different roles in my success in bringing this book to reality. One is Dr. Tom Krygowski, who first supported me in developing the structure of the book and encouraged me during the past several years to bring the book to life. Tom also assisted me in the development and teaching of several short courses in the area of MEMS and MOEMS. I truly appreciate his guidance and his support. Another special person who should share with me almost all of the materials I have included in this book is Dr. Monte Khoshnevisan who was my driving force during almost a decade when I was in Rockwell. Monte was one of the frontrunners in bringing micro-optics and then MOEMS to commercial life and sincerely supported me through Rockwell and governmental funds to accomplish this mission. It is his encouragement to realize the power of micro-optics and the importance of merging that with MEMS for which I am truly grateful.

I would also like to thank two executives from Revoltech Microsystems in Europe, Dr. H. Shafazand and Mr. A. Aria, both of whom encouraged me to work on development of this book. I appreciate their support and their willingness to take responsibility for the business in my absence.

I am also very grateful to my wife, Fariba Motamedi. Without her steadfast backing, this research would not have been completed. I am especially indebted to her for encouraging me virtually every day to keep me in "resonance" during the past three years of participation in this work.

Finally, I would also like to thank the SPIE Press staff who have done an excellent job in making this book pleasant for readers. Those who closely supported me during this mission were Mr. Timothy Lamkins, Ms. Sharon Streams, Mr. Rick Hermann, and Mr. Eric Pepper. I especially thank Eric for his pursuance and encouragement and his promise to make this book a special one. A special thanks also goes to Tim Lamkins who was nice, friendly, and enjoyable to be with during this journey.

M. E. Motamedi
January 2005

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