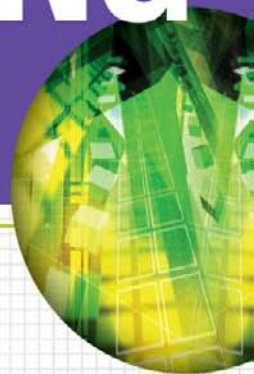


**ELECTRONIC  
ENGINEERING**

# **ADVANCED MEMS PACKAGING**



**JOHN H. LAU  
CHENG KUO LEE  
C. S. PREMACHANDRAN  
YU AIBIN**

# **Advanced MEMS Packaging**

*This page intentionally left blank*

# Advanced MEMS Packaging

John H. Lau  
Chengkuo Lee  
C. S. Premachandran  
Yu Aibin



New York Chicago San Francisco  
Lisbon London Madrid Mexico City  
Milan New Delhi San Juan  
Seoul Singapore Sydney Toronto

Copyright © 2010 by The McGraw-Hill Companies, Inc. All rights reserved. Except as permitted under the United States Copyright Act of 1976, no part of this publication may be reproduced or distributed in any form or by any means, or stored in a database or retrieval system, without the prior written permission of the publisher.

ISBN: 978-0-07-162792-4

MHID: 0-07-162792-8

The material in this eBook also appears in the print version of this title: ISBN: 978-0-07-162623-1, MHID: 0-07-162623-9.

All trademarks are trademarks of their respective owners. Rather than put a trademark symbol after every occurrence of a trademarked name, we use names in an editorial fashion only, and to the benefit of the trademark owner, with no intention of infringement of the trademark. Where such designations appear in this book, they have been printed with initial caps.

McGraw-Hill eBooks are available at special quantity discounts to use as premiums and sales promotions, or for use in corporate training programs. To contact a representative please e-mail us at [bulksales@mcgraw-hill.com](mailto:bulksales@mcgraw-hill.com).

Information contained in this work has been obtained by The McGraw-Hill Companies, Inc. (“McGraw-Hill”) from sources believed to be reliable. However, neither McGraw-Hill nor its authors guarantee the accuracy or completeness of any information published herein, and neither McGraw-Hill nor its authors shall be responsible for any errors, omissions, or damages arising out of use of this information. This work is published with the understanding that McGraw-Hill and its authors are supplying information but are not attempting to render engineering or other professional services. If such services are required, the assistance of an appropriate professional should be sought.

#### TERMS OF USE

This is a copyrighted work and The McGraw-Hill Companies, Inc. (“McGraw-Hill”) and its licensors reserve all rights in and to the work. Use of this work is subject to these terms. Except as permitted under the Copyright Act of 1976 and the right to store and retrieve one copy of the work, you may not decompile, disassemble, reverse engineer, reproduce, modify, create derivative works based upon, transmit, distribute, disseminate, sell, publish or sublicense the work or any part of it without McGraw-Hill’s prior consent. You may use the work for your own noncommercial and personal use; any other use of the work is strictly prohibited. Your right to use the work may be terminated if you fail to comply with these terms.

THE WORK IS PROVIDED “AS IS.” MCGRAW-HILL AND ITS LICENSORS MAKE NO GUARANTEES OR WARRANTIES AS TO THE ACCURACY, ADEQUACY OR COMPLETENESS OF OR RESULTS TO BE OBTAINED FROM USING THE WORK, INCLUDING ANY INFORMATION THAT CAN BE ACCESSED THROUGH THE WORK VIA HYPERLINK OR OTHERWISE, AND EXPRESSLY DISCLAIM ANY WARRANTY, EXPRESS OR IMPLIED, INCLUDING BUT NOT LIMITED TO IMPLIED WARRANTIES OF MERCHANTABILITY OR FITNESS FOR A PARTICULAR PURPOSE. McGraw-Hill and its licensors do not warrant or guarantee that the functions contained in the work will meet your requirements or that its operation will be uninterrupted or error free. Neither McGraw-Hill nor its licensors shall be liable to you or anyone else for any inaccuracy, error or omission, regardless of cause, in the work or for any damages resulting therefrom. McGraw-Hill has no responsibility for the content of any information accessed through the work. Under no circumstances shall McGraw-Hill and/or its licensors be liable for any indirect, incidental, special, punitive, consequential or similar damages that result from the use of or inability to use the work, even if any of them has been advised of the possibility of such damages. This limitation of liability shall apply to any claim or cause whatsoever whether such claim or cause arises in contract, tort or otherwise.

### **About the Authors**

**John H. Lau** earned a Ph.D. in theoretical and applied mechanics from the University of Illinois. He has also earned three master's degrees. He currently is a visiting professor at the Hong Kong University of Science & Technology (HKUST). His research interests cover a broad range of enabling technologies for 3D IC and system-in-package integration for RoHS-compliant electronics, optoelectronics, photonics, and MEMS packaging. Prior to joining HKUST, Dr. Lau was the director of the Microsystems, Modules, and Components Laboratory at the Institute of Microelectronics in Singapore for 2 years and a Senior Scientist/MTS at Agilent/Hewlett-Packard in California for more than 25 years. With more than 35 years of R&D and manufacturing experience, he has authored or co-authored more than 400 peer-reviewed technical publications, books, book chapters, and papers. Dr. Lau has received awards from ASME and IEEE, and is a Fellow of both organizations.

**Chengkuo Lee** received a Ph.D. in precision engineering from the University of Tokyo, and has also earned two master's degrees. He worked as a researcher in several labs and then managed the MEMS device division at the Metrodyne Microsystem Corporation in Taiwan. Dr. Lee co-founded Asia Pacific Microsystems, Inc., in Taiwan, and served as vice president. He is now an assistant professor in the Department of Electrical and Computer Engineering at National University of Singapore and a senior member of the technical staff at the Institute of Microelectronics in Singapore. He has authored or co-authored about 200 conference papers, extended abstracts, and peer-reviewed journal articles, and holds eight U.S. patents in the MEMS and nanotechnology fields.

**C. S. Premachandran** earned a master of technology degree in solid state technology from the Indian Institute of Technology, Madras. He has held managerial/executive positions at Indian Telephone Industries, Sun Fiber Optics, and Delphi Automotive Systems. Since 1998 he has worked as a member of the technical staff in

the Microsystems, Modules, and Components Laboratory at the Institute of Microelectronics, Singapore. He has authored or co-authored more than 50 conference papers and journal articles and holds 10 U.S. patents. He is a Senior Member of IEEE. His research interests are in MEMS and biosensor, optical, and advanced packaging.

**Yu Aibin** received a Ph.D. in electrical and electronic engineering from Nanyang Technological University in Singapore. He is a senior research engineer in the Microsystems, Modules, and Components Laboratory at the Institute of Microelectronics in Singapore. His research interests include advanced packaging and MEMS design, fabrication, and packaging. Dr. Yu has authored or co-authored more than 60 technical publications.

---

# Contents

Foreword .....	xv
Preface .....	xvii
Acknowledgments .....	xxi
<b>1 Introduction to MEMS .....</b>	<b>1</b>
1.1 Introduction .....	1
1.2 Commercial Applications of MEMS .....	2
1.3 MEMS Markets .....	2
1.4 Top 30 MEMS Suppliers .....	5
1.5 Introduction to MEMS Packaging .....	5
1.6 MEMS Packaging Patents since 2001 .....	6
1.6.1 U.S. MEMS Packaging Patents .....	6
1.6.2 Japanese MEMS Packaging Patents ...	21
1.6.3 Worldwide MEMS Packaging Patents .....	27
References .....	43
<b>2 Advanced MEMS Packaging .....</b>	<b>47</b>
2.1 Introduction .....	47
2.2 Advanced IC Packaging .....	47
2.2.1 Moore's Law versus More Than Moore (MTM) .....	47
2.2.2 3D IC Integration with WLP .....	49
2.2.3 Low-Cost Solder Microbumps for 3D IC SiP .....	52
2.2.4 Thermal Management of 3D IC SiP with TSV .....	58
2.3 Advanced MEMS Packaging .....	67
2.3.1 3D MEMS WLP: Designs and Materials .....	68
2.3.2 3D MEMS WLP: Processes .....	72
References .....	76
<b>3 Enabling Technologies for Advanced MEMS     Packaging .....</b>	<b>81</b>
3.1 Introduction .....	81
3.2 TSVs for MEMS Packaging .....	81
3.2.1 Via Formation .....	82
3.2.2 Dielectric Isolation Layer (SiO <sub>2</sub> ) Deposition .....	86



3.2.3	Barrier/Adhesion and Seed Metal Layer Deposition	87
3.2.4	Via Filling	89
3.2.5	Cu Polishing by Chemical/Mechanical Polish (CMP)	91
3.2.6	Fabrication of an ASIC Wafer with TSVs	92
3.2.7	Fabrication of Cap Wafer with TSVs and Cavity	93
3.3	Piezoresistive Stress Sensors for MEMS Packaging	93
3.3.1	Design and Fabrication of Piezoresistive Stress Sensors	93
3.3.2	Calibration of Stress Sensors	95
3.3.3	Stresses in Wafers after Mounting on a Dicing Tape	98
3.3.4	Stresses in Wafers after Thinning (Back-Grinding)	101
3.4	Wafer Thinning and Thin-Wafer Handling	104
3.4.1	3M Wafer Support System	104
3.4.2	EVG's Temporary Bonding and Debonding System	105
3.4.3	A Simple Support-Wafer Method for Thin-Wafer Handling	108
3.5	Low-Temperature Bonding for MEMS Packaging	111
3.5.1	How Does Low-Temperature Bonding with Solders Work?	112
3.5.2	Low-Temperature C2C Bonding	113
3.5.3	Low-Temperature C2W Bonding	122
3.5.4	Low-Temperature W2W Bonding	124
3.6	MEMS Wafer Dicing	126
3.6.1	Fundamentals of SD Technology	126
3.6.2	Dicing of SOI Wafers	129
3.6.3	Dicing of Silicon-on-Silicon Wafers	130
3.6.4	Dicing of Silicon-on-Glass Wafers	130
3.7	RoHS-Compliant MEMS Packaging	133
3.7.1	EU RoHS	133
3.7.2	What Is the Definition of X-Free (e.g., Pb-Free)?	134
3.7.3	What Is a Homogeneous Material?	134
3.7.4	What Is the TAC?	135
3.7.5	How Is a Law Published in the EU RoHS Directive?	135

3.7.6	EU RoHS Exemptions .....	135
3.7.7	Current Status of RoHS Compliance in the Electronics Industry .....	138
3.7.8	Lead-Free Solder-Joint Reliability of MEMS Packages .....	138
	References .....	149
<b>4</b>	<b>Advanced MEMS Wafer-Level Packaging .....</b>	<b>157</b>
4.1	Introduction .....	157
4.2	Micromachining, Wafer-Bonding Technologies, and Interconnects .....	158
4.2.1	Thin-Film Technologies .....	158
4.2.2	Bulk Micromachining Technologies .....	159
4.2.3	Conventional Wafer-Bonding Technologies for Packaging .....	168
4.2.4	Plasma-Assisted Wafer-Bonding Technologies .....	172
4.2.5	Electrical Interconnects .....	172
4.2.6	Solder-Based Intermediate-Layer Bonding .....	175
4.3	Wafer-Level Encapsulation .....	176
4.3.1	High-Temperature Encapsulation Process .....	177
4.3.2	Low-Temperature Encapsulation Process .....	178
4.4	Wafer-Level Chip Capping and MCM Technologies .....	180
4.5	Wafer-Level MEMS Packaging Based on Low-Temperature Solders: Case Study .....	182
4.5.1	Case Study: In/Ag System of Noneutectic Composition .....	183
4.5.2	Case Study: Eutectic InSn Solder for Cu-Based Metallization .....	193
4.6	Summary and Future Outlook .....	202
	References .....	203
<b>5</b>	<b>Optical MEMS Packaging: Communications .....</b>	<b>209</b>
5.1	Introduction .....	209
5.2	Actuation Mechanisms and Integrated Micromachining Processes .....	211
5.2.1	Electrostatic Actuation .....	212
5.2.2	Thermal Actuation .....	215
5.2.3	Magnetic Actuation .....	219

5.2.4	Piezoelectric Actuation	219
5.2.5	Integrated Micromachining Processes	221
5.3	Optical Switches	224
5.3.1	Small-Scale Optical Switches	225
5.3.2	Large-Scale Optical Switches	233
5.4	Variable Optical Attenuators	237
5.4.1	Early Development Work	238
5.4.2	Surface-Micromachined VOAs	240
5.4.3	DRIE-Derived Planar VOAs Using Electrostatic Actuators	242
5.4.4	DRIE-Derived Planar VOAs Using Electrothermal (Thermal) Actuators	252
5.4.5	3D VOAs	254
5.4.6	VOAs Using Various Mechanisms	258
5.5	Packaging, Testing, and Reliability Issues	261
5.5.1	Manufacturability and Self-Assembly	264
5.5.2	Case Study: VOAs	269
5.5.3	Case Study: Optical Switches	275
5.6	Summary and Future Outlook	285
	References	286
<b>6</b>	<b>Optical MEMS Packaging: Bubble Switch</b>	<b>297</b>
6.1	Introduction	297
6.2	3D Packaging	297
6.3	Boundary-Value Problem	302
6.3.1	Geometry	302
6.3.2	Materials	302
6.3.3	Boundary Conditions	305
6.4	Nonlinear Analyses of the 3D Photonic Switch	306
6.4.1	Creep Hysteresis Loops	306
6.4.2	Deflections	307
6.4.3	Shear-Stress Time-History	307
6.4.4	Shear-Creep-Strain Time-History	307
6.4.5	Creep-Strain Energy-Density Range	308
6.5	Isothermal Fatigue Tests and Results	309
6.5.1	Sample Preparation	309
6.5.2	Test Setup and Procedures	309
6.5.3	Test Results	312
6.6	Thermal Fatigue Life Prediction of the Sealing Ring	314

6.7	Appendix A: Package Deflection by Twyman-Green Interferometry Method	314
6.7.1	Sample Preparation	315
6.7.2	Test Setup and Procedure	316
6.7.3	Temperature Conditions	317
6.7.4	Measurement Results	317
6.8	Appendix B: Package Deflection by Finite-Element Method	317
6.9	Appendix C: Finite-Element Modeling of the Bolt	320
6.9.1	Description of the Bolted Model	320
6.9.2	Responses of the Bolted Photonic Switch	322
	References	325
<b>7</b>	<b>Optical MEMS: Microbolometer Packaging</b>	<b>327</b>
7.1	Introduction	327
7.2	Bolometer Chip	329
7.3	Thermal Optimization	330
7.3.1	Final Temperature Stability Testing	334
7.4	Structural Optimization of the Package	335
7.5	Vacuum Packaging of Bolometer	340
7.5.1	Ge Window	342
7.6	Getter Attachment and Activation	344
7.7	Outgassing Study in a Vacuum Package	346
7.8	Testing Setup for Bolometer	347
7.8.1	Package Testing	347
7.8.2	Image Testing	350
	References	352
<b>8</b>	<b>Bio-MEMS Packaging</b>	<b>353</b>
8.1	Introduction	353
8.2	Bio-MEMS Chip	355
8.3	Microfluidic Components	357
8.3.1	Microfluidic Cartridge	357
8.3.2	Biocompatible Polymeric Materials	359
8.4	Microfluidic Packaging	362
8.4.1	Polymer Microfabrication Techniques	362
8.4.2	Replication Technologies	362
8.4.3	Overview of Existing DNA and RNA Extractor Biocartridges	363
8.5	Fabrication of PDMS Layers	364
8.6	Assembly of PDMS Microfluidic Packages	364

8.6.1	Microfluidic Package without Reservoirs	366
8.6.2	Development of Reservoir and Valve	370
8.7	Self-Contained Microfluidic Cartridge	371
8.7.1	Microfluidic Package with Self-Contained Reservoirs	371
8.7.2	Pin-Valve Design	374
8.7.3	Fluid Flow-Control Mechanism	375
8.8	Fabrication	377
8.8.1	Substrate Fabrication	377
8.8.2	Material Selection for the Reservoir Membrane	381
8.9	Permeability of Material	381
8.10	Thermocompression Bonding	384
8.10.1	Bonding of PMMA to PMMA for the Channel Layer	385
8.10.2	Polypropylene to PMMA for Reservoir and Channel Layer	387
8.10.3	Tensile Test	390
8.11	Microfluidic Package Testing	391
8.11.1	Fluid Testing	391
8.11.2	Biologic Testing on a Biosample	392
8.12	Sample Preparation and Setup	394
8.12.1	Pretreatment of the Cartridge	394
8.12.2	PCR Amplification	394
	References	395
<b>9</b>	<b>Biosensor Packaging</b>	<b>397</b>
9.1	Introduction	397
9.1.1	Review of Optical Coherence Tomography (OCT)	398
9.2	Biosensor Packaging	401
9.2.1	Micromirror	401
9.2.2	Single-Mode Optical Fiber and GRIN Lens	401
9.2.3	Upper Substrate	403
9.2.4	Lower Substrate	404
9.3	The Package	404
9.3.1	Configuration of the Probe	404
9.3.2	Optical Properties and Theories	406
9.3.3	Evaluations of Parameters	410
9.4	Optical Simulation	412
9.4.1	Optical Model of the Probe	412
9.4.2	Effect of Mirror Curvature on Coupling Efficiency	415

9.4.3	Effect of Lateral Tilt of a Flat Micromirror on a Curved Sample	417
9.4.4	Effect of Vertical Tilt of a Flat Micromirror on a Curved Sample	419
9.4.5	Effect of Vertical Tilt of a Flat Micromirror on a Flat Sample	420
9.5	Assembly of the Optical Probe	421
9.5.1	Fabrication of SiOB	421
9.5.2	Probe Assembly	422
9.5.3	Probe Housing	425
9.6	Testing of the Probe	427
9.6.1	Optical Alignment	427
9.6.2	Axial Scanning Test Result	427
9.6.3	Probe Imaging	429
9.6.4	Optical Efficiency Testing	431
	References	433
<b>10</b>	<b>Accelerometer Packaging</b>	<b>435</b>
10.1	Introduction	435
10.2	Wafer-Level Package Requirements	437
10.2.1	Electrical Modeling	438
10.2.2	Package Structure	438
10.2.3	Extraction Methodology of the Interconnection Characteristics	442
10.3	Wafer-Level Packaging Process	448
10.3.1	Method 1: TSV with Sacrificial Wafer	450
10.3.2	Method 2: TSV without Sacrificial Wafer	450
10.3.3	Method 3: TSV with MEMS Wafer	452
10.4	Wafer Separation Process	458
10.4.1	Process Integration	460
10.5	Sacrificial Wafer Removal	462
10.6	Wafer-Level Vacuum Sealing	464
10.7	Vacuum Measurement Using a MEMS Motion Analyzer	467
10.8	Reliability Testing: Vacuum Maintenance	469
10.9	Wafer-Level 3D Package for an Accelerometer	471
	References	473
<b>11</b>	<b>Radiofrequency MEMS Switches</b>	<b>475</b>
11.1	Introduction	475
11.2	Design of RF MEMS Switches	475
11.2.1	Design of Capacitive Switches	475

11.2.2	Design of Metal-Contact Switches . . . .	479
11.2.3	Mechanical Design of RF MEMS Switches . . . . .	479
11.3	Fabrication of RF MEMS Switches . . . . .	484
11.3.1	Surface Micromachining of RF MEMS Switches . . . . .	484
11.3.2	Bulk Micromachining of RF MEMS Switches . . . . .	488
11.4	Characterization of RF MEMS Switches . . . .	489
11.4.1	RF Performance . . . . .	489
11.4.2	Mechanical Performance . . . . .	489
11.5	Reliability of RF MEMS Switches . . . . .	492
11.5.1	Reliability of Capacitive Switches . . . . .	492
11.5.2	Reliability of Metal-Contact Switches . . . . .	492
11.6	Summary . . . . .	492
	References . . . . .	493
<b>12</b>	<b>RF MEMS Tunable Capacitors and Tunable Band-Pass Filters . . . . .</b>	<b>495</b>
12.1	Introduction . . . . .	495
12.2	RF MEMS Tunable Capacitors . . . . .	495
12.2.1	Analog Tuning of RF MEMS Capacitors . . . . .	496
12.2.2	Digital Tuning of RF MEMS Capacitors . . . . .	503
12.3	RF MEMS Tunable Band-Pass Filters . . . . .	504
12.3.1	Analog Tuning of a MEMS Band-Pass Filter . . . . .	505
12.3.2	Digital Tuning of an RF MEMS Filter . . . . .	506
12.4	Summary . . . . .	512
	References . . . . .	513
<b>13</b>	<b>Advanced Packaging of RF MEMS Devices . . . . .</b>	<b>515</b>
13.1	Introduction . . . . .	515
13.2	Zero-Level Packaging . . . . .	515
13.2.1	Chip Capping . . . . .	516
13.2.2	Thin-Film Capping . . . . .	523
13.3	One-Level Packaging . . . . .	525
13.4	Reliability of Packaged RF MEMS Devices . . .	526
13.5	Summary . . . . .	528
	References . . . . .	528
	<b>Index . . . . .</b>	<b>531</b>

---

# Foreword

The invention of the bipolar junction transistor and the junction field-effect transistor by Bardeen, Brattain, and Shockley in 1956 foreshadowed the development of generations of smart phones and computers yet to come. The invention of the silicon integrated circuit (IC) by Jack Kilby of Texas Instruments in 1958 and 6 months later by Robert Noyce of Fairchild Semiconductor excited the development of generations of integrations. The proposal of doubling the number of transistors on an IC every 24 months by Gordon Moore in 1965 (also called Moore's law) has been the most powerful driver for the development of the microelectronic industry in the past 44 years. This law emphasizes lithography scaling and integration (in two dimensions) of all functions on a single chip, through system-on-chip (SoC).

Apart from SoC, integration of all these functions can be achieved through system-in-package (SiP) or, ultimately, three-dimensional IC integration, which can be called "*more than Moore*." Based on silicon-platform technology, anything that involves the integration of electronics, photonics, mechanics, chemistry, heat, magnetics, biology, etc., for functionality and system performance when interacting with people and the environment is known as more than Moore. Micro-electromechanical systems (MEMS) is a part of it.

Yole Development forecasted the MEMS market to be \$14 billion by 2012. The packaging cost of MEMS products in general is about 70 percent. Thus MEMS packaging could be a \$10 billion market by 2012. Unlike electronics IC packaging, MEMS packaging is custom-built and difficult due to the moving structural elements. For some MEMS devices, such as resonators, infrared bolometers, and gyroscopes, vacuum packaging is required. For most researchers and engineers, advanced MEMS packaging is the least understood of all. Thus, there is an urgent need to generate a comprehensive book on the current state of knowledge in the design, materials, process, manufacturing, and reliability of advanced MEMS packaging technology.

Institute of Microelectronics (IME), Singapore, one of the research institutes of the Agency for Science, Technology and Research (A\*STAR), has been publishing MEMS papers extensively in a wide spectrum



of journals, conference proceedings, symposia, and workshops. However, there is no single comprehensive compilation of information devoted to state-of-the-art advanced MEMS packaging. This book is written for everyone who can quickly learn about the basics and problem-solving methods, understand the trade-offs, and make system-level decisions. John Lau, Chengkuo Lee, C. S. Premachandran, and Yu Aibin of IME have taken the time and made the effort to complete this book on this timely topic of advanced MEMS packaging.

This book will help focus the attention of practicing engineers and research scientists, as well as faculty and students, on the complex MEMS packaging challenges that must be overcome. I wish that this book will serve future generations of engineers, scientists, and students who will continue to advance the science and engineering of MEMS packaging. With their predecessors' knowledge and their creativity, there is no doubt this wish will come true.

*Professor Dim-Lee Kwong  
Executive Director  
Institute of Microelectronics  
Singapore*

---

# Preface

The last decade witnessed an explosive growth in research and development efforts devoted to advanced microelectro-mechanical systems (MEMS) packaging as a direct result of higher requirements for package footprint, density, and performance and cost advantages over conventional MEMS packages. For the next decade, MEMS devices and packaging will penetrate into IT, telecommunications, automotive, life sciences, medical, and implantable applications. However, like many other new technologies, advanced MEMS packaging still has many critical issues that need to be addressed. In the development of advanced MEMS packaging, the following must be noted and understood: The infrastructure of MEMS devices and MEMS packaging is not well established; MEMS packaging expertise is not commonly available; MEMS packaging is unique and custom-built; MEMS general packaging platform technology is not available; hermetic sealing of the MEMS device is necessary; vacuum packaging is even required for some MEMS devices; vertical electrical feed-through with through-silicon vias (TSVs) is still too costly; bare ASIC die/wafers are not commonly available for three-dimensional (3D) integration; bare thin die/wafer handling is not easy; pick and place is more difficult; low-temperature bonding is not mature enough for high-volume production; rework is more difficult; micro solder bumping, assembly, and reliability are more critical; inspection is more difficult; MEMS assembly testability is not well established; dies shrink and expand; known-good-die; thermal management; wafer dicing; and device/chip cracking during bonding.

In the past few years, some of these critical issues have been studied by experts in the field. Their results have been disclosed in diverse journals and in the proceedings of many conferences, symposia, and workshops whose primary emphases are electrical designs, materials science, manufacturing engineering, or electronic packaging and interconnection. Consequently, there is no single source of information devoted to the state of the art of advanced MEMS packaging technologies for, e.g., inertial, optical, RF, BioMEMS, and medical MEMS devices. This book aims to remedy this deficiency

by presenting in one complete and concise volume a summary of the progress in this fascinating field that has occurred within the past few years. This book is written for everyone so that they can quickly learn the basics, grasp problem-solving methods, understand the trade-offs, and make system-level decisions with advanced MEMS packaging technologies.

This book is organized into five parts. Chapter 1, the first part, briefly discusses MEMS devices, commercial applications, and markets. MEMS packaging is also briefly mentioned, and some of the MEMS packaging patents from the United States, Japan, and the world since 2001 are provided.

Chapter 2, the second part, briefly discusses the state of the art and future trends of advanced integrated-circuit (IC) electronics packaging. It is followed by advanced MEMS packaging, where 10 different designs of 3D MEMS packaging and their assembly processes are presented.

There are two chapters in the third part, where some important enabling technologies for advanced MEMS packaging are presented. In Chapter 3, TSVs, stress sensors, wafer thinning and thin-wafer handling, low-temperature C2C, C2W, and W2W bonding, wafer dicing, and the reliability of RoHS-compliant MEMS packaging are discussed. Chapter 4 focuses on wafer-level packaging, where micro-machining, wafer-level encapsulation, wafer-level chip capping, and a couple of case studies on wafer bonding based on low-temperature solder for MEMS packaging are presented.

The fourth part has six chapters, and its focus is on the applications of advanced packaging on some MEMS devices. Chapter 5 presents an overview of microfabrication technology and major actuation mechanisms in enabling optical MEMS, followed by two well-studied optical MEMS devices in communications: optical switches and variable optical attenuators (VOAs). All aspects of MEMS design, manufacturability, packaging, and reliability are discussed. Chapter 6 presents the packaging and thermal reliability of the solder sealing ring of an RoHS-compliant 3D bubble-actuated photonic cross-connect switch. Emphasis is placed on determination of the thermal fatigue life of the lead-free solder sealing ring under shipping, storing, and handling conditions. Chapter 7 outlines the design, process, packaging, and testing of a bolometer vacuum package. The challenge of vacuum packaging and maintaining the temperature within  $\pm 0.1^\circ\text{C}$ , packaging material and getter selections, and testing are presented. Chapter 8 presents the design, materials, process, and testing of bio-MEMS packaging. Emphasis is placed on the process developments of the microfluidics package and its application to extracting dengue virus from the samples. Chapter 9 presents the design, materials, process, and testing of MEMS packaging of a biosensor (micromirror) in an optical probe, which can take images from body tissues. Chapter 10 presents a wafer-level package with

TSV interconnects and a wafer-level vacuum package with lateral electrical feed-through interconnects for accelerometer devices. For TSV interconnects, the die shear and hermeticity tests are used to characterize the package, and their results are discussed. For wafer-level vacuum packages, the C-V curves subjected to reliability tests and the Q-factor measurement of the vacuum inside the package are presented.

The fifth part of this book covers radio frequency (RF) MEMS and packaging. Chapter 11 presents the design, fabrication, and characterization of RF MEMS switches. Emphasis is placed on mechanical and electrical design for performance, the micromachining and bulk micromachining processes, and maintaining an insertion loss of the MEMS switch that is lower than 0.5 dB up to 40 GHz and an isolation higher than 15 dB at 10 GHz. Chapter 12 presents different RF MEMS circuits, including tunable capacitors and tunable band-pass filters, which consist of different MEMS switches and can be tuned analogically or digitally. Usually the digital tuning approach has a larger tuning range and has more flexibility for constructing different tuning circuits. Chapter 13 presents the zero-level and first-level packaging of RF MEMS switches, which must be packaged in a nitrogen or dry-air atmosphere (for high reliability) owing to hermeticity, temperature, and outgassing constraints. In zero-level packaging, capping of RF MEMS devices can be categorized as chip capping and thin-film capping. In first-level packaging, plastic packaging is the most common solution applicable for frequencies below several gigahertz, and ceramic packages exhibit the potential for good performance into the millimeter-wave region.

For whom is this book intended? Undoubtedly, it will be of interest to three groups of specialists: (1) those who are active or intend to become active in research and development of MEMS devices and packaging, (2) those who have encountered practical MEMS packaging problems and wish to understand and learn more methods for solving such problems, and (3) those who have to choose a reliable, creative, high-performance, robust, and cost-effective packaging technique for their MEMS devices. This book also can be used as a text for undergraduate and graduate students who have the potential to become our future leaders, scientists, and engineers in the electronics, optoelectronics, and photonics industries.

We hope that this book will serve as a valuable reference source for all those faced with the challenging problems created by the ever-increasing interest in MEMS devices and packaging. We also hope that it will aid in stimulating further research and development on optical, electrical, thermal, and mechanical designs, materials, processes, manufacturing, testing, and reliability and more sound applications of advanced packaging technologies in MEMS products.

The organizations that learn how to design advanced MEMS packaging in their interconnect systems have the potential to make