ELECTRONIC
ENGINEERING

# ADVANCED MEMS PACKAGING

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## 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.

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# Contents

# 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. Microelectromechanical 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 microelectromechanical 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 micromachining, 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 ±0.1°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