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COMPREHENSIVE MICROSYSTEMS

EDITORS-IN-CHIEF

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VOLUME ONE

MATERIALS

FABRICATION AND PACKAGING

ELECTRONICS AND SYSTEM DESIGN

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ELECTRONICS AND SYSTEMS DESIGN

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COMPREHENSIVE MICROSYSTEMS

Foreword

Microsystems promise to play a pervasive role in enhancing the quality of life during the next several decades. Emerging today in a plethora of products, they represent a powerful weapon for tackling some of society's most pressing problems, including many in health care, environmental quality, homeland security, energy generation, manufacturing competitiveness, and food production. In a very real sense, microsystems represent the culmination of work in three areas, each of which has sparked a revolution of its own: microelectronics, wireless communications, and sensing technology. Bringing these three areas together, microsystems will gather data from the physical world, interpret those data, and then communicate the results via distributed information networks. Increasingly based on nanotechnology, they will control the cars we drive (and monitor the roads and bridges we drive on), enable new generations of high-density information storage and display devices, revolutionize the diagnosis and treatment of debilitating disorders, and provide interfaces to the cellular, molecular, and atomic levels. Just as microelectronics transformed data processing and communications during the past half-century, microsystems are now reaching out to tackle the problems of the nonelectronic world.

Although microelectronics began with the invention of the transistor shortly after World War II, it really took off with the development of the planar process for integrated circuits in the early 1960s. It was quickly apparent that microelectronics was going to permit great progress in the processing of electronic signals, but the world we live in is not electronic. It is mechanical, optical, chemical, and thermal. Thus, researchers began exploring whether the same lithographic processes used to form integrated circuits could also be used to make devices for converting nonelectronic parameters into electronic form (integrated sensors). By the mid-1960s, researchers were realizing visible imaging devices using integrated circuit techniques, and by the late 1960s they were developing cellular probes, pressure sensors, and other devices using the same technology, augmented by selective silicon etching (later christened "micromachining"). The 1970s saw the development of anisotropic micromachining technology and wafer bonding, both necessary for creating the three-dimensional microstructures needed for transducing real-world parameters into electronic signals. They also saw the first efforts to put integrated sensors into high-volume production as the automotive industry sought to meet new exhaust emissions and fuel efficiency requirements. By the late 1970s, the vision of highly integrated digital-output self-testing auto-calibrating "smart" sensors was in place, but neither the supporting technologies nor the marketplace was quite ready for them.

The 1980s saw other important technologies added to the arsenal of sensor processes, including surface micromachining, LIGA, and deep reactive ion etching. The first serious efforts at commercialization began, and conferences dedicated to integrated sensors were launched. By the end of the decade, integrated sensors were becoming known as microelectromechanical systems (MEMS) and were generating great excitement by realizing actuators as well as sensors using the technology. Uncooled infrared sensors, flowmeters, micromotors, and self-testing accelerometers were being reported. The 1990s saw MEMS become a major worldwide effort and proliferate into a number of subfields, including optical-MEMS, inertial-MEMS, RF-MEMS, bio-MEMS, and microfluidics. Integrated gyros, microvalves, scanning surface probes, ink-jet print heads, DNA chips, and optical projection systems provided the focus for new efforts, fueled in part by new materials and processes. The present decade has seen continued proliferation into new materials, rapid growth in chemical and biological devices, and the joining of sensing (and actuation) technology with microelectronics and wireless interfaces.

These developments have taken sensors well beyond simple transducers to application-driven microsystems that solve complete problems.

Comprehensive Microsystems is a remarkably comprehensive and state-of-the-art look at the microsystems field, assembled by editors who are world leaders in microsystems and by subject authors that are expert in its many constituent areas. It begins by reviewing the diverse set of materials used in microsystems, a set that is steadily expanding to take advantage of properties ranging far beyond those found in silicon alone. The critical issues associated with fabrication and packaging are examined next. High throughput and high yield in forming complex three-dimensional microstructures are important, but unlike microelectronics, where complementary metal oxide semiconductors (CMOS) have become dominant, the diversity of microsystem structures has, so far, resisted process standardization. Both fabrication flows and unit processes still involve considerable innovation. Microsystem packaging is also more difficult than in microelectronics because, by definition, many sensors must directly contact the environment they are trying to measure, and for many devices, packaging at the wafer level is essential both for fabrication yield and for operating performance. The complex issues associated with design in the interdisciplinary multiparameter world of microsystems are discussed next, followed by chapters that examine the state of the art in optical, chemical, biological, and physical microsystems. Available techniques for microactuation are discussed, both for use in their own right (e.g., in ink-jet printers, digital light processors) and for sensor self-test. Important emerging topics are then explored, and the book concludes with comments on interface circuitry for MEMS and a look at three high-volume application areas: automotive, medical, and environmental.

Comprehensive Microsystems is an outstanding resource and window on an exciting new frontier that will be key in solving many of the most important problems facing us in the 21st century, improving the quality of life for our children, our children's children, and ourselves.

Kensall D. Wise
Ann Arbor, Michigan

Preface

Microsystems have emerged from the laboratory and have become essential components in a wide range of medical and industrial products, and research instrumentation. They include not only microelectromechanical systems (MEMS), but all forms of microsensors, microactuators, and interface microelectronics, deployed as enabling components within a larger system or distributed network. Combining high functionality with small dimensions and reduced power consumption, microsystems benefit from mass-fabrication technologies to allow their manufacture in high volumes and, often, at low cost. The inclusion of electronics, when possible, reduces the cost of deployment and use, providing autocalibration and self-testing. The small dimensional scale sometimes allows physical effects to be leveraged in unconventional ways, providing surprisingly high functionality and performance. As a result, microsystems are virtually invisible to most people, yet have become indispensable in many aspects of their lives.

The microsystems field has expanded to embrace a host of technologies. The well-established discipline of microelectronics has now been joined by micromechanics, microfluidics, and microoptics to allow the fabrication of complex, multifunctional integrated microsystems. As a result, the highly interdisciplinary nature of the subject often makes it difficult for researchers to obtain an overview of the technologies and capabilities available in this established yet dynamically growing engineering field. Thanks to a superb collection of authors, reviewers, and Editorial Advisory Board members, we are confident that *Comprehensive Microsystems* represents an authoritative primary reference source that addresses this need.

As its title suggests, the book before you covers virtually all aspects of the microsystems field. In 54 chapters, the work discusses a breadth of topics, which underscores the interdisciplinary nature of research and development in microsystems and MEMS, a spectrum that has few parallels in other technical disciplines. As a readable reference work, *Comprehensive Microsystems* provides engineers, students, and educators with a unified source of information that will prove to be useful for new as well as established microsystems researchers.

The book is thematically divided into sections that cover a variety of topics; the chapters are self-contained, yet cross-referenced, allowing readers to easily obtain relevant related information. The book opens with a section on Materials, including chapters on silicon as well as metals and polymers, and continues with Fabrication and Packaging, in which the topics range from micromachining to self-assembly and packaging. Moving to an overview of some of the basic components used in microsystems, the section Electronics and System Design covers areas including electronic interface circuits and simulation, and Actuation Mechanisms has chapters on electrostatic, magnetic, and thermal actuation.

The exceptionally wide variety of application areas in which microsystems play a role is reflected in the range of sections that follow. Physical Sensing includes contributions on pressure and flow sensors, gyroscopes, and accelerometers, whereas microfluidics, micropumps, and chemical sensors are only a few of the topics found in the section Chemical and Biological Systems. Finally, the rich spectrum of activities discussed in Optical Systems includes micromirrors, the artificial retina, and biophotonics.

Realizing that the MEMS and microsystems fields have led to mature products in a number of industrial applications as well as provided inspiration for research in unexplored areas, the work concludes with a section Industrial Applications, in which chapters discuss radio-frequency MEMS, medical applications, and ink-jets, and finally Emerging Topics, a look toward the future in which MEMS atomic clocks, microcombustion systems, and molecular machine-based nanoelectromechanical systems (NEMS) will see extensive development.

Comprehensive Microsystems provides an extensive cross section through engineering science, from fundamental physics and chemistry to complex, cross-disciplinary systems. The editors-in-chief have been privileged to work with some of the world's leading researchers as authors, reviewers, and editors of the chapters that follow. We hope that you, the reader, will find studying the work as rewarding as we have in assembling it.

Editors-in-Chief

Yogesh B. Gianchandani is a Professor in the EECS Department and holds a courtesy appointment in the Department of Mechanical Engineering at the University of Michigan, Ann Arbor. He received a Ph.D. in electrical engineering from the same university in 1994. Prior to this, he worked as an IC designer, primarily at Xerox Corporation. His research interests include all aspects of design, fabrication, and packaging of micromachined sensors and actuators and their interface circuits. He has contributed to more than 200 papers or patents in this field, and serves on the editorial boards of several journals. He also served as a General Co-Chair for the IEEE/ASME International Conference on Micro Electro Mechanical Systems (IEEE MEMS) in 2002. At the University of Michigan, Prof. Gianchandani has served as the director of the College of Engineering Interdisciplinary Professional Degree Program in Integrated Microsystems. As of 2007, he is on a temporary assignment at the US National Science Foundation, serving in the Directorate for Engineering as a program manager for nano- and microsystems.

Professor Osamu Tabata Born in 1956. He received a MS degree and a Ph.D. degree from the Nagoya Institute of Technology, Nagoya, Japan, in 1981 and in 1993, respectively. Since 1981 for 15 years, he has been with the Toyota Central Research and Development Laboratories, Japan. In 1996, he joined the Department of Mechanical Engineering, Ritsumeikan University, Shiga, Japan. He was a guest Professor of Institute of Microsystem Technology, University of Freiburg and ETH Zurich from September to December 2000 and from January to March 2001, respectively. In 2003, he joined the Department of Mechanical Engineering, Kyoto University, Japan. He is currently Professor in the Department of Micro Engineering, Kyoto University. He is currently interested in the establishment of a technology to realize a unique and novel nanosystem by assembling the various functional components such as a microchip, and a particle, a microcapsule, and a cell, with sizes ranging from the nanometer to micrometer scale on a MEMS/NEMS substrate. He termed this concept as SENS (synthetic engineering for nanosystems), and is pursuing experimental and theoretical research on the establishment of SENS. He is an associate editor of Journal of Micro Electro Mechanical Systems as well as a member of the editorial board of Advanced Micro- and Nanosystems, and Sensors and Actuators. Also he is a program committee member of many International Conferences.

Professor Hans Zappe was born in Paris, France, in 1961 and raised in New York. He received his B.Sc. and M.Sc. in Electrical Engineering from the Massachusetts Institute of Technology in 1983 and his Ph.D. in the same field from the University of California at Berkeley in 1989. He has worked at IBM (Burlington, VT, USA) on silicon VLSI, at the Fraunhofer Institute for Applied Solid State Physics (Freiburg, Germany) on GaAs electronics and high-speed lasers, and at the Centre Suisse d'Electronique et de Microtechnique (Zurich, Switzerland) on integrated optical microsystems and surface-emitting lasers. Since 2000, he has been Professor in the Department of Microsystems Engineering at the University of Freiburg, Germany. His current research interests focus on the development of novel tunable micro- optical components, including polymer, membrane, and liquid-based optics, variable photonic crystals, and optical microsystems for medical diagnostics and clinical applications.

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