The MEMS Handbook

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The MEMS Handbook

Edited by
Mohamed Gad-el-Hak
University of Notre Dame

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Cover Photographs

Foreground: The first walking microrobot with a Swedish wasp relishing a ride on its back. The out-of-plane rotation of the eight legs is obtained by thermal shrinkage of polyimide in V-grooves (PVG). Leg movements are effected by sending heating pulses via integrated heaters causing the polyimide joints to expand. The size of the silicon legs is $1000 \times 600 \times 30$ µm, and the overall chip size of the robot is $15 \times 5 \times 0.5$ mm. The walking speed is 6 mm/s and the robot can carry 50 times its own weight. (Photograph by Per Westergård, Vetenskapsjournalisterna, Sweden, courtesy of Thorbjörn Ebefors, Royal Institute of Technology, Sweden.)

Background: A 12-layer microchain fabricated in nickel using the Electrochemical Fabrication (EFAB) technology. Overall height of the chain is approximately 100 µm and the width of a chain link is about 290 µm. All horizontal links are free to move, while the vertical links are attached to the substrate. By simply including a sacrificial layer beneath the links, the entire chain can be released from the substrate. The microchain is fabricated in a pre-assembled state, without the need for actual assembly. A humble, picnic-loving ant would tower over the microchain shown here. (The two scanning electron micrographs courtesy of Adam L. Cohen, MEMGen Corporation, Torrance, California.)

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Preface

In a little time I felt something alive moving on my left leg, which advancing gently forward over my breast, came almost up to my chin; when bending my eyes downward as much as I could, I perceived it to be a human creature not six inches high, with a bow and arrow in his hands, and a quiver at his back. …I had the fortune to break the strings, and wrench out the pegs that fastened my left arm to the ground; for, by lifting it up to my face, I discovered the methods they had taken to bind me, and at the same time with a violent pull, which gave me excessive pain, I a little loosened the strings that tied down my hair on the left side, so that I was just able to turn my head about two inches. …These people are most excellent mathematicians, and arrived to a great perfection in mechanics by the countenance and encouragement of the emperor, who is a renowned patron of learning. This prince has several machines fixed on wheels, for the carriage of trees and other great weights.

(From *Gulliver's Travels—A Voyage to Lilliput*, by Jonathan Swift, 1726.)

The length-scale of man, at slightly more than 10^0 m, amazingly fits right in the middle of the smallest subatomic particle, which is approximately 10^{-26} m, and the extent of the observable universe, which is of the order of 10^{26} m. Toolmaking has always differentiated our species from all others on Earth. Aerodynamically correct wooden spears were carved by *archaic Homo sapiens* close to 400,000 years ago. Man builds things consistent with his size, typically in the range of two orders of magnitude larger or smaller than himself. But humans have always strived to explore, build and control the extremes of length and time scales. In the *Voyages to Lilliput* and *Brobdingnag of Gulliver's Travels*, Jonathan Swift speculates on the remarkable possibilities that diminution or magnification of physical dimensions provides. The Great Pyramid of Khufu was originally 147 m high when completed around 2600 B.C., while the Empire State Building, constructed in 1931, is 449 m tall. At the other end of the spectrum of manmade artifacts, a dime is slightly less than 2 cm in diameter. Watchmakers have practiced the art of miniaturization since the 13th century. The invention of the microscope in the 17th century opened the way for direct observation of microbes and plant and animal cells. Smaller things were manmade in the latter half of the 20th century. The transistor in today's integrated circuits has a size of 0.18 μm in production and approaches 10 nm in research laboratories.

Microelectromechanical systems (MEMS) refer to devices that have a characteristic length of less than 1 mm but more than 1 μm, that combine electrical and mechanical components and that are fabricated using integrated circuit batch-processing technologies. Current manufacturing techniques for MEMS include surface silicon micromachining; bulk silicon micromachining; lithography, electrodeposition and plastic molding; and electrodischarge machining. The multidisciplinary field has witnessed explosive growth during the last decade, and the technology is progressing at a rate that far exceeds that of our understanding of the physics involved. Electrostatic, magnetic, electromagnetic, pneumatic and thermal actuators, motors, valves, gears, cantilevers, diaphragms and tweezers of less than 100-μm size have been fabricated. These have been used as sensors for pressure, temperature, mass flow, velocity, sound and chemical composition; as actuators for linear and angular motions; and as simple components for complex systems such as robots, micro heat engines and micro heat pumps. Worldwide market projections for MEMS devices tend to be optimistic, reaching $30 billion by the year 2004.

This handbook covers several aspects of microelectromechanical systems or, more broadly, the art and science of electromechanical miniaturization. MEMS design, fabrication and application as well as the physical modeling of their materials, transport phenomena and operations are all discussed. Chapters on the electrical, structural, fluidic, transport and control aspects of MEMS are included. Other chapters cover existing and potential applications of microdevices in a variety of fields including instrumentation and distributed control. The book is divided into four parts: Part I provides background and physical considerations, Part II discusses the design and fabrication of microdevices, Part III reviews a few of the applications of microsensors and microactuators, and Part IV ponders the future of the field. There are 36 chapters written by the world's foremost authorities on this mutidisciplinary subject. The contributing authors come from the U.S., China (Hong Kong), Israel, Korea, Sweden and Taiwan and are affiliated with academia, government and industry. Without compromising rigorousness, the text is designed for maximum readability by a broad audience having an engineering or science background. As expected when several authors are involved, and despite the editor's best effort, the different chapters vary in length, depth, breadth and writing style.

The Handbook of MEMS should be useful as a reference book to scientists and engineers already experienced in the field or as a primer to researchers and graduate students just getting started in the art and science of electromechanical miniaturization. The editor-in-chief is very grateful to all the contributing authors for their dedication to this endeavor and selfless, generous giving of their time with no material reward other than the knowledge that their hard work may one day make the difference in someone else's life. Ms. Cindy Renee Carelli has been our acquisition editor and lifeline to CRC Press. Cindy's talent, enthusiasm and indefatigability were highly contagious and percolated throughout the entire endeavor.

Mohamed Gad-el-Hak
Notre Dame, Indiana
1 January 2001

Editor-in-Chief

Mohamed Gad-el-Hak received his B.Sc. (*summa cum laude*) in mechanical engineering from Ain Shams University in 1966 and his Ph.D. in fluid mechanics from the Johns Hopkins University in 1973. Dr. Gad-el-Hak has since taught and conducted research at the University of Southern California, University of Virginia, Institut National Polytechnique de Grenoble, Université de Poitiers and Friedrich-Alexander-Universität Erlangen-Nürnberg and has lectured extensively at seminars in the U.S. and overseas. Dr. Gad-el-Hak is currently Professor of Aerospace and Mechanical Engineering at the University of Notre Dame. Prior to that, he was a Senior Research Scientist and Program Manager at Flow Research Company in Seattle, WA, where he managed a variety of aerodynamic and hydrodynamic research projects.

Dr. Gad-el-Hak is world renowned for advancing several novel diagnostic tools for turbulent flows, including the laser-induced fluorescence (LIF) technique for flow visualization; for discovering the efficient mechanism via which a turbulent region rapidly grows by destabilizing a surrounding laminar flow; for introducing the concept of targeted control to achieve drag reduction, lift enhancement and mixing augmentation in boundary-layer flows; and for developing a novel viscous pump suited for microelectromechanical systems (MEMS) applications. Gad-el-Hak's work on Reynolds number effects in turbulent boundary layers, published in 1994, marked a significant paradigm shift in the subject. He holds two patents: one for a drag-reducing method for airplanes and underwater vehicles and the other for a lift-control device for delta wings. Dr. Gad-el-Hak has published over 340 articles, authored/edited eight books and conference proceedings, and presented 195 invited lectures. He is the author of the book *Flow Control: Passive, Active, and Reactive Flow Management*, and editor of the books *Frontiers in Experimental Fluid Mechanics*, *Advances in Fluid Mechanics Measurements*, and *Flow Control: Fundamentals and Practices*.

Dr. Gad-el-Hak is a fellow and life member of the American Physical Society, a fellow of the American Society of Mechanical Engineers, an associate fellow of the American Institute of Aeronautics and Astronautics, a member of the American Academy of Mechanics, a research fellow of the American Biographical Institute and a member of the European Mechanics Society. From 1988 to 1991, Dr. Gad-el-Hak served as Associate Editor for *AIAA Journal*. He is currently serving as Associate Editor for *Applied Mechanics Reviews* as well as Contributing Editor for Springer-Verlag's *Lecture Notes in Engineering* and *Lecture Notes in Physics*, for McGraw-Hill's *Year Book of Science and Technology*, and for CRC Press' *Mechanical Engineering Series*.

Dr. Gad-el-Hak serves as consultant to the governments of Egypt, France, Germany, Sweden and the U.S., the United Nations, and numerous industrial organizations. During the 1991/1992 academic year, he was a visiting professor at Institut de Mécanique de Grenoble, France. During the summers of 1993, 1994 and 1997, Dr. Gad-el-Hak was, respectively, a distinguished faculty fellow at Naval Undersea Warfare Center, Newport, RI; a visiting exceptional professor at Université de Poitiers, France; and a Gastwissenschaftler (guest scientist) at Forschungszentrum Rossendorf, Dresden, Germany. In 1998, Professor Gad-el-Hak was named the Fourteenth ASME Freeman Scholar. In 1999, Gad-el-Hak was awarded the prestigious Alexander von Humboldt Prize—Germany's highest research award for senior U.S. scientists and scholars in all disciplines.

Contributors

Professor Ronald J. Adrian
Department of Theoretical and Applied Mechanics
University of Illinois at Urbana–Champaign
Urbana, Illinois
E-mail: r-adrian@uiuc.edu

Professor Ramesh K. Agarwal
National Institute for Aviation Research
Wichita State University
Wichita, Kansas
E-mail: agarwal@niar.twsu.edu

Dr. Glenn M. Beheim
NASA Glenn Research Center
Cleveland, Ohio
E-mail: Glenn.M.Beheim@grc.nasa.gov

Professor Paul L. Bergstrom
Department of Electrical and Computer Engineering
Michigan Technological University
Houghton, Michigan
E-mail: paulb@mtu.edu

Professor Gary H. Bernstein
Department of Electrical Engineering
University of Notre Dame
Notre Dame, Indiana
E-mail: bernstein.1@nd.edu

Professor Ali Beskok
Department of Mechanical Engineering
Texas A&M University
College Station, Texas
E-mail: ABeskok@mengr.tamu.edu

Professor Thomas R. Bewley
Department of Mechanical and Aerospace Engineering
University of California, San Diego
La Jolla, California
E-mail: bewley@ucsd.edu

Professor Kenneth S. Breuer
Division of Engineering
Brown University
Providence, Rhode Island
E-mail: Kenneth_Breuer@brown.edu

Professor Hsueh-Chia Chang
Department of Chemical Engineering
University of Notre Dame
Notre Dame, Indiana
E-mail: hchang@nd.edu

Dr. Liang-Yu Chen
NASA Glenn Research Center
Cleveland, Ohio
E-mail: Liangyu.Chen@grc.nasa.gov

Professor Haecheon Choi
School of Mechanical and Aerospace Engineering
Seoul National University
Seoul, Republic of Korea
E-mail: choi@socrates.snu.ac.kr

Dr. Todd Christenson
Photonics and Microfabrication
Sandia National Laboratories
Albuquerque, New Mexico
E-mail: trchris@sandia.gov

Mr. Adam L. Cohen
MEMGen Corporation
Torrance, California
E-mail: acohen@memgen.com

Dr. Thorbjörn Ebefors
Department of Signals, Sensors and Systems
Royal Institute of Technology
Stockholm, Sweden
E-mail: thorbjorn.ebefors@s3.kth.se

Professor Mohamed Gad-el-Hak
Department of Aerospace and Mechanical Engineering
University of Notre Dame
Notre Dame, Indiana
E-mail: gadelhak@nd.edu

Professor Yogesh Gianchandani
Department of Electrical and Computer Engineering
University of Wisconsin–Madison
Madison, Wisconsin
E-mail: yogesh@engr.wisc.edu

Professor Holly V. Goodson
Department of Chemistry and Biochemistry
University of Notre Dame
Notre Dame, Indiana
E-mail: hgoodson@nd.edu

Professor Bill Goodwine
Department of Aerospace and Mechanical Engineering
University of Notre Dame
Notre Dame, Indiana
E-mail: jgoodwin@nd.edu

Dr. Gary W. Hunter
NASA Glenn Research Center
Cleveland, Ohio
E-mail: Gary.W.Hunter@grc.nasa.gov

Professor George Em Karniadakis
Center for Fluid Mechanics
Brown University
Providence, Rhode Island
E-mail: gk@cfm.brown.edu

Mr. Robert M. Kirby
Division of Applied Mathematics
Brown University
Providence, Rhode Island
E-mail: kirby@cfm.brown.edu

Dr. Jih-Fen Lei
NASA Glenn Research Center
Cleveland, Ohio
E-mail: Jih-Fen.Lei@grc.nasa.gov

Dr. Gary G. Li
OMM, Inc.
San Diego, California
E-mail: gli@omminc.com

Professor Chung-Chiun Liu
Electronics Design Center
Case Western Reserve University
Cleveland, Ohio
E-mail: cxl9@po.cwru.edu

Professor Lennart Löfdahl
Thermo and Fluid Dynamics
Chalmers University of Technology
Göteborg, Sweden
E-mail: lelo@tfd.chalmers.se

Dr. Marc J. Madou
Nanogen, Inc.
San Diego, California
E-mail: mmadou@nanogen.com

Dr. Darby B. Makel
Makel Engineering, Inc.
Chico, California
E-mail: dmakel@makelengineering.com

Professor Kartikeya Mayaram
Department of Electrical and Computer Engineering
Oregon State University
Corvallis, Oregon
E-mail: karti@ece.orst.edu

Mr. J. Jay McMahon
Electrcial Engineering and Computer Science Department
Case Western Reserve University
Cleveland, Ohio
E-mail: jjm@cwru.edu

Professor Mehran Mehregany
Electrical Engineering and Computer Science Department
Case Western Reserve University
Cleveland, Ohio
E-mail: mxm31@cwru.edu

Dr. Oleg Mikulchenko
Department of Electrical and Computer Engineering
Oregon State University
Corvallis, Oregon
E-mail: mikul@ece.orst.edu

Mr. Joshua I. Molho
Department of Mechanical Engineering
Stanford University
Stanford, California
E-mail: jmolho@stanford.edu

Professor E. Phillip Muntz
Department of Aerospace and Mechanical Engineering
University of Southern California
Los Angeles, California
E-mail: muntz@spock.usc.edu

Professor Ahmed Naguib
Department of Mechanical Engineering
Michigan State University
East Lansing, Michigan
E-mail: naguib@egr.msu.edu

Dr. Robert S. Okojie
NASA Glenn Research Center
Cleveland, Ohio
E-mail: Robert.S.Okojie@grc.nasa.gov

Dr. Andrew D. Oliver
Electromechanical Engineering Department
Sandia National Laboratories
Albuquerque, New Mexico
E-mail: adolive@sandia.gov

Professor Alexander Oron
Department of Mechanical Engineering
Technion–Israel Institute of Technology
Haifa, Israel
E-mail: meroron@bsf97.technion.ac.il

Mr. Jae-Sung Park
Department of Electrical and Computer Engineering
University of Wisconsin–Madison
Madison, Wisconsin
E-mail: jae-sung@cae.wisc.edu

Professor G. P. "Bud" Peterson
Provost Office
Rensselaer Polytechnic Institute
Troy, New York
E-mail: peterson@rpi.edu

Mr. David W. Plummer
Sandia National Laboratories
Albuquerque, New Mexico
E-mail: dwplumm@sandia.gov

Professor Juan G. Santiago
Department of Mechanical Engineering
Stanford University
Stanford, California
E-mail: santiago@vonkarman.stanford.edu

Professor Mihir Sen
Department of Aerospace and Mechanical Engineering
University of Notre Dame
Notre Dame, Indiana
E-mail: msen@nd.edu

Dr. Kendra V. Sharp
Department of Theoretical and Applied Mechanics
University of Illinois at Urbana–Champaign
Urbana, Illinois
E-mail: kvsharp@students.uiuc.edu

Professor William N. Sharpe, Jr.
Department of Mechanical Engineering
Johns Hopkins University
Baltimore, Maryland
E-mail: sharpe@jhu.edu

Professor Gregory L. Snider
Department of Electrical Engineering
University of Notre Dame
Notre Dame, Indiana
E-mail: gsnider@nd.edu

Professor Göran Stemme
Department of Signals, Sensors and Systems
Royal Institute of Technology
Stockholm, Sweden
E-mail: goran.stemme@s3.kth.se

Mr. Robert H. Stroud
The Aerospace Corporation
Chantilly, Virginia
E-mail: robertstroud@earthlink.net

Dr. William Trimmer
Standard MEMS, Inc.
Hillsborough, New Jersey
E-mail: william@trimmer.net

Professor Fan-Gang Tseng
Department of Engineering and System Science
National Tsing Hua University
Hsinchu, Taiwan
E-mail: fangang@ess.nthu.edu.tw

Dr. Stephen E. Vargo
SiWave, Inc.
Arcadia, California
E-mail: s.vargo@siwaveinc.com

Mr. Chester Wilson
Department of Electrical and Computer Engineering
University of Wisconsin–Madison
Madison, Wisconsin
E-mail: cgwilso1@students.wisc.edu

Dr. Keon-Young Yun
National Institute for Aviation Research
Wichita State University
Wichita, Kansas
E-mail: kyun@twsu.edu

Professor Yitshak Zohar
Department of Mechanical Engineering
Hong Kong University of Science and Technology
Kowloon, Hong Kong
E-mail: mezohar@ust.hk

Dr. Christian A. Zorman
Electrical Engineering and Computer Science Department
Case Western Reserve University
Cleveland, Ohio
E-mail: caz@po.cwru.edu

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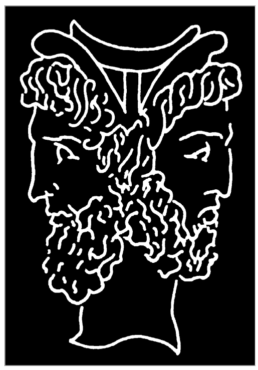
IV The Future

The farther backward you can look,
the farther forward you are likely to see.

(Sir Winston Leonard Spencer Churchill, 1874–1965)

Janus, Roman god of gates, doorways and all beginnings, gazing both forward and backward.



As for the future, your task is not to foresee, but to enable it.

(Antoine-Marie-Roger de Saint-Exupéry, 1900–1944,
in Citadelle [The Wisdom of the Sands])