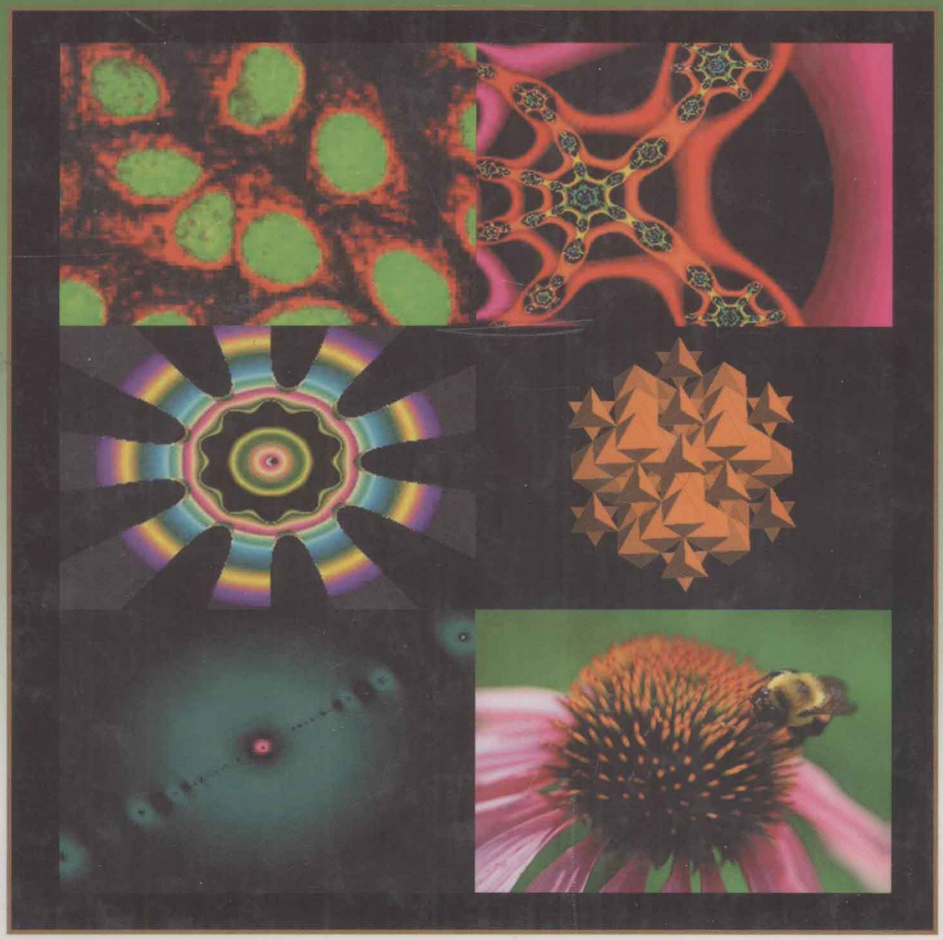
SECOND EDITION

Nano- and Micro-Electromechanical Systems

Fundamentals of Nano- and Microengineering



Sergey Edward Lyshevski

CRC PRESS

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Boca Raton London New York Washington, D.C.

Library of Congress Cataloging-in-Publication Data

Lyshevski, Sergey Edward.
Nano- and micro-electromechanical systems : fundamentals of nano- and microengineering / Sergey Edward Lyshevski.—2nd ed.
p. cm. — (Nano- and microscience, engineering, technology, and medicine series ; 8)
Includes bibliographical references and index.
ISBN 0-8493-2838-1 (alk. paper)
1. Microelectromechanical systems. 2. Nanotechnology. I. Title. II. Series.
TK7875.L96 2004
621.381—dc22 2004057931

International Standard Book Number 0-8493-2838-1
Library of Congress Card Number 2004057931
Printed in the United States of America 1 2 3 4 5 6 7 8 9 0
Printed on acid-free paper

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Fundamentals of Nano- and Microengineering

Nano- and Microscience, Engineering, Technology, and Medicine Series

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Sergey Edward Lyshevski

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Dedication

I dedicate this book to the memory of my beloved father Edward Lyshevski

(1929–2003) and the blessed memory of his family: Peter, Adel, Jadwiga, and Helena.

Preface

This book introduces nano- and microsystems, devices, and structures to a wide audience. The author coherently documents basic fundamentals of nano- and microengineering as well as nano- and microtechnology. Nanotechnology can be viewed as a revolutionary technology that is based on nanoscience that will redefine engineering, medicine, security, etc. For example, evolutionary and revolutionary changes in electronics, electromechanics, optics, informatics, computers, and communication have significant immediate positive impacts on aerospace, biotechnology, electronics, health, informatics, medicine, power, etc. Nanotechnology is viewed as the most significant technological frontier to be developed and utilized in this century. Those developments are positioned on the cornerstone of science and engineering.

Nano-everything has become the buzzword for many fantasists and romantic dreamers who have offered many futuristic and highly speculative viewpoints. Their shocking speculative declarations will unlikely be supported by science, engineering, and technology simply due to fundamental and technological limits. These pseudo nanotechnology futurists/analysts have been optimistically painting rosy pictures and have presented stratospheric imaginary representations that cannot be supported and will probably never materialize. It will be no wonder if soon they shift their attention to *femtotechnology* (1×10^{-15}) or maybe *yoctotechnology* (1×10^{-24}), or armed with string theory and the 10^{-35} domain, maybe even the *negative-thirty-five-power-technology* (there is no prefix for 1×10^{-35}). Fortunately, society has approached nano- and microtechnology from the science and engineering mindset, and promising results have been achieved. However, further focused fundamental, applied, and experimental research is needed to support far-reaching engineering and technological developments without shocking speculations.

The system-, device-, and structure-level basics, applied (hardware- and software-oriented), and experimental analyses are introduced to the reader with an attempt to lead him or her to the nano- and microscience and engineering inroads. With a complete awareness of the different readers' backgrounds and interests, the author understands the challenges. Correspondingly, the multidisciplinary fundamentals are introduced and coherently covered. This book, written for a two-semester senior undergraduate or graduate course in microelectromechanical systems (MEMS) and nanoengineering (including courses in nanotechnology and nanoelectronics), intends to overcome the challenges. A typical reader's background should include calculus and physics.

The purpose of this book is to bring together the various concepts, methods, techniques, and technologies needed to attack and solve a wide array of problems including synthesis, modeling, simulation, analysis, design, and optimization of high-performance nano- and electromechanical systems (NEMS), MEMS, devices, and structures. These NEMS and MEMS are the subclasses of nano- and microsystems, and, in general, the book focuses on nano- and microsystems. Microfabrication aspects and some nanoscale fabrication technologies are covered to assist the readers. The availability of advanced fabrication technologies has been the considerable motivation for further developments. The emphasis of this book is on the fundamental multidisciplinary principles of NEMS and MEMS and practical applications of the basic theory in engineering practice and technology development.

It is evident that due to a wide spectrum of problems and issues, one can have some reservations and suggestions that will be very valuable. Please, do not hesitate to provide

me with your feedback, and I will try to integrate the suggested topics and examples in the future. At the same time, it appears that it is impossible to cover all topics, areas, and technologies due to a wide spectrum of themes, the variety of unsolved problems, and some uncertainties regarding the applicability and affordability of emerging technologies particularly to fabricate nanosystems. This book is written in a textbook style, with the goal to reach the widest possible range of readers who have an interest in the subject. Specifically, the objective is to satisfy the existing growing demands of undergraduate and graduate students, engineers, professionals, researchers, and instructors in the fields of nano- and microengineering, science, and technologies. With these goals, the structure of the book was developed and significantly modified compared with the first edition.

Efforts were made to bring together fundamental (basic theory) and technology (fabrication) aspects in different areas that are important to study, understand, and research advanced nano- and microsystems in a unified and consistent manner. The author believes that the coherent coverage has been achieved. At the end of each chapter, the reader will find homework problems that will allow him or her to practice, apply, and assess the material.

Recent accelerating interest in nano- and microengineering and technologies is due to the 21st century nanotechnology revolution. This eventually will lead to fundamental breakthroughs in the way materials, devices, and systems are understood, utilized, designed, manufactured, and used. Nano- and microengineering will change or refine the nature of the majority of human-made structures, devices, and systems, revolutionizing or enhancing their performance and functionality. Current needs and trends include leading-edge fundamental, applied, and experimental research as well as technology developments. In particular, utilizing application-specific requirements, one needs to synthesize (discover), model, simulate, analyze, design, optimize, fabricate, and characterize nano- and microscale systems, devices, and structures. Recent developments have focused on analysis and design of molecular structures and devices that will lead to revolutionary breakthroughs in informatics, data processing, computing, data storage, imaging, intelligent automata, etc. Specifically, molecular computers, logic gates, switches, resonators, actuators, sensors, and circuits have been devised and studied. Nanoengineering and science lead to fundamental breakthroughs in the way devices and systems are devised, designed, and optimized. High-performance nano- and microscale structures and devices will be widely used in nanocomputers, medicine (nanosurgery, nanotherapy, nonrejectable artificial organs, drug delivery, and diagnosis), etc.

New nanomechanics phenomena, quantum physics and chemistry, novel nanofabrication technologies, control of complex molecular structures, and design of large-scale architectures and optimization, among other problems, must be addressed and examined. The major objective of this book is the development, coverage, and delivery of basic theory (through multidisciplinary fundamental and applied research and coherent studies) to achieve the highest degree of understanding regarding complex phenomena and effects, as well as development of novel paradigms and methods in optimization, analysis, and control of nano- and microsystem properties and behavior. This will lead to new advances and will allow the designer to comprehensively solve a number of long-standing problems in synthesis, analysis, control, modeling, simulation, virtual prototyping, fabrication, implementation, and commercialization of novel nano- and microsystems. In addition to technological developments, the ability to synthesize and optimize systems depends on analytical and numerical methods. Novel paradigms and concepts should be devised and applied to analyze and study complex phenomena and effects. Advanced interdisciplinary research must be carried out, and the objectives are to expand the frontiers of the nano- and microscale-based research through pioneering fundamental and applied multidisciplinary studies and developments.

This book develops and delivers the basic theoretical foundations in order to synthesize, design, analyze, and examine high-performance nano- and microsystems. In addition, the focus is centered on the development of fundamental theory for nano- and microsystems, as well as their components (subsystems and devices) and structures, using advanced multidisciplinary basic and applied developments. In particular, coherent synthesis and design are illustrated with analysis of the phenomena and effects at nano- and microscales, development of system architectures, physical representations, optimization, etc. It is the author's goal to substantially contribute to these basic issues, efficiently deliver the rigorous theory to the reader, and integrate the challenging problems in the context of well-defined applications addressing specific issues. The primary emphasis will be on the development of basic theory to attain fundamental understanding of nano- and microsystems, processes in nano- and microscale structures and devices, and devising novel devices, as well as the application of the developed theory.

It should be acknowledged that no matter how many times the material is reviewed and how many efforts are spent to guarantee the highest quality, the author cannot guarantee that the manuscript is free from minor errors and shortcomings. If you find something that you feel needs correction, adjustment, clarification, and/or modification, please notify me at Sergey.Lyshevski@rit.edu. Your help and assistance are greatly appreciated and sincerely acknowledged.

Author

Sergey Edward Lyshevski was born in Kiev, Ukraine. He received his M.S. (1980) and Ph.D. (1987) degrees from Kiev Polytechnic Institute, both in electrical engineering. From 1980 to 1993, Dr. Lyshevski held faculty positions at the Department of Electrical Engineering at Kiev Polytechnic Institute and the Academy of Sciences of Ukraine. From 1989 to 1993, he was the Microelectronic and Electromechanical Systems Division Head at the Academy of Sciences of Ukraine. From 1993 to 2002, he was with Purdue School of Engineering as an associate professor of electrical and computer engineering. In 2002, Dr. Lyshevski joined Rochester Institute of Technology as a professor of electrical engineering, professor of microsystems engineering, and Gleason Chair. Dr. Lyshevski serves as the Senior Faculty Fellow at the U.S. Surface and Undersea Naval Warfare Centers and Air Force Research Laboratories. He is the author of 11 books (including *Nano- and Microelectromechanical Systems: Fundamentals of Micro- and Nanoengineering*, CRC Press, 2000; and *MEMS and NEMS: Systems, Devices, and Structures*, CRC Press, 2002) and is the author or coauthor of more than 250 journal articles, handbook chapters, and regular conference papers. His current teaching and research activities include the areas of MEMS and NEMS (CAD, design, high-fidelity modeling, data-intensive analysis, heterogeneous simulation, fabrication), micro- and nanoengineering, intelligent large-scale microsystems, learning configurations, novel architectures, self-organization, micro- and nanoscale devices (e.g., actuators, sensors, logics, switches, memories), nanocomputers and their components, reconfigurable (adaptive) defect-tolerant computer architectures, and systems informatics. Dr. Lyshevski has made significant contributions in the design, application, verification, and implementation of advanced aerospace, automotive, electromechanical, and naval systems. He has made 29 invited presentations nationally and internationally and serves as editor of the CRC Press series *Nano- and Microscience, Engineering, Technology, and Medicine*. Dr. Lyshevski has taught undergraduate and graduate courses in NEMS, MEMS, microsystems, computer architecture, microelectromechanical motion devices, integrated circuits, and signals and systems.

Acknowledgments

Many people contributed to this book. First, thanks go to my beloved family. I would like to express my sincere acknowledgments and gratitude to many colleagues and peers. Special thanks to undergraduate and graduate students for whom I have taught courses in nanoscience and nanoengineering, nanotechnology, microsystems, MEMS, and microelectromechanical motion devices. It gives me great pleasure to acknowledge the help I received from many people in the preparation of this book. The outstanding CRC Press team, especially Nora Konopka (Acquisitions Editor, Electrical Engineering) and Regina Gregory (Project Editor), tremendously helped and assisted me by providing valuable and deeply treasured feedback. Many thanks to MathWorks, Inc., for supplying the MATLAB® environment (MathWorks, Inc., 24 Prime Park Way, Natick, MA 01760-1500, http://www.mathworks.com). Partial support of the NSF (NSF awards 0407281 and 0311588) is sincerely acknowledged. (Disclaimer. "Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.") The opportunities to perform the funded research for different agencies, laboratories, and companies under numerous grants and contracts have had a positive impact. Finally, I am sincerely acknowledging the Gleason professorship as well as assistance and encouragements I have received from the administration at the RIT Kate Gleason College of Engineering. Many thanks to all of you.

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Table of Contents