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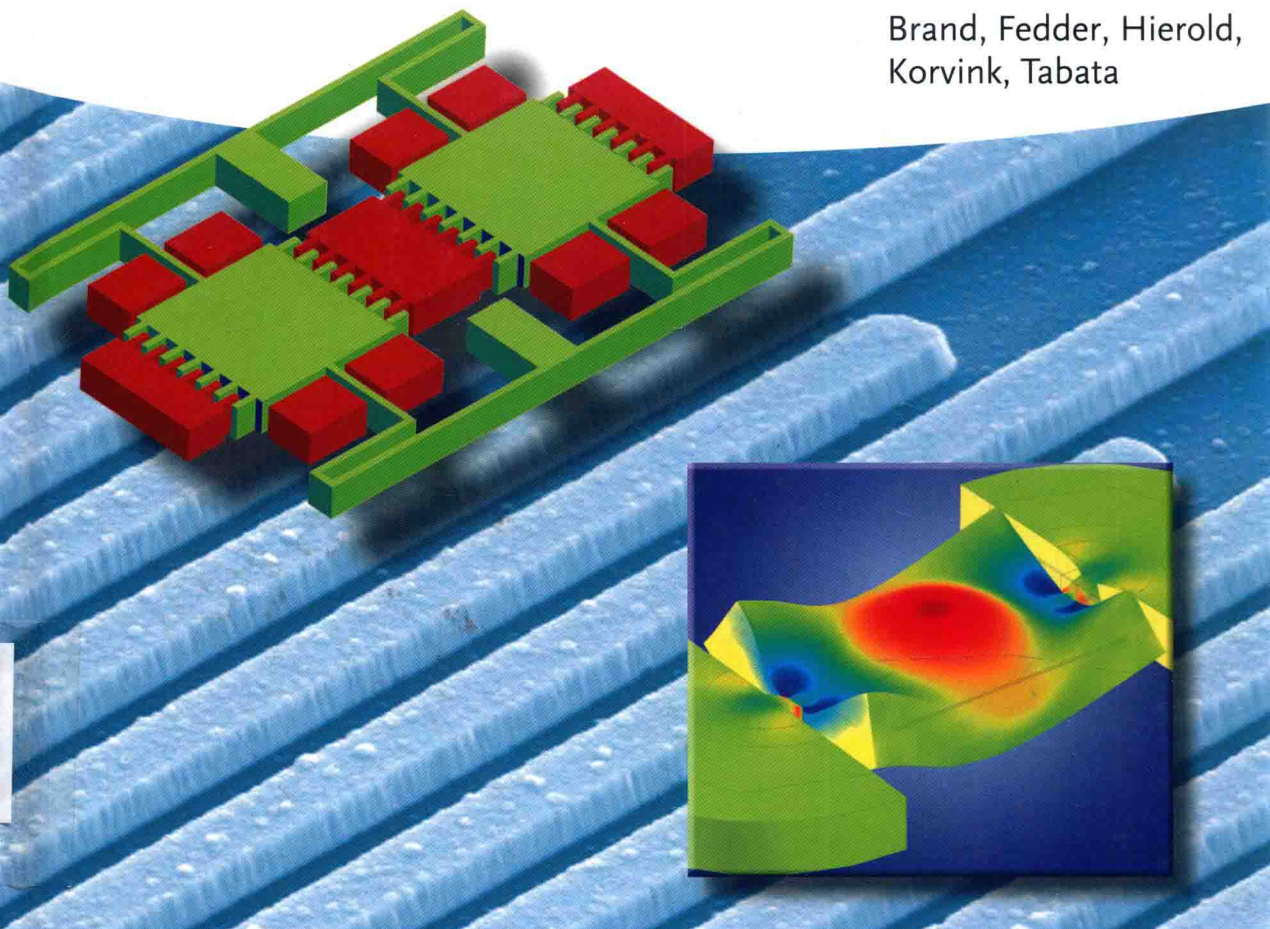
Resonant MEMS

Fundamentals, Implementation and Application

Series Editors:
Brand, Fedder, Hierold, Korvink, Tabata



ADVANCED MICRO & NANOSYSTEMS

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Edited by Oliver Brand, Isabelle Dufour, Stephen M. Heinrich, and Fabien Josse

Resonant MEMS

Fundamentals, Implementation and Application

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Series Editor Preface

You hold in your hands the eleventh volume of our book series *Advanced Micro & Nanosystems*, dedicated to the field of *Resonant MEMS*. We have been very fortunate to enlist Prof. Oliver Brand, Prof. Isabelle Dufour, Prof. Stephen Heinrich, and Prof. Fabien Josse as Volume Editors. All four have extensive expertise in different aspects of *Resonant MEMS* and, as a team, actually have collaborated in recent years, resulting in a number of joint research publications. In a similar way, this book project turned out to be a true team project, from establishing the desired table of contents; to selecting an international team of experts as chapter authors; to assembling, editing, and fine-tuning the contents.

You might ask, why a book on *Resonant MEMS*? Clearly, resonant devices fabricated using MEMS (MicroElectroMechanical Systems) technologies are not new; in fact, one of the early MEMS devices is the *Resonant Gate Transistor*, published by Harvey C. Nathanson and co-workers in the *IEEE Transactions on Electron Devices* in 1967. Over the years, a resonant sensor version of just about every sensor imaginable has been investigated. In general, *Resonant MEMS* (and in particular resonant sensors) promise very high sensitivities, but often come at the expense of a more complicated device design and fabrication. In recent years, modern numerical modeling tools, in particular finite element modeling (FEM) software, and a number of fundamental theoretical studies have helped design better *Resonant MEMS*, and, as a result, first commercial devices based on *Resonant MEMS* have been developed. The best example might be the success of MEMS-based resonant gyroscopes in consumer electronic devices, such as smart phones and gaming consoles. As the field matures, we found a book that summarizes all aspects of *Resonant MEMS*, ranging from the *Fundamentals* to *Implementation* and *Application*, to be very timely. You have the result in your hands, and we hope that you enjoy reading this book as much as we do.

This book would not have been possible without a significant time commitment by the volume editors as well as the chapter authors. We want to thank them most heartily for their effort! Our thanks also go to the Wiley staff for their

strong support of this project. The final printed result once again speaks for itself!

Atlanta, Pittsburgh,
Zurich, Freiburg,
Kyoto, January 2015

Oliver Brand, Gary K. Fedder,
Christofer Hierold, Jan G. Korvink,
Osamu Tabata, Series Editors

Preface

As the editing team for Vol. 11 of the *Advanced Micro & Nanosystems* series, entitled *Resonant MEMS: Fundamentals, Implementation and Application,* we hope that you benefit from this significant collaborative effort among the experts who have kindly contributed to this project. The book's *raison d'être* is to elucidate the various aspects of MEMS resonators, to identify the state of the art in this rapidly changing field, and to serve as a valuable reference tool to the readership, including serving as a springboard for future advances in this discipline.

Given the breadth of the resonant MEMS field, we have elected to group the various chapters of this volume into three parts as indicated by the book's subtitle. Part I, *Fundamentals*, comprises five chapters, each of which focuses on the theoretical description of the underlying physical phenomena that are relevant to virtually all resonant MEMS devices. This part includes detailed treatments on the fundamental theory of mechanical resonance; the effects of viscous fluids (a surrounding gas or liquid) on vibrating microcantilevers; a broad-based examination of various sources of damping (energy dissipation mechanisms); resonant response caused by parametric excitation, i.e., variations in resonator properties as opposed to direct (e.g., force) excitation; and an overview of the fundamentals of the finite element method with specific applications to MEMS resonators. Having laid the fundamental groundwork in Part I, the eight chapters of Part II, *Implementation,* examine how the fundamentals are applied in a practical setting to yield specific types of resonant MEMS devices and how these devices are designed to reliably perform a specific function. In particular, this group of chapters includes detailed discussions of resonant MEMS devices on the basis of the following materials and device designs: capacitive transducers, piezoelectric materials, nanoelectromechanical systems (NEMS), and organic materials (polymers). Also included in Part II are chapters treating the following practical implementation topics: electrothermal excitation methods; the use of embedded channels to overcome challenges posed by liquid-phase applications; hermetic packaging to protect the resonator and to ensure its long-term stability and reliability; and the development of compensation, tuning, and trimming techniques for the realization of high-precision resonators by accounting for variations in material properties, fabrication processes, and environmental operating conditions. Finally, in Part III, *Application*, we have included chapters that are dedicated to particular functionalities. Part III comprises four chapters on resonant MEMS for sensing applications, including the following: inertial sensing (motion detection); chemical detection in both gaseous and liquid environments; biochemical sensing for label-free, quantitative measurement of biomolecules such as proteins and nucleic acids, or even entire cells and viruses; and resonant MEMS-based rheometers for measuring the physical properties of fluids. The final chapter of Part III focuses on energy harvesting applications for converting ambient mechanical vibrations into useful electrical energy.

Finally, we would like to extend a sincere expression of gratitude to all of the chapter authors and their associated institutions, to the editorial staff at Wiley-VCH, especially Martin Preuss and Martin Graf-Utzmann, and to Sangeetha Suresh and the production staff at Laserwords. Without the tireless efforts of all of these people, this book would not have been possible. Also, all four co-editors gratefully acknowledge the financial support of *CNRS* (*France, Projet PICS*, 2012–2014) for the international collaboration required to plan and realize this volume, while three of the co-editors (Brand, Heinrich, Josse) gratefully acknowledge research funding from the National Science Foundation (U.S.) over the period 2008–present. The support provided by both of these funding agencies was instrumental in bringing this book to fruition.

Atlanta, Pessac,
Milwaukee, January 2015

Oliver Brand
Isabelle Dufour
Stephen M. Heinrich
Fabien Josse

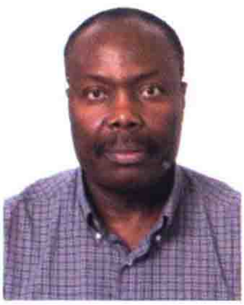
Co-Editors

About the Volume Editors

Oliver Brand, PhD Oliver Brand received his diploma degree in Physics from Technical University Karlsruhe, Germany, in 1990 and his PhD degree from ETH Zurich, Switzerland, in 1994. From 1995 to 1997, he worked as a postdoctoral fellow at Georgia Tech. From 1997 to 2002, he was a lecturer at ETH Zurich and deputy director of the Physical Electronics Laboratory. In 2003, he joined the Electrical and Computer Engineering faculty at the Georgia Institute of Technology where he is currently a Professor. Since 2014, he serves as the Executive Director of Georgia Tech's Institute for Electronics and Nanotechnology. He has co-authored more than 190 publications in scientific journals and conference proceedings. He is a co-editor of the Wiley-VCH book series *Advanced Micro & Nanosystems*, a member of the editorial board of Sensors and Materials, and has served as General Co-Chair of the 2008 IEEE International Conference on Micro Electro Mechanical Systems (MEMS 2008). Dr. Brand is a senior member of the IEEE and a co-recipient of the 2005 IEEE Donald G. Fink Prize Paper Award. His research interests are in the areas of silicon-based microsystems, microsensors, MEMS fabrication technologies, and microsystem packaging.

Isabelle Dufour, PhD Isabelle Dufour graduated from Ecole Normale Supérieure de Cachan in 1990 and received her PhD and HDR degrees in engineering science from the University of Paris-Sud, Orsay, France, in 1993 and 2000, respectively. She was a CNRS research fellow from 1994 to 2007, first in Cachan working on the modeling of electrostatic actuators (micromotors, micropumps) and then after 2000 in Bordeaux working on microcantilever-based chemical sensors. She is currently a Professor of electrical engineering at the University of Bordeaux, and her research interests are in the areas of microcantilever-based sensors for chemical detection, rheological measurements, material characterization, and energy harvesting.

Stephen M. Heinrich, PhD Stephen M. Heinrich earned the BS degree *summa cum laude* from Penn State in 1980 and the MS and PhD degrees from the University of Illinois at Urbana-Champaign in 1982 and 1985, all in civil engineering. Hired as an Assistant Professor at Marquette University in 1985, he was promoted to his current rank of Professor in 1998. In 2000, Prof. Heinrich was awarded the *Rev. John P. Raynor Faculty Award for Teaching Excellence,* Marquette's highest teaching honor, while in 2006 he was a awarded a Fulbright Research Scholar Award to support research collaboration at the *Université de Bordeaux*. Dr. Heinrich's research has focused on structural mechanics applications in microelectronics packaging and analytical modeling of cantilever-based chemical/biosensors and, more recently, MEMS energy harvesters. The investigations performed by Dr. Heinrich and his colleagues have resulted in more than 100 refereed publications and three best paper awards from IEEE and ASME. His professional service activities include membership on the ASCE Elasticity Committee, Associate Editor positions for the *IEEE Transactions on Advanced Packaging* and the *ASME Journal of Electronic Packaging*, and technical review activities for more than 40 journals, publishers, and funding agencies.



Fabien Josse, PhD Fabien Josse received the MS and PhD degrees in Electrical Engineering from the University of Maine in 1979 and 1982, respectively. He has been with Marquette University, Milwaukee, WI, since 1982 and is currently Professor of Electrical, Computer and Biomedical Engineering. He is also an Adjunct Professor with the Department of Electrical Engineering, Laboratory for Surface Science and Technology, University of Maine. He has been a Visiting Professor with the University of Heidelberg, Germany, the Laboratoire IMS, University of Bordeaux, France, and the Physical Electronics Laboratory, ETH Zurich, Switzerland, and IMTEK, University of Freiburg, Germany. His research interests include solid state sensors, acoustic wave sensors, and MEMS devices for liquid-phase biochemical sensor applications, investigation of novel sensor platforms, and smart sensor systems. Prof. Josse is a senior member of IEEE and associate editor (2002–2009) of the *IEEE Sensors Journal*.

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