A Guide to Hands-on MEMS Design and Prototyping

Whether you are a student taking an introductory MEMS course or a practicing engineer who needs to get up-to-speed quickly on MEMS design, this practical guide provides the hands-on experience needed to design, fabricate, and test MEMS devices. You'll learn how to use foundry multiproject fabrication processes for low-cost MEMS projects, as well as computer-aided design tools (layout, modeling) that can be used for the design of MEMS devices. Numerous design examples are described and analyzed, from fields including micromechanics, electrostatics, optical MEMS, thermal MEMS, and fluidic MEMS. There is also a chapter on packaging and testing MEMS devices, as well as exercises and design challenges at the end of every chapter. Solutions to the design challenge problems are provided online.

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Preface

The idea for this book came from a textbook I used in graduate school at Cornell University titled *Introduction to VLSI Systems*, by Carver Mead and Lynn Conway. That textbook, in combination with the MOS Implementation System (MOSIS) Service for integrated circuit prototyping and small volume production, enabled a "hands-on" learning experience that was instrumental in training a new generation of practitioners in very large scale integrated (VLSI) circuit design, layout, and prototyping. This approach democratized VLSI chip design and fabrication by reducing the cost of VLSI circuit prototyping and shortened the turnaround time from years to months, enabling students to design, lay out, and submit chips for fabrication in engineering classes. By providing generic design rules the students did not have to worry about the details for the specific fabrication process. By aggregating small projects into multiproject chips (MPCs) and MPCs into multichip wafers (MCWs), the fabrication cost was decreased by orders of magnitude.

In order to train a new generation of practitioners in MEMS design and prototyping, it is important for students to get a similar hands-on experience. However, hands-on courses on the design, prototyping, and testing of microelectromechanical systems (MEMS) has largely been restricted to universities with cleanroom facilities for semiconductor fabrication. The number of universities with a cleanroom is limited and cleanrooms are expensive to maintain. In addition, they provide too much design freedom that can promulgate the mindset of needing a new MEMS fabrication process for each new MEMS device.

The goal of this text is to guide the student through a MEMS design experience using state-of-the-art computer-aided design tools for layout and modeling, and to submit the design for fabrication in a robust, standard multiproject wafer fabrication process. Many of these processes

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have mature design rules that enable the separation of design and fabrication challenges. If the rules are followed, the students will get what they have designed. While the use of a standard process leads to limitations in the devices that can be fabricated, since the layers and layer thicknesses are set by the standard process, this approach has been used successfully for the development of a number of commercially successful MEMS devices, some of which are described in the text. By using a robust standard multiproject wafer fabrication process, a working prototype device can be fabricated quickly at low cost. The book also analyzes some standard MEMS designs such as the mechanical test (M-Test) structures that were developed by Professor Stephen Senturia's group at MIT. The M-Test structures are straightforward to design and lay out and provide simple MEMS structures for post-fabrication evaluation and testing that do not require specialized metrology equipment. By simply measuring the pull-in voltages of these structures, which can be done with just a probe station and a high-voltage power supply, validation of the design can be obtained and fundamental information about the prototyping process can be extracted.

The book includes a number of examples from student projects in undergraduate (EE115) and graduate (EE215) MEMS design courses that I have taught in the Department of Electrical Engineering at the University of California Santa Cruz. In the quarter-long course the students learn about microelectromechanical systems in various application domains (mechanics, electrostatics, optical, thermal, and fluidic) and then propose a design of their own to meet a set of specifications that they are provided with. They then design their own part and use modeling and simulation to test their designs. Finally, they lay out their designs using state-of-the-art tools and submit them for fabrication on a class multiproject chip that is then aggregated into a multichip wafer for fabrication using a standard process. I encourage all students using standard multiproject wafer fabrication processes to submit reports on their projects for publication in future editions of this book.

The book ends with a case study of a commercial MEMS device, a deformable mirror for applications in adaptive optics, first prototyped using the PolyMUMPS process, that eventually went on to become a product offered by Boston Micromachines Corporation. This case study demonstrates that there is a "path-to-the-sea" from MEMS prototyping in a standard multiproject wafer fabrication process to commercialization of a robust MEMS product. Once the prototype was designed, fabricated, and tested using a multiproject wafer fabrication process, PolyMUMPS,

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the standard process was modified as required to meet the particular product specifications. Future editions will include additional case studies of MEMS products that are developed from prototypes fabricated in standard multiproject wafer processes.

In memory of ERK, LJK and LSK, and in appreciation of RSNK-A, who took the brave steps to avoid the fate of the genetic hand she was dealt.

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