4 System-Level Simulation of Microsystems

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4.1 Introduction

Microelectromechanical systems require a multidisciplinary approach to design, including knowledge of fabrication technology, mechanics, electromechanics, and electronics. In the majority of cases, good MEMS design requires the evaluation of tradeoffs among the fabrication process, micromechanical topology, and sizing. Sensor interface circuits, signal conditioning, and feedback provide additional interactions that affect design choices. This chapter provides an introductory overview to the system-level simulation of microsystems in support of the design effort. Discussion is devoted to microelectromechanical structures with electronics. However, the general methods outlined here have equal applicability in other microsystems, such as microfluidic and micro-optical systems.

Batch fabrication prevalent in MEMS provides the manufacturing capability to make very complex systems with multiple interconnected MEM devices. System complexity for MEMS is measured by both the number of interacting devices and the number of interacting physical domains. For example, a typical surface-micromachined capacitive microaccelerometer incorporates about 5 to 100 devices, depending on the specified granularity of the system partitioning. These elements have mechanical, electrical, thermal, electrostatic, and fluidic interactions. This combined complexity presents a possible design bottleneck that is best handled using structured design techniques, where models are built hierarchically by interconnecting smaller components. At their lowest level, the components are described by behavioral models, equations that directly describe physical behavior. Structured design was successfully introduced to the digital IC design world in the 1980s.\(^1\) Analog electronic circuit design has borrowed these concepts to handle complex analog designs. In 1995, the U.S. National Science Foundation sponsored a seminal workshop to discuss the application of structured design to MEMS.\(^2\) Most of this chapter addresses issues identified at that workshop.
Design is an iterative process where no exact sequence of steps is always followed. Nevertheless, some structure can be imposed on the design process. Any design procedure must start with identifying the function and metrics required or desired by the system. The performance must then be quantified into a set of specifications. How the specifications are met is the purpose of design. For the case of MEMS design, the effort can be partitioned into three general areas: process design, device design, and system design. Successful design efforts may require a combination of innovation in all three areas, or may simply require merging of existing technology from the three areas. Some brief comments about process and device design follow; details on these topics are found in other chapters of this book.

Process design is the combining of individual process steps to form a realizable process flow. The choice of process flow is critical to MEMS performance. A working knowledge is required of material properties and interactions with other materials, fabrication steps and equipment, and photolithographic limitations. New process flows are designed for a variety of reasons, which include:

- Fabricating micromechanical devices of the required dimensions (nm, μm, or mm size)
- Forming devices with materials that have special sensing or actuation properties
- Providing isolated electrical interconnections for microstructures
- Merging micromechanics with electronic circuitry
- Increasing manufacturing yield and reducing cost

These goals are often at odds with each other. Each step in the process flow must be compatible with succeeding steps, accounting for limits to microfabrication capabilities. Microstructural patterning is limited by photolithography over widely varying surface topographies. Deposited thin-film materials must adhere to the underlying surface and not diffuse with time. The temperatures of process steps must not affect materials from prior steps. Etching steps have limits of critical dimensions in both the lateral and vertical dimensions. Material combinations must be chosen with appropriate etch selectivities. The etch steps must avoid undesired side effects such as sidewall deposition. New materials and processes continue to push these limitations.

Device design is the positioning and sizing of functional materials to achieve a given performance. If the fabrication processes can be varied, then device and process design for MEMS are usually closely linked. However, at some point in development, the process flow becomes fixed and constrains the device design space. The necessary base knowledge for MEMS device design includes mechanics of materials, circuit theory, electrostatic