OVERVIEW OF MICROELECTROMECHANICAL SYSTEMS AND DESIGN PROCESSES

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ABSTRACT

New design tools and automation strategies are needed to create robust, cost-effective, and manufacturable micromachined devices and systems. Some of the design automation issues include mixed-technology simulation, material property prediction in the micron-size regime, self-consistency in coupled electromechanical devices, integrated modeling environment, micro-fluid modeling, and synthesis of device geometries and process flows. Advancement in these areas will path the way to full-scale maturity of the MEMS field.

INTRODUCTION

Since the invention of integrated circuits, batch fabrication techniques developed for the microelectronic industry have been used to create micromechanical structures on silicon substrates. A few early examples include the resonant gate transistor [1], silicon diaphragms for pressure sensing [2], and accelerometers [3]. In recent years, the use of planar technologies to develop commercial MEMS devices has become more and more sophisticated, fueled by the escalating demands for microsensors and microactuators with improved performance-to-cost ratio, better reliability, and new functionality over conventional counterparts. High-volume commercial markets based on MEMS technology include the automotive airbag accelerometers [4], pressure sensors [5], and thermal ink-jet printheads [6]. In addition, there are a number of emerging research areas that take advantage of the new functionality enabled by MEMS. A few examples include the study of fluid dynamics in the micron-size regime [7], tribology [8], miniaturized chemical analysis systems [9], and biomedical research [10].

Without exception, the development processes for these microfabricated devices benefited from the use of computer modeling and simulation. In particular, the high-volume commercial devices critically relied on robust modeling to reduce development cycle time. Fortunately, most of the design tools developed for conventional mechanical engineering can be utilized to assist in the mechanical design aspects of MEMS devices. However, micromachining process modeling, among others, is still largely lacking. Therefore, a major portion of the design cycle may still include time-consuming experimental determinations of design space and process improvement to ensure manufacturing robustness. It is estimated that between five to ten years were required to bring these products from the design phase to full-scale production. Further expansion of the MEMS market into more sophisticated and integrated systems would require even longer development cycles, which would jeopardize both the time-to-market competitiveness and development cost of the products. Therefore, new design tools and automation strategies are needed in order to provide robust, cost-effective, fast turn-around, and manufacturable MEMS products for the future. In particular, the characteristics and performance of various fabrication techniques must be simulated together with material property prediction. The electromechanical coupling in certain MEMS devices demands a self-consistent modeling tool. Micro-fluidic devices may require modeling of high-viscous flows and low-pressure damping. Finally, the ability to synthesize process flows and device geometries from function definition will represent the ultimate design automation of micromechanical systems.

MEMS TECHNOLOGIES

The most common fabrication techniques for microelectromechanical systems include three distinct categories: bulk micromachining, surface micromachining, and high-aspect-ratio lithography and plating (LIGA, a German acronym, is commonly used to refer to this technique) [11]. The first two are sometimes mixed to create microstructures with specific functions. Integrated on-chip electronics have also been demonstrated for signal conditioning. Figure 1 outlines the steps of a typical bulk micromachining process, in which anisotropic wet chemical etching is used to create structures from the silicon substrate. Surface micromachining steps are illustrated in Fig. 2, where thin films are sequentially deposited and patterned on top of the substrate, with the final removal of the sacrificial layer to release the movable structures. The LIGA technique, in its most generic form, involves X-ray lithography of thick photoresist on conductive substrate, plating through the developed resist, and injection molding with the plated parts (Fig. 3). These three techniques are compared and summarized in Table I.

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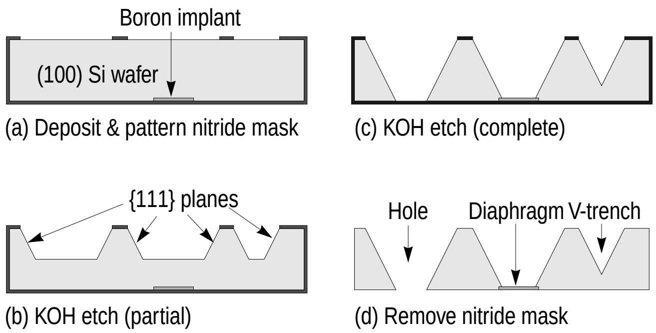

Figure 1. Bulk micromachining.

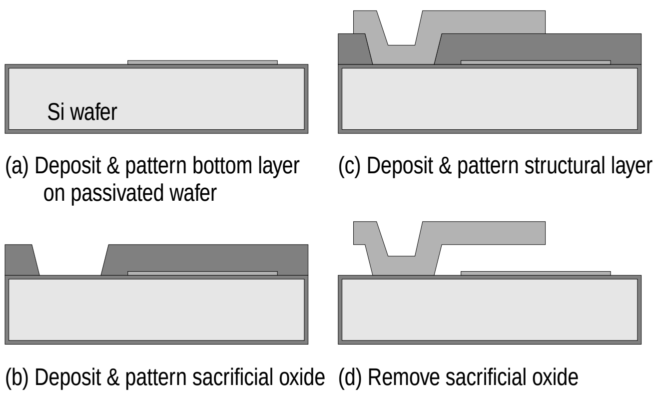

Figure 2. Surface micromachining.

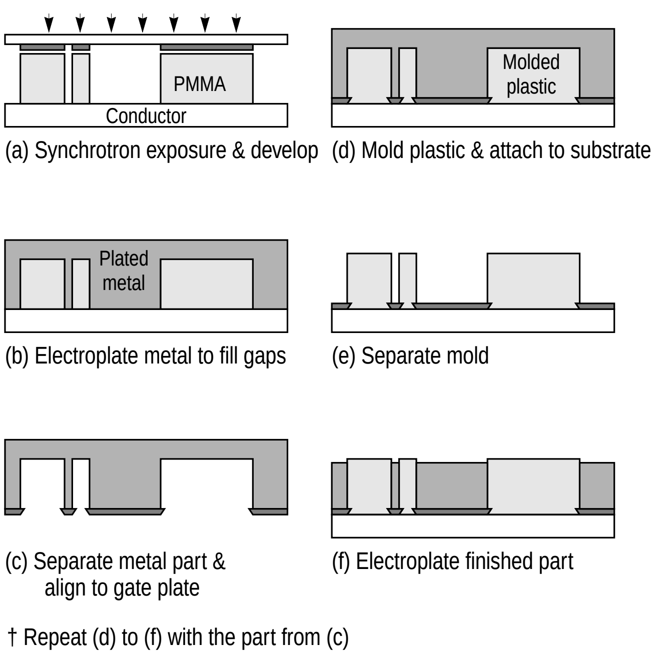

Figure 3. The LIGA process.

Table I. MEMS Technology Comparison

Capability	Bulk	Surface	LIGA
Maximum structural thickness	wafer(s) thickness	5 µm	500 µm
Planar geometry	rectangular	unrestricted	unrestricted
Minimum planar feature size	$\sqrt{2} \times$ depth	1 µm	3 µm
Side wall features	54.74° slope	limited by dry etch	0.2 µm runout over 400 µm
Surface and edge definitions	excellent	mostly adequate	very good
Material properties	very well controlled	mostly adequate	well controlled
Integration with electronics	possible	demonstrated	difficult
Capital investment & costs	low	moderate	high
Published knowledge	very high	high	moderate

DEVELOPMENT CYCLES

Empirical Approach

Without the aid of computer simulation, a typical development path for a MEMS device is illustrated in Fig. 4a. Design of experiment is usually used to maximize the efficiency of each iteration cycle. However, each cycle may take from a few months to over a year, depending on the complexity of the process, equipment setup time, and the extend of functional test. If the fabrication sequence can be modularized, then each process module will first be studied to collect empirical data on the module characteristics, variability, and controllable parameters. Then the complete fabrication sequence is iterated at least a few times to verify prototype functionality. Finally, more iterations are performed to optimize the manufacturing robustness and to minimize manufacturing cost.

Before the device design is finalized, packaging issues must be considered, which can critically influence not only the device characteristics but also the final cost of the product. In addition, signal conditioning and/or control circuits also play an important role in influencing device design. Therefore, device design, packaging, and circuits should be optimized simultaneously both for performance and for cost.

Simulation and Modeling Approach

Figure 4b illustrates how computer simulation can be used to minimize costly fabrication and testing iterations.

The two categories are process simulation and function modeling.

Process simulation

A robust process simulator should be able to accommodate different variations of the fabrication sequence as well as the variety of materials used in the fabrication processes, As a result, a fairly accurate 3-dimensional representation of the resulting device geometry and material property prediction may be used to take the place of many fabrication iterations. Ideally, with a robust process model at hand, only one prototype run is needed for fabrication verification.

The majority of bulk-micromachining processes involves some form of isotropic or anisotropic etching of single-crystalline silicon, gallium arsenide, or amorphous glass, Wafer bonding between silicon-silicon [12], silicon-glass [13], glass-glass, and bonding with intermediate glue layers are often performed to enhance design freedom. It is extremely desirable to model the etching characteristics of various anisotropic alkaline and isotropic acidic etchants on single-crystalline silicon, as well as bonding characteristics between wafers. The ability to model the formation of silicon convex corners with KOH etching, for example, will help in designing corner compensation [14]. Accurate modeling of post-bond stress between wafers will help identify the best bonding approach for certain device design.

Surface micromachined devices, on the other hand, are built from thin film materials such as polycrystalline or amorphous silicon, silicon nitride, silicon dioxide, and various metal thin films [11]. An ideal process simulator will take various thin film deposition parameters as inputs and generate relevant thin film characteristics, such as deposition rate, film morphology, built-in stress, Young's modulus, electrical and thermal conductivities, dielectric constant, refractive index, etc. When wet processing such as post-release rinsing is needed in the fabrication sequence of a suspended structure, a common failure mechanism may occur, which causes the released structures to be pinned to the substrate after the drying process [15]. A robust model on the drying and pinning mechanisms will assist in identifying solutions to permanently eliminate the problem.

High-aspect-ratio lithographed and plated structures require modeling polyimide's response to X-ray radiation, development of the exposed material, the plating process of metal structures, and the plastic molding process. The properties of these structural materials, including the chemistry, built-in stress, the morphology, and the processing histories, can significantly influence the accuracy of the models.

Function Modeling

Microfabricated sensors function by converting one or several physical or chemical conditions into electrical or optical signals, while most actuators perform the inverse functions. For example, pressure sensors translate change in pressure into output voltage or current, and micropumps convert supplied voltage or current into pressure. The modeling of these devices involve electrostatic, electromagnetic, ferroelectric, and piezoelectric phenomena, to name a few. These characteristics are often coupled with static or dynamic mechanical deformation of the microstructures. Therefore, a self-consistent modeling tool is needed to represent the transfer behaviors of these devices [16].

Micropumps and microvalves, in particular, present an important challenge to design automation. In addition to the above mentioned requirements, both compressible and non-compressible fluid dynamic modeling in the micron-size regime are needed. Compressible fluid in that regime may no longer be considered continuum flow. Therefore, simulation algorithms for viscous flow and/or low-pressure damping are needed to assist the design of these devices [7]. Lastly, package modeling and circuit simulation can be used to predict their influence on device performance.

Optimization and Synthesis Approach

The complexity of future MEMS products will become prohibitive unless the current practice of manually assembling geometries on the mask layouts are automated. It will involve the development of some levels of automatic geometry synthesis and optimization, as illustrated in Fig. 4c. These synthesis and optimization programs will contain a substantial database of material properties, process capabilities and constraints, design rules of various technologies, and functional attributes of generic components. With the advent of mixed technology circuits integrated with surface micromachined devices, simulation and synthesis of the integrated MEMS are especially important. Currently, only preliminary work has been done in assembling these programs, which are limited by the available database and design rules [17]. The results of the synthesized geometry and layout can be verified with function simulation and process modeling. Very sophisticated "self-taught" or "learning" programs will be needed in the future to truly generate a computer-optimized MEMS device.

CONCLUSION

After several decades of development, the MEMS field continues to grow at an exponential pace, driven by both high-volume commercial markets and innovative research areas enabled by new functions made possible by MEMS technology. Bulk micromachining, surface micromachining, and LIGA represent the three categories of MEMS technology. The development process of most high-volume MEMS devices, hampered by the lack of systematic design automation and relying on costly prototype iterations, currently takes five to ten years. At least some forms of modeling and simulation for both the process and the function will help the experienced MEMS designers reduce the development cycle time and cost. Ultimately, certain level of computer synthesis and optimization will be needed when the complexity and sophistication of MEMS systems become too large to be tackled even by experienced designers in a cost- and time-effective manner.

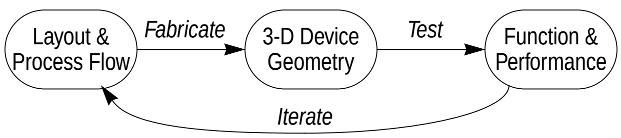

Figure 4a. Empirical approach of MEMS design cycle

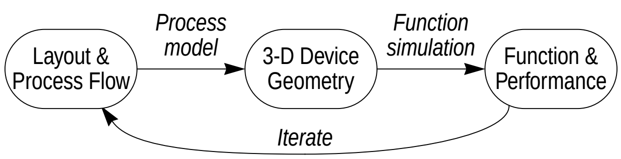

Figure 4b. Model & simulation approach of MEMS design cycle

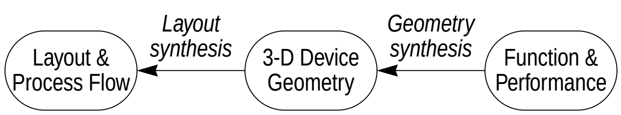

Figure 4c. Synthesis & optimization approach

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