Sandia Agile MEMS Prototyping, Layout Tools, Education and Services Program

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ABSTRACT

Research and development in the design and manufacture of Microelectromechanical Systems (MEMS) is growing at an enormous rate. Advances in MEMS design tools and fabrication processes at Sandia National Laboratories' Microelectronics Development Laboratory (MDL) have broadened the scope of MEMS applications that can be designed and manufactured for both military and commercial use. As improvements in micromachining fabrication technologies continue to be made, MEMS designs can become more complex, thus opening the door to an even broader set of MEMS applications. In an effort to further research and development in MEMS design, fabrication, and application, Sandia National Laboratories has launched the Sandia Agile MEMS Prototyping, Layout Tools, Education and Services Program or SAMPLES program.

The SAMPLES program offers potential partners interested in MEMS the opportunity to prototype an idea and produce hardware that can be used to sell a concept. The SAMPLES program provides education and training on Sandia's design tools, analysis tools and fabrication process. New designers can participate in the SAMPLES program and design MEMS devices using Sandia's design and analysis tools. As part of the SAMPLES program, participants' designs are fabricated using Sandia's 4-level polycrystalline silicon surface micromachine technology fabrication process known as SUMMiT (Sandia Ultra-planar, Multi-level MEMS Technology). Furthermore, SAMPLES participants can also opt to obtain state-of-the-art, post-fabrication services provided at Sandia such as release, packaging, reliability characterization, and failure analysis.

This paper discusses the components of the SAMPLES program including an overview of the education and training available through the program, brief discussions on the design and analysis tools in use at Sandia, an overview of the SUMMiT fabrication process, examples of designs fabricated using the SUMMiT process, an overview of post–fabrication services available at Sandia, and information on how to become a participant in the SAMPLES program.

KEYWORDS

Microelectromechanical Systems (MEMS); Silicon Micromachining; Surface Micromachining; Chemical-Mechanical Polishing (CMP)

1. Introduction

Sandia National Laboratories' MDL has established itself as a world leader in the development and application of surface micromachining technology. Not only has Sandia developed 4 and 5 level surface micromachining technologies, but Sandia has also developed the technology to monolithically integrate micromachines with control electronics on the same chip. [1][2][3] Numerous successful microelectromechanical designs have been developed and fabricated at Sandia. These include microengines, transmission systems, sensors, thermal actuators, positionable optics and micro-locking systems. In an effort to leverage Sandia's success and advance research and development in MEMS design, fabrication, and application, Sandia has launched the Sandia Agile MEMS Prototyping, Layout Tools, Education and Services Program or SAMPLES program. The SAMPLES program provides a means for MEMS designers to utilize Sandia's state-of-the-art 4-level polysilicon surface micromachining technology to prototype new designs. The SAMPLES program is comprised of four basic areas: (1) Education and Training, (2) Design Tools and Rules, (3) Agile Prototyping using the 4-level SUMMiT process, and (4) Post-Fabrication Services available at Sandia.

The following sections provide an overview of each aspect of the SAMPLES program including, education and training on design rules and tools, the 4-level surface micromachining fabrication technology, design examples and participation information.

2. Education and Training

In order to design MEMS for fabrication in the SUMMiT process, it is critical that designers gain an understanding of the intricacies of the SUMMiT fabrication process. Due to the complexity of the process that results from the ability to design using four independent layers of polysilicon, Sandia has implemented two short courses to provide education on the SUMMiT process as well as introduce designers to the MEMS design tools and rules necessary to design for the SUMMiT process. The first course, or Introductory Course, provides an overview of MEMS designs and applications developed and/or fabricated at Sandia, discusses the SUMMiT process, and introduces designers to the design and analysis tools used at Sandia. The second, or Advanced Course, focuses on design by providing further information on the intricacies of designing for the SUMMiT process as well as hands-on training using the design and analysis tools developed at Sandia.

3. Design Tools and Rules for the SUMMiT Process

As part of the SAMPLES program, Sandia has implemented several tools to aid designers in creating designs that can successfully be fabricated using the SUMMiT process. Sandia uses AutoCAD Revision 14 as the primary design layout tool. Designs up to a 4660 X 4660 micron square may be created. This square "module" is defined as an AutoCAD prototype file by Sandia and is the starting point of all SUMMiT designs. Designers begin with the template and can develop their designs from scratch or can make use of a Standard Components Library. The Standard Components Library is a library of basic components used frequently in the design of MEMS. The Standard Components also serve the function of a teaching aid, allowing designers to learn design methods from example devices. The Standard Component Library contains designs for actuators, microengines, gears and transmissions. All designs in the Standard Components Library have a proven history of successful fabrication and operation with Sandia designs.

To further aid the development of successful designs, Sandia has developed a Design Rule Checker. The Design Rule Checker is a tool used to check designs for errors that can result in problems during fabrication such as unanchored polysilicon devices and improperly defined features outside of photolithographic limits. SAMPLES participants are introduced to the tools through the courses described in Section 2. The prototype file is readily available to program participants. Remote Design Rule Checking is also available to program participants. However, due to the nature of the information contained in the Standard Components Library, the Standard Components Library must be purchased. Furthermore, licensing agreements are required to purchase the Standard Components Library. As part of SAMPLES training, a compact disc containing information and examples of the tools used for the SUMMiT process is provided to participants. A second, more detailed compact disc containing the template, Design Rule Checker and the Standard Components Library has been developed and is currently being tested with the University of California-Berkley and Bosch. The released version of the detailed compact disc should be available for purchase by participants by October 1998.

4. Agile Prototyping Using the 4-level SUMMiT Process

SAMPLES designs that successfully pass the Design Rule Checker can be submitted to Sandia for fabrication using the 4-level polysilicon surface micromachining fabrication process known as the SUMMiT process (Sandia Ultra-planar, Multi-level MEMS Technology). This section will describe the SUMMiT process. For ease in explanation, the Wedge Stepper Motor (Figure 1), designed at Sandia National Laboratories, will be used as an example.

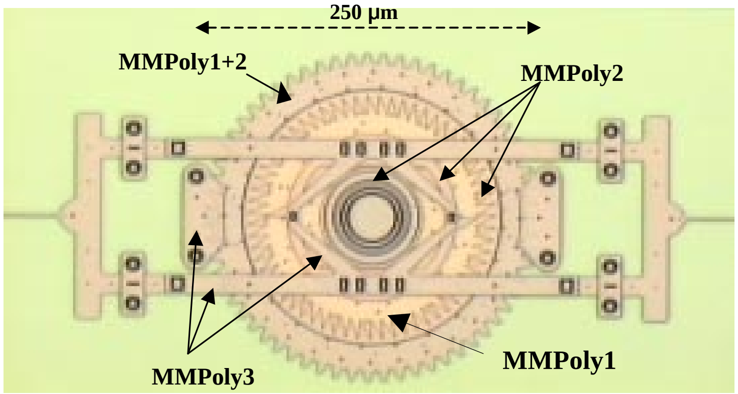


Figure 1. The Micromachine Wedge Stepper Motor designed by James Allen of Sandia National Laboratories and fabricated using the SUMMiT process.

The SUMMiT fabrication process begins with a bare n-type, <100> silicon wafer. A 0.63 µm layer of silicon dioxide (SiO_2) is thermally grown on the top of the bare wafer. This layer of oxide acts as an electrical insulator between the single-crystal silicon substrate and the first polycrystalline silicon layer (MMPoly0). A 0.8 µm thick layer of low-stress silicon nitride (SiN_x) is deposited on top of the oxide layer. The nitride layer acts as an etch stop protecting the underlying oxide from wet etchants during processing. A 0.3 µm thick layer of doped polycrystalline silicon (Si) known as MMPoly0 is deposited on top of the nitride layer. MMPoly0 is not a structural layer, but it is usually patterned and is used as a mechanical anchor, electrical ground, or electrical wiring layer. Following MMPoly0 deposition, the first sacrificial layer of oxide (SacOx1) is deposited. Tetraethylorthosilicate or TEOS is the material used for all sacrificial oxide layers. SacOx1 is 2 µm thick. Upon deposition of SacOx1, dimples are patterned and etched into the oxide. The dimples (primarily used prevent stiction between MMPoly0 layer and the MMPoly1 structure) are formed from MMPoly1 (the next polysilicon deposition). The dimple depth is approximately 1.5 µm. Figure 2a shows a cross section of the Wedge Stepper Motor following the dimple etch.

Following the dimple etches, the SacOx1 is patterned and etched to open anchor sights for subsequent layers of structural polysilicon. The SacOx1 etches are performed using an anisotropic reactive ion etch (RIE) and extend through the entire oxide layer, stopping at the interface between SacOx1 and the MMPoly0 layer. MMPoly1 deposited over the SacOx1 layer will be anchored or bonded to MMPoly0 at the SacOx1 cuts, and will also act as an electrical connection between MMPoly0 and MMPoly1. The portions of sacrificial oxides not etched away during the pattern and etch processes remain and hold the polysilicon structures in place until a release process is performed at the end of the SUMMiT fabrication process.

Upon completion of the SacOx1 pattern and etch, the first structural layer of polysilicon consisting of a 1 µm thick layer of doped poly (MMPoly1) is deposited. The N-Type polysilicon is doped with phosphine gas. Figure 1 shows the components of the Wedge Stepper Motor constructed out of MMPoly1.

When MMPoly1 has been deposited, patterned and etched, a 0.5 µm layer of TEOS oxide (SacOx2) is deposited on MMPoly1. Figure 2b depicts the deposition and patterning of SacOx2 on top of MMPoly1. The SacOx2 layer provides a conformal coating both on top of MMPoly1 and around the perimeter of the MMPoly1 cuts. SacOx2 separates the next structural layer of polysilicon (MMPoly2) from MMPoly1.

A 1.5 µm thick layer of doped polysilicon, MMPoly2, is deposited following SacOx2 deposition, patterning, and etching. An anisotropic reactive ion etch is used to etch not only MMPoly2 layers but also composite layers of MMPoly1 and MMPoly2 (laminated together to form a single layer approximately 2.5 µm thick). Figure 1 shows the components of the Wedge Stepper Motor constructed out of MMPoly2 and MMPoly1+2, and Figure 2c shows the Wedge Stepper Motor cross-section after the MMPoly2 etch.

With the MMPoly2 etch complete, approximately 6 µm of TEOS oxide (SacOx3) is deposited on the MMPoly2 layer. Chemical-mechanical polishing (CMP) [4] is used to planarize the oxide to a thickness of about 2 µm above the highest point of MMPoly2. Following planarization, SacOx3 is patterned and etched. Patterning and etching of SacOx3 is similar to SacOx1 in that both dimples and the geometry of the upper layer of poly are defined by etching SacOx3. Dimple cuts are etched completely through SacOx3 using RIE, then an additional 0.3 µm to 0.5 µm of oxide is deposited to provide a spacing layer between the bottom of the dimples (formed by deposition of MMPoly3) and the top of MMPoly2. Following the oxide backfill for the dimples, SacOx3 vias are etched to create mechanical and electrical connections or anchors between MMPoly2 and MMPoly3. Figure 2d depicts the Wedge Stepper Motor cross section following SacOx3 etch.

When the SacOx3 etches are complete, a 2 µm thick layer of doped poly (MMPoly3) is deposited on the CMP planarized SacOx3 layer to create the final structural layer of polysilicon. Figure 1 shows the components of the Wedge Stepper Motor constructed out of MMPoly3, and Figure 2e shows a cross-section of the Wedge Stepper Motor following MMPoly3 deposition, pattern and etch.

After MMPoly3 has been patterned and etched, SUMMiT fabrication is complete. In order to achieve functional parts, however, the parts must be released. Release is accomplished by etching all remaining, exposed oxide away with a 100:1 HF:HCl wet etch. Following the wet release etch, a drying process can also be employed using simple air evaporation, supercritical CO_2 drying, or CO_2 freeze sublimation to reduce stiction effects. Figure 2f depicts a cross sectional view of a released Wedge Stepper Motor.

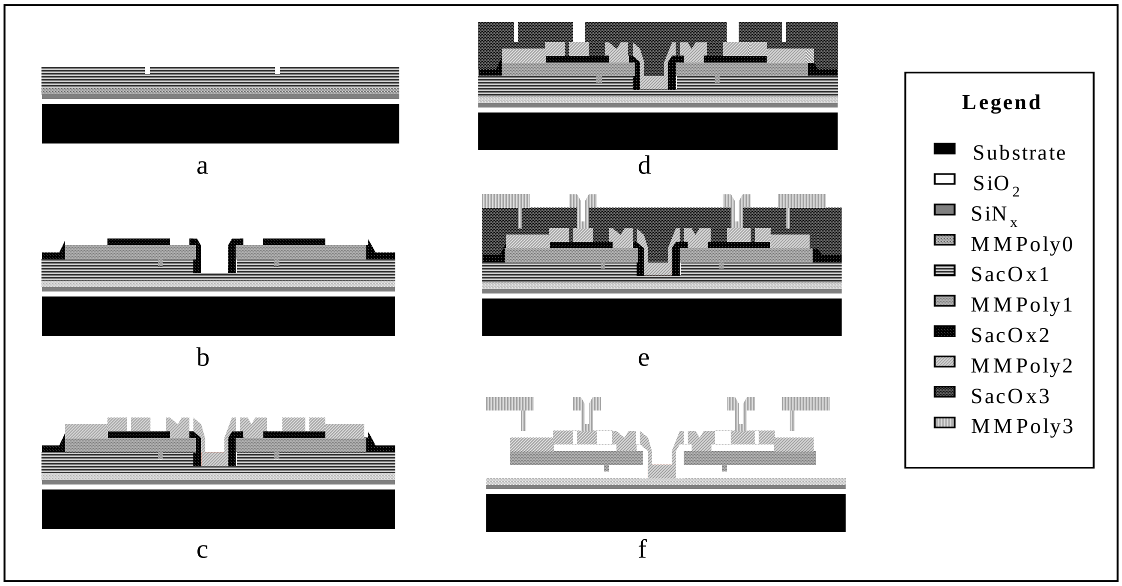


Figure 2. SUMMiT Process Flow Schematic for the Micromachine Wedge Stepper Motor.

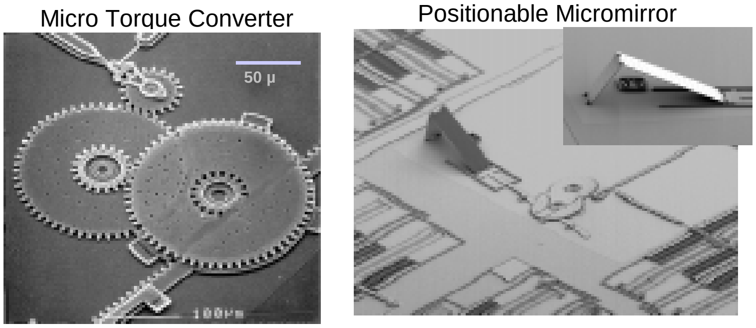
Figure 3 shows an example of a Sandia positionable micromirror design submitted using SAMPLES design tools and fabricated in the SUMMiT process. The positionable micromirror is actuated by driving a standard microengine which then drives a micro torque converter attached to a moveable rack attached to the micromirror.

5. Post-Fabrication Services available at Sandia

Sandia is world renowned not only in MEMS design and fabrication, but also in MEMS post-fabrication processing. In particular, Sandia has done significant research and development in release processes, anti-stiction processing, packaging, test and characterization and reliability studies. [5] [6] [7] As a participant in the SAMPLES program, designers receive <u>unreleased</u> modules. SAMPLES participants interested in post-fabrication services such as release, packaging, test and characterization and reliability studies can discuss these issues with the corresponding Sandia organization's points of contact introduced during the Introductory Course.

6. SAMPLES Participation Information

Anyone wishing to become a SAMPLES program participant can begin the process by registering for the Introductory Course. Course registration and further information on the SAMPLES program can be found on the Sandia National Laboratories Intelligent Micromachine Initiative web site at http://www.mdl.sandia.gov/Micromachine.



Micro Torque Converter

Positionable Micromirror

Figure 3. Micro Torque Converter (transmission) and Positionable Micromirror designed by M. Steven Rodgers of Sandia National Laboratories and fabricated in the SUMMiT process.

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REFERENCES

1. J. Smith, "Micromachined Sensor and Actuator Research at Sandia's Microelectronics Development Laboratory", Proc. of Sensors Expo Anaheim '96, April, 1996 pp. 119-123.
2. M. S. Rodgers, J. J. Sniegowski, S. L. Miller, C. C. Barron, and P. J. McWhorter, "Advanced Micromechanisms in a Mult-Level Polysilicon Technology", SPIE Micromachining and Microfabrication Process Technology, Austin, TX. Sept. 29, 1997, Vol. 3224, pp. 120-130.
3. J. J. Sniegowski, "Multi-layer Enhancement to Polysilicon Surface-Micromachining Technology", IEDM 97 International Electron Devices Meeting, Washington, DC, Dec. 7-10, 1997, pp. 903-906.
4. J. J. Sniegowski, **"**Chemical Mechanical Polishing: Enhancing the Manufacturability of MEMS", (Invited paper) SPIE Micromachining and Microfabrication Process Technology, Austin, TX, Oct. 14, 1996, Vol. 2879, pp. 104-115.
5. B. K. Smith, J. J. Sniegowski, and G. J. LaVigne, "Thin Teflon-Like Films for Eliminating Adhesion in Released Polysilicon Microstructures" (Invited paper) 1997 International Conference on Solid-State Sensors and Actuators, Chicago, IL, June 16-19, 1997, Vol. 1, pp. 245-248.
6. D. M. Tanner, N. F. Smith, D. J. Bowman, W. P. Eaton, and K. A Peterson, **"**First Reliability Test of a Surface Micromachined Microengine Using SHiMMeR", SPIE Micromachining and Microfabrication Process Technology, Austin, TX., Sept. 29, 1997, Vol. 3224, pp. 14-23.
7. S. L. Miller, J. J. Sniegowski, G. LaVigne, and P. J. McWhorter, "Friction in Surface Micromachined Microengines", Proc. SPIE Smart Electronics and MEMS, San Diego, Feb. 28-29, 1996, Vol. 2722, pp. 197-204.