Learning MEMS Design, Simulation and Fabrication Through 3-D Printing

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ABSTRACT

This paper presents a cost-effective learning tool for modeling and simulating the microfabrication process and design aspects of MEMS devices using three-dimensional (3-D) printing. This approach was developed to provide engineering educators a more affordable method for teaching MEMS modeling in settings without a cleanroom. In this approach, by designing and building the MEMS prototypes, the engineers learn by experiencing the process of building a MEMS device from the specifications given. For these prototypes 3-D printers, including the Makerbot Replicator 2X and Stratasys Dimension 1000, are used to create scaled-up models of MEMS devices, specifically a MEMS capacitive switch, MEMS inductor and an MEMS optical switch. Realistic components of MEMS fabrication including conformal layer coating, release etch holes and 3-D printer resolution limitations are part of the design considerations..

Keywords: 3-D printing, education, micro-electromechanical (MEMS) devices, additive manufacturing, education.

1 INTRODUCTION

Current technology, especially in the market of the Internet of Things (IOT) which includes wearables, smart homes and more, is requiring miniaturization and low power consumption of the sensing elements in the system. MEMS are the ideal solution and are increasingly being incorporated in many of these systems. Microelectromechanical systems (MEMS) are miniature elements with low power consumption that consist of mechanical and electrical elements and are manufactured using standard integrated circuit (IC) processes. Companies around the world are increasingly engaging in MEMS system-level design and fabrication. This creates a rising need for highly qualified MEMS engineers that are skilled in design and manufacturing that must be met by university programs. However, the limitation to training these students in the practical and hands-on design of MEMS is the lack of access to expensive clean room equipment and facilities.

3-D printing is an additive manufacturing (AM) process which can be used to create a 3-D object of any geometry and shape. Additive manufacturing is the process of building models by successive addition of the model medium. This is very similar in approach to the layer-by-layer creation of a MEMS device. 3-D printing technology has become increasingly accessible and can be used to simulate the fabrication and design process of MEMS devices without investing a significant amount of time and money in a cleanroom. A key aspect of MEMS devices and their field of study is the ability to visualize and understand the modeling and fabrication processes involved. A 3-D printed design and simulation helps the student better visualize and understand the multilayer MEMS fabrication process while also allowing them to physically examine the final product. Given the lack of access to cleanroom equipment, MEMS courses currently offered typically only examine the theory of fabrication processes. Students focus more on memorizing the processes rather than gaining a conceptual understanding of how these devices are fabricated. In an attempt to provide students with a more meaningful experience and enhance their knowledge of the process of design and fabrication of MEMS, the course 'Introduction to MEMS' was redesigned so that students are required to generate 3-D prototypes of MEMS devices using the processes and fundamentals they learn in class.

A number of papers have discussed improving the MEMS modeling and educational process [1]-[4]; their focus, however, has been on developing lab modules with the assumption that there is access to cleanrooms. This paper presented here is unique to the use of 3-D printing recreate the fabrication and design process of MEMS devices.

This paper describes a novel approach of using 3-D printed design projects aimed at producing skilled, innovative and career-ready engineers who have a deep understanding of the fabrication and modeling process of MEMS components. In the first design project, students individually use SolidWorks [5] and their understanding of Miller indices to generate 3-D print models for the crystalline planes of [100]-oriented and [110]-oriented wafers with [100]-aligned mask features. In the second assignment, students then apply their understanding of the properties of materials and the basics of microfabrication wet etching techniques on silicon wafers by creating the 3-D profiles of an isotropic and anisotropic etch, given a specific mask outline. For a MEMS device fabrication understanding, students are grouped in pairs, and required to design, build and print the step-by-step model of a capacitive MEMS switch or MEMS inductor scaled to a larger size. Each step used in the cleanroom fabrication process is replicated using a Stratasys Dimension 1200es 3-D printer [6]. Finally, to better understand the limitations of lithography resolution, material properties and mechanical requirements and system

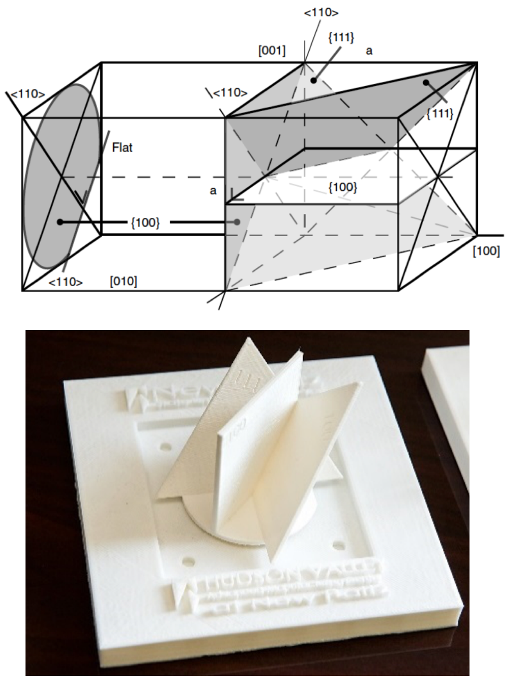


Figure 1: (a) Illustration given to the students [10] and, (b) 3-D printed prototype [8].

control and design, the final project requires students to use a Replicator 2X to scale up and successfully realize an optical MEMS device that can move with two-degree of freedom.

2 MILLER INDICES AND ETCHING

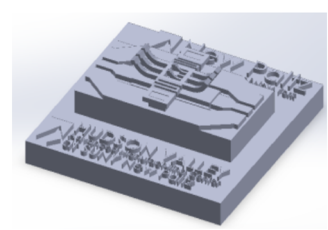
The first important stage of learning about MEMS design is to understand the miller indices in a Silicon wafer. Miller indices define directional and planar orinetation within the crystal lattice of a silicon wafer and are used to guide an etch to create various 3-D geometries and structures. Etching is one of the microfabrication processes used to remove material layers during the creation of the MEMS device. Understanding orientation requirements and the correct timing of an etch process to create sharp and well-controlled features is very important. Students should understand the geometric relationships between the different crystalline planes within a silicon wafer lattice to appreciate the different profiles that result from an isotropically or anisotropically chemically etched silicon wafer. Two projects were designed to train the students on these two fundamental concepts.

In the first assignment, students evaluate a [100] silicon wafer patterned and etched with a mask aligned to the [100] and [110] plane [13] as shown in Fig. 1(a). Using their angle and geometry calculations, the students create scaled-up 3-D printed models with labeled extrusions of the primary crystalline planes from the silicon wafer surface. Fig. 1(b) illustrates an example of a printed model with extruded crystalline planes for a [100] silicon wafer with a mask aligned to the [100] plane.

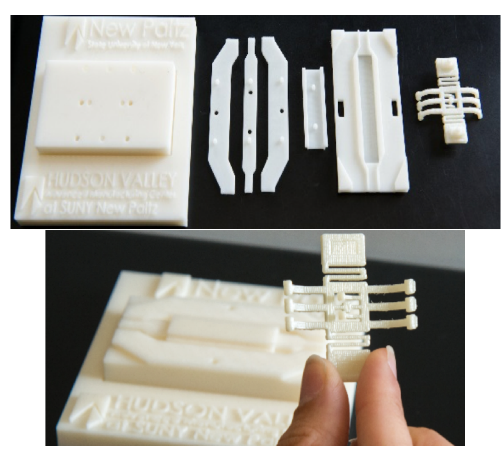
In assignment two, the students are required to generate 3-D models of the resulting etch profile in a silicon wafer given a mask of specific geometry. They are provided with various mask geometries (including a rectangle, square and circle) and told which primary orientation the mask is aligned to ([110] or [100]). They are also given specifications including chemical etchant used, and the required etch depth. Using their understanding of the etch process, crystalline planes, and trigonometry, students then calculate the resultant profile, taking into consideration undercut and over-etch. This exercise of creating the 3-D model helps the students better conceptualize the crystalline planes.

3 MEMS DEVICE MASK DESIGN AND FABRICATION

To better understand the mask design and fabrication process, a project was created where students are assigned a MEMS device such as the MEMS switch presented by authors in [7]. Using SolidWorks, the students scale up the device, and generate a 3-D model and the step-by-step process masks associated with the model. Positive photoresist is assumed for the design of the masks. The devices are then “fabricated” using the fused deposition modeling (FDM) 3-D Stratasys Dimension 1200es printer located in the Hudson Valley Advanced Manufacturing Center (HVAMC) at SUNY New Paltz [9]. The shunt MEMS capacitive switch presented in [7] consists of gold



(a)



(b)

Figure 2: (a) SolidWorks 3-D model of MEMS switch, (b) 3-D print of the scaled-up MEMS switch with an overall footprint of 5cm by 5cm [8].

coplanar waveguide signal and ground lines, a thin dielectric layer for isolation and a switch bridge. The switch beams are designed to warp up for increased up-state isolation with the use of a thin chromimum layer on top of the gold structural layer. The printing resolution limit of the Dimension printer, which can print layer thicknesses of 254µm [6], creates a layout design limitation similar to the limitation of the lithography exposure system.

A MEMS switch is typically released in a common fabrication process by removing the sacrificial photoresist layer using acetone. This release process is recreated in this project using the Stratasys SCA-1200 support-removal system where the support structure is dissolved using a lye-base solution. The student pair who created the 3-D printed prototype illustrated in Fig. 4 scaled-up the device dimensions by a factor of 35, except for the switch thickness, where the thickness was scaled up to measure 1 mm. Details such as conformal coating during deposition and anchor post indents, as illustrated in Fig. 4, were also included to create a more realistic rendering of a fabricated MEMS device.

4 FULLY INTEGRATED MEMS DEVICE

In this project, the student group is asked to design a scaled-up 3-D prototype of the bi-axial MEMS optical switch designed by authors in [14] using SolidWorks [5], and ‘fabricate’ it using a MakerBot 3-D printers located in the Hudson Valley Advanced Manufacturing Center (HVAMC) [9]. Choice of material is entirely up to the design group and can be either polylactic acid (PLA) [16] or acrylonitrile butadiene styrene (ABS) printed using fused deposition modeling (FDM) [16]. The design process should be iterative, where several improvements and adjustments must be made to the design to overcome print failures, eventually resulting in a successful print. Students first scale their device to be able to successfully print the device within a 15 cm by 20 cm foot print. They then generate a sequence of masks assuming positive photoresist to illustrate how the device would have been made if they had access to a clean room. Images of the top-view of the masks as well as step-by-step cross sectional images of the process should be included with a detailed description of what processes would have been used should they have had access to a clean room.

4.1 Layout Scaling and 3-D Print

The 3-D printing process shares several common issues faced when going through lithography and microfabrication. Some of these issues include resolution limitations, layer thickness tolerances, adhesion and material stress, poor adhesion or delamination, contamination and print failure. During the design of the scaled-up model of the mems optical switch, there were limitations of the MakerBot printers. Some of these limitations included the layer height as well as the width of the filament. The resolution limitations in the xy-axis is related to the stepper motors that are used. The typical stepper motor for this application can accomplish 1.8 degrees per step [13]. With the MakerBot build plate being a rectangular, this means that the x-axis will travel further per step of the stepper to cover the distance reducing the resolution in that axis. It was determined that the lowest resolution of the layer height is .1mm with the standard resolution being .2 mm, and the width of the filament is fixed at .6 mm. Table 1 lists the dimensions of the original and scaled-up model. All the provided dimensions were scaled up by a factor 30. This value was chosen to design the smallest possible model while maintaining the ability to demonstrate the mechanism in action without printing failure.

Table 1: Dimensions provided and scaled as well as the actual dimension used

	Original Dimension (mm)	Scaled-up Dimension (mm)
Mirror Aperture Size	0.8	24
Mirror Thickness	0.06	1.8
Width of Beams	0.047	1.41
Length of Beams	0.72	21.6
Thickness of Beams	0.06	1.8

4.2 Mechanical Simulation

For the analysis of the 3-D model, the design layout was imported into ANSYS mechanical simulation sofware, and the simulation was run for both axes of rotation. The students were asked to consider the two options for printing material, PLA or ABS with very different printing and mechanical properties. Shown in Fig. 3 is a sample of the stress analysis results obtained by a student group of their scaled-up model with PLA as the structural material.

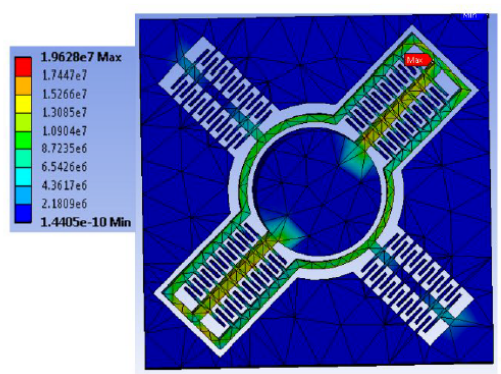


Figure 3: Sample of stress analysis performed by one student group in ANSYS for load applied to the scaled-up MEMS optical switch design using PLA as the structural material.

Once the group can successfully print the device, focus is dedicated to the movement of the optical MEMS switch, with two degrees of movement. Attention must be paid to the material's mechanical property to allow for flexure and movement without failing or buckling. Detailed description of these properties and how they have been accounted for in the design of the system must be included in the report. Also, a description of the actual FDM process and how that can impact intrinsic stress properties of the chosen 3-D printing material must be included, reference any articles found on that topic.

4.3 Actuation Mechanism and Control

Next, the actuation of the mems optical switch must be designed. This can be accomplished in several ways; the student is given free choice of how. The optical switch design must be able to move between both degrees of motion and the user should be able to control each degree of movement individually. A microprocessor of the students' choice should be included to automate the system and allow the user control on how far to move the switch in either direction.

For instance, one design team used a pulley system with fishing string. The pulley system was regulated with two stepper motors that were controlled using an Arduino nano. Fig. 4 illustrates a completed 3-D printed fully integrated scaled-up optical MEMS prototype. A joystick was incorporated into the design for ease of angle actuation and to replace the need of two individual potentiometers.

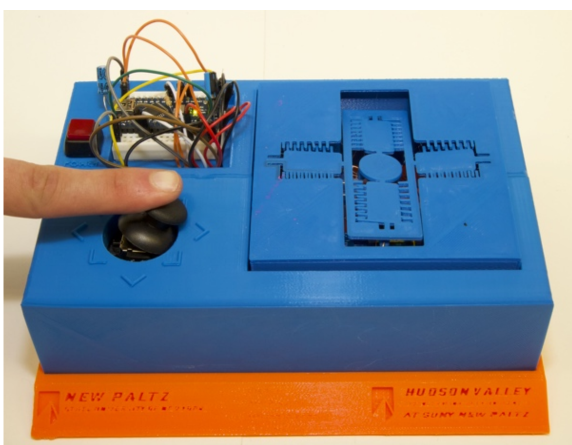


Figure 4: 3-D printed scaled-up version of optical MEMS device fully automated with two gears and an Arduino uno.

5 CONCLUSION

This paper has illustrates how useful 3-D printing can be for the modeling of a MEMS device's design, implementation and mechanical analysis. Several projects presented present more cost-effective methods to teach MEMS design and fabrication processes when there is a lack of access to high-cost clean room facilities.

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