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# Implementation of a MEMS Laboratory Course with Modular, Multidisciplinary Team Projects

John Lee, *San Jose State University*
Stacy H. Gleixner, *San Jose State University*
Tai-Ran Hsu, *San Jose State University*
David W Parent, *San Jose State University*

# AC 2007-1572: IMPLEMENTATION OF A MEMS LABORATORY COURSE WITH MODULAR, MULTIDISCIPLINARY TEAM PROJECTS

**John Lee, San Jose State University**

JOHN LEE is an Assistant Professor in the Department of Mechanical and Aerospace Engineering at San Jose State University. He teaches in the areas of microelectromechanical systems (MEMS), manufacturing processes, mechanical design, and dynamics. He conducts research in microfluidics and micromechanics applied to MEMS design and fabrication. Contact: sjlee@sjsu.edu.

**Stacy Gleixner, San Jose State University**

STACY GLEIXNER is an Associate Professor in the Department of Chemical and Materials Engineering at San Jose State University. She teaches courses on introductory materials engineering, electronic materials, solid state kinetics and thin film deposition. Prof. Gleixner has an active research program in microelectronics and microelectromechanical systems (MEMS). Contact: gleixner@email.sjsu.edu.

**Tai-Ran Hsu, San Jose State University**

TAI-RAN HSU is a Professor in the Department of Mechanical and Aerospace Engineering at San Jose State University. He teaches dynamics, engineering analysis and microsystems design, manufacture and packaging. His research interest is in the electromechanical design of MEMS and reliability in assembly and packaging of microsystems. Contact: tairan@email.sjsu.edu.

**David Parent, San Jose State University**

DAVID PARENT is an Associate Professor in the Department of Electrical Engineering at San Jose State University. He teaches courses and conducts research in semiconductor device physics, integrated-circuit (IC) manufacturing, digital/mixed signal IC design and fabrication, and microelectromechanical systems (MEMS). Contact: dparent@email.sjsu.edu.

# Implementation of a MEMS Laboratory Course with Multidisciplinary Team Projects


## Abstract

This paper presents the implementation and outcomes of a hands-on laboratory course in microelectromechanical systems (MEMS), co-developed by a multidisciplinary team of faculty from mechanical engineering, electrical engineering, and materials engineering. Central to the design of the course is an emphasis on implementing modules that are able to overcome critical barriers related to (1) diverse academic background from different majors and (2) practical limitations in microfabrication facilities. These points are vital for promoting MEMS education, because they expand the student pool and reach audiences that need a cost-effective way to support instructional laboratory experiences in MEMS without the broader infrastructure that is often limited only to large research institutions.

Laboratory projects emphasize skills in design, fabrication, and testing, while a classroom lecture portion of the course provides corresponding background theory. The paper provides technical description of three modular projects that have been implemented in the course. These encompass a variety of MEMS fabrication approaches, including surface micromachining, bulk micromachining, and soft lithography. These distinct methods are exercised in three corresponding devices: a silicon pressure sensor, an aluminum suspended beam, and a polymer microfluidic chip. These projects illustrate principles and reinforce student learning of important phenomena commonly involved in MEMS, such as piezoresistivity, electrostatics, stiction, residual stress, and electrokinetics. The modules are arranged with different levels of emphasis among design, fabrication, and testing, to reach higher levels of Bloom's Taxonomy while simultaneously balancing time and resource constraints in a practical manner. Feedback from student opinions and plans for improvement are also presented.


## Introduction

The multidisciplinary subject of microelectromechanical systems (MEMS) requires a broad range of background knowledge and skills. MEMS engineering demands important contributions from the fields of mechanical engineering, electrical engineering, materials engineering, and other disciplines. In an effort to make hands-on MEMS education more accessible to engineering students, a new laboratory course has been developed and instituted at San José State University, built upon a framework reported previously[1]. This framework addresses two critical barriers that limit effective learning in MEMS: (1) different course pre-requisite background for students coming from a broad range of academic majors, and (2) prohibitive overhead in terms of facilities, cost, and time for microscale prototyping and fabrication. The problem of mixed background knowledge is addressed by assembling student teams such that the members collectively satisfy specific *functional* pre-requisites, even though they come with a wide variety of prior course backgrounds. The problem of limited design freedom under practical constraints is addressed by using lower-resolution geometric design rules and standardized processes that facilitate semi-custom design[1].

The course developers (i.e. authors of this paper) firmly believe that *design*, *fabrication*, and *testing* are three essential activities in which students must engage in order to effectively learn the subject of MEMS. Participating in all three activities increases the opportunities for satisfying the wide variety in conditions of learning. Successfully meeting the conditions of learning helps students learn more efficiently and gain appreciation for subject matter[2]. This paper reviews the first full implementation of the course in Fall 2006, with emphasis on how project modules were arranged to have students actively participate in all three aspects of design, fabrication, and testing. These modules are then discussed in the context of the levels at which they satisfy learning objectives, and retrospectively examined based on student survey feedback.

## Project Modules

The spectrum of MEMS fabrication methods can be divided into a small number of major categories. Historically the most fundamental and conventional distinction has been *bulk micromachining* versus *surface micromachining*[3, 4]. In more recent years, the contemporary relevance of nanotechnology and biotechnology also bring great prominence to a third category, replication by *soft lithography*[5, 6]. Accordingly, these three methods are covered by the course.

Rather than developing a single comprehensive exercise or term project, we have taken the strategy of using short instructional modules. After considering the vast variety of MEMS devices, applications, and fabrication methods, we narrowed options down to three modules for this project. The modules focus on the three major categories of soft lithography, surface micromachining, and bulk micromachining. Some characteristics of each method are listed in Table 1. As is the case with integrated circuits, a rough but often correct estimate of complexity and cost is the minimum number of masks needed to create the selected device. These modules in the table are arranged from simplest to most complex.

**Table 1. Characteristics of Selected MEMS Project Modules**

| *Type of Device* | *Microfluidic Chip* | *Suspended Beam* | *Silicon Membrane* |
|---|---|---|---|
| Common MEMS Applications | Electroosmotic separation<br>Particle sorting | RF switch<br>Resonant gate transistor | Pressure sensor<br>Diaphragm valve |
| Examples of Engineering Principles | Electrokinetic flow<br>Fluid scaling laws<br>Polymer processing | Electrostatics<br>Resonance<br>Beam theory | Piezoresistivity<br>Bridge networks<br>Plate deformation |
| Number of Masks | 1 | 1 or 2 | 4 |
| Facilities requirements | Spin coating; UV lamp; hotplate; fume hood. | Oxidation furnace; metal evaporation; photolithography equipment; chemical wet bench. | Oxidation/diffusion furnace; metal evaporation; photolithography equipment; chemical wet bench, plasma etching, wafer bonding |

Any of a large variety of devices[7] could have been selected for each of the three project modules, but an electrophoresis *microfluidic chip*, an aluminum *suspended beam*, and a piezoresistive silicon *pressure sensor* were chosen for the Fall 2006 implementation. Each of these devices and their fabrication methods are described further in the sections below.

*Microfluidic Chips by Soft Lithography*

A microfluidic chip for capillary electrophoresis[8], for example, can be designed and fabricated using only a single photolithography mask. It is therefore very favorable to prototyping under limited resources in time and facilities. A common implementation (which is indeed the method used for this class) is to pattern a master with SU-8 ultrathick photoresist, followed by casting of the soft elastomer polydimethylsiloxane (PDMS) to form the structural body of the chip. The basic process is shown for a microvalve device[9] in Figure 1 below.

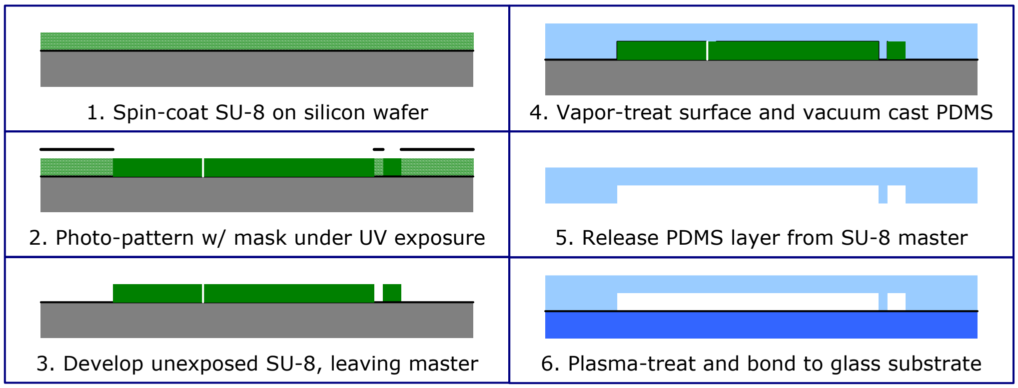


**Figure 1. Process Sequence for Microfluidic Chips by Soft Lithography**

The master pattern on a 100-mm silicon wafer and an example of a finished microfluidic chip is shown in Figure 2. Channel height was approximately 50 microns and channel width varied from 25 microns to 100 microns. Length of the long horizontal separation channel was approximately 60 millimeters.

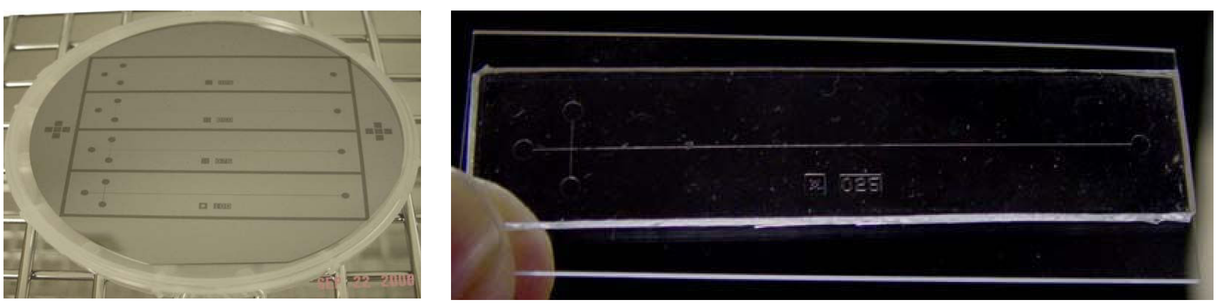

**Figure 2. Fabrication Master (left) and Completed Microfluidic Chip (right)**

Equipment limitations and time constraints did not allow the chips to be fully tested under electroosmotic flow, but the completed chips were tested under pressure-driven flow for different channel dimensions. An example of student data is shown in Figure 3.

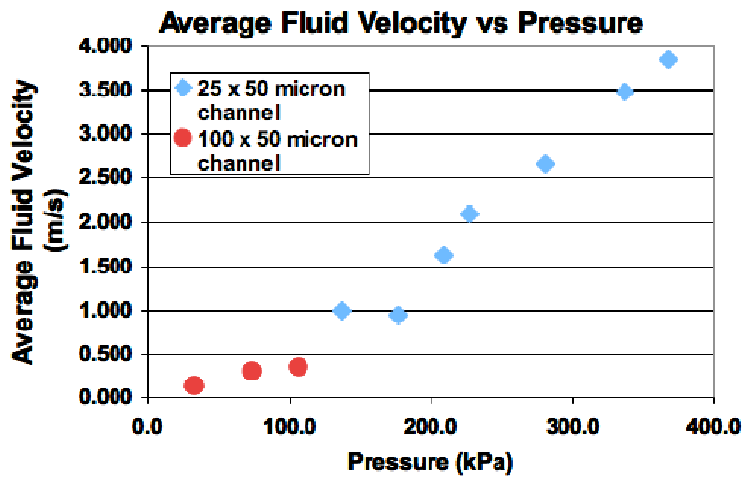


**Figure 3. Average Fluid Velocity vs. Pressure for Different Microchannel Sizes**

*Suspended Beams by Surface Micromachining*

The suspended beam project offered the greatest design freedom for students, because no mask set was provided. Students were given a set of design and fabrication constraints, and then were responsible for designing their own masks with computer-aided design (CAD) tools. An example of one type of device (a tilting micromirror) and the associated analytical predictions based on idealized electrostatics and beam mechanics equations is shown in Figure 4.

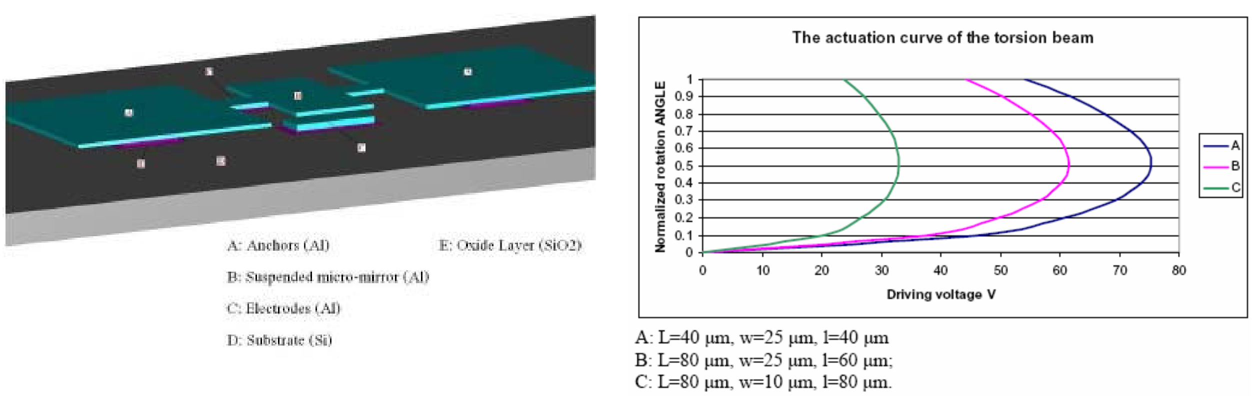


**Figure 4. CAD Model of Electrostatic Micromirror (left) and Analytical Predictions for Actuation (right)**

An example list of design rules that were presented to the students is as follows. The students were required to abide by such constraints as they performed their geometric design. These constraints are typical of low-resolution masks made by laser photoplotting, as opposed to costly traditional microelectronics masks made by electron-beam writing, for example. There is an order-of-magnitude difference in cost, with the former less than $30 per mask and the latter above $400 per mask. Students still learn to design under clear constraints, but without being limited by the prohibitive cost associated with unique designs.

- The default thickness of the sacrificial oxide is 1.0 micron.
- The default thickness of the metal film is 1.0 micron.
- Supporting structures (e.g. posts) in the oxide layer should be no smaller than 2X the size of the largest released features in any lateral dimension, and preferably at least 100 microns in any lateral dimension.
- Released structures (e.g. beams) should be no wider than 40 microns at the widest point. Broader regions (e.g. plates) may be included with proper placement of supplemental etch windows.
- Supplemental etch windows (for sacrificial material removal) should be at least 10 microns in any lateral dimension.
- Wafers should have at least a 5 mm exclusion zone (usable space) around the perimeter.

The interdisciplinary aspect of design was revealed as students were required to choose and justify their device selection, and perform parametric analytical study of anticipated performance. In the example of a torsion mirror above, one intersection between domains was based on the interaction between electrostatics and mechanics of deformable solids. Another student group parametrically designed their mask features based on the required force to close the tips of micro-grippers, and the third team designed suspended resonant beams for chemical detection based on a change mass from selective binding phenomena.

Unfortunately time limitations and the demands of the bulk micromachining and soft lithography modules meant that the suspended beams were not functionally tested, but several observations using scanning electron microscope (SEM) images as shown in Figure 5 were used for discussion of important surface micromachining phenomena, such as stiction, selectivity of sacrificial etching, and curling from residual stress.

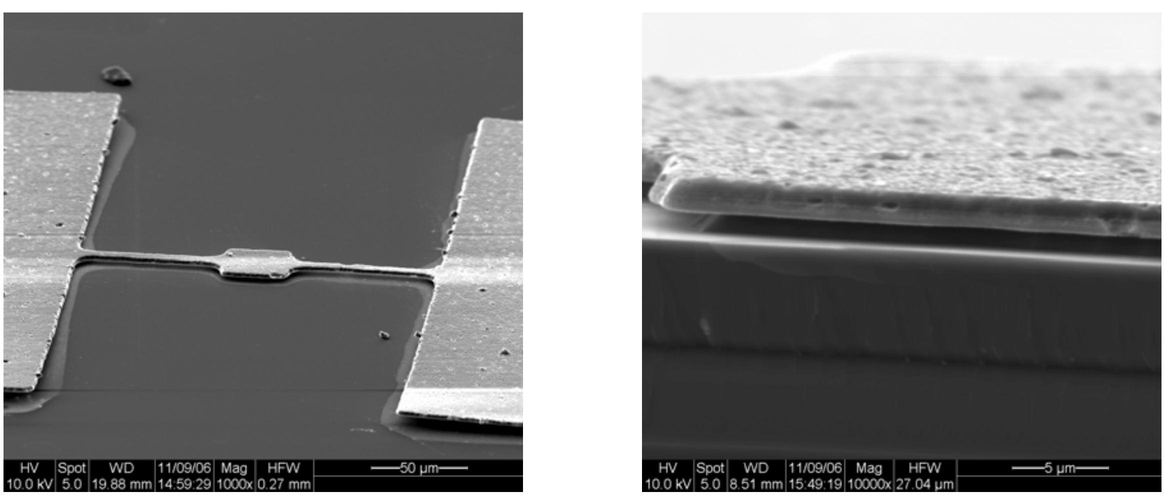


**Figure 5. SEM Image of a Suspended Mirror (left), and Close-Up View Showing the Underside Etch (right)**

*Pressure Sensors by Bulk Micromachining*

The pressure sensors by bulk micromachining represented the most lengthy process. Students were given the mask set and the process sequence in Figure 6. Students did conduct functional testing of pressure sensors on a modified wafer probe station from Signatone Corporation (Gilroy, CA) running Metrics ICS software (Metrics Technology, Inc, Albuquerque, NM). Failure of wafers-in-progress (by pitting that led to membrane failure) necessitated using sensors fabricated by previous students (from an earlier pilot course), but the design of the sensors was identical. The failure serendipitously provided opportunity to conduct process troubleshooting and investigation of "what-if" scenarios to understand the root cause. Results from functional testing of the working devices are shown in Figure 7.

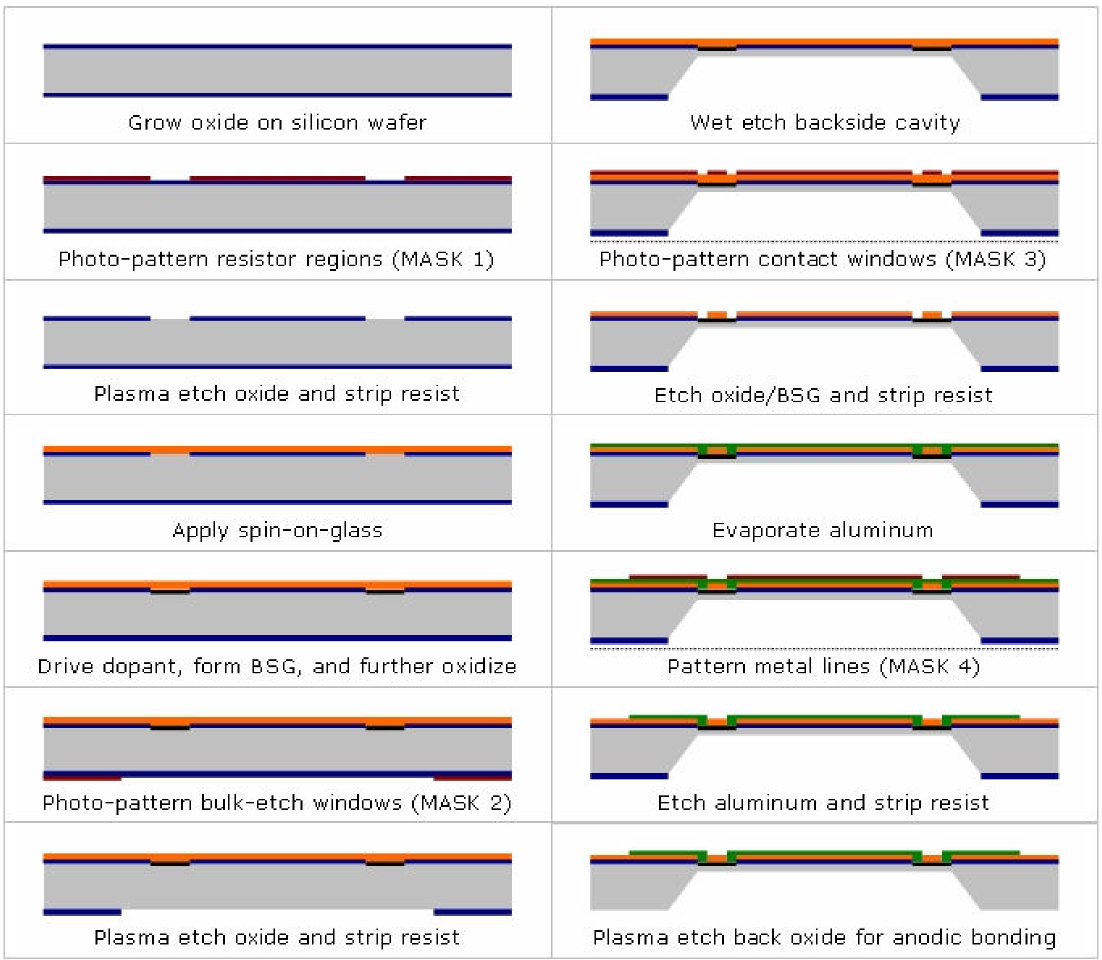


**Figure 6. Process Sequence for Piezoresistive Silicon Pressure Sensor**

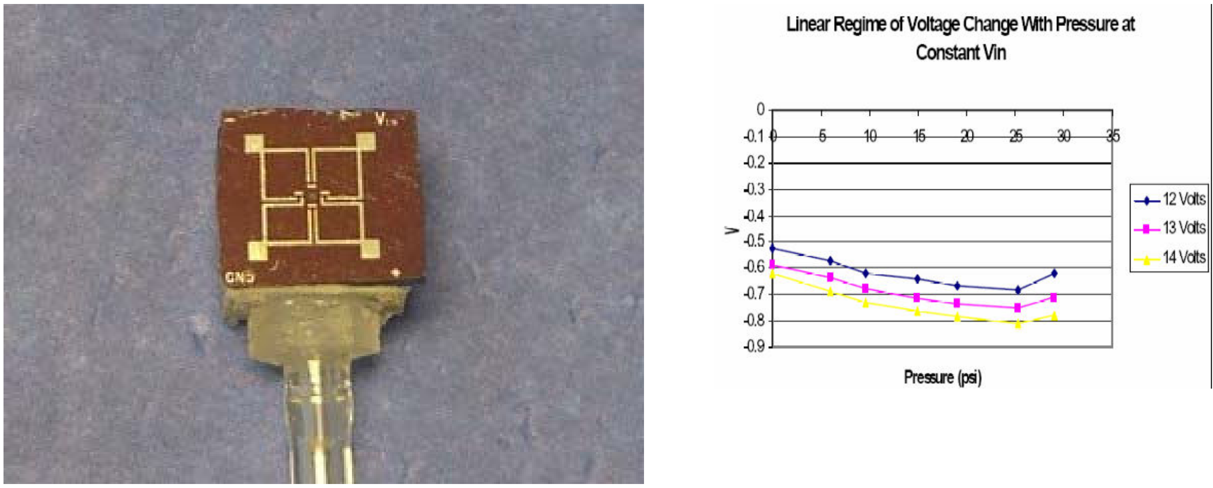


**Figure 7. Pressure Sensor Mounted for Testing (left), and Experimental Data (right)**

## Levels of Learning and Module Flexibility

Table 2 below describes the level of involvement in each major activity for each of the three projects. The six categories of Bloom's Taxonomy[10] have elements of subjective opinions and are sometimes difficult to distinguish with fine resolution. So for the sake of this discussion an aggregated set of levels will be used as follows:

- "Low-level" corresponds to Level 1 (remembering) and/or Level 2 (understanding).
- "Mid-level" corresponds to Level 3 (applying).
- "High-level" corresponds to Level 4 and above (analyzing, evaluating, and creating).

**Table 2. Project Modules and Levels of Learning in Design, Fabrication, and Testing**

| *Project Module* | *Design* | *Fabrication* | *Testing* |
|---|---|---|---|
| Suspended Beams by Surface Micromachining | High | Mid | |
| Pressure Sensors by Bulk Micromachining | | High | High |
| Microfluidic Chips by Soft Lithography | | Mid | Low |

While it is desirable to achieve higher levels of learning across all cases, practical constraints such as facilities, cost, and time will often limit such ability. This modular arrangement offers flexibility. A very important part of this scheme is that instructors are free to rearrange both the content and the level of emphasis for each module depending on preferences and constraints. A few brief examples of variants are listed below.

- An instructor with much expertise in surface micromachining could accordingly use relatively lower levels activity in that module, as long as some higher-levels of learning are addressed in other modules.
- A proof-mass accelerometer could be the device explored for bulk micromachining rather than a pressure sensor. Such a device has been successfully incorporated in other instructional MEMS environments.

- A pneumatic microvalve could be the device explored for soft lithography rather than an electrophoresis chip.

**Student Feedback**

In the Fall 2006 semester there were 12 students. Six were Mechanical Engineering majors, five were Materials Engineering majors, and one was and Electrical Engineering major. In addition, the Teaching Assistant as well as another lab assistant who audited several sessions were both Electrical Engineering majors. According to standard Institutional Review Board policy at the university, each student was informed verbally and in writing that their participation was entirely voluntary, anonymous, and unrelated to their course grade. Nine of the twelve students chose to participate in the survey, and detailed results are included in the Appendix.

A first series of questions asked if the students recognized merit in each of the three major types of activities: design, fabrication, and testing. Also captured was their self-assessment on whether or not the course provided the opportunity to engage in each of these activities. There was almost unanimous recognition that all three activities were important and unanimous agreement from each student that they in fact engaged in all three aspects.

The next set of questions explored the multidisciplinary aspects of the course. There was almost unanimous agreement that students were required to work on projects that required interdisciplinary knowledge and skills beyond their native academic discipline or "comfort zone". Also near unanimous agreement that the collective background and qualifications of each team as a whole was sufficient to address the requirements of each project, even if not all team members had sufficient prerequisite experience as individuals. One outlier response showed disagreement in both cases above. Also notable is the fact that despite a very heavy workload, the majority of students (7 out of 9) responded that they would not sacrifice one of the modules (soft lithography, surface micromachining, bulk micromachining) to reduce workload and allow more time to spend on remaining modules.

**Next Steps**

Referring back to Table 2, a shortcoming of this past implementation is that no one module completed a full span from design to fabrication to testing. Even if practical limitations require that only two out of three of these core activities are accomplished, for future course implementation it would be highly desirable to ensure that a design-testing connection is made, to maximize the learning experience derived from observing how one's design decisions truly affect final performance. One option would be to use partial foundry service such as MEMSCAP (Durham, NC) to bypass the relatively slow turn-around associated with on-site fabrication.

Also, beginning in Fall 2007 the lecture component of the course will be moved to online format using the WebCT product from Blackboard.com (Washington, D.C.) The purpose is two-fold, with one purpose being the ability to overcome scheduling conflicts from the variety of student majors that span across multiple departments. The second purpose for migrating to online lecture format is to enhance the modularity of content, so that the content may be more portable not only for diverse opportunities within our university (e.g. intersession courses, research training, etc.), but also more broadly to other institutions and regions. The Fall 2006 course was already taught with partial WebCT delivery, and this provides a head-start to developing a fully-online implementation of the lecture portion beginning in Fall 2007. In concept some of the lab activities may also be remote with video streaming and other media tools, but these authors are still committed to providing the richest learning experience with live, hands-on laboratory activities.

**Conclusions**

The completion of this first complete course offering in hands-on MEMS shows that it is indeed possible to cover three major topics (soft lithography, surface micromachining, bulk micromachining) in one academic semester. The consensus from student feedback indicated that all three modules were valued and none would be readily sacrificed. The idea of staggering the activities of design, fabrication, and testing also provided an option to engage in these important activities, even if not comprehensively in any one module.

An important area in need of improvement is sequencing of the projects. Students as well as the instructor encountered difficulty in running the modules with overlapping activities (e.g. testing microfluidic chips while writing reports on suspended beams). Therefore, a constructive area for course redesign would be refinement of activity scheduling to move the modules more sequentially, as opposed to in parallel.

A lasting benefit of this work is the practical experience in developing a hands-on MEMS course for students of different academic backgrounds under the constraints of limited facilities. Project modules with multi-disciplinary teams and low-resolution design rules broaden the student pool and make the activities more practically affordable in an instructional setting.

**Acknowledgements**

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## Appendix: Student Survey Results

QUESTION 1

Open-ended design is an important part of developing knowledge and skills in MEMS. For this question, include "simulation" as a subcategory of "design".

○ a. Strongly Disagree ○ b. Disagree ○ c. Neutral ○ d. Agree ○ e. Strongly Agree

**Response Summary**

| Answer | Value | Frequency Distribution |
|---|---|---|
| - | 0% | 1 |
| a | 0% | 0 |
| b | 0% | 0 |
| c | 0% | 1 |
| d | 0% | 3 |
| e | 0% | 4 |

QUESTION 2

I had opportunity to explore open-ended design in at least one project module.

○ a. Strongly Disagree ○ b. Disagree ○ c. Neutral ○ d. Agree ○ e. Strongly Agree

**Response Summary**

| Answer | Value | Frequency Distribution |
|---|---|---|
| a | 0% | 0 |
| b | 0% | 0 |
| c | 0% | 0 |
| d | 0% | 3 |
| e | 0% | 6 |

QUESTION 3

Hands-on fabrication is an important part of developing knowledge and skills in MEMS.

○ a. Strongly Disagree ○ b. Disagree ○ c. Neutral ○ d. Agree ○ e. Strongly Agree

**Response Summary**

| Answer | Value | Frequency Distribution |
|---|---|---|
| a | 0% | 0 |
| b | 0% | 0 |
| c | 0% | 0 |
| d | 0% | 4 |
| e | 0% | 5 |

QUESTION 4

I had opportunity to engage in hands-on fabrication of a variety of MEMS structures or devices.

◯ a. Strongly Disagree ◯ b. Disagree ◯ c. Neutral ◯ d. Agree ◯ e. Strongly Agree

**Response Summary**

| Answer | Value | Frequency Distribution |
|---|---|---|
| a | 0% | 0 |
| b | 0% | 0 |
| c | 0% | 0 |
| d | 0% | 5 |
| e | 0% | 4 |

QUESTION 5

Functional testing is an important part of developing knowledge and skills in MEMS.

◯ a. Strongly Disagree ◯ b. Disagree ◯ c. Neutral ◯ d. Agree ◯ e. Strongly Agree

**Response Summary**

| Answer | Value | Frequency Distribution |
|---|---|---|
| a | 0% | 0 |
| b | 0% | 0 |
| c | 0% | 1 |
| d | 0% | 2 |
| e | 0% | 6 |

QUESTION 6

I had opportunity conduct functional testing of at least one MEMS device.

◯ a. Strongly Disagree ◯ b. Disagree ◯ c. Neutral ◯ d. Agree ◯ e. Strongly Agree

**Response Summary**

| Answer | Value | Frequency Distribution |
|---|---|---|
| a | 0% | 0 |
| b | 0% | 0 |
| c | 0% | 0 |
| d | 0% | 5 |
| e | 0% | 4 |

QUESTION 7

I was required to work on projects that required interdisciplinary knowledge and skills beyond my native academic discipline or "comfort zone".

○ a. Strongly Disagree ○ b. Disagree ○ c. Neutral ○ d. Agree ○ e. Strongly Agree

**Response Summary**

| Answer | Value | Frequency Distribution |
|---|---|---|
| a | 0% | 0 |
| b | 0% | 1 |
| c | 0% | 0 |
| d | 0% | 4 |
| e | 0% | 4 |

QUESTION 8

The collective background and qualifications of each team as a whole was sufficient to address the requirements of each project, even if not all team members had sufficient prerequisite experience as individuals.

○ a. Strongly Disagree ○ b. Disagree ○ c. Neutral ○ d. Agree ○ e. Strongly Agree

**Response Summary**

| Answer | Value | Frequency Distribution |
|---|---|---|
| a | 0% | 0 |
| b | 0% | 1 |
| c | 0% | 0 |
| d | 0% | 5 |
| e | 0% | 3 |

QUESTION 9

Working with teammates from different academic disciplines (e.g. ME, EE, MatE) helped me learn things or see perspectives that I likely may not have encountered if I had worked with teammates solely within my own discipline.

○ a. Strongly Disagree ○ b. Disagree ○ c. Neutral ○ d. Agree ○ e. Strongly Agree

**Response Summary**

| Answer | Value | Frequency Distribution |
|---|---|---|
| a | 0% | 0 |
| b | 0% | 1 |
| c | 0% | 1 |
| d | 0% | 3 |
| e | 0% | 4 |

QUESTION 10

This class has increased my likelihood to pursue further education or professional opportunities in the area of MEMS.

a. Strongly Disagree | b. Disagree | c. Neutral | d. Agree | e. Strongly Agree

**Response Summary**

| Answer | Value | Frequency Distribution |
|---|---|---|
| a | 0% | 0 |
| b | 0% | 1 |
| c | 0% | 1 |
| d | 0% | 3 |
| e | 0% | 4 |

QUESTION 11

Receiving instruction from different faculty members in different areas of relative expertise contributed significantly to my learning experience.

a. Strongly Disagree | b. Disagree | c. Neutral | d. Agree | e. Strongly Agree

**Response Summary**

| Answer | Value | Frequency Distribution |
|---|---|---|
| a | 0% | 0 |
| b | 0% | 1 |
| c | 0% | 2 |
| d | 0% | 3 |
| e | 0% | 3 |

QUESTION 12

Having guest speakers from industry contributed significantly to my learning experience.

a. Strongly Disagree | b. Disagree | c. Neutral | d. Agree | e. Strongly Agree

**Response Summary**

| Answer | Value | Frequency Distribution |
|---|---|---|
| a | 0% | 0 |
| b | 0% | 1 |
| c | 0% | 1 |
| d | 0% | 2 |
| e | 0% | 5 |

QUESTION 13

Having three separate projects spanning three different device types as well as three major categories of microfabrication (surface-micromachined suspended beams, bulk-micromachined pressure sensors, soft-lithography microfluidic chips) is an ambitious and challenging endeavor. Spanning less would allow significantly greater detail in one or two modules. Retrospectively, how would you have preferred to experience these modules?

- a. As is. Although implementation can be improved, all three modules should stay.
- b. Focus on surface micromachining; give up bulk micromachining and soft lithography.
- c. Focus on bulk micromachining; give up soft lithography and surface micromachining.
- d. Focus on soft lithography; give up surface micromachining and bulk micromachining.
- e. Keep surface micromachining and bulk micromachining; give up soft lithography.
- f. Keep bulk micromachining and soft lithography; give up surface micromachining.
- g. Keep soft lithography and surface micromachining; give up bulk micromachining.

**Response Summary**

| Answer | Value | Frequency Distribution |
|---|---|---|
| a | 0% | 7 |
| b | 0% | 0 |
| c | 0% | 0 |
| d | 0% | 0 |
| e | 0% | 1 |
| f | 0% | 0 |
| g | 0% | 1 |