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Introduction

Many of the most popular and advanced consumer products in recent years reveal a strong trend toward engineering more functionality in smaller dimensional scale. Examples of technology areas include wireless communication, portable audio, and digital video. Accelerometers in laptop computers, pressure sensors inside automobile tires, and micromirrors for wide-area video displays are some specific transducers that show how microelectromechanical systems (MEMS) are growing more ubiquitous in engineered systems. Other common examples include disk read/write heads, inkjet printing nozzles, and bio-analysis chips.^{1,2} Such devices add relatively little cost to engineered products, yet contribute dramatic benefits in safety, speed, reliability, and functional performance. MEMS enable new products using much less spatial volume and lower material consumption than the sensors and actuators from decades ago, and furthermore serve as an enabling bridge for the growing commitment to nanotechnology³. Multidisciplinary engineering education in MEMS is therefore essential for keeping pace with the needs and trends of modern technology.

There is a need for more enriching opportunities in MEMS education, but significant barriers and constraints limit the ways in which hands-on education is accessible to a broad learning audience. Although most engineering schools and colleges are now and may continue to be organized primarily under traditional “compartmentalized” disciplines, innovations in pedagogy and collaboration help spread MEMS and other contemporary technologies to widening audiences. However, in addition to the multidisciplinary nature of hands-on MEMS there is a very practical and fundamental problem that few universities nationwide are able to offer *hands-on* experience in microfabrication at the undergraduate level. So in addition to pedagogical and teamwork challenges are the often prohibitive obstacles of facilities and cost.

The most perceptible goal of the authors’ present work in MEMS education is to develop an undergraduate hands-on course in MEMS, with a variety of modules to reflect a representative set of the many different applications and technologies involved. This course development project will be manifested as an interdepartmentally cross-listed course, developed in detail by the authors throughout the 2005-2006 academic year. Processing steps and some design variants will be practiced in with the help of student assistants, and the course will be offered in Fall 2006. Beyond the obvious goal of the course is a firm commitment to very active interdepartmental collaboration. In addition, we also place dedicated emphasis on empowering students with open-ended MEMS experiments that can be conducted even with limited resources.

This paper presents work-in-progress in terms of a framework that we have structured to support effective joint development among faculty from different engineering backgrounds, spanning mechanical engineering (ME), electrical engineering (EE), and materials engineering (MatE). The framework is organized in short instructional modules designed to span not only major

device types and different fabrication technologies, but also different levels of resource requirements. An example of using *functional* prerequisites--rather than *course* prerequisites--is presented for one module, wherein each functional prerequisite must be satisfied by at least one member of each student team that will undertake the module. Roles of the faculty course designers are arranged to manage the complementary and essential aspects of design, fabrication, and testing. Each of these is essential to hands-on learning. As the work is still in progress, we do not present a formal set of conclusions, but do close with our observations on how these elements have served the module development process midstream.

Related Work and Prior Experience

Multidisciplinary MEMS instruction has presented a stimulating topic for engineering education in terms of specific courses^{4,5,6} as well as MEMS curriculum at a broader scale.⁷ Teaching innovations are making continual progress toward the instruction of micro-scale engineering. Recurring themes are the vital need for collaboration across multiple departments and the inherent challenge of creating an effective learning environment for students that come from different academic majors. There are many challenges and merits of multidisciplinary and interdisciplinary course development in general, and every such endeavor has many practical and organizational issues involving roles, audience, problem selection, and timing⁸. In addition to MEMS, other contemporary engineering topics that have drawn dedicated attention for multidisciplinary instructional development include microelectronics⁹ and more recently nanotechnology¹⁰.

Faculty teams at our institution (including authors of this work) have direct experience developing laboratory courses in microelectronics process engineering¹¹ as well as in mechatronics¹². These courses provide a foundation of experience in curriculum coordination and instructional module development. This experience with collaborations across materials engineering, electrical engineering, mechanical engineering, and chemical engineering highlight a history of cooperative and multidisciplinary approaches to engineering education.

This present work specifically in MEMS was preceded by a one-unit pilot course offered by one of the co-authors in Spring 2005. Scope was primarily limited to learning how relatively standard microelectronics process steps could be extended and applied to MEMS-specific structures such as silicon membrane cavities and microfluidic channels. New techniques beyond the conventional microelectronics processing taught in our other lab courses include two-sided etching, wafer bonding,¹³ and soft lithography.¹⁴ Although enrollment in this pilot course by coincidence had an equal balance of four mechanical engineering students and four electrical engineering students, there was no formal attention to managing student skill sets other than partnering ME students with EE students in team exercises. Limited by the one-unit time allocation, instruction focused on the fabrication processes, with little attention to design and no actual device testing. The pilot course did reveal some specific “backfill” topics because of differences in student background. This challenge of mixed backgrounds is also highlighted by other MEMS educators in related situations.⁵ Examples of new topics for EE students included beam theory and plate mechanics, and new ones for ME students were sheet resistance and excitation/sense principles for bridge circuits.

Challenges and Solution Strategies

The challenges facing laboratory-based learning in MEMS are comprised of both pedagogical issues as well as practical constraints, and neither category may be underestimated. Table 1 combines some specific examples of both pedagogical and practical issues collected from related course development work as well as the authors' direct experiences. The solutions strategies that are relatively unique to the present work are highlighted by asterisk (*) and are discussed further below.

Table 1. Challenges for laboratory-based MEMS and proposed solution strategies.

<i>Challenge</i>	<i>Solution Strategy</i>
Multidisciplinary content. Different methodologies, terminologies, and areas of academic emphasis.	Multidisciplinary team of course developers. All project work arranged in teams that favor mixed student backgrounds.
Varying constraints in equipment availability, budget levels, and schedule.	Flexible technical modules, selected and organized based on device type as well as fabrication method.
Different levels of student preparation in different subject areas, knowledge, and skills.	Clearly articulated team functional prerequisites*, rather than course prerequisites.
Lack of open-ended problem-solving opportunities, limited by high demand in cost and time.	Semi-custom design flow* and low-resolution rapid prototyping*.
Contemporary and industry relevance.	Active engagement in applied research with collaborators in industry, and case studies based on current MEMS journal and conference literature.
Unforeseen obstacles, lack of <i>a priori</i> assessment data on best practices.	Formal and informal advisory relationships with experienced MEMS lab developers outside our local team.

Team Functional Prerequisites. Intentionally to reach the widest audience of students, the only mandatory course prerequisites are basic math, physics, and chemistry at the freshmen and sophomore levels. A first engineering course in materials, mechanics, or circuits is also required, but any given student is not necessarily expected to have satisfied all three of these. Instead, we have chosen to define “team functional prerequisites” (TFPs). Team functional prerequisites are an articulation of specific knowledge components that the authors have developed from our own individual disciplines (ME, EE, MatE). Through collaborative discussion, we draft, modify, and update the TFPs that are most directly relevant to MEMS.

Table 2 shows an example from part of a draft worksheet used by the authors in the process of developing a cantilever beam module that uses surface micromachining. This TFP worksheet is neither comprehensive nor complete, but reveals the emphasis on action words and designates specific assignment of a lead person or “owner” for determining what constitutes proficiency with each TFP.

Table 2. Partial Worksheet for Team Functional Prerequisites - Cantilever Beam Module

Team Functional Prerequisites (TFP's) <i>To achieve significant forward progress with this module, each team must have at least one member who can proficiently...</i>	Faculty Lead (Initials)	Appears in
Calculate the equivalent stiffness and mechanical resonant frequency of a cantilever beam	TH	ME130, E189
Solve a second order linear differential equation	TH	ME130, E110
Determine the stored energy in an RLC circuit.	DP	Phys, ME106
Express stored energy in complex (real & imaginary) notation.	DP	EE98
Interpret the frequency plots associated with RLC filters.	DP	EE110, EE98
Translate between mechanical and electrical stiffness-inertia-damping modeling.	JL	ME147, EE132, ME130, ME106
Calculate the electrostatic force between electrodes and relate to geometric parameters.	JL	MatE25, MatE153, ME189
State the characteristic dimensional scale and size limits in photolithography, etching, and deposition.	DP	EE/MatE 129, EE128, ME189
Distinguish isotropic and anisotropic etching characteristics	SG	EE/MatE 129, ME189
Calculate etch selectivity between two different materials.	SG	EE/MatE 129, ME189
Pattern a wafer using photolithography, including finding contrast curves.	DP	EE/MatE 129
List ways in which process variables affect the thickness and uniformity oxide and metal films.	SG	EE/MatE 129
Explain how process variables (specifically in oxidation, evaporation, and annealing) affect material properties.	SG	EE/MatE 129
Apply probing techniques to measure the resistance between two surface contacts on a wafer	DP	MatE25, MatE153, ME106
Describe the environmental effects on electromechanical behavior (e.g. squeeze film damping).	TH	ME189
List safety rules for working in a microelectronics fabrication laboratory.	SG	EE/MatE 129

Also shown in the table are courses at our institution in which the prerequisites would ordinarily be met. However, it is important to emphasize that the TFPs are not *course* prerequisites, which experience has shown to be in conflict with promoting cross-departmental student enrollment. In many cases, individual students will lack multiple functional prerequisites for a lab module, and this is why they are expressed as *team* functional prerequisites. Team functional prerequisites are action-based learning objectives that are required from past experience, but not necessarily for each and every individual. An important benefit is that students are not hindered by a need to take a lengthy series of prerequisites to begin their active involvement in MEMS education. Team formation will be guided by the course instructor in a survey matching process before each module begins.

Two important features not shown in the TFP table are tracking of missing knowledge and mapping to levels of Bloom's Taxonomy. As we the course developers continue to refine the TFPs, we are not only evaluating how each module TFP maps to Bloom's levels¹⁵, but we are also uncovering specific ones that may be lacking in prior courses taken by an adequate fraction

of prospective students. This detailed knowledge guides us in preparing short primers (tutorials), owned by the faculty lead of each TFP that requires one. Primers take various forms such as short instructor notes, independent reading assignments, or detailed equipment instructions. Primers intentionally have narrow scope according to the TFPs, such as “calculating mechanical resonant frequency of a cantilever beam” or “measuring resistance with contact probes”. Aware of important observations made by others regarding overloaded course content⁵, we design these such that not all individuals necessarily have to be fully proficient for the team to succeed.

Semi-Custom Design Flow. The major obstacles to managing open-ended design problems ultimately come down to facilities, cost, and time. A founding goal of our project has been to enable students to synthesize new solutions in terms of design, process development, and experimental testing. Affordable prototyping becomes the pivotal factor for making open-ended problem-solving practical in terms of implementation. Students will therefore apply *semi-custom design flow*, a principle inherited from and practiced in integrated circuit design.^{16, 17} This we believe to be a creative and innovative concept that is relatively new to MEMS and especially to MEMS education. Semi-custom design involves using a partial set of common mask layouts and templates to save cost and time, while still providing opportunity for students to perform custom experiments. For example, in the cantilever beam example mentioned above, it is possible to have fixed processes for sacrificial layer deposition, (structural) metal deposition, and sacrificial etch, while opening some freedom for students to target specific design objectives (e.g. resonant frequency) by altering beam thickness and gap clearance, and even lateral dimensions using a single custom mask.

Low-Resolution Rapid Prototyping. Extensive use of lower-resolution photomasks further benefits low cost and fast turnaround time. Both of these factors have very high relative merit under the constraints of an instructional course. The cost difference is several hundreds of dollars for a traditional glass-chromium mask (that can routinely define ~1 micron features) and merely a few tens of dollars for a laser photoplotting mask (which is acceptable for ~10-micron features).¹⁸ In many cases, for instructional purposes it is not necessary to have submicron mask resolution to produce working piezoresistors, mechanical beams, or liquid microchannels, for example.

We intentionally omit reliance on external MEMS foundries to overcome wafer processing limitations. While the use of external foundry services is a very reasonable alternative, for this project we have elected to develop the fabrication sequences without required outsourcing for any of the technical modules. This challenges us to develop complete hands-on experience in-house, and also avoids reliance on funds allocated specifically for external fee-based services. We acknowledge that management of outsourcing is a valuable skill in modern industry practice, but for the current project choose to emphasize student learning by first-hand experience with hands-on processing.

Development Framework and Technical Modules

Student Learning Objectives. In contrast to the TFPs needed for building a capable team at the *onset* of each MEMS module, conventional student learning objectives (SLOs) define what students should be able to do *after* completing a module. Table 3 shows examples of SLOs associated with the same cantilever beam module described previously.

Table 3. Student Learning Objectives - Cantilever Beam Module

Student Learning Objectives (SLO's) <i>Each student who fully contributes to the team and successfully completes this module will be able to...</i>
State specific examples of practical micro sensors, actuators, or circuit components that are based on surface micromachined cantilever beams.
Select geometric parameters and material properties required to achieve a target resonant frequency for a microscale cantilever beam.
Apply oxidation, photolithography, film deposition, and etching to fabricate simple free-standing structures with air gap underneath.
Use semiconductor test instrumentation to run a frequency-swept excitation of an electrostatically actuated resonator, and determine the dominant resonant frequency.

Background Expertise. As inherent to its name, the topic of microelectromechanical systems integrates both mechanical and electrical disciplines, and these fundamentally can not be separated from materials issues.¹⁹ The makeup of our development team representing ME, EE, and MatE, covers what we see as a minimum set of combined disciplines, although we fully recognize very meaningful inputs from applied sciences and other engineering disciplines.

Functional Leadership. Aside from background discipline, we also recognize that MEMS education should concurrently address design, fabrication, and testing as three essential components. Accordingly, among ourselves we have assigned champions to each aspect. In our case we happen to have an ME investigator to lead design problem definitions, a MatE investigator to lead fabrication and process engineering, and an EE investigator to lead interfacing and testing. Other combinations are equally valid, but this scenario corresponded well with individual relative strengths. These roles establish ownership, create interdependencies, and provide checks and balances. Such organization promotes frequent dialog and puts success of the total effort in perspective across design, fabrication, and testing.

Module Organization. Rather than developing a single comprehensive exercise or term project, we have taken the strategy of using short instructional modules that allow us to articulate learning outcomes and identify levels of depth in Bloom's Taxonomy with greater specificity.¹⁵ After considering the vast variety of MEMS devices, applications, and fabrication methods, we narrowed options down to three modules for this project. Characteristics of these modules are summarized in Table 4. As is the case with integrated circuits, a rough but often correct estimate of complexity and cost is the number of masks, and these modules are arranged from most simple to most involved.

Table 4. Characteristics of Selected MEMS Technical Modules

<i>Type of Device</i>	<i>Microfluidic Chip</i>	<i>Cantilever Beam</i>	<i>Silicon Membrane</i>
Common MEMS Applications	Protein separation Particle sorting	RF switch Resonant gate transistor	Pressure sensor Diaphragm valve
Examples of Engineering Principles	Electrokinetic flow Fluid scaling laws Polymer processing	Electrostatics Resonance Beam theory	Piezoresistivity Bridge networks 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

Process sequence diagrams to illustrate the two other modules (aside from the cantilever beam already discussed previously) are shown below. Figure 1 shows a microfluidic valve with a laterally-deformable membrane acting as a pinch valve, and Figure 2 shows a conventional silicon-membrane pressure sensor with piezoresistive bridge network. Aside from the functional engineering differences, what is particularly relevant for illustration in this paper is the difference in levels of complexity and corresponding resource requirements.

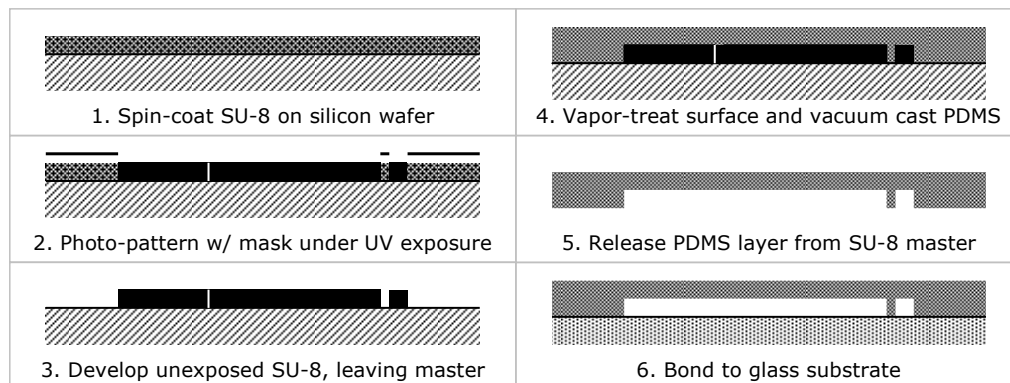


Figure 1. Process Sequence for Micro Pneumatic Valve

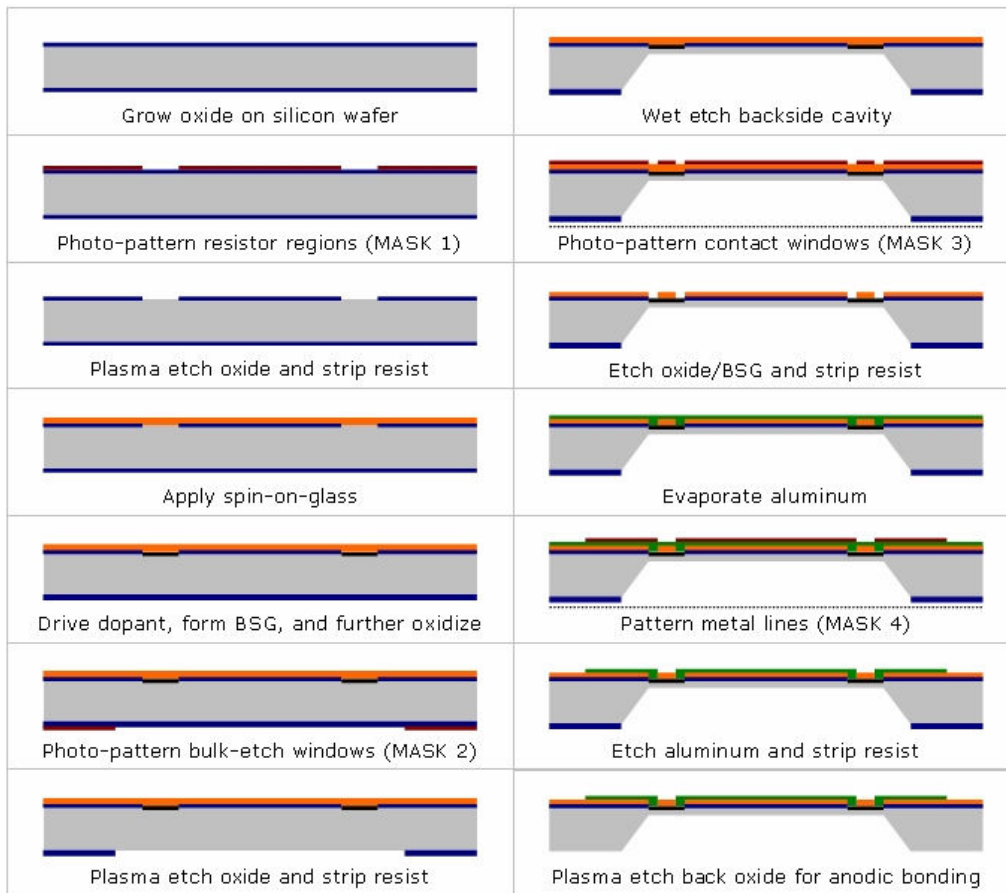


Figure 2. Process Sequence for Pressure Sensor

The microfluidic device is a relatively passive microchannel device that could be actuated in a hybrid mode with an external piezoelectric disk or electromagnetic plunger. The pressure sensor is a more complex device in which sensing elements are fully integrated within the process. However, both share the same framework of using team functional prerequisites and semi-custom design flow, with assigned faculty roles to integrate design, fabrication, and testing across disciplines.

Conclusions

With the work accomplished thus far, the authors have created and continue to refine a framework and process for effective multidisciplinary collaboration in course design. From our own collective experiences and from reviewing related work, we have identified important challenges that are particularly relevant to laboratory-based MEMS education, and have proposed solution strategies. “Team functional prerequisites” and “semi-custom design flow” serve as integral parts of our approach. We have assigned cross-cutting functional leadership to cover the three aspects of design, fabrication, and testing, which are fundamental to any MEMS problem. Selection of a small set of MEMS educational modules has allowed us to capture a representative set of applications and fabrication technologies. While the modules are structured in a common framework, each has unique aspects that flexibly address scope and constraints in

facilities, cost, and time. Summative assessment regarding the success of this effort awaits final implementation with students in Fall 2006, and presently active work includes establishing the specific assessment methods for evaluating student performance and impact.

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