The 18 mm^2 Laboratory: Teaching MEMS Development With the SUMMiT Foundry Process

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***Abstract*—This paper describes the goals, pedagogical system, and educational outcomes of a three-semester curriculum in microelectromechanical systems (MEMS). The sequence takes engineering students with no formal MEMS training and gives them the skills to participate in cutting-edge MEMS research and development. The evolution of the curriculum from in-house fabrication facilities to an industry-standard foundry process affords an opportunity to examine the pedagogical benefits of the latter approach. Outcomes that are assessed include the number of students taking the classes, the quality of work produced by students, and the research that has emanated from class projects. Three key elements of the curriculum are identified: 1) extensive use of virtual design and process simulation software tools; 2) fabrication of student-designed devices for physical characterization and testing; and 3) integration of a student design competition. This work strongly leveraged the university outreach activities of Sandia National Laboratories (SNL) and the SNL SUMMiT MEMS design and fabrication system. SNL provides state-of-the-art design tools and device fabrication and hosts a yearly nationwide student design competition. Student MEMS designs developed using computer-aided design (CAD) and finite element analysis (FEA) software are fabricated at SNL and returned on 18-mm^2 die modules for characterization and testing. One such module may contain a dozen innovative student projects. Important outcomes include an increase in enrollment in the introductory MEMS class, external research funding and archival journal publications arising from student designs, and consistently high finishes in the SNL competition. Since the SNL offerings are available to any US college or university, this curriculum is transportable in its current form.**

***Index Terms*—Educational technologies, finite element methods, MEMS, microelectromechanical systems, microfabrication.**

I. Introduction and Background

THE WORLD of microelectromechanical systems (MEMS) continues to expand, with increasing numbers of devices moving from the laboratory into commercial applications. Thanks to research and development programs in academia and industry, MEMS commercial successes such as inkjet printer heads, pressure sensors, and accelerometers have been joined in high-volume production by devices for video displays and microphones. As both an active research area and a major commercial technology, MEMS is an important venue for pedagogical innovation.

Incorporating MEMS into the undergraduate and graduate engineering curriculum presents major infrastructure challenges. This paper describes a course sequence that combines virtual design and prototyping, off-site fabrication, and hands-on characterization experiments to provide the benefits of laboratory experience while avoiding the acquisition and maintenance costs of a MEMS processing facility. It also describes the use of a sponsored nationwide design competition to motivate students and spur innovation.

Since the early 1990s, a wide range of MEMS curricula has emerged, typically reflecting the resources and research interests of the individual institutions [1]–[5]. Most of these curricula offer a laboratory experience in device fabrication, device characterization, or both. The laboratory components may be physical, using actual MEMS devices and real processing and measurement tools, or virtual, using computer simulation. Since microdevices may behave very differently than their macroscale counterparts, hands-on testing and characterization are critical to developing appropriate intuition. Fabrication experience provides insight into the manufacturing limitations that are an important factor in MEMS design. For example, surface micromachining processes typically make use of a tightly constrained sequence of material deposition, pattern, and etch. The order, composition, and thickness of each layer are completely prescribed, while the designer has wide latitude in specifying the planar pattern.

Fabrication and characterization laboratories present differing resource challenges. It is extremely difficult to develop and maintain fabrication facilities for educational purposes, particularly if they are to reflect the state of the art. Even a basic facility requires a significant initial investment, followed by recurring maintenance and operating expenses. Access is typically limited to a handful of students at a time, who require monitoring by an experienced instructor. Thus, equipment and materials costs, and space and supervision requirements, severely limit the number of students in a class. Furthermore, while relatively inexpensive tools can be used to teach basic principles, production of sophisticated MEMS devices requires equipment and expertise that is out of the reach of most universities.

In contrast to the expense associated with acquiring and maintaining fabrication equipment, useful and informative visualization, characterization, and test of many MEMS devices can be accomplished affordably with optical microscopy,

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a probe station, and standard electrical sources and meters. Characterization is further facilitated if the MEMS is packaged in a standard configuration. Using this approach, it is possible to equip a teaching laboratory with multiple MEMS characterization workstations at a reasonable cost.

This comparison suggests that a cost-effective approach to a hardware-based MEMS curriculum is to perform design and analysis using virtual modeling and prototyping tools and to send the resulting student projects to an off-site MEMS foundry for fabrication. The finished devices can be provided to students for hands-on characterization and test. This model emphasizes design over fabrication and minimizes costs. It is the philosophy underlying the present form of a three-course microsystems sequence at Texas Tech University (TTU), Lubbock, that has evolved significantly since its inception in 2000.

A. Origin of the TTU MEMS Curriculum

The curriculum was initiated with National Science Foundation (NSF) support covering equipment maintenance, operation, and personnel expenses [6], [7]. The courses proved popular, but the intensive physical fabrication format was not sustainable.

In 2004, finite-element simulations replaced the physical laboratory components. Students still enjoyed the course, and enrollment remained strong, but many participants lamented the loss of the laboratory experience. Late in 2004, TTU joined Sandia National Laboratory's (SNL) University Alliance Program (UAP), thus leveraging the enormous infrastructure represented by the SNL Sandia Ultra-planar Multi-level MEMS Technology 5 (SUMMiT V) design and fabrication system. Features include extensive design and analysis software, libraries of predesigned components, and access to the state-of-the-art SNL SUMMiT V fabrication process. The use of SUMMiT software tools for virtual design, off-site fabrication at SNL facilities, and physical characterization and test of student-designed MEMS enabled a cost-effective curriculum combining virtual and physical experiences. Removing the cost and capacity bottleneck of an on-campus fabrication laboratory, while providing an affordable and effective characterization and test experience, led to an improved pedagogy for teaching MEMS to a larger contingent of students. UAP membership also includes the option of competing in the annual SNL UAP student MEMS design competition. Teams of undergraduate and graduate students develop entries for the annual competition, guided by senior graduate students. This provides the peer-mentoring and competitive elements that were identified as keys to the success of the original MEMS course sequence [6], [7].

Basing class activities on an external standard process like SUMMiT has other advantages. When course content is linked to a standard process, as the standard evolves so does the level of technology taught. Using continually supported computer-aided design (CAD) and simulation software, and presenting devices from the literature as case studies, greatly increases the number of effective instruments for instruction. MEMS and integrated circuit (IC) manufacturers have reduced or eliminated in-house fabrication facilities in favor of contracts with independent foundries. Working through a foundry teaches students valuable skills for these industries.

The current SUMMiT-based TTU MEMS curriculum has proven to be financially sustainable, effective, and popular. Innovative MEMS devices designed by course students have been published in top archival journals, have supported funded research proposals and projects, and have consistently won or placed highly in the SNL UAP MEMS student design competition. While the curriculum heavily leverages the SNL UAP, the authors believe the overall educational format is extendable. An example is the introductory MEMS course reported by Lin [8]. Students were allowed a 1-mm^2 area to design a device to be fabricated using the MUMPs foundry process. One hundred such projects could be accommodated on the standard 1-cm^2 chip. Other external or internal MEMS design competitions could also serve to motivate the projects.

B. Sandia National Laboratories SUMMiT V Foundry Process

Despite the wide variety of MEMS devices, there are only a few MEMS foundries. Two of the most prominent processes are MEMSCAP's MUMPS and SNL's SUMMiT. Both are used by a wide range of commercial and university customers [9]. The SUMMiT V process consists of five polysilicon structural layers and four silicon dioxide (SiO_2) sacrificial layers. It can be used to build extraordinarily sophisticated electromechanical devices, including micro engines, gears, hinges, and chains [10]–[13].

Among the aspects that make SUMMiT particularly amenable to educational usage is the accompanying design and visualization software. For a nominal one-time fee, UAP membership supplies US colleges and universities with a comprehensive suite of software tools and training in their use. Proprietary SNL plugins provide specialized functionality for the popular AutoCAD software package. AutoCAD layout tools are used to construct the series of two-dimensional photolithography masks that ultimately define the MEMS devices. Many engineering students have experience with AutoCAD prior to taking the MEMS class, and so come up to speed rapidly. Similar tools are used throughout the MEMS and IC industry, and students trained on the AutoCAD software have a relatively easy time learning other layout systems.

The thicknesses of the polysilicon and SiO_2 layers composing a SUMMiT device are predefined. However, the designer has enormous latitude in creating patterns within the xy-plane. A 2-D visualization tool includes detailed models of each deposition and etch process, allowing the user to predict the cross sections of the fabricated device with remarkable accuracy. The top of the 2-D visualizer screen shows a cross section of each photomask layer. The bottom of the screen shows the SUMMiT layers that result at each step. The layers may be individually examined and manipulated. Thus, this is an excellent tool for teaching the photolithography, deposition, and etch processes and exploring how they influence the final structure.

In addition to the 2-D tool, there are two 3-D utilities that provide models of the device being designed. The *3D Visualizer* produces a 3-D model of a device in just a few seconds. Most of the topographical information is omitted, but the image is a very useful overview. Layers can be removed or separated to investigate specific issues. The *3D Modeler* provides a detailed and accurate topological picture, but can take several hours to render a large device. These images are readily used for journal articles and other professional presentations. Once rendered, the model can be cross-sectioned to reveal additional details. Efficient SUMMiT V design requires that the user understand the strengths and limitations of each of these tools and apply them appropriately. The course instructors frequently use 3-D models to explain the fabrication process.

The SNL software tools come with a vast library of passive and active dynamic devices that have been developed and tested at Sandia. These include a torsional ratcheting actuator that can turn gears and drive linear racks, as well as linear electrostatic actuators that provide single-axis translation. Library parts can be utilized in their entirety simply by pasting them into the design area, or selected portions may be broken out. This feature allows the designer to speed through standard aspects of the design and focus on creativity and innovation since, literally, the (spinning) wheel does not need to be reinvented. Students can start the development of a new device by analyzing the features of working library devices, providing critical insight that increases the probability of achieving working devices of their own.

All fabrication processes have lists of dos and don'ts, called *design rules*. SUMMiT has an extensive set of design rules enforced to prevent undesirable interactions between the numerous processes and layers. Even a minor violation may ruin a device and possibly other devices on the same chip. Given the time and cost needed to produce actual devices, preventing these problems is crucial. However the complex rules are a big hurdle when developing sophisticated, multilevel devices. To lower the barriers to successful fabrication, Sandia provides an online error-checking mechanism that flags violations of minimum feature size, proper overlay geometry, and other guidelines. Once a layout file passes the design checker, it is ready to be fabricated. By using the online checker, following the design rules, and learning from library parts and other successful devices, the number of design/production cycles to produce a successful device is minimized.

A key aspect of most foundry processes, including SUMMiT, is the sharing of a die site by multiple customers to reduce fabrication costs. The die site is the area a photolithography tool can pattern in one exposure, typically about 25 mm^2. SUMMiT devices are produced on 6-in silicon wafers, and each die is segmented into eight 2.82×6.34 mm^2 (18 mm^2) modules. In the final processing steps, individual chips are diced and placed into a hydrofluoric acid bath (HF), which dissolves the sacrificial SiO_2 layers, freeing the remaining polysilicon layers to move. After supercritical carbon dioxide cleaning, the released chips are treated with a coating to reduce the effect of stiction—a nanoscale phenomena that induces adhesion between contacting parts.

For the annual UAP MEMS student design competition, each competing institution submits a chip layout, which may contain multiple MEMS devices [14]. A panel of experts judges the entries. The winning design is fabricated; often, many of the other entries are also fabricated. Participants typically receive about 25 unpackaged chips three to four months after the final layout file is submitted. Sandia charges $\sim$\$17 000 for 200 MEMS chips through their SAMPLES program (2011 price), so free fabrication is a meaningful incentive for the participating schools.

II. MEMS Curriculum, Innovation, and Assessment

The NSF program that initiated the TTU MEMS courses described here had the goal of integrating technologically relevant cutting-edge research into the engineering curriculum. The desired outcome was a curriculum that both teaches students about the latest developments in the most important emerging technologies and prepares participants to be better researchers. The revisions to the MEMS classes have the same goal, through educating a large group of students in the most current MEMS technologies, providing participants with an understanding of the various facets of the engineering development process, and bringing potential MEMS engineers to the point of developing devices with research and/or commercialization merit. Success is assessed through the number of students taking the courses, the quality of student coursework, and the number of publications and research projects supported by designs and devices initiated in the MEMS classes.

The teaching strategy for the MEMS sequence is the organization of class activities around a state-of-the-art MEMS fabrication system. Student interest is cultivated through a tradition of success in a national design competition and by encouraging creativity and individuality in student design projects. Due to the long design and build cycles, knowledge transfer from one group (class year) of students to the next is of paramount importance.

A. MEMS Course Sequence Description

As noted previously, the MEMS courses have gone through various iterations in content. This section describes the content of the courses since focusing on the SUMMiT process (2004–2009). It also provides information regarding the students taking the classes over that time period. The three-course sequence (Table I) was developed to meet the needs of both MEMS novices and advanced students. Undergraduate upperclassmen and all stages of graduate students enroll in these courses. Approximately 67% of the students taking the introductory course (MEMS I) were electrical engineers, and 30% were mechanical engineers. The graduate/undergraduate split is 55%/45%. Most MEMS I students will not be employed in the MEMS area after graduation. However, many will work in fields where emerging micro- and nanotechnologies are being applied. The concepts and knowledge taught in the courses transcend the specifics of MEMS. This partially explains the high level of interest in the courses over the years.

MEMS I gives students a broad perspective on microsystems and covers a variety of fabrication processes. A series of traditional lectures address scaling, MEMS/semiconductor processing, economic/commercialization constraints, and case studies of specific devices such as the Texas Instruments Digital Micromirror Device (TI DMD). In-class tutorials demonstrate various software packages.

The coursework is project-based with four main assignments. The first three are used to introduce students to: 1) gathering, analyzing, and synthesizing prior research; 2) using design and modeling software tools; and 3) using computer simulation tools. The fourth project is an integrative capstone design project. While physical test and characterization is a standard component of the MEMS II and III courses, a series of physical laboratory exercises based on packaged SUMMiT V devices

TABLE I
COMPONENTS OF THE THREE-COURSE MEMS SEQUENCE

	MEMS I	**MEMS II**	**MEMS III**
Knowledge	MEMS overview	Advanced concepts	Research context
	Literature search Case studies		
Software skills	AutoCAD SUMMiT Design ANSYS	AutoCAD SUMMiT Design ANSYS Basic-LabVIEW	AutoCAD SUMMiT Design ANSYS Advanced-LabVIEW
Communication	Paper Powerpoint presentations	Paper (submitted to design competition) Powerpoint presentations	Journal article Powerpoint presentations
Lab skills	MEMS operation	Basic testing	Research-level testing
Project management	Group project	Design competition	Mentoring design competition

has recently been introduced in MEMS I as well. This provides hands-on, interactive reinforcement of the course topics. Since many of these devices are based on student designs from previous semesters, the class gets a preview of what they will soon be capable of accomplishing.

The first assignment is a literature review wherein the student reviews three archival journal articles of their own choosing in a specific microsystems subfield. Students are tasked with comparing and contrasting the three articles, with specific attention to the fabrication processes, materials, performance limits of the devices, underlying physics governing device operation, and the commercial applications and viability of the technology. This exercise plunges the student into the complexities of MEMS device development and introduces concepts that might not be explicitly covered in class until later in the semester. Questions arise as the students wrestle with unfamiliar terminology and ideas. For many students—especially the undergraduates—this is their first introduction to technical journal articles and their first opportunity to learn correct citation technique. The proliferation of on-line resources, and poor habits learned in less rigorous academic settings, has made learning proper scholarly attribution an issue of utmost importance for all students. The literature review sets the tone for the course philosophy of encouraging students to find topics of particular interest to them, which culminates in the final project. It is a general observation that people work harder and spend more time on things that interest them. Graduate students are encouraged to pick projects that complement their other research activities. Anecdotal evidence indicates that this approach increases the time and energy that students devote to their projects.

The assignment is critiqued on the choice of articles, proper citation technique, explanation of device function and underlying physics, comparison of fabrication processes, and discussion of commercialization aspects. The assignment format is intentionally left open-ended, thus there is quite a large variation in length and level of detail. Student reports range in length from just a few pages to more than 20 pages. The best outcomes are associated with reports that are 6–10 pages long. These usually contain careful summaries of the individual articles, with original analysis and conclusions that highlight the main technical contributions. Typically, longer reports include lengthy but superficial rewording of the source articles without in-depth understanding or analysis, and shorter responses simply recap the paper abstracts and include a few extracted figures. This assignment gives the instructors a good initial perspective on the commitment level and analytical abilities of the class.

The second project introduces students to the AutoCAD-based SUMMiT V software tools discussed previously, through the design of a simple electrostatically actuated micromirror. The project is meant to familiarize students with the software and to introduce the numerous SUMMiT V design rules. These design rules govern such things as the minimum feature size and separation between components. The design rules must be observed if the device is to be allowed on a SUMMiT V die. This is an important lesson applicable to many industrial manufacturing systems. Students can choose a micromirror design from the literature, or they can design a device of their own imagining. It is rare to see a novel design this early in the course.

The micromirror design project is evaluated on the student's ability to work within the design rule constraints, as well as on the quality of the student's oral and written presentations. The students must explicitly address target performance metrics and again must demonstrate proper citation technique. Presentations must include 2-D cross-section 3-D visualizer and 3-D modeler depictions. In addition to use of the MEMS design tools, this assignment strengthens technical presentation skills. This aspect of the project is broadly applicable beyond MEMS design.

The third project utilizes finite element analysis (FEA) and simulation tools for MEMS design. ANSYS and COMSOL are two multiphysics FEA simulation packages available at TTU; these and many others are suitable for predicting MEMS behavior. FEA software is now common in academia and industry. It can greatly reduce development and prototyping time and costs. However, the learning curve for FEA software is steep, and the more exposure that students have to such packages, the greater their skill and comfort level. Thus, learning FEA software provides lasting benefits to the students, regardless of the technology area they eventually pursue.

Students are given 4 h of in-class tutorials on the use of a commercial FEA package (usually ANSYS) followed by the third project, which is the evaluation of competing electrothermal actuators, including hot-arm/cold-arm and chevron (bent beam) designs. These devices are quite amenable to FEA analysis, and various tutorials are available to supplement the course instruction. This assignment gives students a working knowledge of the FEA software, sufficient to relate the voltage applied to the device to the actuator displacement and force.

This assignment also contrasts two common ways to obtain a solid model of the device, namely building the model in the FEM program itself, or importing a file from a standalone CAD program. Material constants, finite element(s) with the applicable degrees of freedom, mesh density, boundary conditions, and loads (voltage, force, pressure, etc.) may all be specified. For a basic MEMS device simulation, only about 30 commands are needed, but once FEA principles and ANSYS conventions are understood, additional commands are added very quickly. Perhaps the most important concept taught by this exercise is that learning how to navigate the interactive help facility is much more productive than attempting to memorize individual functions.

In this assignment, an ANSYS macro is given for a particular chevron device, and the students are asked to use the model to improve the design. Success requires the students to understand the commands used to generate the models, to be able to run the simulation and interpret the results, and to modify the original code to test potential design improvements. A final aspect of this project asks the students to explore the issue of device scaling. Much of the scientific and technological interest in micro and nano devices arises from differences in the ways that diverse physical forces scale at the micro and nano realms. This is vividly illustrated by Joule heating and conduction heat transfer, which are rapid processes at the micro/nanoscale, but much slower at the macroscale. For example, microscale chevron actuators can be driven to $\sim 500^{\circ}$C and back to room temperature hundreds of times per second. The principles on which electrothermal microactuators are based could not be competitively applied at the macroscale. Similarly, familiar macroscale electromagnetic motor designs are at best impractical novelties for MEMS devices. These topics are introduced in the classroom lecture and reinforced in the third project by the ANSYS-based scaling analysis.

Teams of two to four students are formed for the final project, which integrates the tools and knowledge gained throughout the semester. When possible, these teams match engineers from different departments and mix undergraduates and graduate students. Students are tasked with developing a MEMS device that can be fabricated in the SUMMiT V process. The students are challenged to develop a new device or a device design that is a significant improvement on existing devices. This is a daunting challenge, but creative students have responded with truly novel ideas. The teams have two to three weeks to generate an idea that is then presented in the classroom. Faculty and students critique, and sometimes reject, the idea. Two weeks later, the teams present updated and refined versions of their projects, incorporating previous criticism. Then, during finals week, the teams give final presentations on their concept and turn in a report in the form of a draft journal article. Because the teams are small, and the projects ambitious, there is typically no danger of one or two students carrying the entire load. The final report should include a review of the relevant literature, AutoCAD/SUMMiT cross-sectional and 3-D figures that display the design, and finite element simulation validating the underlying device physics. In addition, the students should include a draft test plan for the fabricated MEMS. Final oral presentations by the student teams are heavily weighted in the final grade. Most students end up in jobs requiring oral and written technical presentation, and bolstering these skills is a key objective.

B. *Evaluating Learning Outcomes in MEMS I*

As noted above, the MEMS I final project requires students to tie together the concepts and skills learned over the course of the semester. The quality of the final projects is a primary means of evaluating the course effectiveness. This data can only be properly interpreted with reference to the knowledge base of the entering students. Therefore, on the first day of class, students are given a "pretest" to gauge their general MEMS knowledge and awareness. Responses take many different forms. Some are fairly terse with little detail, but rather mention small size and possible applications. Other responses indicate a basic knowledge of what MEMS devices are, why one would want microdevices, and in what applications they are found. Many discuss the TI DMD, reflecting the active institutional cross-fertilization between TTU and TI. However, though students may comprehend DMD function in general terms, they rarely demonstrate a deeper knowledge of MEMS manufacturing. Inspired by popular fiction and speculative science writing, many students imagine medical microrobots traveling the blood stream, battling pathogens, and repairing damaged organs. Students also commonly propose biomimetic MEMS versions of biological organisms. Many of the ideas are unrealizable using current or foreseeable technology, but they inspire creativity and set high expectations that can be translated into more realistic technical goals. These unrealistic preconceptions are quickly corrected within the first couple of lectures, which survey the state of the art of MEMS devices. There are frequently students who want to build devices using magnetic or piezoelectric actuation. In the first SUMMiT V lecture, these students learn why the SUMMiT process largely precludes these options.

Once the course turns to design and fabrication, the material becomes more technically challenging and presents students with many obstacles to master. Special attention is given to teaching the use of subtractive processes since many students have difficulty with the design of etch masks and sacrificial layers. The degree to which these critical concepts are mastered is assessed through the final projects and, to a lesser degree, the micromirror assignment. Another MEMS characteristic that often confounds students at first is the inevitable coupling between different functional aspects of the devices. For example, heating in a thermal actuator cannot typically be restricted to the actuating members only, nor can currents and voltages in an electrostatic device be confined to the designated electrodes. This is fundamentally different from the compartmentalization familiar from macroscale engineering systems, in which insulated wires carry voltage and current, sealed power-trains carry mechanical power, and the like. Understanding of this concept is assessed through the chevron design and analysis assignment, in which the thermal expansion of all elements, not just the chevron arms, must be taken into account. Finally, certain aspects of the SUMMiT process seem to have a steep learning curve for students. These include the need for etch release holes to access sacrificial layers and use of the special "dimple" structures primarily intended to prevent stiction. Awareness of these fabrication issues is assessed using the final project.

The final papers and presentations demonstrate that, by the end of the course, the students have significantly increased their knowledge and understanding of MEMS technology, including, for most, overcoming the common fallacies mentioned above. The final oral presentations and the subsequent question-and-answer period reveal the true level of understanding of the students. In free-form Q&A, the ability (or inability) to articulate reasoning processes and engineering procedures is clearly displayed.

Two faculty instructors evaluate each presentation, each using a standard form to ensure uniform scoring. All students in a group receive the same score, unless it is clear that a particular student has done more or less than their fair share of the work. This scoring system emphasizes the value of teamwork and reflects common scenarios from the engineering workplace.

The final paper should encompass the same material as the presentation and be written in a style suitable for a standard archival journal format. The paper must include an abstract, introduction, literature review, design overview, computer simulations, and device test and characterization plans. On average, the quality of the final work product from the final project has been high. Students usually demonstrate significant gains in MEMS-related knowledge, along with improved facility with broader engineering and scientific skills. The high quality of the best student work is most clearly shown by the number of MEMS I final projects that have resulted in conference proceedings, journal articles, and externally funded research projects.

C. MEMS II Class

MEMS II is completely project-based and revolves around developing entries to Sandia's annual University Alliance Program MEMS Design Competition. The usual protocol is to carry forward the most promising designs from MEMS I. TTU joined the SNL UAP in the Fall of 2004 and entered the inaugural SNL MEMS design contest, held in Spring 2005. This contest has been instrumental in shaping the overall curriculum structure and driving the format of the MEMS II class. The design competition deadline is approximately two thirds of the way through the spring semester, giving MEMS II students a mere 10 weeks to finalize a design and write their contest entry around it. This aggressive timeline places a premium on mastering SUMMiT V design tools and generating candidate design ideas in the MEMS I class. The MEMS II students are expected to propose improved and more thoroughly realized designs, and more detailed simulations, for the competition. Whenever possible, experienced MEMS III students participate as peer-mentors to small groups of MEMS II students. These are typically graduate students involved in MEMS research for their degree work. As for the MEMS I final project teams, an effort is made to match different engineering disciplines and to mix graduate and undergraduate students. MEMS II/III students gain insight into the physical significance of their modeling and simulation work through hands-on characterization and test of MEMS devices designed by previous MEMS II classes and fabricated at SNL. The experience of working with actual devices provides invaluable insight to the capabilities and limitations of the virtual design process.

One of the key benefits of SNL UA membership is the fabrication of student designs by Sandia. This is free for the winning design contest entries, and often for others as well. Finalized CAD files for those who qualify are sent to Sandia in mid-May. Fabrication takes three months. In October, fabricated devices are sent to participating schools for testing and characterization. Thus, characterization is usually done by students who were not involved in the device design. This handoff of devices from one class year of students to the next necessitates careful documentation—another engineering skill with broader applicability. As the new class of MEMS I/II students learns about contest entries from previous years, and as they experimentally test the effectiveness of those designs, they often come up with ideas for improvements. The result is that the MEMS II class considers both incremental advances on previous designs as well as completely new concepts.

MEMS I is aimed at two types of students. One is interested in learning about the emerging areas of micro- and nanotechnology and how they are impacting other fields, but is not expecting to be a MEMS specialist. The other is interested in deeper study in MEMS, leading to MEMS research or a career in the MEMS industry. Typically, only the latter type continues into MEMS II. These students are typically very interested in the technology, and it is rare that they do not give the class a high priority. The smaller size of the MEMS II class (10–15 students) allows extensive one-on-one technical interactions between students and instructors. MEMS research students and experienced senior graduate students act as peer-mentors and provide technical continuity. Students interact frequently with the faculty instructors as they develop entries for the design competition. Student work is evaluated based on the device design, advanced simulations, final paper, and final presentation. Evaluation is similar to MEMS I, but expectations are higher given the greater experience, knowledge, and skills of the student.

D. MEMS III Class

The MEMS III class has exclusively been taken by graduate students engaged in advanced MEMS research. Most have previously taken MEMS I and II, but these are not prerequisites. MEMS III provides a framework for developing leadership and project management skills, as well as for further improvement of written and oral communication skills. MEMS III students serve as peer-mentors and lab instructors for MEMS I and MEMS II. The students are evaluated on mentoring and device characterization and test. MEMS III students are required to prepare a paper for submission to a MEMS conference and/or journal.

III. Results and Discussion

This section reports the outcomes of the MEMS courses, using as metrics the class enrollments, the quality of devices developed, and the research potential of the devices.

A. Course Enrollments

One of the primary goals of the MEMS I class is to provide a basic understanding of micro- and nanotechnology to a broad cross section of students. The success of this objective can be partially assessed by student enrollment numbers. The MEMS courses are offered as Mechanical Engineering (ME) and Electrical Engineering (EE) graduate and undergraduate electives. In Table II, the MEMS I class enrollment is shown for the seven-year span 2003–2009. From 2005 to 2008, there was a large increase in MEMS I enrollment. The 2008 enrollment was viewed as an exceptional number that would undoubtedly decline, but even so the 2009 enrollment was much lower than expected. Known causes of this decrease include a near-doubling of available graduate courses in EE in the Fall 2009 semester compared to historical levels and the availability of the class during the Summer 2009 session. In Fall 2009, for unknown reasons, the course dropped in popularity among ME students.

The historical enrollment of the MEMS I classes indicates that there is a broad interest in this technology area. The current version of the MEMS I course has been designed to accommodate the increased enrollment. Moving forward, the physical

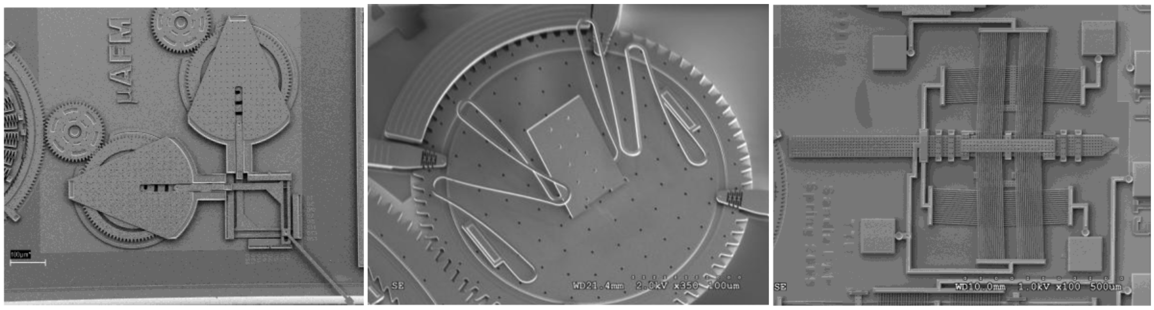

Fig. 1. *(left)* Two-axis micro-stage. *(middle)* Spinning 45° tilted micromirror. *(right)* Bidirectional linear probe.

TABLE II
MEMS I (XE X385) AND II (XE X386) CLASS ENROLLMENTS: 2003–2009

Class	F 03	S 04	F 04^	S 05	F 05	S 06	F 06	S 07	F 07	S 08	Su 08	F 08	S 09	Su 09	F 09
EE 4385	5		7		12		13		18		10	15		3	3
ME 4385	0		1		3		1		5		0	17		0	1
EE 5385	6		9		9		9		15		0	23		5	9
ME 5385	11		3		3		6		17		4	10		0	0
Total	**22**		**20**		**27**		**29**		**55**		**14**	**65**		**8**	**13**
EE 4386		3		1		8		4		2			1		
ME 4386		0		0		0		0		0			0		
EE 5386		6		7		5		5		7			5		
ME 5386		6		0		1		2		3			0		
Total		**15**		**8**		**14**		**11**		**12**			**6**		

^ Joined Sandia's University Alliance Program 10/04
F = Fall semester, S = Spring semester, Su = Summer semester

testing and characterization component are being further developed in order to provide the earliest possible hands-on experience with actual MEMS devices in a way that is scalable to even higher numbers of participants (~ 50). The MEMS II class has always had much fewer students than MEMS I due to the narrower focus and the limited number of students pursuing M.S. or Ph.D. degrees in MEMS. The MEMS III class has averaged three students per year and has only been taken by MEMS research students.

B. Quality of Device Designs

Assessing the quality of device designs occurs at multiple levels. Internally, as described above, device designs are evaluated through class presentations and papers. Externally, device designs and accompanying papers are submitted to the Sandia design competition, where they are rigorously judged in the two categories of "Novel Design" and "Characterization and Reliability" by MEMS experts from around the country. Over the first six years of the competition, TTU student teams have taken first place four times (2005: Novel Design; 2006, 2009, and 2010: Characterization and Reliability). This consistent level of high performance, as judged by objective third parties, validates the structure of the TTU MEMS curriculum. It sets a high standard for future participants, but it also creates a tradition of excellence and the expectation of success.

C. Publications and Research Funding

Devices arising from the TTU MEMS curriculum and SNL student design competition have been innovative and interesting enough to serve as the basis for archival journal publications and conference proceedings and for research proposals and externally funded research projects. These include the following: a two-axis stage [15], [16] in 2005; a piston micromirror [17], cantilever sensors [18] and resonant sensors [19] in 2006; a microgripper [20], a linear actuator [21]–[24], a spinning micromirror [25], [26], and a nonlinear control micromirror [27] in 2007; and a MEMS array/remote access [28]–[30] in 2008.

Most often, iteration is required to refine a student design to the point of publication. However, the class is structured to encourage this process. Four examples of this will be given. In 2005, a biaxis micro-positioning system was designed to scan a probe over a distance of 110 μm in two directions (Fig. 1). The device was inspired by the operation of an atomic force microscope. Once fabricated, the device was tested and found to work as designed. In 2006, an updated version of the system was designed with bidirectional actuators, allowing the probe

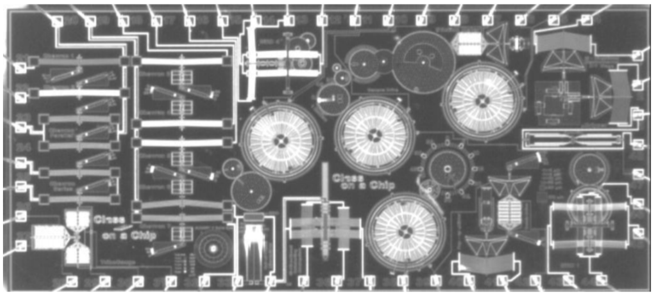

Fig. 2. Image of MEMS device array used in the Class on a Chip System. The chip area is 2.82×6.34 mm^2 ($\sim$18 mm^2).

to go both forward and backward. The second version was only partially successful, but showed the way to a third-generation device with nearly complete functionality. The second-generation device also provided the basis for a research proposal that led to an externally funded program in precision microscale positioners. This example illustrates that advanced research goals can be achieved by sequential teams of relatively inexperienced students.

A second example is a micro-cantilever array that can be functionalized through wet chemistry techniques and used in standard sensing configurations using an optoelectronic system. This student project was advised by an expanded interdisciplinary faculty team, including researchers in the Departments of Chemical Engineering and Chemistry. The work led to an archival journal publication [22] and served as the basis for an (unfunded) proposal.

The third and fourth examples are a micro-periscope (a spinning, 45°-tilted micromirror) and a bidirectional ratcheting linear drive (shown in Fig. 1). The micro-periscope device [30] was published in a premier MEMS journal, the *Journal of Microelectromechanical Systems* (JMEMS), and a paper on the linear drive [28] is in press. Both projects were presented at an international MEMS conference.

IV. Future Work: Class on a Chip System

The Class on a Chip System is the next step in the curriculum development efforts. A detailed description is beyond the scope of the present paper, but briefly, the technology incorporates an array of MEMS devices (Fig. 2) on a single SUMMiT V chip powered by a custom power supply and controlled by a LabVIEW GUI. A microscope is used to image individual devices. The system allows for expanding operation of MEMS devices in the MEMS I class and is also suitable for use in other courses. The chip includes a wide range of devices, making possible experiments in physics, engineering, and micro/nanotechnology.

The Class on a Chip System directly results from MEMS course sequence activities. Because the devices are controllable by the user and their behavior is easily observed, they encourage self-guided exploration and enable students to develop a strong empirical sense for what comprises a workable and efficient design. This prevents commonly observed design errors, such as incorporating actuators that do not provide enough displacement or making features too small or too big.

V. Conclusion

This paper has described a MEMS course sequence incorporating the design, fabrication, and testing of SUMMiT MEMS devices and culminating in the Sandia MEMS Design Competition. The result is a productive learning cycle in which students first receive a strong foundation in MEMS technology, then study and characterize existing devices, and finally develop and design entries for a national student design competition. The design competition motivates the class both by building excitement and team spirit and by imposing hard deadlines. Successes achieved by previous classes inspire and challenge future classes to match or surpass them.

Students completing the first two courses are encouraged to serve as peer-mentors for the following year. This approach builds team spirit, student confidence, and a tradition of excellence and provides enough continuity and accumulation of expertise to produce sophisticated devices of significant research value. This curriculum provides an exciting avenue for an in-depth educational and research experience on complex microscale systems. It provides a forum for creative, open-ended design by interdisciplinary teams. Other educational benefits include learning about semiconductor and MEMS processing and constraints, utilizing 2-D and 3-D CAD tools, utilizing software simulation, and building devices to support individual research projects.

Publications and funded grants based on MEMS class student designs demonstrate the depth of the educational experience and illustrate that the educational aspects of the MEMS curriculum complement the MEMS research endeavor. This interaction between research and coursework remains active and fruitful. Other ongoing work includes the development and further integration of the Class on a Chip System MEMS-based laboratory into the MEMS classes both at TTU and other universities. Internet connectivity for the system has also been developed and tested.

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