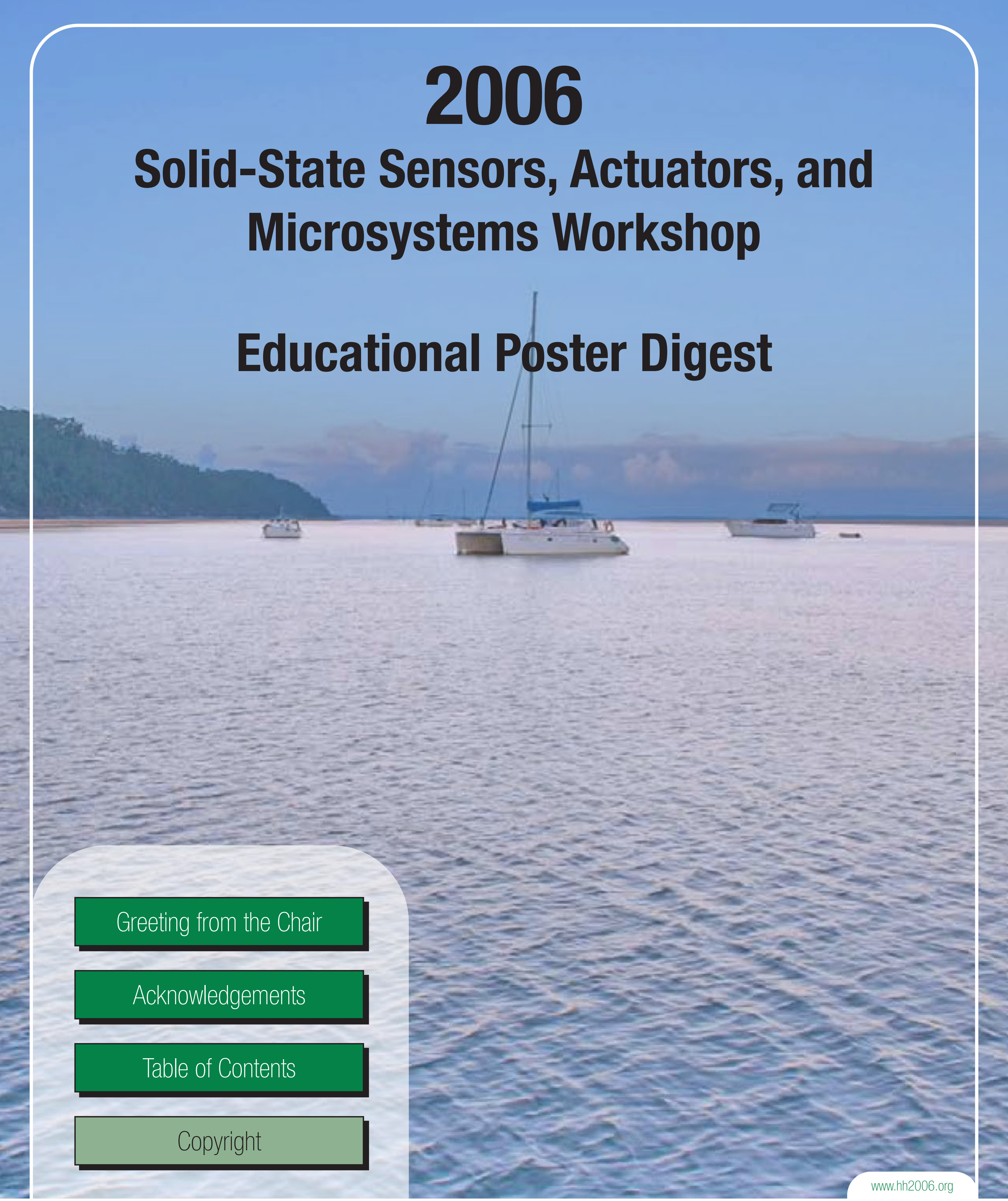


2006

Solid-State Sensors, Actuators, and Microsystems Workshop

Educational Poster Digest

Greeting from the Chair

Acknowledgements

Table of Contents

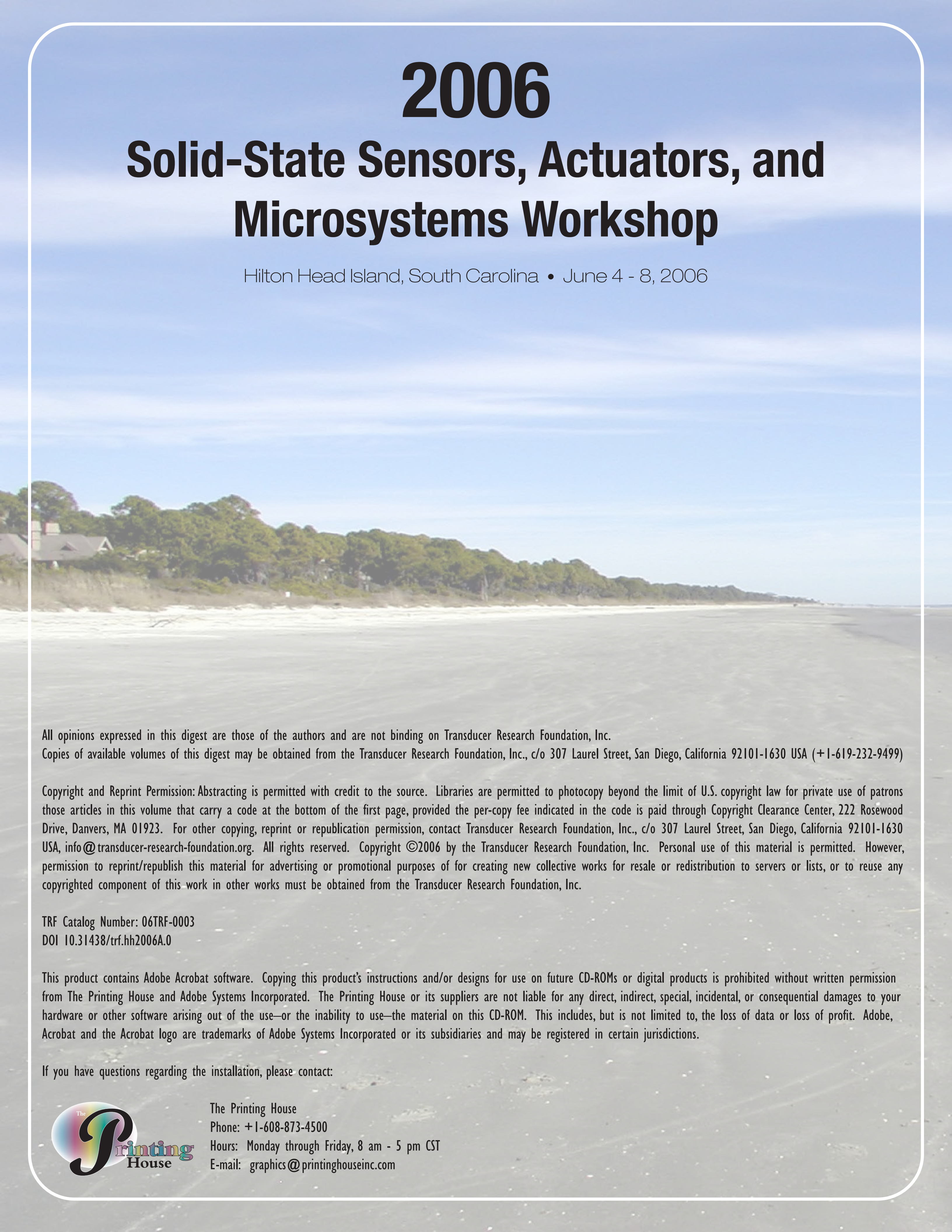
Copyright

www.hh2006.org

Sponsored by the
Transducer Research Foundation, Inc.
Additional support provided:
National Science Foundation and National Aeronautics
and Space Administration Goddard Space Flight Center

Hilton Head Workshop
June 4 - 8, 2006 • Hilton Head, South Carolina
Editors: Leland “Chip” Spangler, Thomas W. Kenny, and Martin A. Schmidt

TRF Catalog Number: 06TRF-0003
DOI 10.31438/trf.hh2006A.0



2006

Solid-State Sensors, Actuators, and Microsystems Workshop

Hilton Head Island, South Carolina • June 4 - 8, 2006

All opinions expressed in this digest are those of the authors and are not binding on Transducer Research Foundation, Inc.

Copies of available volumes of this digest may be obtained from the Transducer Research Foundation, Inc., c/o 307 Laurel Street, San Diego, California 92101-1630 USA (+1-619-232-9499)

Copyright and Reprint Permission: Abstracting is permitted with credit to the source. Libraries are permitted to photocopy beyond the limit of U.S. copyright law for private use of patrons those articles in this volume that carry a code at the bottom of the first page, provided the per-copy fee indicated in the code is paid through Copyright Clearance Center, 222 Rosewood Drive, Danvers, MA 01923. For other copying, reprint or republication permission, contact Transducer Research Foundation, Inc., c/o 307 Laurel Street, San Diego, California 92101-1630 USA, info@transducer-research-foundation.org. All rights reserved. Copyright ©2006 by the Transducer Research Foundation, Inc. Personal use of this material is permitted. However, permission to reprint/republish this material for advertising or promotional purposes of for creating new collective works for resale or redistribution to servers or lists, or to reuse any copyrighted component of this work in other works must be obtained from the Transducer Research Foundation, Inc.

TRF Catalog Number: 06TRF-0003
DOI 10.31438/trf.hh2006A.0

This product contains Adobe Acrobat software. Copying this product's instructions and/or designs for use on future CD-ROMs or digital products is prohibited without written permission from The Printing House and Adobe Systems Incorporated. The Printing House or its suppliers are not liable for any direct, indirect, special, incidental, or consequential damages to your hardware or other software arising out of the use—or the inability to use—the material on this CD-ROM. This includes, but is not limited to, the loss of data or loss of profit. Adobe, Acrobat and the Acrobat logo are trademarks of Adobe Systems Incorporated or its subsidiaries and may be registered in certain jurisdictions.

If you have questions regarding the installation, please contact:

The Printing House
Phone: +1-608-873-4500
Hours: Monday through Friday, 8 am - 5 pm CST
E-mail: graphics@printinghouseinc.com

Greetings from the Technical Program Chairman

The technologies used in sensors, actuators and microsystems, MEMS, MOEMS and related fields at the nanometer scale are inherently complex and multi-disciplined. People involved in these technologies have expertise in several core subject matters: electronics, optics, mechanics, chemistry, materials, etc. What makes the technology even more challenging is the complex interactions between these subjects and the interaction of the resulting devices with the physical world. Ultimately what drives the technology are people who can apply knowledge of these subjects to specific applications where cost, size, performance and reliability are the primary metrics for success.

The foundation for the success of any discipline lies in a broad and diverse education process. The educational challenges in our field are enormous and the demand is great. To help fill this educational demand, universities have developed a wide range of multi-disciplinary classes and curriculums. These non-traditional educational efforts can be grouped under the broad term of “MEMS Education”. The continued demand for students trained in these diverse subjects and the broad range of educational approaches has lead the Technical Program Committee to explore “MEMS Education” as a workshop topic in and of itself. The desire is to create a forum where the educational needs and the approaches to filling them can be examined in a way that is beneficial to both.

Introducing a new subject matter into a prestigious meeting such as the Sensors, Actuators and Microsystems Workshop must be done very carefully. After solicitation and review of the MEMS Education abstracts, it became clear that there was a wide range of interpretations as to what constituted MEMS Education. Abstracts included curriculum overviews, educational pedagogy, descriptions of individual courses, and descriptions of specific laboratory modules. The TPC felt that all the abstracts would be of interest to Workshop participants and since there are no established metrics for peer review, it was decided to publish all of them this year. Given the historically stringent acceptance criteria at the Hilton Head Meeting, we also felt that accepting these abstracts as regular oral or poster paper would not be appropriate. The result is the publication of this digest and as well as the special “MEMS Education Poster Session” held on Wednesday night.

It is also understood that this initial effort should probably be modified for subsequent meetings. Given the interactive nature of this Workshop, and the opinionated people that attend, we intend to explore, in several different forums, whether or not this effort should continue, and if it should continue, begin establishing the expectations and ground rules that are needed for this evolution. We trust that you will be free with your ideas and suggestions both during and after this meeting.

I would like to thank Marty Schmidt for his work in reviewing the submitted abstracts and the recommendations he has made to the Technical Program Committee. I would also like to thank Beth Pruit for providing the initial motivation for this work. Katharine Cline and her colleagues at PMMI are to be acknowledged for their help in incorporating this subject into the workshop. Thanks goes to the National Science Foundation and NASA for help in publishing this digest and to the Transducers Research Foundation for their broad support of this meeting. And finally, thanks goes to Tom Kenny whose leadership and contagious energy and enthusiasm has helped continue the tradition of excellence in this meeting.

Sincerely,

Chip Spangler

Leland “Chip” Spangler

Acknowledgement

We gratefully acknowledge support by the National Science Foundation (NSF) and the National Aeronautics and Space Administration Goddard Space Flight Center (NASA-GSFC) the MEMS Education track at this conference. These MEMS Education printed proceedings and poster session were supported by NSF grant ECS-0503895 and a NASA-GSFC educational grant.

Table of Contents

EDUCATIONAL POSTER DIGEST

Solid-State Sensors, Actuators, and Microsystems Workshop

2006
Hilton Head Island, South Carolina
June 4 - 8

A MEMS/MICROSYSTEM CURRICULUM WITH INTERNATIONAL DISSEMINATION

L. C. McAfee, K. Najafi, Y.B. Gianchandani, K. D. Wise, and M. M. Maharbiz
Engineering Research Center for Wireless Integrated MicroSystems
Electrical Engineering & Computer Science Department, The University of Michigan
Ann Arbor, MI 48109-2101, UNITED STATES

D.M. Aslam
Engineering Research Center for Wireless Integrated MicroSystems
Electrical and Computer Engineering Department, Michigan State University
East Lansing, MI, 48824, UNITED STATES

P.L. Bergstrom, C.R. Friedrich
Engineering Research Center for Wireless Integrated MicroSystems
Electrical Engineering Dept and Mechanical Engineering Dept, Michigan Technological University
Houghton, MI 49931, UNITED STATES

ABSTRACT

The Engineering Research Center for Wireless Integrated MicroSystems has developed five core courses that provide a broad comprehensive curriculum in MEMS and microsystems for upper-level undergraduate students, graduate students, and industry professionals. The curriculum design has flexibility that invites development of other core courses, as well as related technical electives and breadth electives. The core courses provide instruction in MEMS, microsystems, laboratory measurements, societal impact, and a major design experience. The course enrollments have been high. The existence of this core curriculum has also led to the establishment of a Master of Engineering degree in Integrated Microsystems; thus, industry professionals have a focused set of coursework, while flexibility permits custom tailoring of the total course package to serve individual preferences. Distance education dissemination of the courses as whole courses, or as discrete portions of course materials, is available. The core courses originate at the University of Michigan and have been distributed to Michigan State University, Michigan Technological University, Howard University, University of Puerto Rico – Mayaguez, and Western Michigan University. Rochester Institute of Technology has used course materials from the core courses in its offerings. Other institutions that have used the course web-streaming video and course materials are University of Lille, Darmstadt University, and Middle East Technical University.

This paper has descriptions about the curriculum design process across the three partnering universities, resources for (and development of) individual course materials, development of primary and secondary instructors, as well as the responsibilities and preparation of local instructors at the receiving institutions (universities and industry). Also, alternative methods for MEMS-based distance education at a reasonable cost are described.

INTRODUCTION

The Engineering Research Center (ERC) for Wireless Integrated MicroSystems (WIMS) has developed five core courses (Figure 1) that provide a broad comprehensive curriculum in MEMS and microsystems for upper-level undergraduate students, graduate students, and industry professionals. The five core courses originate at the University of Michigan (UM): *Introduction to MEMS* (EECS 414), *Integrated Microsystems Laboratory* (EECS 425), *Advanced MEMS Devices and Technologies* (EECS 514), *Advanced Integrated Microsystems* (EECS 515), and *Societal Impact of Microsystems* (EECS 830). The first of these courses has now been disseminated worldwide, while the second is exploring ways of porting a laboratory course to different universities. The *Societal Impact* course explores the global societal challenges that will be faced by students during their careers and how microsystems will be used to address them. Each course is a four credit-hour course; however, EECS 830 is a two credit-hour course.

During a two-day WIMS education retreat that was well attended by faculty members of the three core-partner universities, the WIMS MEMS/microsystem curriculum was designed to (1) provide students with a comprehensive background in fabrication, MEMS/microsystems theory, practice, applications, and technology, (2) accommodate students from broad disciplines across science and engineering by developing a first course that had minimal prerequisites in science (physics and chemistry), math, and engineering, (3) use the first course as the only prerequisite for the remaining core courses, (4) develop course materials with the expectation that distance education with web-based dissemination would be a primary format, (5) serve undergraduate and graduate students, as well as serve practicing professionals, (6) be available for students at all three partnering universities (UM, MSU, MTU), (7) develop skills in critical assessment of diverse technologies and devices, (8) develop engineering project management skills, (9) be a core set of requirements for a graduate professional degree program to accommodate practicing professionals desiring an advanced degree, and (10) be flexible enough to encourage creation of other courses with links to broad interdisciplinary areas. All of these design goals have been met (and in many cases exceeded), with high student enrollment in all the core courses at WIMS ERC partnering universities. Several of the courses have been adopted by other universities, nationally and internationally. Curriculum approvals and local course numbers have been obtained at Michigan State University (MSU) and Michigan Technological University (MTU). Also, these courses have been used at Western Michigan University (WMU), University of Puerto Rico – Mayaguez (UPRM), Howard University (HU), and Rochester

06TRF-0003/hh2006/$20©2006TRF
DOI 10.31438/trf.hh2006A.1

Institute of Technology (RIT) in the United States, and internationally at the University of Lille, Darmstadt University, and Middle East Technical University.

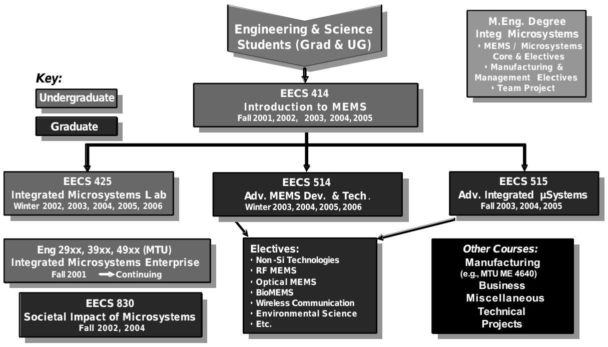


Figure 1. *WIMS ERC MEMS and Microsystems Curriculum Design.*

In addition, technical electives offered include *Integrated Analog/Digital Interface Circuits* (EECS 511), *RF Wireless MEMS* (EECS 598A), and *BioMEMS Through the Developing Organism* (EECS 598B). These courses have led to the inclusion of MEMS and microsystem topics in other courses as well, from sophomore year to the advanced graduate level.

The following segments of this paper describe ways that the goals were addressed and have progressed. Issues associated with development of each course from EECS 414 to EECS 830 are presented in this paper. Enrollment in each course is presented in a table including all courses. Factors are presented associated with distance education and a master of engineering degree program. A list of acronyms is at the end of this paper.

INTRODUCTION TO MEMS (EECS 414)

One of the main challenges in MEMS education has been teaching the ***first*** course to novice ***undergraduate*** students. Several questions immediately arise as one begins to prepare such a course. Who is taking the course and what backgrounds do they have? What should be the prerequisites, if any? Should the first course be available to most engineering students, or should access be limited by adding one or several prerequisites? When is the right time to take this course? What should be taught in the course, what should be the balance between theory and practice/technology, and what is the objective of the course? Should it have a lab component, should it have a major design project, or should it have several projects? Should design and software tools be taught? If the course is available to both undergraduate and graduate students, how can they be accommodated in a single course, or should they be? What does/would industry like to see in this course? Is one course sufficient to prepare students for practicing MEMS in industry? Undoubtedly many institutions have faced these and other questions as they attempted to prepare such a course. A few answers/decisions for these questions are presented here, along with the philosophy and experience gathered at the University of Michigan over the past five years since we started teaching an "Introduction to MEMS" course.

We believe that the first course should be open to all engineering and science students with an interest in learning about MEMS, irrespective of their discipline. The only requirements are basic math, physics, chemistry, and a basic background in electrical and mechanical physics as is typically offered in most engineering/science curricula. This introductory course is designed for students who are not familiar with MEMS, microfabrication and micromachining technologies, integrated circuits, or non-electrical devices and systems. The course has discussion sections that enhance both mechanical and electrical background areas for science majors (such as physics and chemistry majors, etc.) and other engineering majors (such as non-EE and non-ME) students. The course has also been taken via the internet by students at several other institutions, and challenges in this area have been identified.

Since micromachining technology affects all aspects of MEMS, the course starts with a detailed coverage of microfabrication and micromachining, including planar thin-film processes, photolithographic techniques, deposition and etching techniques, wafer bonding, and electroplating. These topics are followed by a detailed coverage of surface, bulk, and electroplating micromachining technologies and review of example devices. A designer of MEMS requires knowledge and expertise across several different disciplines. Therefore, this course pays special attention to teaching of fundamentals of transduction mechanisms (i.e. conversion of non-electronic signals to electronic signals), including capacitive, piezoresistive, and thermal techniques, and design and analysis of micromachined sensors and actuators. The course also introduces students to MEMS-specific computer-aided design (CAD) simulators, including Coventorware and ANSYS. Assignments allow students to use CAD tools to simulate a few sample structures and compare their operation to calculated values.

Figure 2 summarizes the topics covered in EECS 414 (highlighted in **bold**) in the context of all topics that we think eventually should be covered in an effective MEMS curriculum. The first course *Introduction to MEMS* (EECS 414) is the only prerequisite needed for follow-on courses. During its first offering in Fall Term 2001, a textbook *Microsystem Design* [**1**] was designated. After that term, the reading materials resources have been course notes and PowerPoint slides that were developed by UM faculty, as well as numerous designated journal and conference articles [**2-4**]; these resources better match the content and flow of the course. These resources have been readily shared and provided to others who seek to develop a course at their institution.

Materials/Fabrication	**Transducers**	**Microsystems**
Materials	Energy Domains	*Circuits*
Silicon & Related	**Electrical**	*Sensor & Actuator*
Semiconductors	**Mechanical**	*A-D Conversion*
Non-Silicon	**Thermal**	
Micro-Fabrication	Chemical/Gas/Bio	*System*
Photolithography	Optical/Radiative	*Architecture,*
Planar		*Partitioning*
Microfabrication	Transduction	*Signal Processing*
Micromachining	Techniques	*Power Issues*
Photolithographic	**Capacitive**	*Power/Energy*
(Parallel)	**Piezoresistive**	*Source*
--- Planar	**Thermal**	*Power Dissipation*
--- Si Etching &	Magnetic	*Management*
Machining	Piezoelectric	*Noise and Signals*
Non-Photographic	Resonant	*Sources*
(Serial)	Tunneling	*Limits*
--- Non-planar, 3D	Optical/Radiative	*Communication*
--- Standard	Others	*Testing & Calibration*
Precision	**Sensors**	*Integration*
Machining	**Actuators**	*Packaging*

LEGEND:
Bold --- Introduction to MEMS (EECS 414)
Plain --- Advanced MEMS Devices and Technologies (EECS 514)
Italic --- Advanced Integrated Microsystems (EECS 515)

Figure 2. *Content Topics for Three Core Courses.*

Table 1 shows the enrollment in the course (at all institutions), including the breakdown of undergraduate and graduate students taking the course at the University of Michigan for the past five years. Although the initial enrollments in the course were mostly graduate students, it now has a 2:1 ratio of undergrads to grads. This trend clearly indicates the growing interest in MEMS as a discipline often required by industry.

Table 1. *Enrollment History by Groups in* Introduction to MEMS (EECS 414)

	2001	2002	2003	2004	2005
UM Ugrad Students	20	26	61	52	57
UM Grad Students	37	40	43	25	26
UM Total Students	**57**	**66**	**104**	**77**	**83**
University Dis.Ed. Stds	25	23	42	45	48
US Total Students	82	89	146	122	131
Industry Dis.Ed. Stds			3	5	3
International Dis.Ed.Stds		29	20	31	64
Total StudentsWorldwide	**82**	**118**	**166**	**158**	**198**

INTEGRATED MICROSYSTEMS LABORATORY (EECS 425)

In this one-semester laboratory course, students work in four-person teams; they define, design, fabricate, and test a microsystem of their choice. The microsystems realized typically consist of a two-chip combo: a transducer chip and a circuit chip, fabricated over the course of a 14-week semester (six weeks in microsystem design, five weeks in fabrication, and three weeks in test). The course accepts senior and first-year graduate students from either a device or circuit or MEMS background and serves as a major design experience for undergraduates. It allows students to understand the interactions among design, fabrication, and test, and for many this course is the only chance they will ever have to take a chip all the way from inception to final test. Students come from various engineering majors (electrical, mechanical, biomedical, and chemical), as well as from physics.

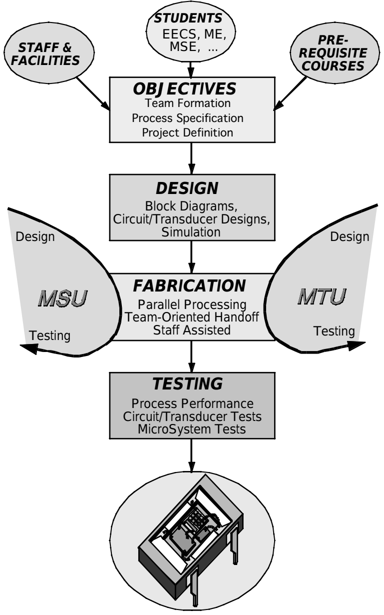


Figure 3. *Activity Flow for* Integrated Microsystems Laboratory *(EECS 425).*

Figure 3 shows the activity flow for the course, consisting of two 80-minute lectures per week plus one 3-hour laboratory session. The lectures are taped and available over the web, permitting the course to be taken at other universities (currently Michigan State and Michigan Tech) with an on-site instructor. Designs created by students at MSU and MTU are fabricated at UM (during those fabrication weeks, MSU and MTU students fabricate other devices in their own laboratories) and are then returned to them for testing. For the circuitry, a five-mask ion-implanted silicon-gate LOCOS E/D NMOS process is used. While this process lacks the performance of a full CMOS process, it can be run in five weeks or less and exposes students to a full range of process steps. For the transducers, a silicon-on-glass (dissolved-wafer) process is used, allowing a wide range of devices to be realized in six masks and allowing wafer bonding and diffused etch-stops to be illustrated. The students are given the processes and a 2mm x 2mm die area for each chip and are challenged to get the best performance they can from whatever design they elect to realize.

Figure 4 shows a die photograph and close-up of a typical transducer die, while Figure 5 shows one of the circuits realized in the course along with one team in cleanroom garb. Mask fabrication and ion implantation are done in foundries, with students performing all other processing steps, except for those processes involving chemical vapor deposition that are done by engineering staff. Visible imagers, pressure sensors, accelerometers, g-switches, tactile imagers, micro-flowmeters, micro-mirror arrays, mass sensors, and Pirani gauges have been realized. The course projects often find their way into student resumes and occasionally receive broader exposure. A project two years ago won second place in the Design Automation Conference (DAC) student design contest and was featured there and at the International Solid-State Circuits Conference.

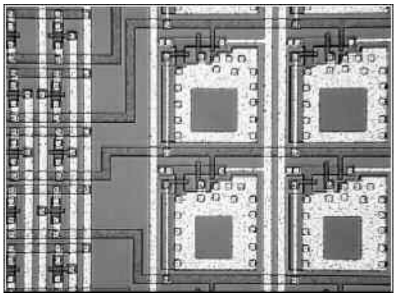


Figure 4. *Visible Imager Transducer Die for* Integrated Microsystems Laboratory *(EECS 425).*

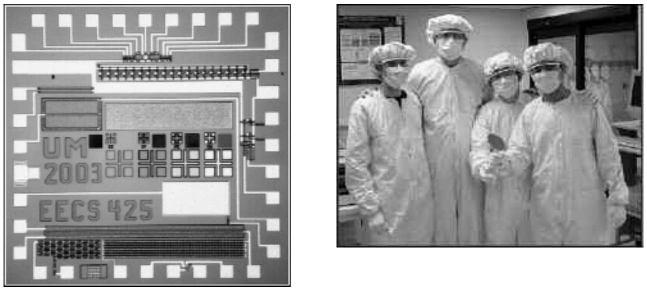


Figure 5. *An IC produced in the* Integrated Microsystems Laboratory *(EECS 425) and a photo of students in the cleanroom.*

ADVANCED MEMS DEVICES AND TECHNOLOGIES (EECS 514)

EECS 514 is largely an Advanced MEMS Technologies course as it continues the MEMS topics started in EECS 414, as indicated in the Figure 2 list of topics. EECS 514 covers advanced topics dealing with MEMS technologies, transduction mechanisms, and microfabricated sensors and actuators. Many emerging micromachining technologies, such as laser and electro-discharge micromachining, and non-conventional materials, such as silicon-carbide and diamond are discussed. Transduction techniques, including electromagnetic, piezoelectric, resonant, tunneling, and others are presented.

The course reviews different types of sensors for measurement of physical parameters such as acceleration, rotation rate, and pressure, as well as chemical and gaseous parameters for gas and chemical sensing applications. It also reviews different micro-actuation techniques and their application in MEMS. The course also reviews MEMS for use in microfluidics and in biomedical applications. An important part of this course is a design project carried out in teams who develop, simulate, and design a device of their choice, and present their findings in a technical article. MEMS-specific CAD tools such as Coventorware and ANSYS are used to design and model the devices. The course is highly structured, with two intermediate presentations and a final one at the end of the course. Typically, students read 25 to 40 papers [**5-7**], and 6 to 8 student reports. A highlight assignment is students working in teams to develop sensor or actuator concept MEMS; see Figure 6 for a sample of three concept projects. The concept of an NSF-style panel discussion and peer review procedure is discussed. (However, the reports are not written in proposal style, and the students are not expected to project beyond their findings to propose work that will be done in the future. That approach comes up in EECS 515.) All students provide individual assessments of all projects at the end of the course. Students have been from several engineering majors: electrical, mechanical, biomedical, and chemical engineering, as well as from applied physics. All course materials, including lecture notes and lecture videos, are available via the web.

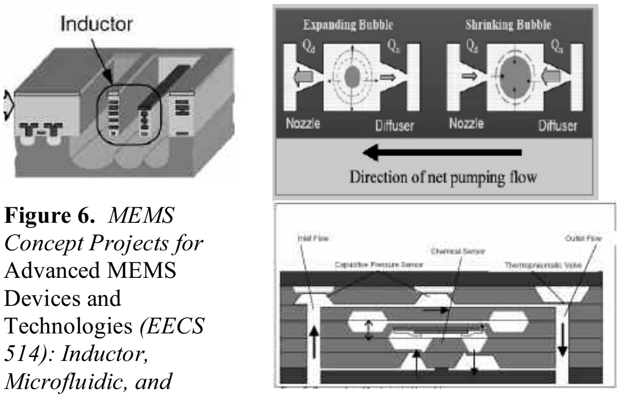


Figure 6. *MEMS Concept Projects for* Advanced MEMS Devices and Technologies *(EECS 514): Inductor, Microfluidic, and Integrated Sensors Devices.*

ADVANCED INTEGRATED MICROSYSTEMS (EECS 515)

EECS 515 is an Advanced Integrated Microsystems course, building upon the MEMS topics and microsystems introduction presented in EECS 414. Prerequisites for this course include the equivalent of EECS 414 or EECS 514, and graduate standing. The students are also expected to have a working knowledge of basic analog circuits. It is desired that students would have completed EECS 425, but not required. EECS 515 is the third in the 414, 514, 515 trio of courses that was developed as part of the MEMS/Microsystems core curriculum (with topics identified in Figure 2). As such, it is directed primarily at graduate students and industry professionals who have already achieved a level of comfort with MEMS technology, and are familiar with the important transduction methods, device concepts, and fabrication techniques. As in EECS 514, students read 25 to 40 papers [**5-7**], and 6 to 8 student reports. For EECS 515, a highlight assignment is students doing an NSF-style proposal centered around a microsystem design to solve an application; see Figure 7 for a microsystem design template, and a diagram for a cardiac stent microsystem project.

The topics covered in this course are a mix of device and circuit issues that are closely inter-related and are critical to a full understanding of microsystems. They include, for example, general ways to analyze noise in electronics and sensors; various kinds of interface circuits for capacitive, resistive, tunneling and other kinds of sensors; proportional integral controllers; dithering and modulating circuits; switched-capacitor interface circuits; correlated double-sampling; calibration schemes; system organization; digital bus protocols for transducer systems; packaging; and cost projections. The topics are relevant to both industrial practice and microsystems research, and address both fundamental and practical problems that arise in this field of engineering. An important part of this course is the team project, which requires students to develop research proposals that are then reviewed by the class in NSF-style panels, using both technical merit and broader impact as evaluation criteria. The EECS 515 project bears similarity to the project in EECS 514, but with important differences. a) The project report is written proposal-style, so the work performed during of the semester is intended to provide convincing preliminary results for the proposal. The students are encouraged to think of the strategic end goals, and determine the best minimum set of calculations, simulations, and analysis to address them. b) The proposals are required to include systems aspects, and thus must cover a circuit in addition to a sensor or actuator. c) Budgeting and milestone planning for the proposed work are required. Students have been from several engineering majors: electrical, mechanical, biomedical, and chemical engineering, as well as from applied physics. This course is available to distance education students via the web.

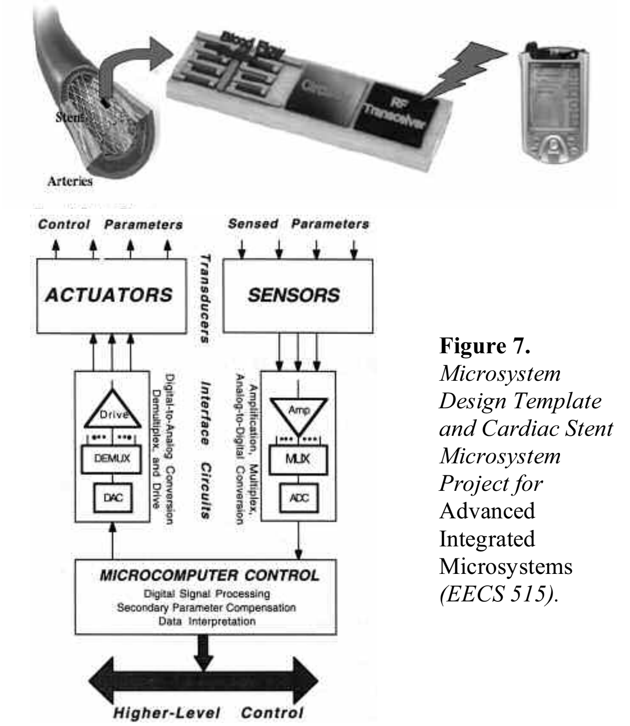


Figure 7. *Microsystem Design Template and Cardiac Stent Microsystem Project for* Advanced Integrated Microsystems *(EECS 515).*

SOCIETAL IMPACT OF MICROSYSTEMS (EECS 830)

During the next two decades, microsystems are expected to have a pervasive impact on society as they are used to couple electronics to the non-electronic world. Microsystems will be used to monitor our environment (global warming, pollution, improved weather forecasting), provide homeland security, improve transportation systems (vehicles and infrastructure), and spark dramatic progress in health care (genetics, proteomics, wearable and implantable microsystems for diagnostic and therapeutic use). This course explores the societal challenges that will be faced by our present engineering students during their careers and how microsystems can be used to address them. As a two credit-hour course, the class meets once per week in a two hour session; the basic format is an hour-long (invited) seminar presentation followed by an hour of questions and discussion.

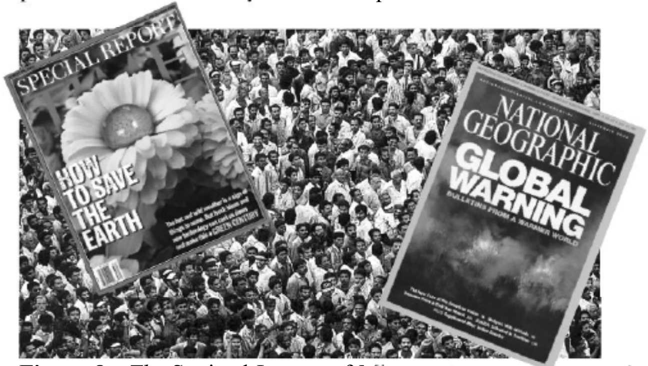


Figure 8. *The* Societal Impact of Microsystems *course examines coming societal challenges and ways that microsystems will help address them. The course includes a component of engineering ethics, explores the origins of innovation, and considers the pioneering developments that have led us to where we are .*

Seminar speakers have included former astronauts, experts on transportation and global warming, and industrial and governmental leaders in the area of health care. Topics have included clean air, clean water, homeland security, manufacturing, global warming, population growth and its implications, nanotechnology, space exploration, and medical implants, as well as engineering ethics. Students have regular homework assignments and select a topic of interest to them on which to do a term report. These oral reports have been very successful in allowing fascinating looks at many additional topics. In addition to societal challenges, the course also offers the opportunity to examine pioneers in electronics, from Benjamin Franklin to Robert Noyce, to obtain insight into the origins of innovation and the challenges faced in the past. Figure 8 and caption provide a glimpse of the course integration of societal challenges. The designated textbook is *Engineering Tomorrow* [**8**]. The course is available over the worldwide web.

DISTANCE EDUCATION DISSEMINATION (AND LOCAL INSTRUCTORS)

At the education retreat, it was decided that distance education dissemination would be the expected delivery mechanism for each core course, and that elective courses would be identified (or developed) that used distance education methods. The core courses originate at UM. How could students at MSU, MTU, and industry be served well? It was decided that local instructors would be available at MSU and MTU for several purposes: provide face-to-face office hours, grade homework, administer and grade exams, and assign grades to students at that university. Each university was encouraged to obtain course approvals with course numbers at their university, and to assign credit hours consistent for their university; course approvals and local numbers were obtained at Michigan State University and Michigan Technological University. University term calendars are different. The student tuition payment is to his/her university, and there is no financial sharing of tuition funds. Costs to disseminate by distance education are borne by the originating university.

EECS 414 and EECS 830 use a high-quality high-cost dissemination of its course materials. Video is captured by a trained camera operator in a classroom studio with excellent lighting and sound capture facilities. The course materials and streaming video are posted to the class web site about one hour after the "live" class session. EECS 514 and 515 use a more cost-effective dissemination process; video is captured by a WIMS staff operating a camera; the course materials and streaming video are posted to a university web site usually within a day after the "live" class session. Methods are being explored to port a laboratory based course (EECS 425).

COURSE ENROLLMENTS

Enrollment in each course has been consistently high. Except for the societal impact seminar course, each course is offered once per year, thereby necessitating a renewed student population each year. EECS 414 is a door-opener course, one that permits many students to get a glimpse of the MEMS and Microsystems area. Its enrollment numbers have ranged from 57 to 104 students at UM, plus about 50 students total at all USA distance education remote sites. The undergraduate-to-graduate student ratio is now about 2:1, different from the first years of the course that had a ratio about 1:2. EECS 425 is likewise a pseudo-door opener course, attractive because of its MEMS/Microsystems content and its ABET satisfying major design experience. EECS 425 enrollment is limited by laboratory space capability. Table 2 has enrollment history since the inception of the MEMS and Microsystems curriculum. For each course, two numbers are provided: the first number is the enrollment of local students at the originating university; the second number is the enrollment of distance education students (remote students, industry professionals, etc).

Table 2. *Enrollment History for MEMS/Microsystems Courses*

Acad.Yr.➔	2000-2001	2001-2002	2002-2003	2003-2004	2004-2005	2005-2006
EECS 414		**57 + 25**	66 + 23	104 + 45	77 + 50	83 + 51
EECS 425	13 + NA	**26 + 16**	31 + 16	42 + 7	39 + 5	48 + 13
EECS 514			**30 + 6**	16 + 6	25 + 18	29 + 13
EECS 515				**17 + 2**	14 + 3	10 + 4
EECS 830			**21 + 10**		18 + 5	
LEGEND:						
Enrollments are listed in format: UM + Distance Education						
Bold numbers are first time course in MEMS/ systems curric'm						
EECS 425 was an *Integrated Circuits Lab* 3-credits course until 2001; it is now an Integrated systems Design 4-credits course.						

A table similar to Table 1 has been prepared for each core course, though not included in this paper for space considerations. The core courses have been received exceptionally well as evidenced by student course evaluation scores at UM; the rating scores for both course and teacher are among the best for undergraduate and graduate courses in the EECS Department at UM. Evaluations at MSU and MTU each use a different set of questions. Course evaluations by distance education students use yet another evaluation instrument. At UM, each undergraduate course has been mapped to a subset of 14 degree program outcomes (as done for ABET criteria). EECS 414 addresses 9 of the 14 program outcomes. Depending on the term, EECS 425 has addressed 10 or 11 of the 14 program outcomes.

MASTER OF ENGINEERING IN INTEGRATED MICROSYSTEMS DEGREE PROGRAM

The development of the core curriculum also led to the establishment of a Master of Engineering (M.Eng.) degree in Integrated Microsystems. The degree program accommodates students and industry professionals with a wide variety of backgrounds in engineering, basic sciences, and industry manufacturing and management. The requirements of this program include the core courses, technical electives, breadth electives, and an industry-oriented team project. The technical electives include courses in fabrication technology, integrated circuits, RF MEMS and wireless communication, optical MEMS, microfluidics, bioMEMS, and environmental sensing. The breadth electives include manufacturing, management, quality engineering, financial analysis and other industry-relevant courses. The industry-oriented team project partners the student with a faculty member and industrial personnel in a project suggested by an industrial application. The team project is a very effective way to increase interactions and expose students to real-world applications and problems. Degree approval was secured at UM in 2002. MTU already had a generic Master of Engineering degree program. The M.Eng. degree can be completed by students taking coursework over the web.

OTHER CONSIDERATIONS

The significance of this curriculum development initiative includes numerous factors. First is a coordinated set of comprehensive MEMS and Microsystems courses and educational resources that are readily shared internationally. The course materials are generously shared, either as a delivered course via distance education, or as a transfer of course materials to faculty who decide to teach the course locally at their university. A second factor is the progressive educational and learning continuum for students with clearly identified links between the courses. Several renowned faculty contributed to development of the courses and course materials. Another factor was the tremendous cooperation and goodwill among faculty at the initial three-partner State of Michigan universities (MSU, MTU, UM).

Building upon the MEMS/Microsystems core courses curriculum, other new related courses that have been offered include *Integrated Analog/Digital Interface Circuits* (EECS 511), *RF Wireless MEMS* (EECS 598A), *BioMEMS Through the Developing Organism* (EECS 598B), and *Micromanufacturing Processes* (MTU MEEM 4640/5640). Also, the existence of the core courses has led to the inclusion of MEMS and microsystem topics in other courses as well, from sophomore year to the advanced graduate level.

At Michigan Tech, a course *Micromanufacturing Processes* (MTU MEEM 4640/5640) is a technical elective from a mechanical engineering perspective, developing a broader perspective to students in the program. Course topics include: Scaling analysis, micrometrology methods and instruments, precision measurements and practices, lithographic processes, diamond machining, micromilling, microdrilling, micro EDM (electrical discharge machining), and analytical modeling of processes and normal practices.

SUMMARY

The Engineering Research Center for Wireless Integrated MicroSystems (WIMS ERC) has developed five core courses (Figure 1) that provide a broad comprehensive curriculum in MEMS and microsystems. Upper-level undergraduate students, graduate students, and industry professionals from engineering (electrical, computer, mechanical, biomedical, chemical, aerospace) and science (physics, chemistry, applied physics) have enrolled in the courses. Additional new technical and breadth elective courses have grown out of the core. Students are able to complete a master degree locally on campus or via distance education web online technology. Course enrollments have been consistently strong. Other universities, nationally and internationally, have used the courses in whole, or used course materials to further their own course offerings.

ACKNOWLEDGEMENT

The Engineering Research Centers Program of the National Science Foundation under Award Number EEC-9986866, wholly or partly, supports the WIMS Education program and projects.

REFERENCES

[1] Stephen D. Senturia, Microsystem Design, Kluwer Academic Publishers, 2000.

[2] Digest of Technical Papers, *International Conference on Solid-State Sensors and Actuators (Transducers 'xx)*, 1985 through 2001.

[3] Digest of Technical Papers, *Solid-State Sensor and Actuator Workshop*, Hilton Head, South Carolina, Series 1984 through 2000.

[4] Proceedings, *IEEE International Micro Electro Mechanical Systems (MEMS) Conference*, 1987 through 2006.

[5] S. Ballandras, M. Wilm, M. Gijs, A. Sayah, E. Andrey, J.-J. Boy, L. Robert, J.-C. Baudouy, W. Daniau, and V. Laude, “Periodic Arrays of Transducers Built Using Sand Blasting and Ultrasound Machining Techniques for the Fabrication of Piezo-Composite Materials,” *IEEE Ultrasonics Symposium,* pp. 871–874, 2001.

[6] L. Spietz, K. W. Lehnert, I. Siddiqi, and R. J. Schoelkopf, “Primary Electronic Thermometry Using the Shot Noise of a Tunnel Junction,” *Science*, v. 300, pp. 1929–1931, 20 June 2003.

[7] S. P. Woods, K. Lee, and J. Bryzek, “Overview of the IEEE-P1451.2 Smart Transducer Interface Module,” *Analog Integrated Circuits and Signal Processing*, 14(3), pp. 165–177, November 1997.

[8] Engineering Tomorrow: Today's Technology Experts Envision the Next Century, Janie Fouke (Editor), T. E. Bell and D. Dooling (Writers), Institute of Electrical and Electronics Engineers, Inc, 2000.

LIST OF ACRONYMS AND ABBREVIATIONS

ABET	Accreditation Board for Engineering & Technol’y
CMOS	Complementary-Symmetry Metal Oxide Semiconductor Process (see EECS 425)
Dis.Ed.Stds.	Distance Education Students
E/D	Enhancement/Depletion Circuit Structure
EECS	Electrical Engineering and Computer Science
ERC	Engineering Research Center
LOCOS	Local Oxidation of Silicon (see EECS 425)
MEMS	Microelectromechanical Systems
MSU	Michigan State University
MTU	Michigan Technological University
NSF	National Science Foundation
UM	University of Michigan
US	United States (see Table 1)
WIMS	Wireless Integrated MicroSystems

ADAPTING INTERDISCIPLINARY MEMS TEACHING AND TRAINING IN A "SMALL" FACULTY ENVIRONMENT

Shekhar Bhansali
BioMEMS and Microsystems Laboratory, Department of Electrical Engineering, University of South Florida
4202, E.Fowler Avenue, Tampa, FL 33620, USA

ABSTRACT

This paper highlights the unique curriculum modifications that enable MEMS education to keep pace with changing industry dynamics even in a "small" faculty environment. In a rapidly widening MEMS discipline, the methods outlined address an increasing need to impart the diverse technical fundamentals within a single course. Suitable education in the field requires an interdisciplinary syllabus and thus necessitates an innovative curriculum. This paper outlines two course modules currently being taught at the University of South Florida that are based upon these educational improvements. This paper intends to initiate a discussion on what should be an accepted definition of a MEMS course and what is the market expectation of the skill set that a student acquires as an outcome of the course.

INTRODUCTION

Rapid advancements in the field of microsystems coupled with its continued relevance to diverse sensor applications have been the seed for current revolution in MEMS education. Changing industrial needs have broadened the required knowledge base of students. There is thus an increasing need to diversify the technological background on which MEMS courses are built.

In order to address the issue, universities with critical mass of faculty active in the area of MEMS have established programs with 5-7 MEMS related courses. Many engineering schools have multiple course offerings covering different aspects of fundamentals, design, processing, materials and application aspects, while others schools use few faculty to offer a sequence of MEMS courses. While some schools focus on rendering sequential courses dealing exclusively on the design and fabrication aspect of a MEMS device separately, many combine to deliver multiple specialized courses such as Optical MEMS, BioMEMS, etc. These courses are often listed as electives with the introductory course forming the core. Institutions with small faculty environment are not able to cater to the demands of the rapidly widening MEMS discipline by conventional course designs. These institutions have to combine selected functional modules to offer relatively few sequence of courses. This constraint has resulted in a specialized course design that attempts to incorporate the diversity and details of the technological topics within a single course.

The content of the courses designed at USF also addresses the fact that the next generation of student community would be required to pursue research/work in a collaborative and interdisciplinary manner to achieve scientific breakthroughs and solve complex problems. Various funding agencies promote interdisciplinary programs around MEMS that require cross disciplinary graduate and undergraduate education. Consequently, the USF MEMS curriculum has undergone a major revision resulting in the revamping of the underlying objectives that include "the cultivation of desire to understand and assimilate non-disciplinary information to implement new solutions using MEMS".

As a part of continued discussion, the MEMS courses offered in the department of Electrical Engineering at the University of South Florida are presented as case studies. The architecture of these specially designed modules with course features and evaluations are illustrated. The inherent challenges involved in teaching a course comprising a wide spectrum of audience are also highlighted.

MEMS COURSES AT USF

A. Chem. /Bio Sensors & Microfabrication

USF's academic program in the area of bio-MEMS has grown significantly over the past five years and is the cornerstone of NSF sponsored IGERT and Bridge to the Doctorate programs at USF. The programs, designed to work at the intersections of various disciplines, draw students from diverse backgrounds: Engineering (Electrical, Chemical, Mechanical, Computer Science, and BioMedical), Medicine, Arts and Sciences (Chemistry, Physics, and Biology) and Marine Science. The first interdisciplinary course - 'Chemical/Biological Sensors and Microfabrication' has been designed to engage the diverse audience. The course has been designed for graduate and senior undergraduate students. The content has been designed to go start with concepts of various sciences by describing their role in state of the art MEMS devices. Theoretical concepts in physics, chemistry, biology, materials science, electrical engineering and mathematics are related to their practical implementation in these devices. Recognizing the span of concepts covered, students are not expected to have an all-inclusive background in the relevant sciences. Thus the course does not have any prerequisite requirements. However, exposure to introductory courses in physical/analytical chemistry is generally advised.

Unlike conventional course designs, this introductory course reviews and concentrates on building a strong foundation on various sensing principles (physical, chem., and bio) with emphasis on suitable micromachining techniques required for real-time microsystem implementation.

To ensure a continued engagement of the diverse student body, MEMS processes and strategies are studied in relation to specific environments, applications and conditions. This helps students understand the various dynamics involved beyond the scientific principle of operation. For example, the human skin is introduced as a smart interface to seamlessly couple multifunctional micromachined systems for useful data extraction. In this case, issues that arise as the micro system and blood and/or other fluids interact are discussed leading to discussions on materials and bio-compatibility. Next compatibility in the context of marine environment is discussed, leading students to dwell on the issues of design changes to respond to the environment.

06TRF-0003/hh2006/$20©2006TRF
DOI 10.31438/trf.hh2006A.2

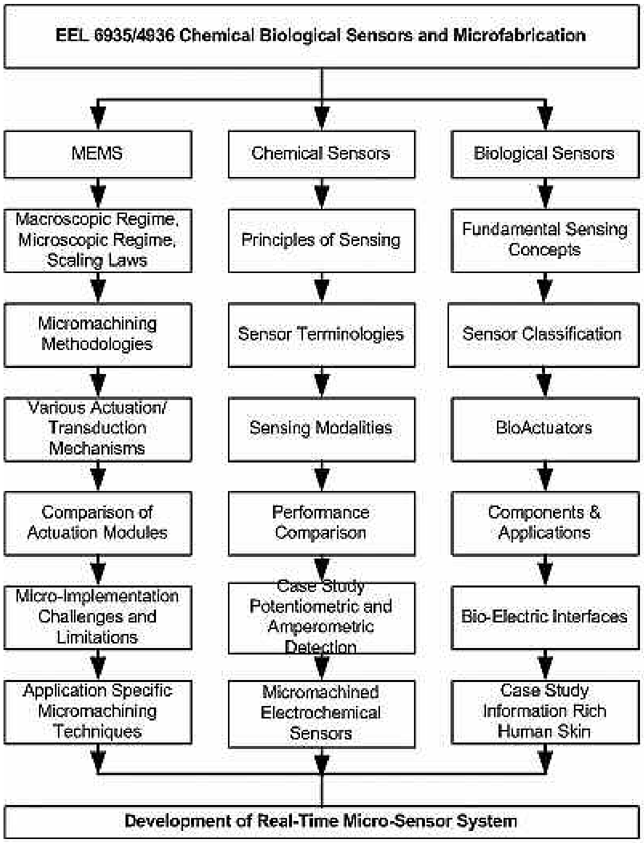


Figure 1. Flow Chart Illustrating the Design and Architecture of the Introductory Course

The course content is illustrated in Figure 1. It uses a top-down approach, i.e., understanding of how the system functions at the macroscopic level is gained first and then suitable approximations or modification to the existing theory are made at the microscopic level. Starting with the explanation of sensing principles across various domains, sensor classification and terminologies are described for students to understand industry relevant tolerance and specifications. Various sensing modalities are compared for students to appreciate the application specific suitability of each technique. Information on the different actuation/transduction mechanisms are provided, supplemented by their fabrication methods. In this course, the concepts are conveyed through the use of prototype models, handouts, visual aids, power point slides, guest lectures, paper reviews and in-house demo of processes.

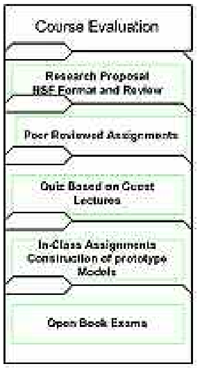


Figure 2: Course Evaluation Criteria for the Introductory Course

To leverage the diverse back ground of the class, students are asked to develop an NSF style proposal (figure 2) based on their idea of MEMS application that would be relevant in their field of expertise. The personal information is removed from the proposals and they undergo a panel review. The panel is formed of the students and moderated by the instructor. The students evaluate and rank the proposals with a clear understanding that only 15% of the proposals can be in the highly recommended category (i.e. get a 100%) score. This unique andragogic exercise serves to enhance the thought process while enabling students to learn more about different areas of interest. Panel discussions facilitate constructive criticisms with appraisal of the subject while drafting proposals improves technical writing, a critical skill set required by the corporate world.

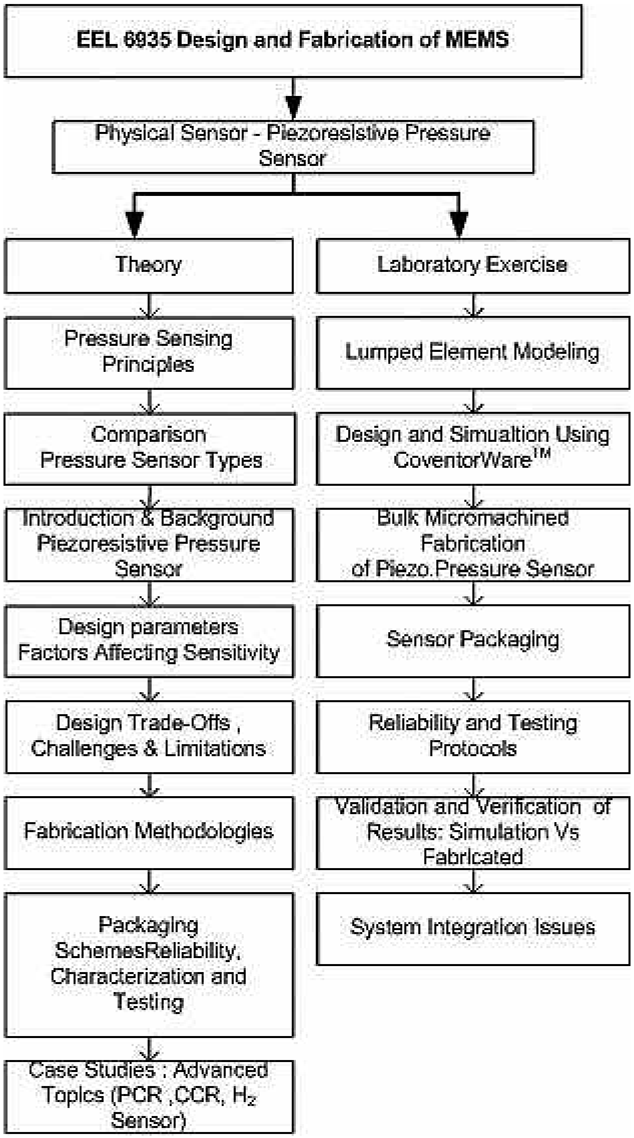


Figure 3: Flow Chart Illustrating the Architecture of the Advanced MEMS Course

OUTCOMES AND CHALLENGES

Over the past three years the students have consistently stated that there is too much and too diverse reading involved. They have rated the panel discussion as the single biggest learning experience as it helps them understand the different perspectives of the same issues and also how people feel. One of the foremost challenges in teaching this course has been the absence of a single prescribed textbook. Students are provided with and advised to follow tailor made handouts. They are encouraged to study in interdisciplinary teams. This is facilitated by requiring them to review and document the current state of the art technology published in papers and patents. The course continues to be team taught and the integration of sciences and engineering continues to be challenge.

B. Design and Fabrication of MEMS

This second course in the two course sequence, discusses the design aspects, provides students with hands on fabrication and looks at uses case studies in development of micro systems. The students build and test a pressure sensor namely a piezoresistive pressure sensor. This course facilitates the understanding of experimental validation of simulated results and design trade-offs to optimize system performance. Figure 3 illustrates a flow-chart describing the course structure.

The course aims at developing a skill set for applying the fundamental concepts of MEMS in (a) designing and modeling MEMS based piezoresistive pressure sensor, and (b) fabrication and testing of the pressure sensor. The design component of the course requires the use of CoventorWare^{TM} 2005 to create, simulate and refine device models. Implementation of a pre-designed device in a clean room environment imparts hands-on experience in fabrication. Case studies include advanced topics from microfluidics such as micromachined PCR (Polymerase Chain Reaction) reactors, optical devices like CCRs (Corner Cube Retro Reflectors), geared mirrors and microhotplate H_2 gas sensor systems. These special modules emphasize on the design and fabrication constraints from a system's perspective.

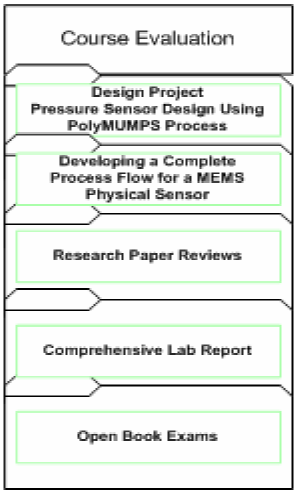


Figure 4: Course Evaluation Criteria for the Advanced Course

As part of evaluation criteria (figure 4) , the students are asked to design, simulate and validate a similar MEMS device/system using industry standard PolyMUMPS process with appropriate calibration and testing protocols.

Outcomes

The course contents and evaluation criteria are designed to impart the students with required skill set needed for survival in the fast paced sensor industry. With the completion of this course students are able to: a) identify and understand interactions across domains; b) analyze failure modes; c) account for the discrepancy between simulated and experimental values.

Most non-engineers find the conventions and conversions (e.g. lumped element modeling) the hardest to follow and have consistently shown a performance that lags mechanical engineers. The mathematical base of students from different disciplines is very different and continues to be a challenge.

Conclusions

The paper describes the two course MEMS sequence and the content of the courses being taught at USF. The courses attempt to cover diverse areas in detail. The success resulting from the courses (panel review) and the challenges (student diversity, student background and the volume of information) are presented with a goal of initiating a discussion on what should be the required content of a MEMS course.

Acknowledgements

The author acknowledges the support of Praveen Kumar Sekhar and Puneet Khanna, TAs in the preparation of this paper. The educational activites were developed under NSF awards CAREER: ECS-0239262 and IGERT: DGE-0221681

AN INTERDISCIPLINARY LABORATORY COURSE IN MICROSYSTEM DEVELOPMENT

Kensall D. Wise, Katharine T. Beach, Terre F. Briggs, Robert J. Gordenker, and Mayurachat N. Gulari
Engineering Research Center for Wireless Integrated MicroSystems
The University of Michigan, Ann Arbor, MI, USA

ABSTRACT

An interdisciplinary course in microsystem development is described in which students define, design, fabricate, and test a two-chip microsystem. A six-mask dissolved-wafer MEMS chip and a five-mask E/D NMOS LOCOS circuit chip are used to implement a wide variety of devices, including visible imagers, pressure sensors, accelerometers, g-switches, tactile imagers, cursor controllers, pressure-and-thermally-based flowmeters, micro-mirror arrays, thermal mass sensors, and Pirani gauges. The course teaches interdisciplinary teamwork and emphasizes the interactions among design, fabrication, and test, producing working microsystems in a single 14-week term.

INTRODUCTION

Integrated sensors, MEMS, and microsystems have developed over the past forty years driven by innovative process technology, microstructures, and applications. While microelectronics has managed to coalesce around CMOS technology, no single standard process exists for MEMS because of the divergent structures and device types needed. At the same time, reading out high-performance sensors resolving sub-femtofarad capacitance variations (or equivalent resistive changes) demands the integration of electronics with the transducer, either monolithically or as a multi-chip hybrid.

Educational programs in MEMS and microsystems must teach a variety of topics, including materials, transduction mechanisms, microstructures, process technologies (e.g., micromachining and wafer bonding), interface circuit design, and system partitioning. In addition to lecture courses, it is important that students have the opportunity to create a microsystem for themselves. This experience should include defining the microsystem function, designing it, fabricating it, and actually seeing it work. Going through this process allows the student to experience the pride of creating a chip from start to finish and to understand the interactions among design, fabrication, and testing. In no other way, can the importance of topics such as design for testability be fully appreciated nor can the tradeoffs in balancing an overall process flow be properly understood. For some students, this experience is the entry point into a doctoral program where it will be repeated in far greater detail, but for many it will be the only time in their careers that they have the opportunity to take an idea from inception to working silicon. Such an experience is even more valuable for these students, giving them a basis for working effectively across the boundaries that occur in industry among design, fabrication, and test.

This paper describes a one-semester course offered at the University of Michigan that allows undergraduate seniors and first-year graduate students to define, design, fabricate, and test a two-chip microsystem of their choosing. The MEMS chip is implemented using a six-mask dissolved-wafer process that includes two boron etch-stop diffusions and anodic silicon-glass wafer bonding. Although alternative processes are possible (i.e., surface-micromachined, front-undercut or back-etched bulk processes), this process was chosen because of its ability to implement a wide range of different transducer functions while illustrating a wide set of process steps. The readout/interface chip is implemented in a five-mask doubly-implanted silicon-gate 1M/1P E/D NMOS LOCOS process. While a full CMOS process would be preferable, the added process complexity is not possible in a five-week fabrication cycle. The use of a two-chip combo as opposed to a single monolithic chip allows the two processes to be run in parallel, shortening the fabrication cycle. This course was run for many years as an integrated circuit laboratory but was broadened in 2001 to a four-credit *Integrated Microsystems Laboratory*. As the result of this topic shift, changes in prerequisites, and the creation of an important feeder course for our entire microsystems program (*Introduction to MEMS*), enrollment has gone from 15 in 2001 to 48 in 2006, shifting from mostly graduate students to mostly undergraduates. The course serves as a major design experience for undergraduates.

DESIGN

Entering the course, students are provided with a fixed die area for each chip (2mm x 2mm), with process flows for each chip, and with fixed pad positions consistent with the probe cards used during the testing phase of the course. Course prerequisites require that students enter the course with either a solid-state electronics background (a basic course in p-n junction theory and devices, and a circuits course) or a MEMS background (the introductory course mentioned above). They are asked to form project teams of four persons and are encouraged to include a mix of backgrounds and experience. While most students come from electrical engineering, it is common for students from biomedical, chemical, mechanical, and materials engineering to take the course as well. The use of teams allows the students to learn from each other and experience working in a (hopefully) synergistic group, where it is up to them to plan the project execution and to coordinate individual activities. Thus, the course attempts to teach interdisciplinary teamwork. Three-person teams would perhaps be preferable, but four person teams are helpful in handling enrollment pressures.

Figure 1 shows the activity flow in the course. After forming teams, the students select a microsystem function to implement. Typically a dozen or so project ideas are suggested, but the students are free to select something of their own choosing and often do. They are encouraged to define it in terms of a practical application and to consult the literature to learn about similar functions reported there. About two weeks are spent defining the microsystem function and reducing it to block diagram form. The course consists of two 80-minute lectures per week and one four-hour laboratory session. The laboratory sessions are used during the design phase of the course for group interactions, for one-on-one discussions with the instructor, and for supplementary lectures

06TRF-0003/hh2006/$20©2006TRF
DOI 10.31438/trf.hh2006A.3

on various topics as needed. With the block diagrams completed, the students proceed to fill in the blocks with specific transducer and circuit designs. These are full-custom designs done on workstations running Cadence or Mentor Graphics software, with simulations run in CoventorWare, SPICE, and SUPREM. The lectures present the details of MOS device and circuit design. Prior to 2001, a VLSI design course was required as a prerequisite, primarily so that students were familiar with the design tools. Since then, that prerequisite has been dropped and we have held an evening tutorial session on the design tools during the third week of the course. This has been adequate to allow the designs to go forward. The lectures are taped and accessible over the web, allowing the course to be taken at both Michigan State and Michigan Tech with an on-site instructor. Students at these participating universities go through the same procedures as the students at Michigan, submitting their completed designs over the web. All designs are incorporated into two multi-project mask sets, reflecting the MOS and MEMS chips. For example, with forty students at Michigan and eight at Michigan State, we would have twelve project chips per mask set. We also add test chips on each mask set that contain alignment marks, in-process test patterns, and test devices for process evaluation. For example, the circuit test chip contains resistors for determining the poly and diffused bulk sheet resistances, a transistor string for device characterization (enhancement, depletion, field), metal-to-poly and poly-to-substrate capacitors for oxide and C-V measurements, a ring oscillator (propagation delays), and test inverters.

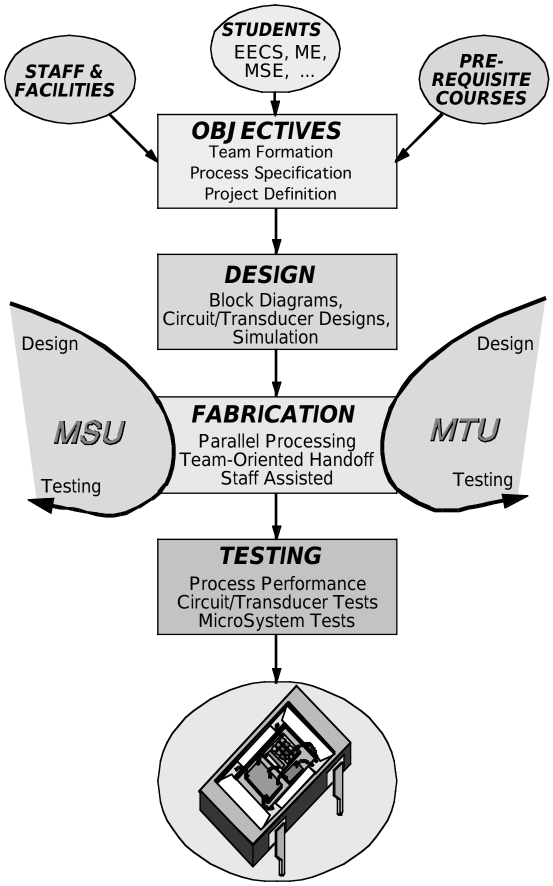


***Fig. 1:** Activity flow in the Integrated Microsystems Laboratory course.*

At the end of five weeks, tape-out occurs and the designs are sent out for mask making. Graduate student mentors are sometimes used to help particular teams with their individual design challenges. First masks are typically returned within three days of submission.

FABRICATION

Figures 2 and 3 show the process flows for the MOS and the MEMS processes, respectively. Minimum features of 6µm and alignment tolerances of 3µm are used for the circuit chip, with somewhat larger features on the MEMS chip. These are adequate for the equipment used and allow 100-200 transistor circuit designs to be implemented as needed. Processing uses 100mm silicon and glass (Pyrex) wafers.

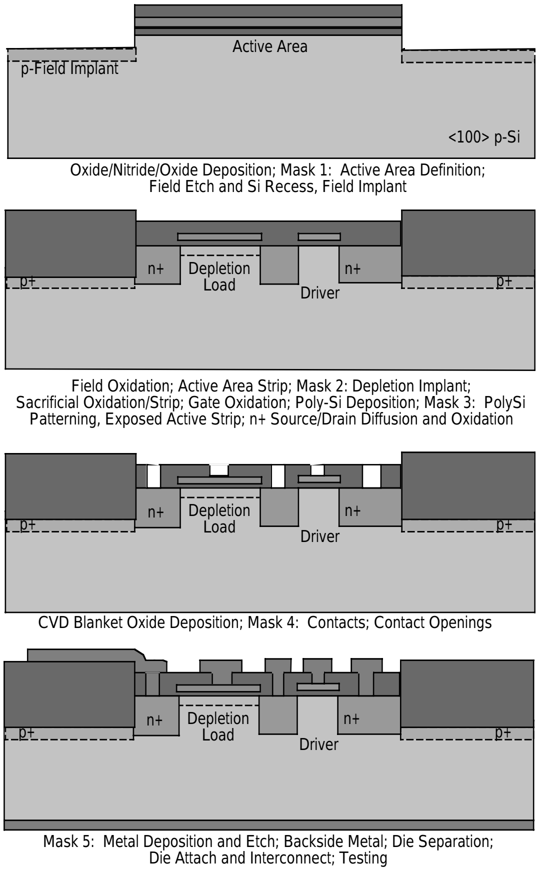


***Fig. 2:** Process flow for E/D NMOS circuits.*

During lecture sessions, micromachining, wafer bonding, silicon oxidation, diffusion, metallization, and pattern transfer are discussed. Laboratory sessions are carried out in a dedicated Class 10,000 Instructional Laboratory equipped for lithography, wet oxide and metal etching, field and well oxidations, phosphorus source-drain diffusions, plasma etching, and metallization (sputtering). The field and depletion implants are done in a commercial foundry, and the chemical vapor deposition (CVD, nitride, poly, and LTO) steps, gate oxidation, boron etch-stop diffusions, and dry etching is done by engineering staff in the adjacent Class 10/100 research cleanroom. Wafer bonding and microstructure release etching are also done by staff but is videotaped and shown to the class. In a typical afternoon laboratory session, the section is split into two or three sub-sections to allow more students to be are also done by staff but is videotaped and shown to the class. In a typical afternoon laboratory session, the section is split into two or three sub-sections to allow more students to be accommodated and to reduce waiting time in using the equipment. Students quickly learn to perform the various process steps themselves, although sessions are supervised by two people at all times. Those taking the course at remote sites (e.g., Michigan State) do processing in their own laboratories while their designs are fabricated as part of the multi-project activities at Michigan. Finished wafers are returned to them for testing. Figure 4 shows views of completed MOS and MEMS wafers in these process flows.

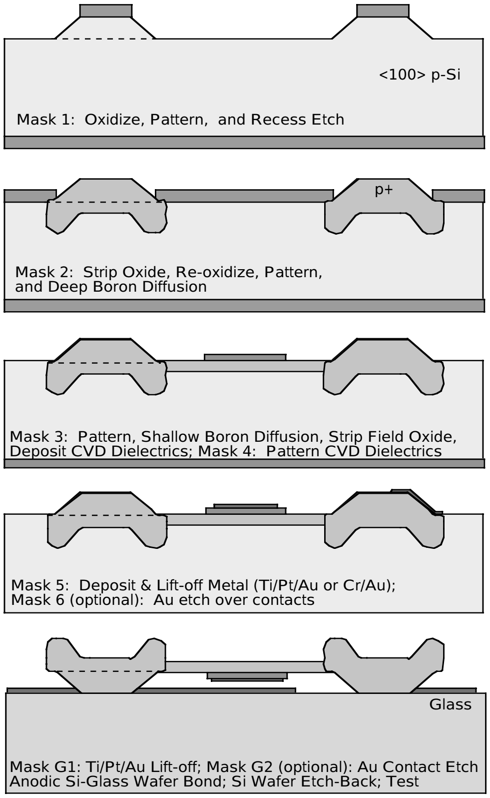


Fig. 3: *Dissolved-wafer process flow for the MEMS chip.*

TESTING

Testing is carried out by teams using two Suss probe stations equipped with television monitors and equipment racks that contain power supplies, pulse generators, oscilloscopes and other instrumentation. Students sign up for three-hour testing blocks and begin by characterizing the test chip (Fig. 5). A previous assignment prepares the students by asking them to characterize the test chip from a previous year. One week is therefore devoted to measuring a variety of device characteristics (thresholds, breakdown voltages, contact linearity, C-V characteristics) and comparing them to theory. Channel lengths and mobilities are extracted from these measurements. Students then move to testing their circuit chips, again at the wafer level, and then to their MEMS devices. The dissolved-wafer process is consistent with the realization of capacitive devices and the use of electrostatic self-test, both of which are advantageous. Capacitive devices, in particular, are significantly easier to read out because of their relatively high sensitivities and their compatibility with Schmitt oscillators and other mostly-digital circuits as opposed to more difficult amplifier circuit designs. For final testing, the wafers are diced and the two-chip combos are mounted in packages to allow them to be tested as a complete microsystem.

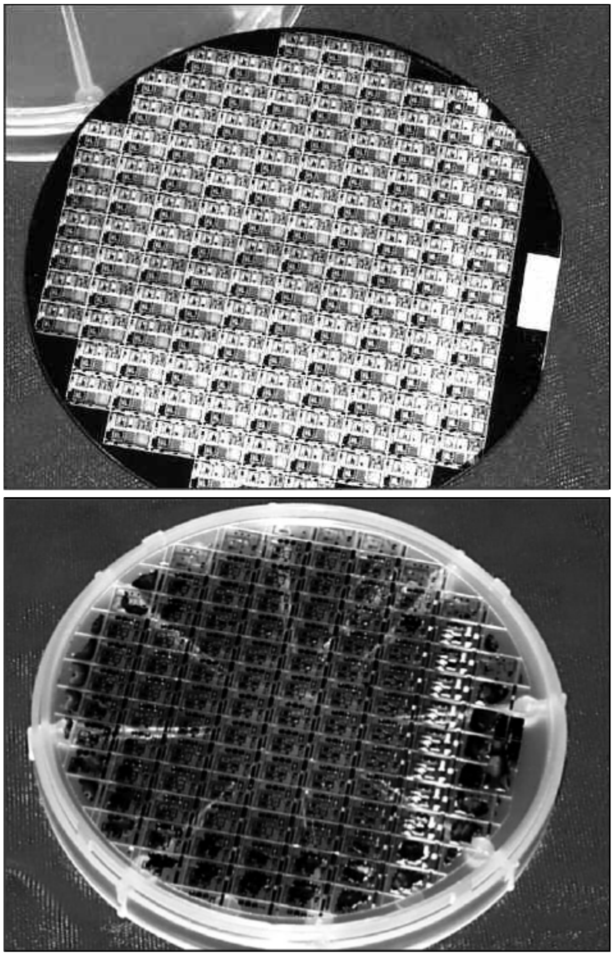


Fig. 4: *Views of completed MOS and the MEMS wafers.*

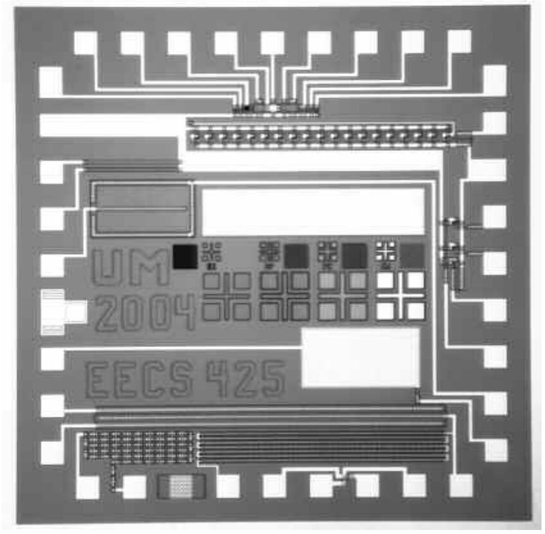


Fig. 5: *Top view of the MOS test chip used for device and process characterization.*

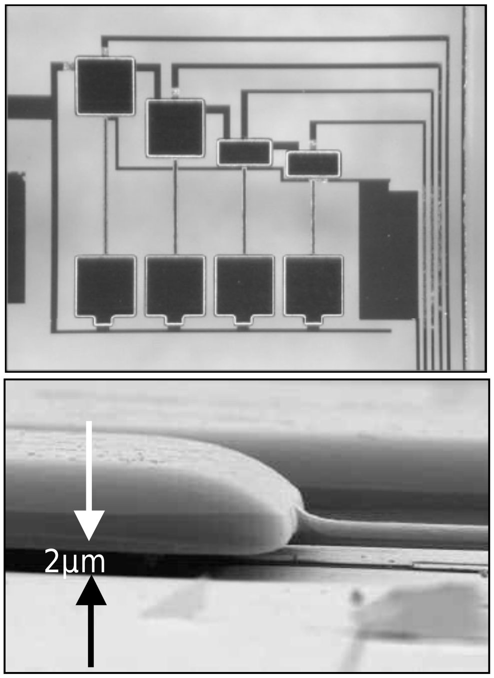


Fig. 6: *Top view and SEM side view of a silicon-glass g-switch realized in the dissolved-wafer process.*

Figure 6 shows an example of a g-switch realized in the course. The diffused wafer process here uses a deep (10-12µm) etch-stop for structural elements and a shallow diffusion (2-3µm) for diaphragms and some beams. Here, a deep diffusion is used for the proof mass and the anchor areas while a shallow diffusion is used for the beam itself. The capacitive gap in this and other structures is targeted at 2-3µm. Such devices are useful for shock sensing (e.g., in packages during shipment) and when combined with CMOS circuitry can do so with virtually no power dissipation. Figure 7 shows some of the other MEMS devices realized in the course. Device yields vary by structure but are typically in the range of 40-60 percent, with most yield loss occurring due to handling of the relatively delicate microstructures. This yield is more than sufficient for class purposes.

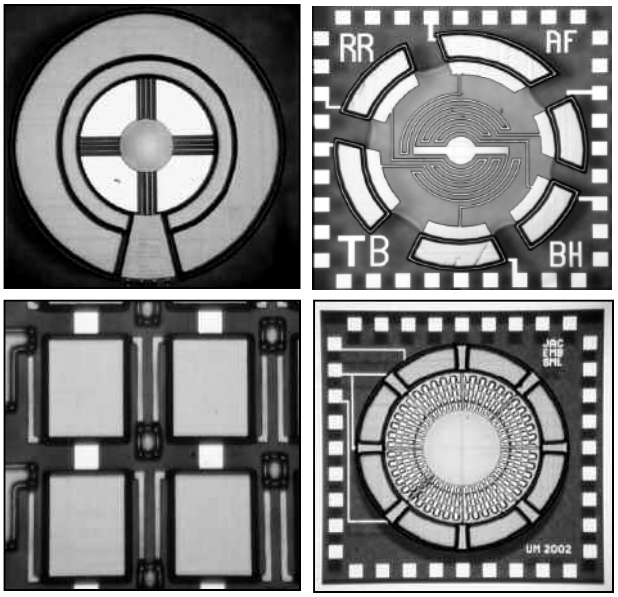


Fig. 7: *Top views of four MEMS devices: (clockwise from top left) Pirani gauge, thermal mass sensor, tactile imager cells, and capacitive microphone.*

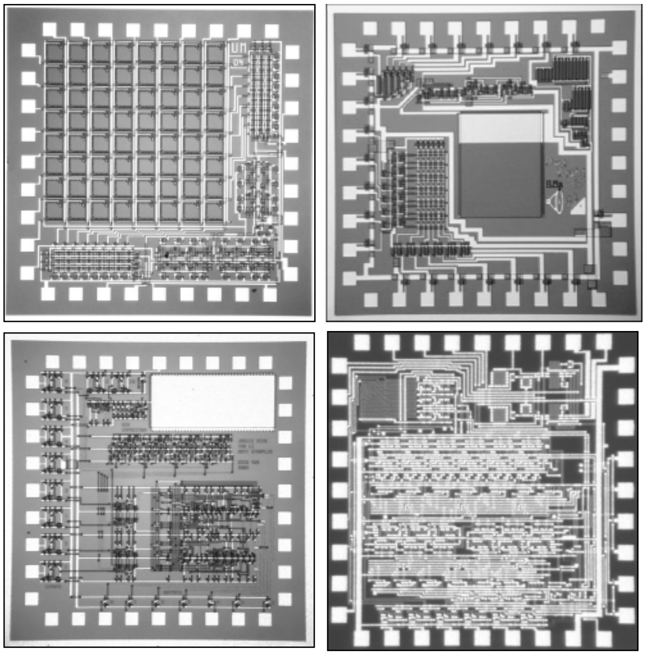


Fig. 8: *Views of several MOS interface chips realized in the course: (clockwise from top left) visible imager, Pirani gauge, micro-mirror display, accelerometer. microphone. All dice: 2mm x 2mm.*

Figure 8 shows a set of typical MOS interface circuit chips realized in the class. The process uses a recessed self-aligned field and a gate oxide thickness of 40nm. Aluminum metal is used with a 425°C sintering step to improve the contacts. Circuit yields are typically greater than 80%.

CONCLUSIONS

Integrated microsystem development is taught in a one-semester laboratory course at the University of Michigan. The microsystems are implemented as two-chip combos using a dissolved-wafer MEMS process and an E/D NMOS circuit process, run in parallel. The students spend approximately five weeks in design, five weeks in fabrication, and three weeks in test. Homework assignments are used together with typically three quizzes, a mid-term report (covering design), a final report (covering design, fabrication, and test), and a presentation to the class. The class is very demanding and yet very popular with the students, typically being featured on resumes and in job interviews. In six years (2001-2006), the course has trained over 200 students with an average course evaluation ("this is an excellent course") score of 4.7/5.0. In 2003, one of the course projects was submitted to the ISSCC/DAC design contest and won second place in the conceptual category.

Acknowledgment

Course development was supported by the Engineering Research Centers Program of the National Science Foundation under Award Number EEC-9986866.

BENCHTOP POLYMER MEMS AS A LOW-COST EDUCATIONAL TOOL

Mario Urdaneta, Remi Delille, Elisabeth Smela
Mechanical Engineering Department, University of Maryland
College Park, Maryland, USA

As microsystems become ubiquitous and nanotechnology increases in importance, it becomes ever more imperative to include these topics in engineering curricula. One of the most effective ways to teach microfabrication methods is through hands-on laboratories in clean rooms since MEMS structures are manufactured using a unique set of techniques, and students do not have an intuitive grasp of the underlying concepts. Most educational institutions, however, do not have the facilities required to offer such labs, so that MEMS courses are limited to lectures. It would therefore be useful if there were meso-scale lab demonstrations that could be done in standard laboratories, or even in classrooms, to convey the basic concepts, such as masking, sacrificial layers, alignment, and so forth.

We present the concept of a MEMS kit with associated lesson plans that can be used to give students hands-on fabrication experience that is analogous to what is done in a clean room, but on a larger scale so that no expensive equipment is needed. The photoresist analog is a photopatternable adhesive that can be used in room light and exposed through transparency masks with a handheld UV lamp. Among the concepts that can be demonstrated are photolithography (exposure, alignment, developing), etching (Figure 2), sacrificial layers, lift-off, shadow masking, electroplating in templates ("poor man's LIGA"), micromolding of PDMS, microstamping, and laminar flow in microchannels (see Figure 3). Devices that can be fabricated include single and multi-level microchannels, check valves, and bilayer thermal actuators. The supplies that are required for the photolithography are shown in Figure 1, and their total cost is less than $500. Below, we outline a sample lesson plan for a laminar flow device.

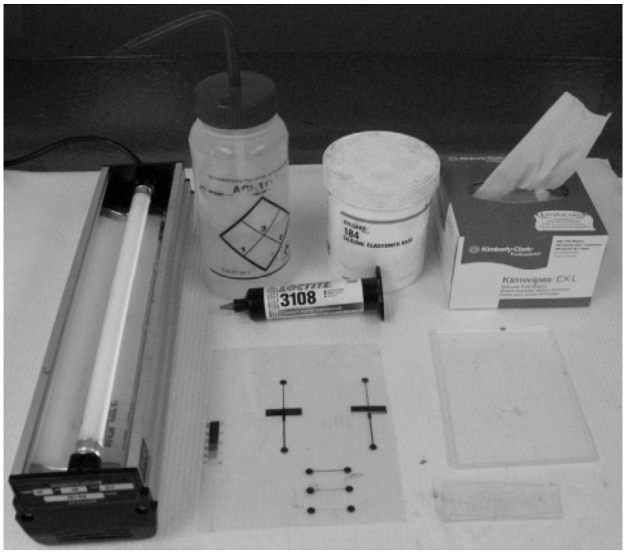


Figure 1. *Supplies needed for demonstrating photolithography include a hand-held UV lamp, Loctite adhesive, transparency masks, paper tissue, PDMS elastomer base, ethyl acetate or acetone, glass slides, and a sheet of acrylic.*

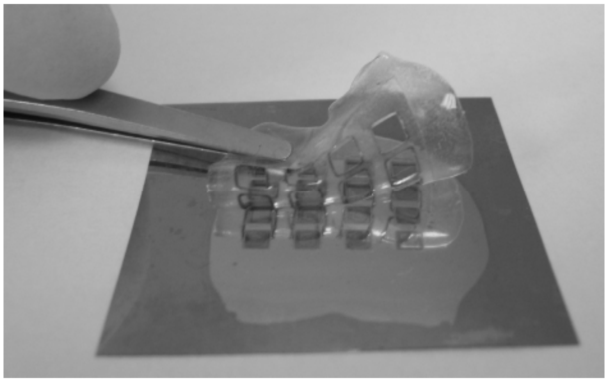


Figure 2*. An etch mask being removed from a metal-coated Kapton film after wet etching. Such concepts can be demonstrated in a classroom environment using minimal infrastructure.*

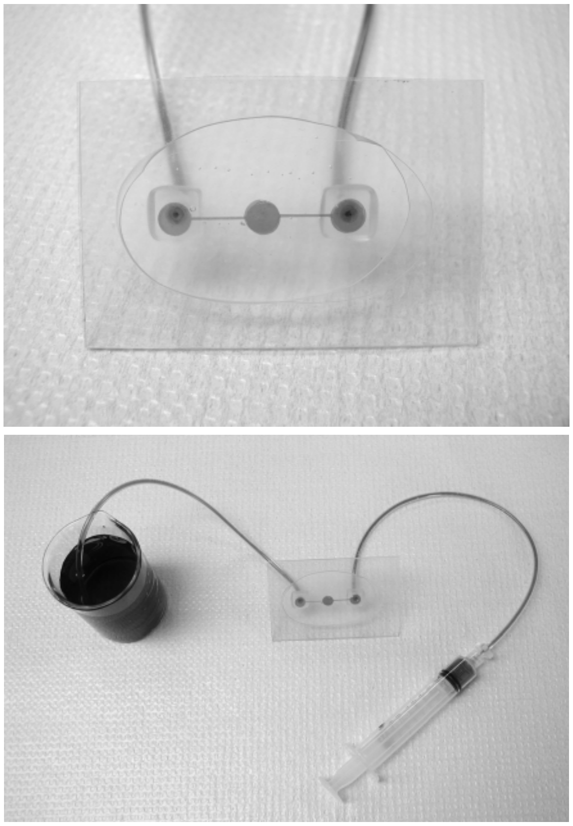


Figure 3*. Two-level microfluidic devices such as this can be fabricated.*

06TRF-0003/hh2006/$20©2006TRF
DOI 10.31438/trf.hh2006A.4

SAMPLE LESSON PLAN:
FABRICATION OF A LAMINAR FLOW DEVICE

This demonstration is based on the 1994 paper by Branebjerg et al.: J. Branebjerg, B. Fabius, P. Gravesen, “Application of Miniature Analyzers from Microfluidic Components to µTAS,” A. van den Berg and P. Bergveld [eds.], Proceedings of Micro Total Analysis Systems Conference, Twente, the Netherlands, Nov. 21-22, pp. 141-151, 1994.

1 Background

a. Microfluidics

Microfluidics refers to the manipulation of fluids at the microscale. The manipulations include chemical mixing (e.g. for drug synthesis), DNA or protein separation (for example by electrophoresis), and cell sorting. One emerging application for microfluidics is µTAS, or micro total analysis systems, which seek to integrate entire laboratories onto a microchip… *[truncated in the interest of space]*

b. Laminar Flow

Fluid mechanics at the microscale is greatly affected by scaling laws: viscous forces become large while inertial forces all but disappear and the surface-area-to-volume ratio increases, making diffusion an important transport phenomenon. The ratio between the inertial and the viscous forces is given by the Reynold’s number: $Re = D_h\rho u/\mu$, where D_h is the channel’s hydraulic diameter, ρ is the fluid density, u is the velocity, and μ is the dynamic viscosity. Whether flow is laminar (the local velocity vector points downstream) or turbulent depends on the Reynold’s number. In microfluidics fluid flow is almost always laminar because the channel is so small. This makes it impossible for fluids to mix through convection…

For more information about flow properties at small scales:
-E.M. Purcell, “Life at low Reynold’s numbers”, American Journal of Physics vol 45, pages 3-11, 1977.

For more information on laminar flow:
-R. Fox, A. McDonald, P. Pritchard, *Introduction to Fluid Mechanics*, Wiley, 2003.

c. Diffusion

Diffusion is the movement of chemical species down a concentration gradient…

Species will diffuse while they are being carried by a flow. Species in an infinitely thin fluid element will spread out to a width of approximately $\sqrt{D\tau}$ during a time τ, where D is the diffusivity…

For more on diffusion:
-S. Senturia, Microsystem Design, Kluwer Academics Publishers, 2001

2 Pre-Lab Discussion

1. Given that the diffusion coefficient for most molecules in water is on the order of 10^{-5} cm^2/sec, and given a channel cross section of 300 µm x 100 µm, how long must the channel be for two fluids colored yellow and blue to mix if they are fed into this channel from a Y-junction such as the one shown in step 4?
2. Sketch what you think will happen over a 3 cm long channel.
3. …

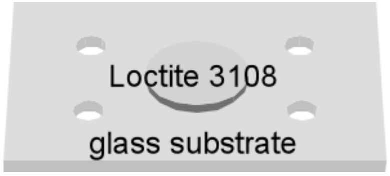
3 Material List

3” by 2” glass slide with four pre-drilled 1/16” diameter holes
3” by 2” glass slide with no holes
1 dual syringe
4 plastic tubes and connectors
Loctite 3108 elastomer precursor
transparency mask #3 (cut to 3” by 2”)
yellow and blue food coloring
water
magnifying glass
Spectroline EN-180 UV lamp (center wavelength 365 nm)
acetone
transparency strips (cut to 2.75” by 0.25”)
transparency cover (cut to 3” by 2”)

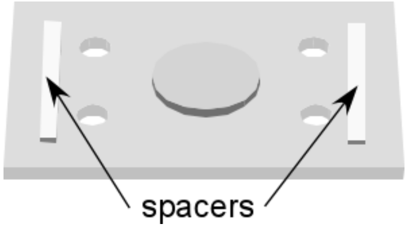
4 Fabrication Instructions

Step 1. Insert connectors into the four port holes, then surround the connectors with a small amount of Loctite 3108 (~0.5 mL) and expose to ultraviolet light for 30 seconds to glue the connectors in place and prevent leakage.

Step 2. Dispense approx. 2 mL of Loctite 3108 onto the center of the glass substrate.



Step 3. Place the two spacers (transparency strips, 100 µm thick) on the outside of the four port holes. These will determine the thickness of the polymer layer (i.e. the height of the microchannel).



EVOLUTION OF THE HILTON HEAD WORKSHOP RESEARCH COMMUNITY

Adam D. Troy, Guo-Qiang Zhang, and Mehran Mehregany
Department of Electrical Engineering and Computer Science
Case Western Reserve University
Cleveland, Ohio USA

ABSTRACT

In this paper, we analyze the evolution of the Hilton Head Workshop research community using our new "sliding window" approach to network theory. To do so, we follow the Hilton Head Workshop from its inception, i.e., the first meeting in 1984, through 2004, the latest meeting. The Hilton Head Workshop research community and the field it represents have undergone many changes over the last 20 years, during which over 2000 researchers (i.e., paper authors) have published over 730 papers. Because the Workshop's inception date coincides closely with the emergence of MEMS as a distinct field and the Workshop's coverage is quite focused on MEMS, its evolution over the last 20 years provides insight into the evolution of the MEMS research community, particularly in North America. We find that the community has grown significantly since 1984, although it needs more time to become a fully "mature" community. Our analysis shows that the sliding window approach paints an accurate and realistic picture of the Hilton Head research community.

INTRODUCTION

Modern scientific research relies heavily on collaboration. This is due to many factors such as increasing researcher specialization, increasing expense of equipment and materials, as well as an increasing pressure to publish. At its core, collaboration is largely a *social* enterprise, requiring personal interaction between the participants, with varying levels of success. In order to begin collaborating, researchers must be introduced to one another in one form or another. New knowledge and ideas that have not yet been formally published often pass from one researcher to another in an informal fashion. Collaboration has been shown empirically and through studies to increase publication output [**1**]. The above reasons make "social networks" an ideal tool to study communities of researchers. In social networks, nodes represent people; a pair of nodes is connected by an edge if there is a relationship between the corresponding individuals, collaboration in this case. In the context of research communities, since publication data is archived, co-authorship can be used to identify collaboration. Social network studies of such communities can reveal a great deal about collaboration within the community, provide an indication of the maturity of the community, and reveal influential members of the community.

BACKGROUND

In this work, we study a research community as represented by its collaboration network. Collaboration (or co-authorship) networks are networks where nodes represent authors and an edge between two nodes indicates that the corresponding authors have been co-authors of a common paper. The notion of scientific collaboration networks was introduced by Price in 1965 [**2**]. A well-known example is the Erdös collaboration graph [**3**], from which Erdös numbers are derived.

Collaboration networks have seen recent interest from two different perspectives: social networks and complex networks. Sociologists, anthropologists, and psychologists often use social networks to study relationships between individuals in groups. Individuals are represented as nodes of a network and edges between them represent their relationship. Traditional studies of social networks can reveal information about how organizations are run and structured, the nature of human interaction and individual roles. Most social network research deals only with relatively small networks and does not include studies of network evolution, mostly due to the lack of availability of such data.

In the 1950s and 1960s, mathematicians Erdös and Rényi published their seminal papers establishing the study of *random networks* [**4**]. Random networks consist of a static collection of vertices where each pair of vertices is connected by an edge based on some fixed probability. Since that time, scientists have assumed that most networks of interest are governed by the theorems proposed by Erdös and Rényi. Recently however, scientists from various disciplines, physics most predominantly, have been studying large networks and have concluded that the old models do not accurately reflect the properties of most large networks. In order to address this deficiency, the study of *complex networks* has emerged as a thriving area of research. The most notable property of complex networks is the power law distribution of the degree of the nodes [**5**], where the degree of a node is the number of other nodes to which it is connected. Complex networks contain very few nodes with high degrees (referred to as hubs), but many nodes with very low degrees. Complex networks also display the "small world" property introduced by Watts and Strogatz [**6**]. Networks that display the small word property have a very short average distance between each pair of nodes. The distance between two nodes is calculated as the smallest number of links connecting the pair of nodes. If no path exists between two nodes, the distance between them is said to be infinity. This property is related in spirit to the popular notion of "six degrees of separation" [**7**], referring to the phenomenon that anyone in the world is only six acquaintances away. Complex networks occur almost everywhere. Examples include cell proteins, food chains, the topology of the internet, and the World Wide Web among many others.

Due to the recent interest in complex networks, several researchers have studied scientific collaboration networks. Collaboration networks are popular for complex network studies due to the availability of large data collections for analysis. Barabási [**8**] has studied the evolution of two scientific collaboration networks, mathematics and neuroscience, from a complex network perspective. In those studies, the network evolution is studied cumulatively by adding each year's activities to the network created by the activities of the previous years. Newman has similarly studied static collaboration networks ranging from biology, physics, mathematics [**9**], to computer science and biomedical research [**10**]. Newman's work focuses on comparison of various statistics and properties of the different networks rather than network evolution. Additional studies on various co-authorship networks appear in [**11,12**].

METHODOLOGY

In this section we present the definitions that are basic to our study. First, we discuss the networks we use to represent research

06TRF-0003/hh2006/$20©2006TRF
DOI 10.31438/trf.hh2006A.5

ommunities. Next, we define the sliding window perspective for network evolution observation.

We represent research communities using relatively simple social networks. Each author in the community is represented as a node or vertex in the network. An edge exists between two vertices if and only if the authors represented by the nodes have collaborated as co-authors on a paper. A graph so constructed contains many nodes and edges. This graph is a good approximation of the relationships in the community that facilitate the production of research and publications. These relationships are also likely to provide the conduit for unobserved discussion and transfer of ideas within the community. Many other more complex representations are possible. For example, weighted edges could be used to represent the strength of the relationship between the co-authors, or multiple classes of links could be used to represent relationships between authors such as those who belong to the same institution or attended the same workshop. For a thorough review of networks and their properties see references **[13,14]**.

One of the unique and important aspects of our work is the use of something we refer to as the "sliding window perspective". The main idea behind the sliding window perspective is that, when analyzing the network representing a community at a specific instance in time, the network should be constructed using only the data from recent, time-relevant collaborations rather than the cumulative history of collaborations. The sliding window approach reveals a completely different kind of network topology. For example, when analyzing the network for a particular year, we may only use the previous several years of the network data for edge construction even if a twenty-year history of the community of interest is available. The main argument for this perspective is that, when the goal is to analyze a specific community as it actually exists at a specific instance in time, the collaborations which took place a significant period of time earlier (and have not been renewed recently) are not an indication of an existing connection in the network representing the community structure at the current time. The sliding window approach is crucial to studying the lifetime dynamics of a community network. Communities not only add members as time passes but also lose members as these members change field or retire, though these "exits" are not explicit. The sliding window perspective also provides a simple way of capturing this process. A related idea was used by Jin for modeling growth in social networks **[15]**. The sliding window is the basis upon which all of our observations are presented in this paper.

The size (i.e., how long back from the point of interest) of the window is highly dependent on the specific community of interest. The goal is to choose the window size that best approximates the network as it actually existed in that moment of time. We recommend choosing a window that is large enough to include all but the most extreme time-spans between successive collaborations for the same pair of authors. The idea behind this is that if two authors collaborate again after their initial collaboration a link must have still been present between them in the network to facilitate this new collaboration. If a window is chosen that is much smaller, links between collaborating authors will fall out of the estimated network when they likely still exist. If the window is chosen to be much larger, older relationships that no longer have an effect on the community or no longer exist will remain in the estimated network.

ANALYSIS

In order to get some intuition for how much the community has changed, Figs. 1 and 2 show the community initially after the 1984 meeting and lately after the 2004 meeting, respectively. The dramatic growth of the community is evident from these figures. In 1984, the separate clusters of the network are formed by those authors who are co-authors of a single common paper. By 2004, the community has become much more complex, displaying several large clusters along with many small, single-paper clusters. The large clusters of Fig. 2 are often sub-communities containing authors who all belong to a common institution such as a university, laboratory, or company.

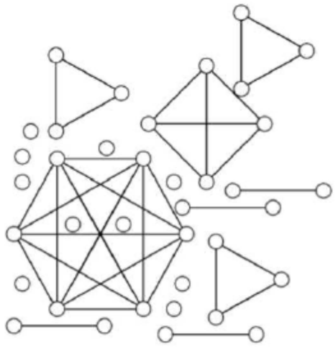


Figure 1. *The Hilton Head community social network as it appeared after the 1984 meeting.*

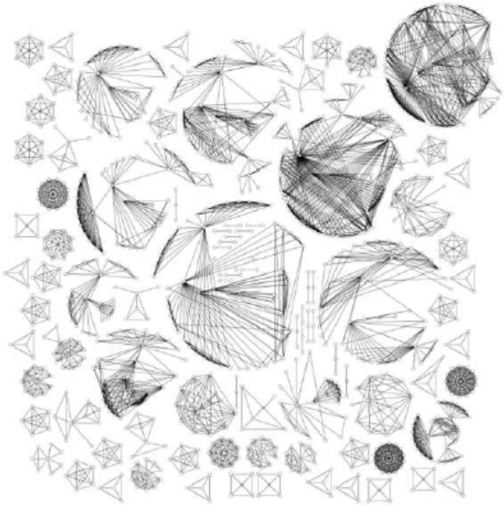


Figure 2. *The Hilton Head community social network as it appeared after the 2004 meeting with a six-year sliding window.*

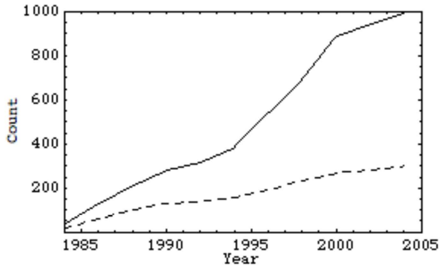


Figure 3. *Evolution of number of authors (solid) and number of papers (dashed) for a six-year sliding window.*

In this work, we use a sliding window of six-years. Therefore for each of the statistics discussed, the observations were gathered from a network constructed from the year shown and the preceding five years (other than the networks for 1984 and 1986, of course), for a total of three conferences per observation. Figure 3 shows the evolution of the number of authors and papers over the past twenty years of the community's life. In 1984, 37 researchers founded the community, while in 2004 the community had 989 researchers, a 26-fold increase over 20 years! This increase is an indication not only of an increase in the average number of authors per paper, but also an increase in the diversity of the authors in the community, i.e., as opposed to the same small group of authors contributing papers year after year.

Figure 4 shows the evolution of the average number of papers per author, authors per paper, and collaborations per author. These statistics clearly portray the infancy of the MEMS discipline at the time of the founding of the Hilton Head Workshop, when authors often worked alone or in relatively small groups, whereas authors now have many collaborators, both on a per paper basis and overall. Figure 5 shows the evolution of the average component size for the 20-year lifetime of the community. In 1984, components were made up of only those authors which were co-authors on a single common paper, causing the average number of authors per paper (Fig. 4) and the average component size to be the same. This is in contrast to the current average component size, 10.6, which is significantly higher than the current average number of authors per paper of 4.5 (Fig. 4). This indicates that authors are collaborating with more researchers than would be explained by the increase in the average number of authors per paper and also that authors are collaborating with different groups of researchers for different papers. Additionally the growth of the number of components seems to have leveled off, implying that old components are merging and new authors are being introduced as part of existing components.

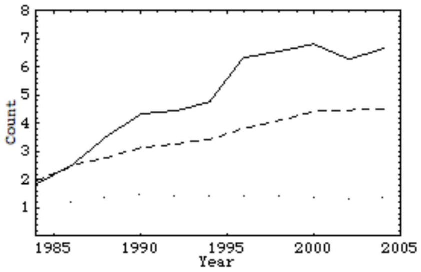


Figure 4. *Evolution of average number of collaborations per author (solid), average number of authors per paper (dashed), and average number of papers per author (dotted) for a six-year sliding window.*

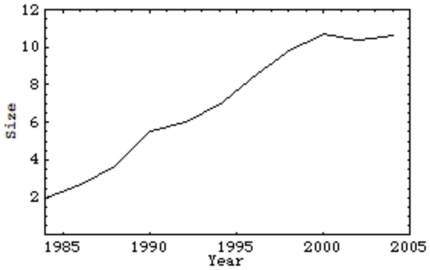


Figure 5. *Evolution of average component size for a six-year sliding window.*

Mature collaboration networks are dominated by a "giant component" which encompasses most authors (80%-90%) in the community [**9**]. Figure 6 shows the size of the giant component as a percentage of the total network size. Clearly, the size of the giant component remains quite small. The declines in the size of the giant component are not due to the giant component shrinking, but rather the size of the total network increasing. The normalized disconnected diameter (NDD) of the network, a metric developed by the authors of this paper, is shown in Fig. 7. The NDD measures how closely the members of the community are connected. An NDD of one indicates that the network is completely disconnected (or each node is maximally separated from the others), consisting only of single nodes with no connections; an NDD of zero indicates that each node has a connection to every other node (or each node is minimally separated from the others). The NDD metric is an extension of the standard network diameter [**14**] which in our view does not adequately deal with disconnected networks of the type studied here. (A full analysis of the properties and uses of the NDD metric will appear elsewhere.) The NDD for the Hilton Head community remains quite high, indicating that the community is still quite disconnected— most researchers are not connected to one another.

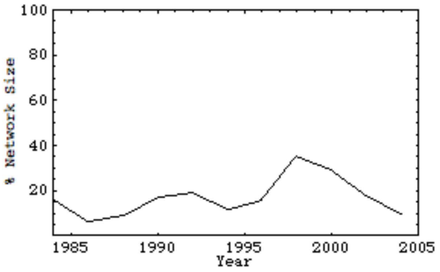


Figure 6. *Evolution of the size of the giant component as a percentage of total network size for a six-year sliding window.*

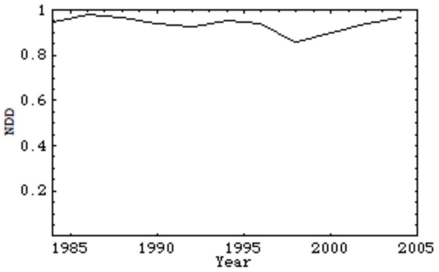


Figure 7. *Evolution of the normalized disconnected diameter of the network for a six-year sliding window.*

An important role that a researcher can play in the network is that of a "connecter". Connectors are those researchers with the greatest "betweenness" scores. The betweenness score for each author is the number of shortest paths between pairs of authors that the author lies on. These researchers are important because they have the most influence on the network at large in terms of information flow. Table 2 shows the top five betweenness authors for the past six meeting years. The most interesting authors in this table are those that are not also network hubs. Hubs have high betweenness values because they have a large number of collaborators. Those authors which are connectors but have a relatively low number of collaborators are likely to be connectors between separate sub-communities of researchers, such as Mark Sheplak in 2002, for example. Interestingly, at least between 1984 and 2004, the betweenness peaked in 2000 with significantly higher values than were seen before and after that time, which roughly corresponds with the peak in the size of the giant component seen in Fig. 6.

In order to illustrate the importance of authors with high betweenness (but not being network hubs), Fig. 8 shows the local network around Mark Sheplak in 2002, who had a betweenness score of 6411 at that time. It is clear from the figure that though Sheplak had relatively few direct connections (9), he played and extremely important role in this cluster, providing a path between the two sub-communities visible in the figure. Sheplak is the single connector in this cluster, if he were not present, there would be no path between the two sub-communities.

Year	Author	Betweenness
2004	Thomas W. Kenny	5250
	David J. Beebe	2184
	Martin A. Schmidt	1924
	Roger T. Howe	1922
	Albert P. Pisano	1800
2002	Thomas W. Kenny	11193
	James H. Smith	6496
	Mark Sheplak	6411
	Roger T. Howe	5694
	Antonio J. Ricco	5054
2000	Thomas W. Kenny	28071
	Roger T. Howe	14524
	Stephen D. Senturia	12463
	Yiching A. Liang	11249
	John R. Gilbert	11070
1998	Stephen D. Senturia	23990
	John R. Gilbert	18587
	James H. Smith	18271
	Thomas W. Kenny	17447
	Roger T. Howe	12896
1996	William J. Kaiser	3816
	Stephen D. Senturia	3413
	Khalil Najafi	2758
	Thomas W. Kenny	2614
	G. K. Ananthasuresh	2553
1994	Stephen D. Senturia	1130
	Mehran Mehregany	906
	Khalil Najafi	823
	Kensall D. Wise	736
	Gregory C. Frye	428

Table 1. *Top five betweenness authors for meeting years of 1994 through 2004.*

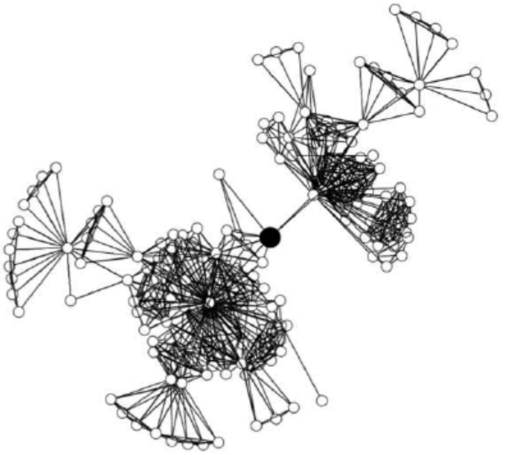


Figure 8. *The local network centered around Mark Sheplak (large black circle) in 2002 with a sliding window of six-years.*

CONCLUSION

The Hilton Head workshop research community has undergone great change over the past twenty years. Starting with 37 founders, the community is now made up of nearly one thousand authors. Though the community has grown significantly, it is still quite disconnected when compared to other research communities. There are clear indications that the community is maturing. A distinct group of hub authors has emerged, a property of complex networks. Authors are collaborating with more authors than would be explained simply by an increase in the average number of authors per paper. This has caused the average component size to increase significantly. The continuation of these trends will cause the giant component to grow in size, connecting more authors to one another and decreasing the normalized disconnected diameter. As the community matures, the productivity of its members should increase as it provides a better environment for collaboration and communication.

A limitation of social network analysis of communities of this type is that the membership is controlled artificially in that papers and therefore authors are reviewed before acceptance. Therefore, growth in the field may not be directly evident in the social network. This is not likely to have any great effect on our conclusions however, because such changes will be indirectly evident. As the community grows and the number of papers submitted increases, conference organizers will in-turn increase the size of the conference, accepting more papers.

In contrast to our sliding window analysis, a classical cumulative analysis would have provided some different conclusions. The giant component, for example, would have been significantly larger by 2004 (70% of network size), which in turn would cause the NDD to be lower, (0.48). We argue though, that such observations would not be valid, as they include collaborations from twenty years in the past.

One limitation of this work is that it includes the collaborations of only one workshop in a larger field. There are likely many collaborations between the authors that are not represented in this workshop. As an analysis of this single workshop though, it still provides interesting insight.

REFERENCES

[1] S. Lee and B. Bozeman, "The Impact of Research Collaboration on Scientific Productivity", *Social Studies of Science*, *35*, pp. 673-702, (2005).

[2] D.J. de Solla Price, "Networks of scientific papers", *Science*, *149*, pp. 510-515, (1965).

[3] V.Batagelj and A. Mrvar, "Some analyses of Erdös collaboration graph", *Social Networks*, *22*, pp. 173-186, (2000).

[4] P. Erdös and A. Rényi, "On random graphs", *Publicationes Mathematicae*, *6*, pp. 290-297, (1959).

[5] A.L. Barabási and E. Bonabeau, "Scale-free networks", *Scientific American*, *288*, pp. 60-69, (2003).

[6] D.J. Watts and S.H. Strogatz, "Collective dynamics of "small-world" networks", *Nature*, *393*, pp. 440-442, (1998).

[7] J. Guare, "Six Degrees of Separation", Vintage Books, (1990).

[8] A.L. Barabási, H. Jeong, R. Ravasz, Z. Néda, A. Schubert, and T. Vicsek, "Evolution of the social network of scientific collaborations", *Physica A*, *311*, pp. 590-614, (2002).

[9] M.E.J. Newman, "Coauthorship networks and patterns of scientific collaboration", *Proceedings of the National Academy of Science, USA*, *101*, pp. 5200-5205, (2004).

[10] M.E.J. Newman, "Who is the best connected scientist? a study of scientific coauthorship networks", In H. Frauenfelder E. Ben-Naim and Z. Toroczkai, editors, *Complex Networks*, pp. 337-370. Springer, (2004).

[11] J.W. Grossman, "The evolution of the mathematical research collaboration graph", *Congressus Numerantium*, *158*, pp. 202-212, (2002).

[12] M.A. Nascimento, J. Sander, and J. Pound, "Analysis of sigmod's co-authorship graph", *SIGMOD Record*, *32*, pp. 8-10, (2003).

[13] R. Albert and A.-L. Barabási, "Statistical mechanics of complex networks", *Review of Modern Physics*, *74*, pp. 47-97 (2002).

[14] S.N. Dorogovtsev and J.F.F. Mendes, "Evolution of networks", *Advances in Physics*, *51*, pp. 1079-1187, (2002).

[15] E.M. Jin, M. Girvan, and M.E.J. Newman, "The structure of growing social networks", *Physical Review E*, *64*, pp. 381--399, (2001).

HANDS-ON MEMS: BUILDING COMPETENCE THROUGH PRACTICAL LEARNING EXPERIENCES

L.G. Fréchette[1, 2], C.W. Wong[2], K. Chin[3], G. Georgiou[3], K.F. Farmer[4], F. Miller[5], V. Modi[2]

[1] Université de Sherbrooke, Dept of Mechanical Engineering, Sherbrooke, QC, Canada
[2] Columbia University, Dept of Mechanical Engineering, New York, NY, USA
[3] New Jersey Institute of Technology, Department of Physics, Newark, NJ, USA
[4] TSI Incorporated, Shoreview, MN, USA
[5] Lehigh University, Microelectronics Research Laboratory, Bethlehem, PA, USA

ABSTRACT

Over the past 5 years, we have developed an education program in MEMS with original activities that build student competences in the development of MEMS devices. This paper first presents the underlying philosophy of education adopted here, which focuses on *competence* as opposed to knowledge. The specific pedagogical activities or tools developed and used for our MEMS course will then be presented, including: lectures, case-studies, virtual microfabrication software, a focused design project with clear goals, and hands-on testing of specially designed MEMS devices.

INTRODUCTION

It is particularly challenging to adequately prepare students in the field of micro-engineering since the development of microelectromechanical systems (MEMS) is both highly multidisciplinary and technology-intensive. Typical MEMS devices can integrate elements traditionally associated with distinct fields of engineering and science, including mechanical, electrical, and chemical engineering, applied physics, chemistry, and biology. For example, the development of a MEMS optical switch may require elements from structural mechanics, electrostatics, material science, circuits, and photonics, while a microfluidic biosensor may involve fluid and mass transport, microelectronics, control theory and molecular biology to name a few. The micro and nanofabrication technologies available to implement such microsystems are typically based on semiconductor manufacturing, which is an important body of knowledge in itself. Novel devices constantly introduce new requirements which push the limits of current fabrication technology, leading to the development of less traditional materials and fabrication approaches.

It is therefore not likely for a student to acquire comprehensive knowledge in *all* the disciplines used in the design of MEMS and master the broad range microfabrication technologies involved in their implementation. The question is then: what should a MEMS course or program accomplish? If the objective is to prepare the student to undertake the development of MEMS in industrial or academic settings, then the course should aim at raising his level of *competence* in doing so. In this article, we present our competence-based learning approach for MEMS followed by the curriculum, pedagogical activities, and tools that we have developed to implement it. This work has evolved over the past 5 years through the increasing interaction of faculty members at the New Jersey Institute of Technology (NJIT), Columbia University, Lehigh University, and the Université de Sherbrooke [2].

COMPETENCE-BASED LEARNING

In defining the content of our MEMS course, we focused on activities that cover the spectrum of skills and knowledge required for the development of MEMS, while minimizing the need for extensive facilities. Generally, competence will be gained by developing [1]:

1) scientific or disciplinary *knowledge*;
2) technical skills or *aptitudes*;
3) personal and interpersonal skills or *attitude*.

Development of the student's aptitudes and attitude are equally important as scientific knowledge, given the *innovation-driven* nature of MEMS. The students should develop competence to pursue the following steps: Invention – Design – Implementation – Operation. The competencies required to realize these four steps go beyond disciplinary knowledge, to include aptitudes and attitude, as illustrated in Figure 1. In class, these are implemented through a combination of: lectures, homeworks and examinations, case studies, hands-on MEMS laboratories, virtual microfabrication and a team design project. The contributions of these activities to the various skills and attitudes to be developed are listed in Table 1. The following sections will describe the overall course curriculum, followed by the main activities: Hand-on MEMS testing laboratories, ICLAB virtual microfabrication software, and team design projects.

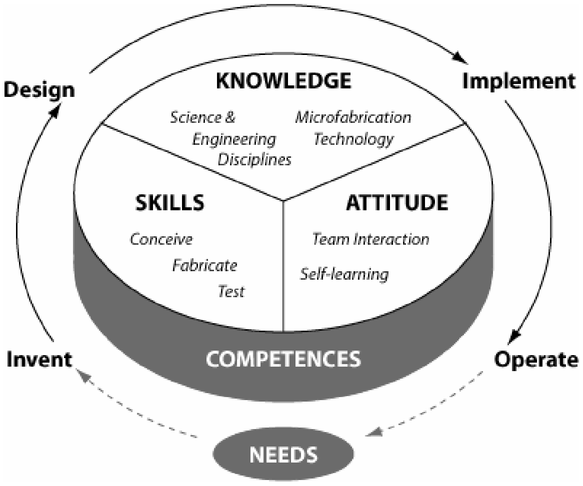
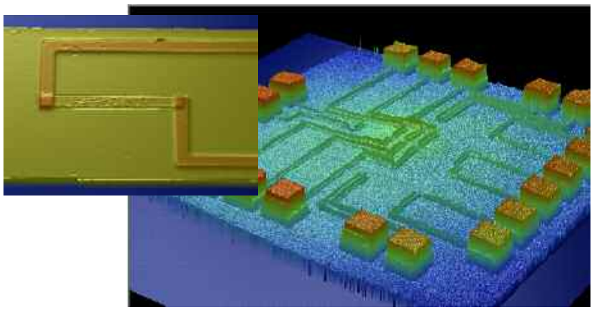


Figure 1 – Competency-oriented MEMS education: the underlying philosophy that guides the choice of pedagogical activities for the MEMS course.

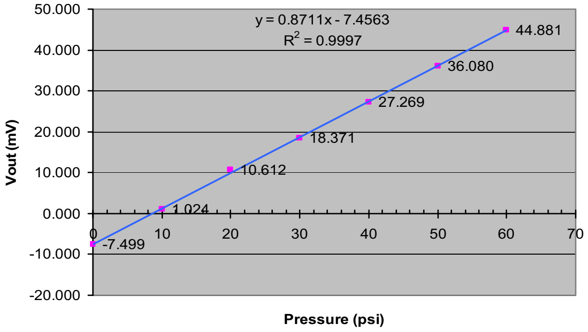
COURSE CURRICULUM

The activities used in our MEMS courses have evolved over the past years, and have not necessarily all been used simultaneously. The course is aimed towards new graduate students or engineering seniors. Typically, the first half of the semester focuses on lectures to provide an introduction to 1) MEMS markets, applications, and scaling; 2) MEMS materials and fabrication methods, with emphasis on silicon micromachining and process integration; 3) MEMS operating and transduction principles including: mechanics, dynamics, electrostatics, piezoresistance, piezoelectricity, and thermo-mechanics; 4) MEMS device concepts, for pressure, acceleration, and rotation, as well as more advanced devices; 5) Microfluidics: Flow, heat and mass transfer at small scales; electrokinetics; power MEMS and bioMEMS; 6) Photonics and optical MEMS; 7) MEMS device design, simulation tools, and characterization techniques, and MEMS packaging concepts. Case studies are used to contextualize and integrate the material presented. Individual homework is mainly used for evaluation, as well as a mid-term exam. The main textbook used for the course is that of Senturia [3], but the students are also recommended to consult Kovacs [4] as necessary.

The second half of the time in class is devoted to more practical activities, during which the students will gain hands-on experience in testing MEMS sensors and actuators specifically designed for educational purposes, design a MEMS device, and familiarize themselves with microfabrication with a unique cleanroom simulation software. The following sections will describe these activities.



(a) Pressure sensor w/ multiple resistors



(b) Wheatstone bridge output versus pressure

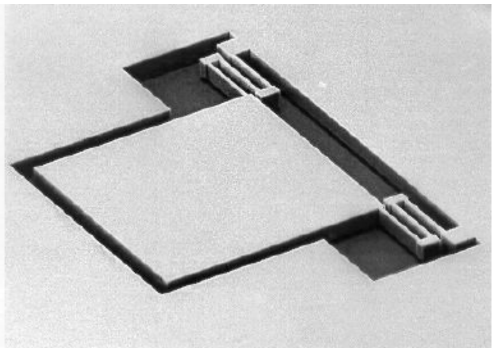
Figure 2 – Piezoresistive pressure sensors used for the hands-on test laboratories, specially designed for educational purposes: a) Optical profilometer image of the various piezoresistors located on the membrane, showing one resistor in insert; (b) Experimental measurements by the students at Columbia, showing the Wheatstone bridge output as a function of applied pressure for selected resistances.

HANDS-ON MEMS LABORATORIES

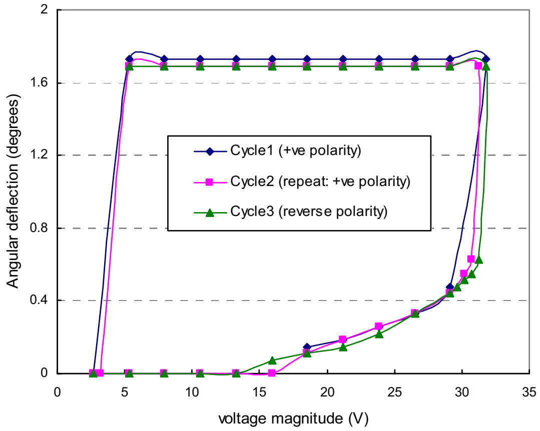
In the hands-on laboratories, two MEMS devices are tested: 1) a piezoresistive pressure sensor; and 2) an electrostatic actuator. They were specially developed for educational purposes by Prof. K. R. Farmer at NJIT [2].

The pressure sensor shown in Fig. 2 consists of a single crystal silicon membrane formed by anisotropic wet etching and has multiple diffused strain gauges (piezoresistors) distributed over the membrane. The students can first perform individual measurements of resistance as a function of the applied pressure. The stress distribution over the membrane, as determined by the various piezoresistors, can be compared to analytical and finite element solutions in order to better understand the structural mechanics involved. Various Wheatstone bridge configurations are then evaluated to highlight the importance of circuits in transduction (sample results are shown in Fig. 2b).

The electrostatic actuator is a micromirror attached by a torsionnal spring, as illustrated in Fig. 3a. It is formed by deep reactive ion etching of a thin Si wafer (50 microns) that is bonded over a pit in a thick silicon substrate. An oxide layer between the wafers allows the application of a potential between the mirror and the substrate. The resulting electrostatic force pulls the mirror down and makes it rotate about the torsionnal springs. Measurements of deflection are simply taken by tracking a light beam that is reflected off the tilting mirror as a function of applied voltage (Fig. 3b).



(a) Electrostatic micromirror



(b) Angular displacement versus DC voltage

Figure 3 – Electrostatic torsion micromirror (actuator) used for the hands-on test laboratories. It allows investigation of electrostatic actuation, including pull-in, hysteresis, and even fluidic damping (dynamic response tests, not shown here).

In this laboratory, the students have the opportunity to explore the non-linear behavior of electrostatic forces and the pull-in instability phenomena. When comparing the results to simple analytical solutions, the students must explain why the mirror remains down even when the applied potential is lowered below the pull-in value. This pushes the students to better understand the balance between the forces involved and the origin of the pull-in instability. Dynamic response testing was also conducted with naturally underdamped and overdamped devices to illustrate the behavior of this second order system and introduce the concept of viscous damping. These measurements were simply done with a function generator in open air, since a sufficient range of damping ratios can be achieved through changes of the geometry.

Throughout these laboratories, the students develop their experimental skills and procedures, learn to interpret and analyze experimental data, while stimulating their curiosity and excitement for MEMS. Unlike commercial MEMS, these educational test devices are not completely packaged so students can manipulate the chips and directly measure their dimensions. The presence of superfluous piezoresistors or multiple geometries further enhance the learning experience. Relatively simple instrumentation is used such that these laboratories could be implemented at other institutions with minimal investment.

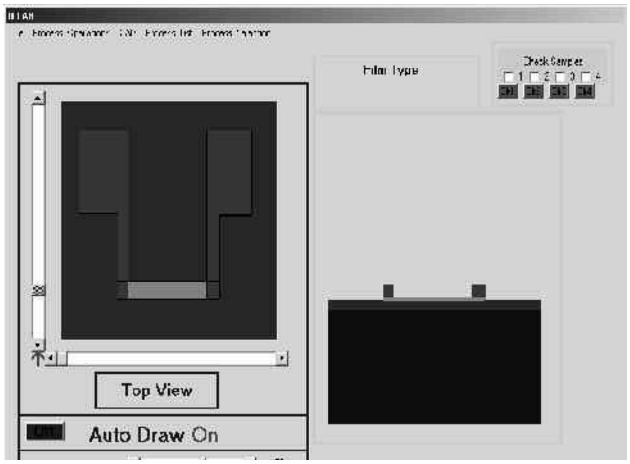
VIRTUAL MICROFABRICATION

To familiarize the students with cleanroom equipment and processing, a virtual microfabrication environment is used: ICLAB by F. Miller [5]. Unlike commercial MEMS software (Coventor, Intellisuite), ICLAB simulates the consecutive processes in real time (or faster), requires control of the process equipment through schematics while respecting realistic constraints, and allows students to see their wafer cross section as it is etched or films deposited (Fig. 4a).

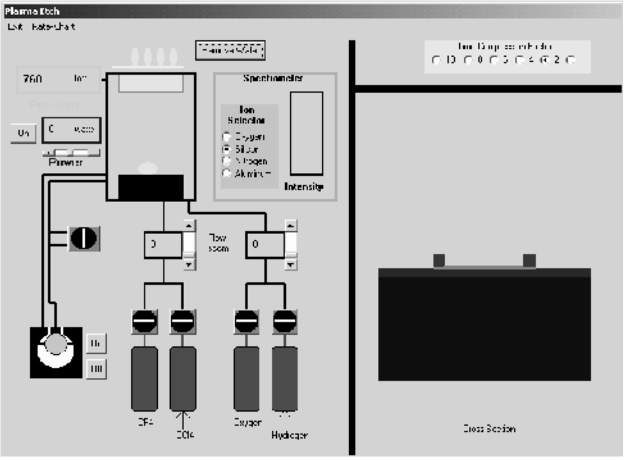
For example, Fig. 4b displays a virtual sputter-etching system. The student must operate the system by first loading a wafer into the vacuum chamber. Next the pump is started and the air pumped out of the chamber. Valves are opened to allow selected gases to flow into the chamber. Flow meters must be set to adjust gas flow and chamber pressure. Power is turned on and set to the desired level. Etching will now start but only if the pressure is within the correct range, a wafer is actually in the chamber and the combination of films on the wafer and etch gas would actually allow etching to occur.

As the etch proceeds, the student will be able to watch the etching progress by viewing a cross section of the wafer. A basic spectrometer is available to assist with endpoint detection. Etching is stopped by turning off power. If the student does not turn off power etching will continue until everything that can etch is removed from the wafer (including the wafer).

All of the individual processes available in ICLAB operate in the same manner as the plasma etching described above. They include oxidation, ion implantation, lithography, chemical etching, CVD, PVD, CMP, and wafer cleaning. Limited backside processing was added to allow MEMS processing. Students carry out individual process steps and immediately see the results of their action. Students can feel free to explore the virtual processing environment where mistakes provide valuable learning experience but cost nothing in terms of lost materials, lost lab time, or student safety.



(a) Top and cross section view of wafer



(b) Virtual plasma etch system

Figure 4 – ICLAB: a virtual cleanroom processing environment that allows the students to de-mystify cleanroom processing and microfabrication.

The use of virtual fabrication software allows hands-on microfabrication experience, without the cost, time, and infrastructure requirement associated with real cleanroom experience. It also helps the students appreciate the challenges related to process integration, such as thermal budgets, selectivity, and materials compatibility. This software is mostly used to complement the lectures on microfabrication, but has also been used for case studies and design projects.

TEAM DESIGN PROJECTS

The initial portion of the cycle shown in Fig. 1 is implemented with a MEMS design project. It starts either from a specific need or from an original idea. The students must invent and design a MEMS device that addresses the need or that implements the idea. At Sherbrooke, the students first translate the needs into requirements and specifications, and then undertake the design of a novel MEMS device to meet them. At Columbia, the topics are proposed and supported by faculty members. This approach has been fruitful, since some projects have led to further research and development as thesis projects, based on innovative directions from the students themselves.

Teams are typically formed of students with different backgrounds to favor multidisciplinary interactions and cover the range of disciplines required for a project. During the design process, the students need to deepen their knowledge beyond the level covered in class in one or more disciplinary areas. They must also define a viable process flow for their device, which often proves to be very challenging without expert assistance. Faculty or graduate mentors therefore play an important role in the quality of the projects. Students have consistently remarked that they learnt more during the actual design project process.

A final group report and presentation is scheduled, with a panel of faculty judges. Throughout the activities in the second half of the semester, the students develop their competencies for MEMS design, fabrication, and characterization while improving their knowledge of the physics and fabrication processes used in the development of MEMS.

DISCUSSION AND CONCLUSIONS

The pedagogical activities and tools presented above have been very well received by the students, based on their end-of-term course evaluations and comments. Enrollment has continuously increased, going from 16 students in 2002 to 37 students in 2005 (Columbia). Although the majority of students have been from mechanical engineering (avg. 80%), there has been students from electrical engineering, applied physics, biomedical engineering, civil engineering, and industrial engineering.

Although the competence-based learning approach with hands-on testing, virtual microfabrication and project projects would benefit from further development, these activities appear to be well suited for teaching MEMS. Since MEMS is inherently a device or product oriented field, it is amenable to practical, hands-on activities. Unfortunately, MEMS technology is less accessible due to the cost of cleanroom infrastructures and the lack of MEMS devices dedicated for education. Through the work presented here, the objective has been to alleviate some of these limitations to make hands-on MEMS education widely accessible. Portions of this work have been supported by NSF 02-043; this support is gratefully acknowledged.

REFERENCES

[1] Proulx, D., Brouillette, M., Charron, F., Nicolas, J. “A New Competency-Based Program For Mechanical Engineers”, Presented at the CSME Forum 1998, Ryerson Polytechnic Univ., Toronto,19-22 May 1998.

[2] Fréchette, L., Modi, V., Miller, F., Farmer, K.R., “Hands-on MEMS”, 15th Biennial University/Government/Industry Microelectronics Symposium, Boise, Idaho, June 30 - July 2, 2003.

[3] Senturia, S. D., *Microsystem Design*, Kluwer, Boston, 2001.

[4] Kovacs, G., *Micromachined Transducers Sourcebook*, McGraw Hill, New York, 1998.

[5] Miller, F., “Virtual Reality in Microelectronics Laboratory Instruction,” Proc. of the 14th Biennial University/Government /Industry Microelectronics Symp. Richmond, VA, June 18-20, 2001.

Table 1 – List of competencies developed in the MEMS course with the pedagogical activities. Stars (* or **) indicate the level of contribution of each activity to the skill or attitude developed.

SKILLS / APTITUDES / KNOW-HOW	Lectures homework, reading	Case Studies	Design Project	Hands-on Test Labs.	ICLAB virtual fab.	Clean-room fab.[1]
Define needs		**	*			
Identify potential applications for MEMS	*	**	*			
Conceive a device: principles and layout	*		**			
Develop a microfabrication process flow	*	*	**		*	*
Design the device quantitatively	**		**			
Analyze the device behavior	**	*	*			
Fabricate the device					*	**
Develop and integrate microfab. processes	*				*	**
Characterize the device and fab. results				**		**
Package the MEMS device		*		**		
Test the device performance				**		
Integrate the MEMS in an application		*	*	*		

ATTITUDE						
Self-learning from the literature	**	*	*			
Interaction with people in other disciplines			**	*		*
Work in teams			**	**		
Communicate effectively			*	*		
Proper cleanroom behavior						**
Maintain a log book of R&D activities			*	*		*

[1] NOTE: Cleanroom fabrication was not an activity in the current MEMS course at Columbia or Sherbrooke, but a tour of the cleanroom is included to strengthen the learning process.

INTRODUCTORY MICROMACHINING AND MEMS COURSE FOR GRADUATE AND UNDERGRADUATE STUDENTS

Jack W. Judy[1] **and Paulo S. Motta**[2]

[1]Electrical Engineering Department, University of California, Los Angeles, Los Angeles, CA 90095 USA
[2]Innovative Micro Technology, Goleta, CA 93117, USA

ABSTRACT

An undergraduate-level course that provided an introduction to the fields of MEMS, with an emphasis on the processes used to microfabricate MEMS, was first developed at UCLA in 1998. It has served well to quickly ramp-up new MEMS graduate students that have lacked prior experience with MEMS. It has also given undergraduates and students even outside of the school of engineering, an opportunity to be exposed to micromachining and MEMS. A comprehensive, weekly, and hands-on laboratory session gave all students a greater appreciation for the capabilities and limitations of micromachining processes and MEMS devices. Due to excessive popularity and safety limitations on the number of students allowed into each lab session, the course was split into two separate courses: a lecture-only course and a laboratory course. Now students from nearly any background can learn about MEMS and could be the seeds of future uses of MEMS technology in their chosen discipline. These courses also serve as a spring board into the formal MEMS graduate program at UCLA, as well as into the MEMS industry.

I. MOTIVATION AND BACKGROUND

Since 1998, UCLA has offered introductory MEMS courses specifically designed for both undergraduate and graduate students. Up until that time, MEMS courses at universities were primarily, if not exclusively, offered at the graduate-student level. The motivation behind offering MEMS courses also at the undergraduate level was driven by the following: (1) the growing MEMS industry demanded a MEMS-aware/knowledgeable work force at all levels (Ph.D., M.S., and B.S.); (2) the expanding diversity of MEMS applications attracted students from many different backgrounds with no prior knowledge of micromachining; (3) the core material on MEMS fabrication is easily accessible to undergraduates (i.e., no upper-division prerequisites are truly required). With NSF Career-Award funding, a course titled "Introduction to Micromachining and MEMS" was designed to consist of two major components: a main lecture sequence and weekly hands-on laboratory sessions. Later, due to popularly and safety constraints, the course was split into two separate courses: a lecture-only course and a lab course.

An important issue in the teaching of micromachining and MEMS is the reality that the students taking the course will have very different backgrounds. For example, we found it common for graduate students from mechanical engineering to have no knowledge or experience with IC fabrication and other micromachining techniques. In addition, students from outside of engineering, such as those in the life sciences or medicine, will lack much of the engineering background that is typically taken for granted, and thus will also struggle in a micromachining and MEMS class taught at the graduate-level. This is particularly unfortunate, since the field of MEMS gains tremendously by the involvement of people from diverse backgrounds, because of the unique needs, applications, and abilities of their field.

We have found that an undergraduate course on micromachining and MEMS is an excellent instrument for addressing these issues. The level of the course makes it much easier to cover sufficient background material, which enables students with no knowledge of micromachining or MEMS to participate. Adding a laboratory component facilitates the solidification of this first-time learning experience. After taking this course, students from almost any background are able to go on to the graduate-level courses in MEMS with confidence.

It is well known that providing hands-on learning experiences is one of the most effective ways of teaching. This is particularly true when there are many details that are important, yet can easily be passed over in lecture or are quickly forgotten. Good examples of material like this are micromachining processes and MEMS. Describing a micromachining process or, for example, the stiction problem in MEMS, and actually experiencing them are two very different things. Clearly the hands-on lesson will be longer lasting and is also likely to provide additional unexpectedly valuable lessons.

II. COURSE STRUCTURE AND DESIGN

Initially, the lecture and laboratory components were integrated into one common course. However, to ease enrollment limitations (described later in the text) and to provide full credit to the students and instructors for their effort, the course was split into two courses: a lecture-only course (two 2-hour lectures/week) and a laboratory course, which consists of a weekly lab-oriented lecture (2 hours/week) and a weekly lab session (4 hours/week). Although potentially a large number of students may enroll solely in the lecture-only course (~100 students in 2003), enrollment in the lab course is greatly limited by safety concerns (max of 10 students in each of the 6 weekly lab sessions) and requires co-enrollment in the lecture-only course. Due to UCLA being on a quarter system, instruction is carried out over 10-week quarters.

A. *Prerequisites*

Since this course is intentionally designed for students with almost any background, the prerequisites include a nominal exposure to college-level chemistry, calculus, and physics.

B. *Textbook*

There is no single textbook that is optimal for this undergraduate micromachining and MEMS course. Currently chapters from multiple texts [1-6] are compiled with selected conference and journal papers into a single course reader.

C. *Lecture Course*

The purpose of this lecture course is to provide both a broad perspective of the field in general and to instruct the students on the fundaments and theory involved in each of the major micromachining process technologies. The course begins by introducing the field of MEMS and provides examples to demonstrate its broad utility, stimulate interest, and promote a curiosity for how MEMS are made. After the basic concept of micromachining is introduced, vital micromachining processes are described. A week-by-week breakdown of the material covered in the lecture course is given below in Table 1. Weekly homework assignments are used to allow students to practice the lessons taught in lecture.

06TRF-0003/hh2006/$20©2006TRF
DOI 10.31438/trf.hh2006A.7

Table 1. *Outline of the lecture course.*

Week	Lecture Material
1a	Introduction, Overview, and History of MEMS
1b	Applications of MEMS with Examples
2a	Process Flow and Crystallography
2b	Chemical Safety, Clean Rooms, Cleaning Procedures
3a	Mask Making, Layout, Photolithography Basics
3b	Photolithography Tools
4a	Wet Etching (Isotropic, Anisotropic)
4b	Wet Etching (Anisotropic)
5a	Vacuum Systems
5b	Midterm Exam
6a	Plasmas and Dry Etching (Plasma Etching)
6b	Dry Etching (RIE, Sputter Etching, Ion Milling)
7a	Physical Vapor Deposition (Evaporation, Sputtering)
7b	Diffusion
8a	Ion Implantation
8b	Thermal Oxidation
9a	Chemical Vapor Deposition (LPCVD, PECVD)
9b	Electroplating and Design of Experiments (DOE)
10a	Design of Experiments (DOE), Process Integration
10b	Process Integration

Obviously, a 10-week quarter is not long enough to include a thorough discussion of advanced microfabrication processes (e.g., advanced lithography, thick-film lithography, soft lithography, DRIE, wafer bonding, electroless plating, photo-electro-chemical etching, chemical-mechanical polishing, stiction and release techniques, batch-assembly techniques, and the mechanical properties of thin-films). As a result, a follow-on graduate-level MEMS-fabrication course is offered at UCLA (EE M250A / MAE M280 / BME M250A: MEMS Fabrication), which is designed to cover these more advanced topics. MEMS-design issues are covered in the second graduate-level MEMS course offered at UCLA (EE M250B / MAE M282 / BME M250B: MEMS Design). To make up for the lack of advanced material in the undergraduate course described here, in each lecture the relevance of the material covered is briefly related to MEMS by the inclusion of pertinent examples taken from the MEMS literature.

D. Laboratory Course

The primary purpose of the laboratory course is to provide hands-on experience fabricating, testing, and characterizing MEMS, in a manner that compliments the content delivered in the lecture-only course. Specifically, the student gains hands-on experience in photolithography, etching (wet and dry surface and bulk micromachining), metal deposition (evaporation, sputtering, and electrodeposition), and several metrology tools (microscope, profilometer, probe station, four-point probe, and spectrometer). The devices that are fabricated as part of this laboratory include: accelerometers, thermal micoractuators, magnetic microactuators [7] and microsensors, fiber-optic switches, neural probes, and pressure sensors (Figs. 1 and 2). The fabrication process is described in a later sub-section.

Although there are 6 separate 10-student (max) laboratory sessions, there is a common lecture specifically for this lab course to insure the students are fully briefed and prepared for the upcoming lab sessions. This laboratory course is taught in the instructional wing of the UCLA Nanoelectronics Research Facility (Nanolab), known as the UCLA Microfabrication Instructional Laboratory (Microlab), which is discussed in more detail below. A week-by-week breakdown of the material covered in the laboratory-course lectures and lab sessions is given below in Table 2.

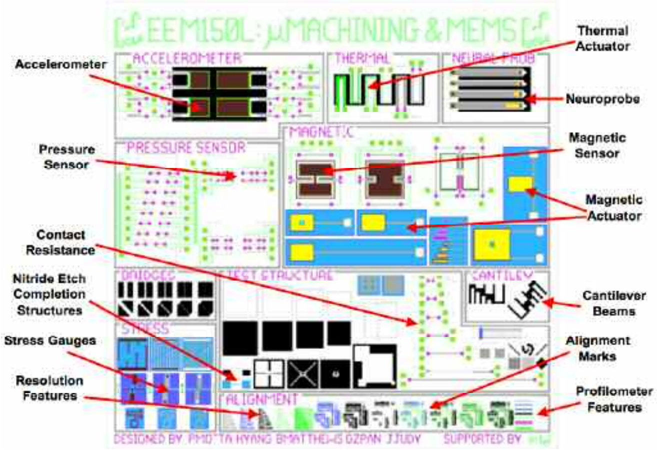


Fig. 1. *Chip layout with devices and test structures indicated.*

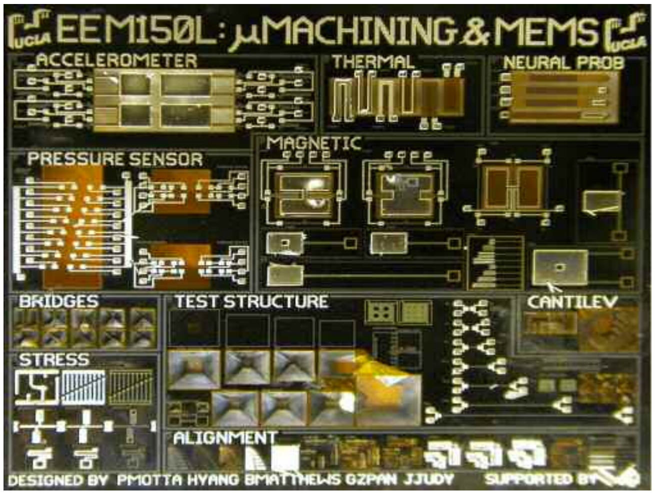


Fig. 2. *Photograph of an individual die fabricated in 2004..*

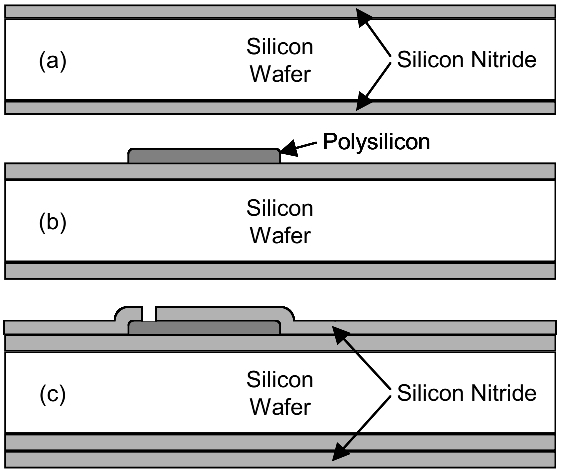
Table 2. *Outline of the laboratory course.*

Week	Laboratory Material (*Lecture* / Lab)
Lec 0	Admin, Overivew, Photolithography, Metrology
Lab 1	**Safety Instruction, Walk Through, and Introduction to Photolithography and Metrology**
Lec 1	Process Flow, LPCVD, Dry Etch, Profilometry
Lab 2	**Photolithography, Poly Dry Etch, Profilometer**
Lec 2	Alignment, LPCVD, Dry Etching, Spectrometry
Lab 3	**Mask Alignment, Nitride Dry Etch, Nanospec**
Lec 3	Front-to-Backside Alignment, Dry Etch, I-V Testing
Lab 4	**Dry Etch, Front-to-Backside Alignment, I-V Test**
Lec 4	Vacuum Systems, Evaporation, Lift-Off
Lab 5	**Dry Etch, Evaporation, Lift-Off**
Lec 5	Electroplating
Lab 6	**Electroplate Ni (Thin Through-Mask Plating))**
Lec 6	Anisotropic Silicon Etch and Release
Lab 7	**Electroplate Ni (Over-Mask Plating), KOH Etch**
Lec 7	Device Physics, Testing, and Characterization
Lab 8	**Device Testing and Characterization**
Lec 8	Thanksgiving Holiday
Lab 9	**Device Testing and Characterization**
Lec 9	Device Physics, Testing, and Characterization
Lab 10	**Device Testing and Characterization**
Lec 10	Review Session and Class Photo

E. Microfabrication Process Flow

The objective of the design of the MEMS chip (Fig. 2) is to enable the demonstration of the fabrication of various MEMS microsensors and microactuators using a single fabrication process that takes 7 weeks to complete. The fabrication process (Fig. 3) consists of 7 photolithography steps, 6 etching steps, and 6 deposition steps. There are 16 chips per wafer, and in each chip contains over 100 devices: microsensors (accelerometers, pressure sensor, resonant magnetometers), microactuators (torsional magnetic microactuator [7], thermal microactuator), and microstructures (neural probe, stress test structures, bulk micromachining test structures). The diversity of devices fabricated was made very high to provide the students with an opportunity to test and become familiar with different types of microsensors and microactuators. However, since the process was obviously not optimized for any of the devices, the performance of each device is far less than that possible with an optimized process.

Starting with a single-side polished, <100> oriented, p type, 500 µm thick silicon wafer, a 2-µm-thick low-stress silicon nitride is deposited using a low pressure chemical vapor chamber (LPCVD). Silicon nitride serves as both an insulator and as the mechanical layer. Next, a 1-µm-thick layer of LPCVD polycrystalline silicon (poly) is deposited and doped with boron. Polysilicon was chosen because it is piezoresistive (i.e., its resistance changes as a function of stress) and it is used as the sensing element in various devices on the chip. Polysilicon is also used as a sacrificial layer for other devices that are produced by surface micromachining. Once the polysilicon layer is patterned, the wafer is covered with another 1-µm-thick layer of low-stress silicon nitride. This layer also serves as a mechanical layer for surface micromachined structures and as the encapsulation to protect the resistors from the release etch. To enable the creation of bulk micromachined devices, openings are created on the backside of the wafer that are aligned to features on the front side. This is accomplished by using a front-to-backside alignment tool (Karl Suss MA-6). Once an opening is created in the upper nitride layer to reveal the polysilicon layer, electrical connection is made to the piezoresistors. A 0.1-µm-thick Cr/Ni layer is then deposited by evaporation to form the seed layer for electrodeposition. Next a 5-µm-thick layer of low-stress nickel is electroplated to form the electrical interconnects. Since some devices require a large volume of metal to serve as the proof mass and as the magnetic torque element, another 25 µm of electroplated nickel are deposited in specific regions. The release of the device is accomplished by etching exposed single-crystal silicon and polycrystalline silicon with potassium hydroxide (KOH)



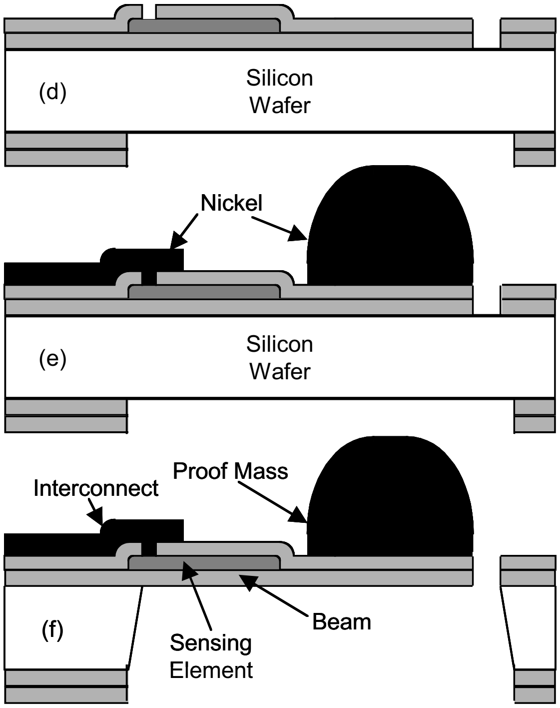


Fig. 3. *Schematic diagram of the fabrication process flow followed in the hands-on laboratory course. With this process the student can produce a wide variety of surface-micromachined and bulk-micromachined microsensors and microactuators.*

F. UCLA Microfabrication Instructional Laboratory

The Microlab instructional facility is a 306 m2 (3300 ft^2) class 1000 cleanroom capable of processing 100 mm (4”) wafers. It consists of a temperature-controlled and humidity controlled laboratory with integrated photolithography, wet etching, measurement, and lecture rooms. The lecture room is where students are instructed and quizzed about the microfabrication processes they perform. It also contains four probe stations with characterization equipment for device testing. The photolithography room (Fig. 4) contains two parallel processing lines for maximum throughput.

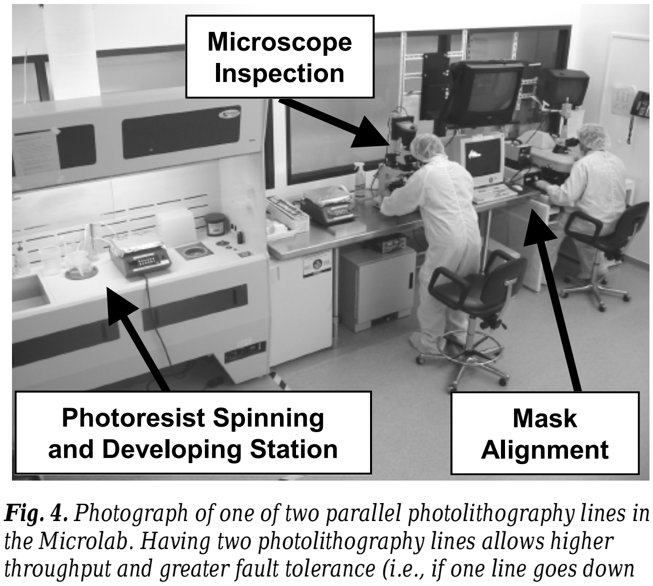


Fig. 4. *Photograph of one of two parallel photolithography lines in the Microlab. Having two photolithography lines allows higher throughput and greater fault tolerance (i.e., if one line goes down the fabrication line may process wafers).*

Each processing line contains a wafer spinner, a Quintel mask aligner for UV exposure, a developing station and sink, and a microscope for inspection (Fig. 4). The etching room consists of two wet benches for wet etching processes. In addition, it contains a programmable spin dryer with 50-wafer capacity, and a Tegal oxygen plasma-etching tool. The measurement room contains a Dektak profilometer and a Nanospec spectrometer. The microlab has a capability of teaching 180 students per year (i.e., 60 students/quarter).

G. *Testing*

Once released, the chips are separated from the wafer (i.e., V grooves fabricated into the wafer by design, allow it to be broken into chips without using a diamond saw) and then tested in one of four probe stations (Fig. 5). Students test all devices, but for brevity, only the accelerometer testing will be mentioned here.

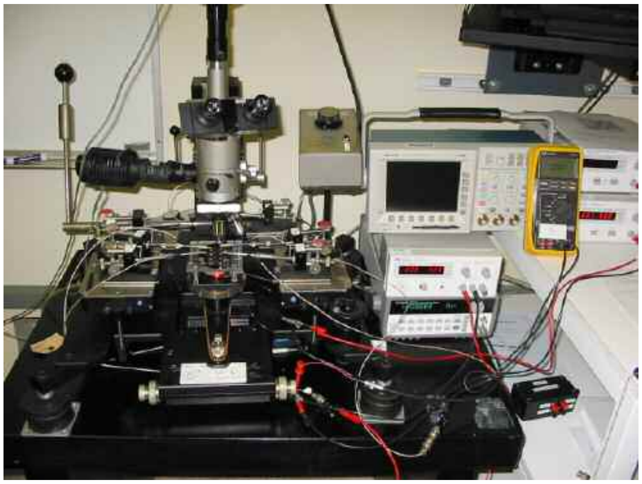


Fig. 5. *One of four probe stations used for device testing.*

The sensing in the accelerometer is done via doped polysilicon piezoresistors, which are laid out on the beams that support the proof mass and are integrated into a Wheatstone bridge circuit (Figs. 6 and 7). Piezoresistance was selected as the transduction mechanism due to its simplicity and robustness. To simulate acceleration, a magnetic field is applied to generate a magnetic torque on the ferromagnetic proof mass. The torque due to the magnetic field can then be related to the measured voltage across the Wheatstone bridge. By knowing the beam deflection, geometry, and material properties, the effective acceleration can be computed.

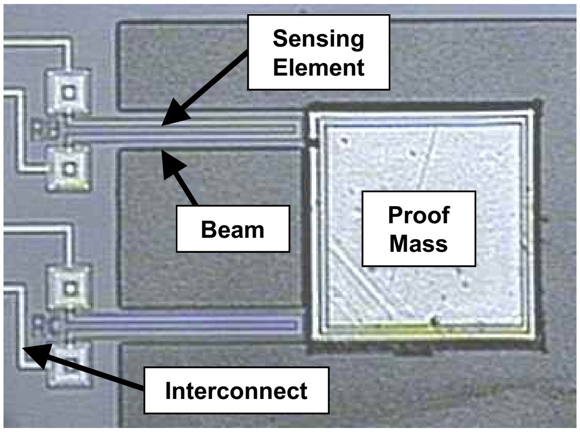


Fig. 6. *Optical image of an accelerometer before being released by a bulk silicon etch. The sensing elements in the accelerometers and pressure sensors are piezoresistors due to their robustness.*

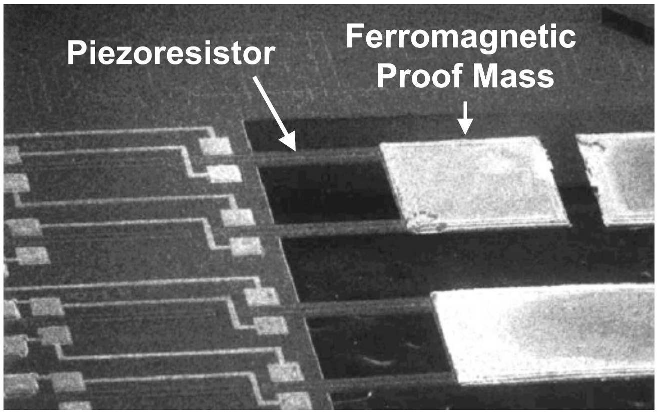


Fig. 7. *SEM image of released accelerometers.*

A plot of the deflection of the tip of the beam versus applied magnetic field is shown in Fig. 8. The error bars are due to experimental error, non-uniform electroplating of the proof mass, non-uniform applied magnetic field, etc. Despite the modest processing variability inevitable in any undergraduate laboratory, good device yield is obtained. The students are amazed, thrilled, and relieved that their hard work all term long has yielded functional devices.

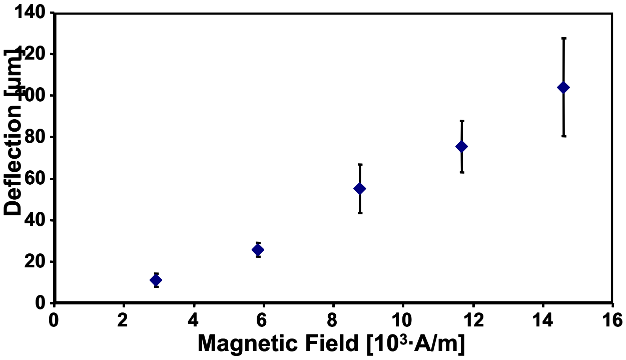


Fig. 8. *Plot of deflection versus magnetic field applied show linear response.*

H. *Trophies*

To provide the students with a symbol of their accomplishment, each year the students are presented with a trophy. This trophy consists of a acrylic block in which a single chip fabricated during their lab session is incased (Fig. 9). Students relate stories about bringing these trophies to job interviews to show what they have accomplished, explain what they did, and explain what MEMS are (if necessary).

Fig. 9. *Photography of the trophies presented to students who successfully complete the lab course.*

I. Student Demographics

The course was taught for the first time in the winter quarter of 1998 on an experimental basis, and a majority of the 12 enrolled students were not from electrical engineering (primarily mechanical engineering and chemical engineering). Figure 10 shows how the enrollment in the course has doubled each year it was taught until it was over subscribed in 2001 and the enrollment was capped at 64 students for laboratory safety reasons. In addition, Figure 10 illustrates how the diverse background of the students in the class has evolved from over time. Although students from chemical engineering (ChemE), civil engineering (CivE), computer science (CS), materials science (MatSci), and even neuroscience and medicine (MD) have taken the course, the majority of the students are in mechanical and aerospace engineering (MAE), electrical engineering (EE), and biomedical engineering (BME).

Figure 11 shows how the level of student in the class has changed over the years (1998-2002: combined course, 2003-2005: lecture-only course). Although these are undergraduate courses, they are clearly very popular with graduate students, as they have consistently made up the majority of the class.

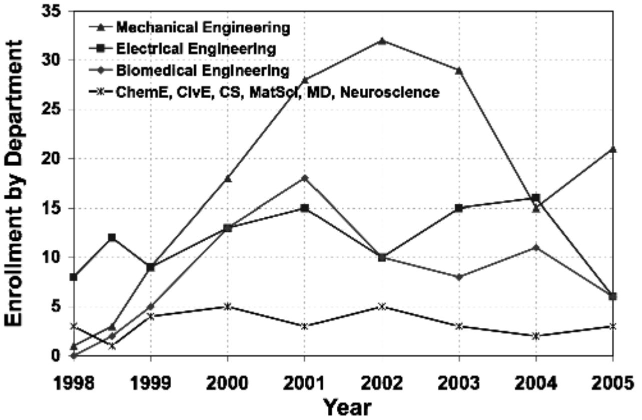


Fig. 10. *Graph of enrolled student departmental affiliation during the years the course has been offered. Note: 1998-2002 correspond to the combined course and 2003-2005 to the lecture-only course.*

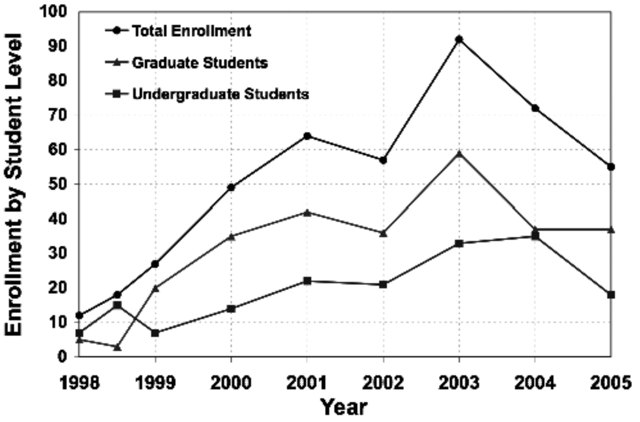


Fig. 11. *Graph of enrolled student level (graduate and undergraduate) during the years the course has been offered. Note: 1998-2002: combined course and 2003-2005: lecture-only course.*

III. LESSONS LEARNED

A 10-week course on micromachining and MEMS technologies has been designed that originally incorporated both a lecture component and a hands-on laboratory component. After three years, we learned that is would be far better to split these components into separate classes. That way many students, who only want to become familiar with MEMS and have no need to gain hands-on experience, would not take the scarce and valuable lab-session slots from a student that vitally needs the hands-on MEMS-fabrication experience provided. Although we have developed a microfabrication process that allows many different surface-micromachined and bulk-micromachined structures to be produced in parallel, an alternative approach with separate, shorter, and less complicated microfabrication processes should be considered.

IV. CONCLUSIONS

Our undergraduate MEMS courses have been taught once a year since 1998. The enrollment has grown from 12, peaking at nearly 100 (lecture-only course), and settling between 60 and 70 students (lecture-only course). The laboratory course is capped at 60 students, and the enrollment is typically between 45 and 60. Although most of the students are from electrical, mechanical, and biomedical engineering, students from many other disciplines, some even outside of engineering (e.g., neuroscience and medicine) have completed and benefited from the course. Despite being undergraduate-level courses, they is very popular with graduate students (66% grads, 34% undergrads). By completing the lecture-only course, the students gain an appreciation for MEMS and an understanding for their fabrication. By completing the laboratory course, the students gain hands-on experience with photolithography, isotropic and anisotropic wet etching, dry etching, physical and chemical vapor deposition, electroplating, MEMS release etching, stiction, and MEMS device testing. This set of undergraduate courses prepares students well to enter the graduate MEMS major field at UCLA offered in the MAE and EE departments [8], or to become active participants in the MEMS and microsystems industry.

V. ACKNOWLEDGEMENTS

This work was supported by an NSF Career Award (ECS 9876285). The authors would like to thank Grant Z. Pan and Eric Chang of the UCLA Microfabrication Instructional Facility for their technical support, and the teaching assistants Brian Matthews, Henry Yang, Chris Folk, and WanYu Wang, for their help developing the fabrication process.

II. REFERENCES

[1] R. C. Jaeger, *Introduction to Microelectronic Fabrication*, Addison Wesley, New York, 2001, ISBN: 0-2014-4494-1.

[2] S. Wolf and R.N. Tauber, *Silicon Processing for the VLSI Era, Vol. 1: Process Technology*, 2nd Edition, Lattice Press, Santa Barbara, CA, 1999, ISBN: 0-9616-7216-1.

[3] M. Madou, *Fundamentals of Microfabrication*, CRC Press, Inc., Boca Raton, FL, 1997, ISBN 0-8493-9451-1.

[4] Richard S. Muller, *Microsensors*, New York: IEEE Press, 1991.

[5] *Micromechanics and MEMS: Classic and Seminal Papers to 1990*, W. Trimmer (Ed.), IEEE Press, New York, NY, 1996, ISBN 0-7803-1085-3.

[6] Gregory T. A. Kovacs, Micromachined Transducers Sourcebook, WCB/McGraw-Hill, 1998, ISBN 0-07-290722-3.

[7] Jack W. Judy, Richard. S. Muller, and Hans. H. Zappe, “Magnetic microactuation of polysilicon flexure structures,” *IEEE Journal of Microelectromechanical Systems*, vol. 4, no. 4, pp. 162-169, 1995.

[8] Jack W. Judy et al., “Comprehensive MEMS Curriculum at UCLA,” *Tech. Dig. Solid-State Sensor and Actuator Workshop* (Hilton Head `06), Hilton Head Island, SC (June 4-8, 2006).

MEMS CURRICULUM AT AUBURN UNIVERSITY'S MICROELECTRONICS CENTER

Ramesh Ramadoss
Alabama Microelectronics Science and Technology Center
Department of Electrical and Computer Engineering
Auburn University
200 Broun Hall, Auburn, AL 36849, USA
email: ramadra@auburn.edu, Tel: 334-844-1879, Fax: 334-844-1809

ABSTRACT

In this paper, a MEMS curriculum developed at the Alabama Microelectronics Science and Technology Center, Department of Electrical and Computer Engineering, Auburn University is discussed. The course curriculum consists of three major components – class lectures (2 lectures per week), Computer-aided design (CAD) sessions and laboratory sessions. CAD sessions and laboratory sessions are conducted on alternate weeks. The objective of this curriculum is to provide a comprehensive understanding of various aspects of MEMS such as principle of operation, design, modeling, simulation, fabrication and characterization. In class lectures, concepts underlying the principle of operation and design of various MEMS devices are discussed. In CAD sessions, industry standard MEMS software is used for design and simulation of MEMS devices. In laboratory sessions, students are trained to carry out hands-on fabrication and characterization of MEMS devices. These three components are systematically structured to enable integrative learning of various materials presented in this course.

INTRODUCTION

Micro-Electro-Mechanical Systems (MEMS) is a rapidly emerging field that utilizes micromachining techniques to fabricate microsensors and microactuators. Micromachining and mechanical movement of microstructures are the key features of MEMS technology. Typical sizes for MEMS devices range from micrometers to millimeters. The advantages of MEMS devices are low cost, high performance, small size, and low weight compared to conventional devices. MEMS has proved to be a revolutionary technology in many application arenas, including accelerometers, pressure sensors, micro-optics, inkjet nozzles, optical scanners, and fluid pumps. MEMS has made a significant impact in many fields, including telecommunications, optics, robotics, and medicine.

In recent years there has been a considerable interest in the development of MEMS curriculum for training next generation engineers needed for the rapidly growing MEMS industry. MEMS curriculum developed at various universities have been discussed in [1]-[3]. In this paper, the MEMS curriculum developed at the Alabama Microelectronics Science and Technology Center, Department of Electrical and Computer Engineering, Auburn University is discussed. In the following sections, course structure and future course development efforts are discussed in detail.

COURSE STRUCTURE

The curriculum consists of three major components – class lectures (2 lectures per week), CAD sessions and laboratory sessions. CAD sessions and laboratory sessions are conducted for three hours on alternate weeks. This 4.0 credit hour course typically spans 16 weeks (one semester).

Lecture Component

In class lectures, basic concepts underlying the principle of operation and design of various MEMS devices are discussed. The topics covered in the class lectures are shown in Table 1. A majority of the topics are covered from the suggested textbook [4] and additional topics are also discussed from advanced books [5] and [6]. As shown in the table, the course is divided into three parts, namely, Part I: Microfabrication and Microstructures, Part II: MEMS Actuators, and Part III: MEMS Sensors.

Table 1: Topics discussed in class lectures

Part I: Microfabrication and Microstructures (6 Weeks)
- Introduction to MEMS
- MEMS Fabrication Processes
- Mechanics of Microstructures
- Mechanics of Beams and Membranes
- Vibration of Microstructures

Part II: MEMS Actuators (5 Weeks)
- Electrostatic Actuator
- Electrothermal Actuator
- Piezoelectric Actuator
- Magnetic Actuator
- RF MEMS Resonators and Filters
- Optical MEMS

Part III: MEMS Sensors (5 Weeks)
- MEMS Accelerometers
- MEMS Gyroscopes
- MEMS Pressure Sensors
- MEMS Microphones

In Part I of the course, fundamentals of microelectronic processes, MEMS fabrication processes such as bulk micromachining, surface micromachining and LIGA techniques, and commercial foundry processes are discussed. Basic mechanics of beams and membranes including concepts such as spring constant, effects of residual stresses on cantilever and fixed-fixed beams, and buckling of beams are discussed. Vibration of microstructures and lumped-

06TRF-0003/hh2006/$20©2006TRF
DOI 10.31438/trf.hh2006A.8

element modeling of second-order systems using spring, mass, and damper are also discussed.

In Part II of the course, various MEMS actuators such as electrostatic, electrothermal, piezoelectric and electromagnetic are discussed. The principle of operation and governing design equations are discussed for various actuators. Then, the use of these actuators in various applications such as RF MEMS and Optical MEMS are also discussed.

In Part III of the course, various MEMS sensors such as accelerometers, gyroscopes, pressure sensors, microphones etc. are discussed. Case study examples such as Freescale Semiconductors pressure sensors and Analog Devices accelerometers and gyroscopes are also discussed.

Computer-aided Design Sessions

The introduction of computer-aided design tools in the mid 1990s drastically changed the design procedures followed for MEMS. Computer-aided analysis and optimization have replaced the design process of iterative experimental modifications of the initial design. In addition to their impact on design practice in industry, CAD tools can play a major role in undergraduate and graduate education. The major impact of CAD tools in MEMS education is in making realistic design examples and case studies available to students. Some advantages of using CAD tools in MEMS education are outlined here - i) the students can learn some of the very basic concepts by repeated computations making use of CAD simulation tools, ii) CAD tools allow the students to explore how the design performance will be affected if the value of a design parameter were to be altered either intentionally or because of the unavoidable tolerances in the values of the components in the fabrication process, iii) CAD tools equipped with field visualizers can be used to learn qualitatively about the reasons for the device's behavior by looking at the distribution of the field (such as stress, charge distribution, temperature distribution, etc.).

Table 2: Computer Aided Design and Simulation of MEMS using CoventorWare [8] (6 Weeks)

CAD #1: CoventorWare getting Started
CAD #2: MEMElectro ("Tutorial 1: Beam Design")
CAD #3: MEMMech ("Tutorial 1: Beam Design")
CAD#4: MEMMech ("Tutorial 4: Modal Analysis")
CAD#5: Co-SolveEM ("Tutorial 3: Beam Simulation Analysis")
CAD #6: MemETherm ("Tutorial 6: Temperature Analysis")

An important aspect of Auburn University's MEMS curriculum is the use of ConventorWare [7], a very widely used MEMS design software for computer-aided design, analysis and optimization of MEMS devices. CoventorWare consists of multi-physics numerical analysis tools such as MemElectro (electrostatic solver), MemMech (mechanical and thermo-mechanical solver), Co-Solve EM (coupled eletromechanical solver), MemETherm (electro-thermo-mechanical solver), etc. CAD assignments involve design, simulation and optimization of various MEMS devices. A list of CAD assignments performed using CoventorWare is shown in Table 2. A majority of the CAD assignments are based on CoventorWare tutorials. The CAD assignments are designed such that the students are exposed to pertinent tools after discussion of the relevant topics in the lectures. For example, after completion of the lectures on basic beam mechanics in Part I the students perform mechanical analysis of a beam using MEMMech in CAD #2. Similarly, the students perform electro-mechanical analysis of an electrostatic actuator in CAD#5 after completion of class lectures on electrostatic actuators in Part II.

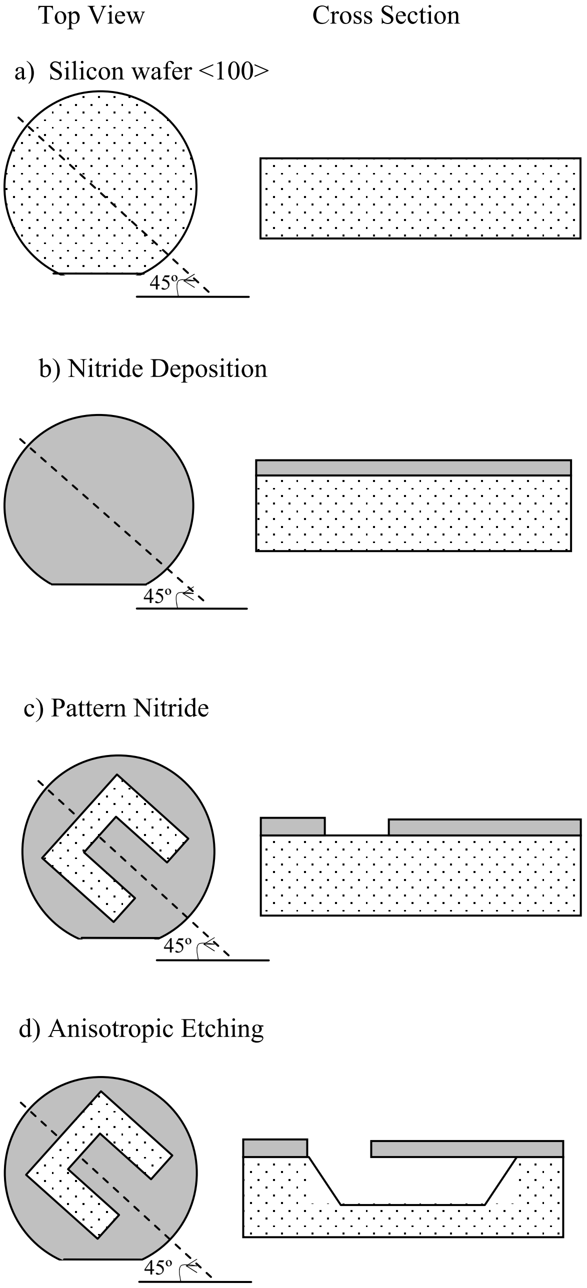


Figure 1: Process flow for bulk micromachining (a) starting substrate <100>, (b) silicon nitride deposition using LPCVD, (c) patterning silicon nitride layer by photolithography, (d) anisotropic etching of silicon substrate using KOH.

Laboratory Sessions

The laboratory sessions provide hands-on experience in the fabrication and testing of MEMS devices using the facilities available at the *Alabama Microelectronics Science and Technology Center (AMSTC)* [7]. The major pieces of equipment used in this course include Karl Suss MA/BA 6 frontside/backside mask aligner, Thermco oxidation and diffusion chamber, Tempress LPCVD system, CHA Industries's Mark 50 dual E-beam/sputter/ion gun deposition system, and STS AOE 100 DRIE system.

The objective of the laboratory sessions is to provide fabrication experience in two most commonly used MEMS fabrication process, namely, bulk micromachining and surface micromachining. Before the start of lab sessions, all the students are required to read the lab safety rules and guidelines. A quiz was conducted to assess students' understanding of safety rules.

Table 3: Laboratory sessions (9 Weeks)

MEMS Fabrication
LAB #1: Introduction to MEMS fabrication facilities
LAB #2-3: Bulk micromachining (2 weeks)
LAB #4-6: Surface micromachining (3 Weeks)

Characterization and Testing
LAB #7: Profile Characterization Using WYKO Optical Profiler
LAB #8: MEMS Actuator Testing
LAB #9: MEMS Pressure Sensor Characterization
LAB #10: MEMS TriaxBoard Accelerometer Demonstration

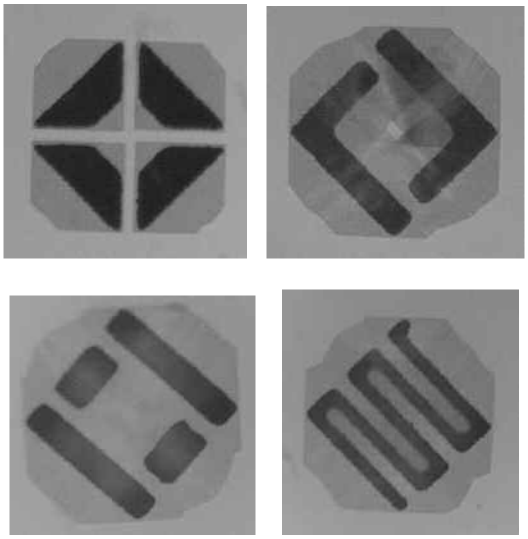


Figure 2: Suspended MEMS structures fabricated using bulk micromachining

In bulk micromachining sessions, the objective is to fabricate suspended microstructures in the silicon substrate. The major process steps involved in this lab are shown in Figure 1. A <100> silicon wafer is used as the starting substrate and silicon nitride is deposited by an LPCVD process. The silicon nitride layer is patterned using standard photolithographic steps such as spin-coating, UV exposure using mask aligner, photoresist development, and plasma etching. Finally, the patterned silicon nitride is used as a masking layer and anisotropic etching of silicon substrate is performed using KOH. Bulk micromachining lab consists of two sessions performed in two weeks. In the first session, the students learn basic steps such as wafer cleaning, silicon nitride deposition, and photolithography. In the second session, the students carry out plasma etching of silicon nitride and anisotropic etching of the silicon substrate. Photographs of various suspended microstructures fabricated after the completion of the bulk micromachining sessions are shown in Figure 2.

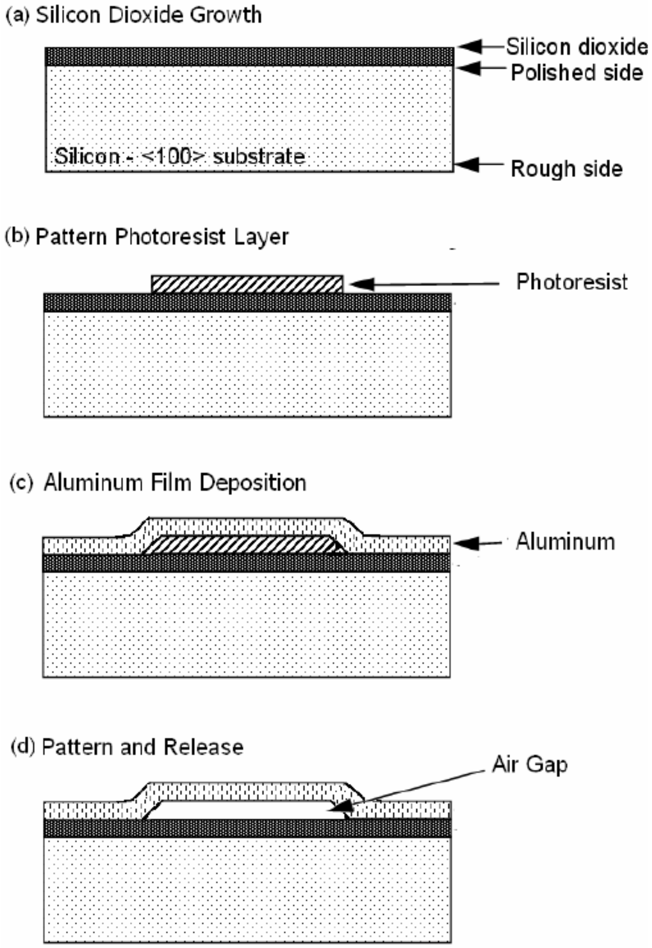


Figure 3: Process flow for surface micromachining (a) silicon dioxide growth using oxidation furnace, (b) defining photoresist sacrificial layer, (c) e-beam deposition of the aluminum structural layer, (d) pattern and release aluminum beams by etching the sacrificial layer.

In surface micromachining sessions, the objective is to fabricate electrostatic MEMS actuators using aluminum as the structural layer. Surface micromachining lab consists of three sessions performed in three weeks. The process flow involved in the fabrication of a clamped-clamped structure by surface micromachining is shown in Figure 3. A thin layer of silicon dioxide is grown on the starting <100> silicon substrate and anchor openings are etched through the oxide layer. The concept of sacrificial layer (soluble/removable) is the basis for fabrication of freestanding microstructures by surface micromachining. A sacrificial photoresist layer is defined on the oxide layer by photolithography. Openings are etched entirely through the sacrificial photoresist layer to provide anchoring point for the structural layer. A thin film of aluminum structural material is deposited and etched to define the required MEMS structure. After etching the photoresist sacrificial layer, the patterned structure is separated from the substrate (except at the anchoring point) by the thickness of the removed sacrificial layer to form a freestanding structure. Photographs of the fabricated clamped-clamped and cantilever beams are shown in Figure 4.

After completion of all the fabrication sessions, '*Characterization and Testing*' sessions are conducted on profile characterization of microstructures using a WYKO optical profilometer and testing of electrostatic actuators using a probe station. Additional laboratory sessions focusing on the characterization of commercially available MEMS devices such as Freescale semiconductor pressure sensors and accelerometers are also conducted.

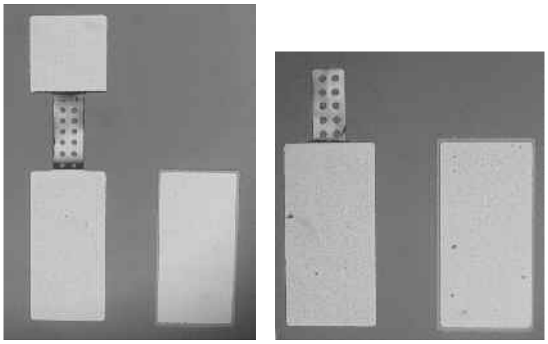


Figure 4: Clamped-clamped beam (left) and cantilever beam (right) fabricated using surface micromachining

A website is being maintained for this course [8]. Typically the materials posted on the website include the course syllabus, weekly schedule, homework assignments, lecture notes, laboratory notes etc. The students have access to and download the needed material at any time and at any place at their convenience.

FUTURE COURSE DEVELOPMENT

Our department has been offering a "Microelectronics Fabrication" course in spring and fall semesters for several years [10]. The infrastructure developed for this course facilitated the implementation of a new MEMS curriculum with hands-on laboratory components. For the past two years, the MEMS course has been experimentally taught as a special topics course once a year. In spring 2005, a total of 20 students from various disciplines such as electrical engineering, mechanical engineering, chemical engineering, and materials engineering were enrolled in this course. Overall, the students find the CAD sessions and laboratory sessions very useful in learning MEMS. The contents covered in the current course structure could be significantly expanded and offered as two MEMS courses "MEMS I: MEMS sensors and actuators" and "MEMS II: MEMS Fabrication". MEMS I could be designed as entry level course for senior-undergraduate and graduate students from various disciplines. MEMS I could emphasize more on the fundamentals of micromachining and MEMS devices. The second course "MEMS II" could focus on providing hands-on laboratory sessions. In "MEMS II" advanced fabrication process could be designed for fabrication of complex MEMS devices. CAD sessions could be included in both courses. MEMS I could introduce the students to device level design and simulation of MEMS devices and MEM II could focus on system level design and simulation of MEMS based Microsystems.

CONCLUSION

A MEMS curriculum consisting of three major components – class lectures, Computer-aided design (CAD) sessions and laboratory sessions is discussed. The introduction of CAD sessions and hands-on laboratory sessions in MEMS education would enable us in bridging the gap between classroom instruction of MEMS and the practice of MEMS in industry. MEMS curriculum that meets the needs of industry would facilitate rapid advancement of the state of technology.

ACKNOWLEDGEMENT(S)

The author would like to thank Charles Ellis, Manager, Alabama Microelectronics Science and Technology center at Auburn University for his help in conducting the laboratory sessions, and the teaching assistants Lia Almeida and Ron Jackson for their help in developing the laboratory sessions. The author would also like to thank Dr. R. C. Jaeger for reviewing this manuscript and Dr. Y. C. Lee, University of Colorado at Boulder, for providing CAD assignments from his MEMS course.

REFERENCES

[1]. P. J. Hesketh, J. G. Boyd, M. J. McNallan, and G. J. Maclay, "Curriculum development in MEMS," *Electrochem. Soc. Interface*, vol. 6, no. 1, pp. 48–51, Spring issue 1997.
[2]. C. Liu, "Integration of a MEMS education curriculum with interdisciplinary research," in *Proc. 1997 Biennial Univ./Government/Ind. Microelectron. Symp*., 1997, pp. 137–140.
[3]. Liwei Lin, "Curriculum Development in Microelectromechanical Systems in Mechanical Engineering," *IEEE Transactions on Education*, Vol. 44, no. 1, Feb. 2001, pp. 61-66.
[4]. Tai-Ran Hsu, "MEMS and Microsystems: Design and Manufacture, McGraw-Hill, 1st edition, ISBN: 0072393912.
[5]. Stephen D. Senturia, "Microsystem Design," Kluwer Academic Publishers, January 2001, ISBN: 0792372468.
[6]. Min-Hang Bao, "Micro Mechanical Transducers: Pressure Sensors, Accelerometers and Gyroscopes," Elsevier Science (Handbook of Sensors and Actuators Series) ISBN: 044450558X, October 2000.
[7]. MEMS fabrication, assembly, and packaging facilities at the Alabama Microelectronics Science and Technology center, Department of Electrical and Computer Engineering, Auburn University: http://spider.eng.auburn.edu/amstc/
[8]. "MEMS Sensors and Actuators" course website: http://www.eng.auburn.edu/~ramadra/mems/
[9]. CoventorWare ver. 2005, Coventor Inc., NC, USA.
[10]. R. C. Jaeger, Y. Tzeng, K. Daneshvar, T. A. Baginski and J. L. Davidson, "The Alabama Microelectronics Science and Technology Center and the microelectronics program at Auburn University," IEEE UGIM '85 Proceedings, pp. 42-45, June 1985.

COMPREHENSIVE MEMS CURRICULUM AT UCLA

Jack W. Judy[1,3], Greg P. Carmen[2], Frank M.-C. Chang[1], Yong Chen[2], Harold H. Fetterman[1], Nasr N. Ghoniem[2], Warren S. Grudfest[1,3], Vijay Gupta[2], Chih-Ming Ho[2,3], Yongho S. Ju[2,3], William J. Kaiser[1], Pirouz Kavehbour[2,3], Chang-Jin Kim[2,3], Robert T. M'Closky[2], Carlo D. Montemagno[2,3], Laurent Pilon[2], Jacob J. Schmidt[3], Eli Yablonovitch[1], and Xiaolin Zhong[2]

[1]Electrical Engineering Department, [2]Mechanical and Aerospace Engineering Department, [3]Biomedical Engineering IDP, University of California, Los Angeles, Los Angeles, CA 90095 USA

ABSTRACT

UCLA has spent the last 15 years pioneering the thorough development of possibly the most comprehensive graduate-level MEMS curriculum in the world, which is jointly offered by the EE and MAE departments. Students from EE and MAE are admitted directly into a formal MEMS major field, complete a set of 4 core courses, take a MEMS preliminary exam, complete the rest of their course work by selecting from MEMS and non-MEMS electives, take a qualifying exam, and complete their theses (M.S. and/or Ph.D.). To date at least 9 specifically MEMS/nano-related graduate-level elective courses have been developed and are presently being offered. To date well over 100 graduate students have completed or are completing this unique program. Those that have graduated have gone on to be productive faculty at U.S. and international academic institutions, engineers at MEMS and non-MEMS companies, and have started a number of MEMS start-up companies.

I. INTRODUCTION AND BACKGROUND

As the field of microelectromechanical systems (MEMS) has grown and matured in research universities, companies, and national laboratories, the demand for well-prepared students and employees in the MEMS field has also grown [1]. To meet this demand, a variety of pedagogical structures have been developed with differing strategies for meeting different facets of this demand. Examples include graduate-level MEMS courses, graduate-level non-MEMS courses, MEMS short courses and tutorials, and most recently undergraduate-level MEMS courses that sometimes include hands-on laboratories.

In the early years of the field of MEMS, much of the education of future MEMS professionals came from training research in classes well developed to meet other specific needs (e.g., analog-circuit design, linear and non-linear elasticity, linear and non-linear dynamics, mechanics of thin-films, materials science, solid-state physics, etc.). Soon, institutions offering single graduate-level courses on MEMS, which primarily covered bulk micromachining, surface micromachining, transduction mechanisms for sensors, force-generation methods for actuators, basic mechanics, and relevant material science. However, given the enormous breadth of such single-course approaches, depth was limited and largely followed the particular individual interests of the students and instructors. Also, at this point no institution offered MEMS as a major field within any academic department (e.g., EE, MAE, etc.). Instead, students were admitted into the major field of their advisor (e.g., solid-state electronics, photonics, mechanical design, etc.) and the students focused their course work and took preliminary exams in these non-MEMS major-field areas. This situation has largely endured at most institutions in the U.S., with the exception being those that hired additional MEMS faculty (or had originally non-MEMS faculty that become active in the MEMS field), which made it possible to offer additional MEMS courses (e.g., MEMS design, BioMEMS, etc.).

II. UCLA MEMS CURRICULUM DEVELOPMENT

The UCLA MEMS curriculum-development process followed that described above, with a few key differences. In the early 1990's a few institutions, such as UCLA, pioneered having two graduate-level MEMS courses. A two-course format allowed the material covered in the original single course to be distributed over twice the amount of time, so that greater depth and breadth was possible. Frequently, the first course focused more on MEMS fabrication (EE M250A / MAE M280) and the second more on MEMS design (EE M250B / MAE M282). At UCLA we went a step further and offered additional courses: (1) a course focused on system-level issues that are important for realizing a complete instrument (EE 250C), (2) a course focused on microscale science, particularly microscale fluid dynamics and heat transfer (MAE 281), (3) a survey course focused on the most recent results presented at MEMS conferences and journals (MAE 287), and (4) an introductory course on basic MEMS fabrication offered at the *undergraduate* level that included a weekly 4-hour hands-on laboratory session (EE M150L / MAE M180L) [2]. As is hopefully made apparent by the course numbers, the MEMS curriculum at UCLA is one that is strongly collaborative between the EE and MAE departments, with the "M" preceding the course number indicating that the course is cross listed with another department.

This set of courses provided the academic critical mass to allow another major UCLA uniqueness / innovation to precede, namely the creation of MEMS as its own *major field* within both the MAE and EE departments. This means that at UCLA, prospective graduate students specifically apply to enter into the MEMS major fields of the EE department or MAE department. These students complete a set of the previously mentioned courses and then their mastery of the topics is tested through a preliminary exam held after the first year. Students who pass are allowed to pursue their PhD in the MEMS major field, often completing an M.S. thesis along the way. Those that cannot pass the MEMS preliminary exam, typically graduate with a M.S. degree in the MEMS major field by completing a thesis or eventually passing a MEMS comprehensive examination (non-thesis option). Although some may feel that MEMS is not appropriate as a major field (e.g., too new, not fundamental enough, what are the key MEMS equations, MEMS should only highlight an academic degree and not be the focus of one, etc.), and there was some resistance at UCLA as well, in the end the UCLA MEMS faculty argued persuasively that the field of MEMS had enough merit (i.e., depth and breadth) to stand on its own. Students working towards a MEMS degree have plenty of other course slots to fill with classes outside of MEMS, which are typically taken in the application area of their thesis research (e.g., biology, chemistry, physics, neuroscience, etc.) or are otherwise complimentary engineering courses (e.g., circuit design, mechanics, control theory, etc.).

Due to the rise of biology and medicine as application areas for MEMS and the corresponding demand for MEMS instruction for biomedical engineering (BME) students, the core MEMS classes are now cross listed with the BME interdepartmental

06TRF-0003/hh2006/$20©2006TRF
DOI 10.31438/trf.hh2006A.9

program (IDP) as well (e.g., EE M150L / MAE M180L / BME M150L, etc.) to facilitate and regulate student enrollment. Although some MEMS courses are cross listed with BME, there is no BME-based MEMS major field. Instead, MEMS is a required component of the bioinstrumentation major field within BME and the MEMS courses are frequently taken by BME students in other major fields (e.g., biomechanics, neuroengineering, etc.).

Another evolution to the MEMS curriculum was the way it has adapted to the rise of "nano", which did much to distract attention away from the field of MEMS – despite nano being perceived by many in the MEMS as largely a logical extension / evolution of the MEMS field or what used to be called chemistry. Although this is quite true for top-down fabrication technologies, it is admittedly not the case for bottom-up fabrication and molecular engineering. Thus we have expanded the official name of the "MEMS" major field to become the "MEMS / Nanotechnology" major field. Additional courses focused on nano-specific and bottom-up approaches have been added to the program (MAE 287, MAE 287L, MAE 258A, BME C251, BME 257) and top-down nano-related content has also been added, when and where appropriate, to the existing core MEMS classes.

In the years leading up to 2006, many other MEMS and MEMS-related faculty have been hired and a many other MEMS courses and MEMS-related courses have been developed and are now offered at UCLA. In the following section, the present UCLA MEMS curriculum and its course offerings will be described. To our knowledge, it represents the most comprehensive MEMS-oriented curriculum in the world.

III. UCLA MEMS CURRICULUM

Although the UCLA MEMS curriculum for graduate students is customized / optimized for each collaborating academic unit (i.e., EE, MAE, and BME), at the heart is a *common core*, which is a set of classes that each academic unit requires its student to take. In addition, each department has its own *department-specific MEMS core*, which is an additional course that when added to the common core represents the subject matter for the preliminary exams. Lastly, there are a number of MEMS classes that students may take as electives to complement their core MEMS knowledge and the classes they take in non-MEMS fields (e.g., the field of the application of their MEMS research project, other engineering electives that support their research, etc.). The following sections describe the (1) common MEMS core, (2) department-specific MEMS core, (3) MEMS minor, (4) MEMS seminars, (5) joint MEMS preliminary exam, and (6) elective MEMS courses offered at UCLA. The rest of this section will describe the motivation, philosophy, and design of each component. A list of all UCLA MEMS courses and a brief description of their content is provided in the appendix.

A. Common MEMS Core

The common MEMS core is essentially MEMS fabrication, which includes the undergraduate MEMS-fabrication course and laboratory and the follow-on graduate-level MEMS-fabrication course. As graduate students matriculate in the fall, some entering MEMS graduate students do not have a sufficient background in micromachining (e.g., do not know the capabilities and limitations of different forms of lithography). Starting them off with a graduate-level MEMS fabrication class with peers that have much more MEMS experience, will either do an injustice to the beginning or advanced students. Our pedagogical strategy has been to require all MEMS graduate students to complete the introductory MEMS course offered at the undergraduate level (EE M150 / MAE M180 / BME M150) unless they can demonstrate an appropriate level of knowledge in that material. Perhaps more importantly, the hands-on laboratory course (EE M150L / MAE M180L / BME M150L), gives students the practical clean-room experience that only the most exceptional MEMS applicant has after completing a B.S. degree in engineering at most universities. As a result, the undergraduate MEMS classes are populated mostly by graduate students (66%). The courses are listed at the undergraduate level for two reasons: (1) the level of material is rather basic, with the biggest challenge being the shear amount of it, and is quite similar to undergraduate IC-fabrication classes; (2) undergraduate students with an interest in MEMS should have easy access to take a MEMS class (i.e., not have to take graduate-level courses) and to get the hands-on experience in the lab. Such laboratory skills and experience will help them should they either decide to enter the MEMS industry with a B.S. degree or apply for graduate school at a school with an active MEMS-research program. After the fall quarter, UCLA MEMS students are fully primed on the basics of MEMS fabrication and have considerable laboratory experience. This makes it possible for them not only to launch into the graduate-level MEMS curriculum, but also to become active in the lab for their research project. The graduate follow-on MEMS fabrication course (EE M250A / MAE M280 / BME M250A) builds upon the undergraduate course by covering more advanced and truly MEMS-specific processes. In addition, a significant emphasis is placed on process integration, with many examples taken from current MEMS literature. For a list of specific topics, please see the course description in the appendix.

B. Department-Specific MEMS Core

For students entering the MEMS graduate program in the UCLA EE department, the required core course is on MEMS design (EE M250B / MAE M282). It is felt that it is critical for EE-based MEMS students to understand the MEMS-design process for a variety of mechanical structures, transduction mechanisms, and actuation mechanisms. In contrast, students entering the MEMS graduate program in the UCLA MAE department are required to take the MEMS core course on micro-scale and nano-scale sciences (MAE 281). It is felt that unlike EE-based MEMS students, MAE-based MEMS students already have an understanding for the design of mechanical structures and motors due to their undergraduate training in these areas. The topic of transduction mechanisms is important, but it was felt that the mastery of microscale and nanoscale phenomena (e.g., micro-scale and nano-scale fluid mechanics, heat transfer, etc.) would be more vital as they are extensions of existing fields of knowledge for MAE students. An alternative way to make up this material is for MAE students to take MAE 284, since it also touches on these concepts.

C. MEMS Minor

As with other major fields in the school of engineering at UCLA, the field of MEMS has a minor. The MEMS minor is a year-sequence of MEMS courses that graduate students from other major fields can complete to satisfy a breadth requirement. The MEMS minor is simply the three courses that represent the common MEMS core and the department-specific MEMS core. Thus students can take the EE-flavored MEMS minor or the MAE-flavored MEMS minor. Of course, students with unique circumstances can petition for a different three-course sequence of MEMS classes for their minor.

D. MEMS Seminars

We do not have a regular dedicated MEMS seminar series at UCLA. Instead, the MEMS seminars are given on an ad-hoc basis in EE, MAE, and BME, and are well advertised to the UCLA MEMS community and beyond through our mailing lists.

E. *Joint MEMS Preliminary Exams*

After the EE and MAE MEMS graduate students complete their respective core courses in MEMS, they will take the MEMS preliminary exam. For efficiency, this exam is organized jointly between MAE and EE. The testing of the core MEMS-fabrication content is done equally by MAE and EE faculty. The testing of the MEMS-design content is largely done by EE faculty, but the MAE faculty also contribute in this area. The testing of the micro-scale and nano-scale science is done by the MAE and BME faculty instructors.

A variety of prelim-exam formats have been used, with the present version being a stable (hasn't changes in a few years) optimization of competing approaches and university regulations: a combination of a written exam and an oral examination. Oral exams are felt to be the most effective at delineating knowledge and ignorance, but written exams are more time efficient and can be instructive about the capabilities of some students.

F. *Elective MEMS Courses*

Due to the hiring of additional MEMS faculty within the engineering school at UCLA, other non-core MEMS-related courses have been developed and are offered as electives to graduate students from MEMS and other major fields. The topics they cover includes:

MAE 284:	Sensors, Actuators, and Signal Processing
MAE 283:	Experimental Mechanics for MEMS
MAE 285:	Interfacial Phenomena
MAE 286:	Molecular Dynamics Simulation
MAE 287L:	Nanoscale Fabrication, Characterization, and Biodetection Laboratory
MAE 288:	Laser Microfabrication
MAE 258A:	Nanomechanics and Micromechanics
BME C251:	Nanofabrication of Biomedical Systems Using Nonconventional Materials
BME 257:	Engineering Mechanics of Motor Proteins and Cytoskeleton

A brief description for each core MEMS courses and the above listed elective MEMS courses is provided in the appendix.

IV. GRADUATES FROM THE PROGRAM

Since 1990, there have been over 100 students that have graduated from or are presently active in the MEMS program from UCLA in EE and MAE with an M.S. degree or M.S. / Ph.D. degrees. Many of these students have gone on to productive careers in academia (both in the U.S. and at international universities), the existing MEMS industry, as well as creating new MEMS start-up companies. The feedback received from our graduates has been quite positive. Instances of constructive criticism have lead to course-content modifications and other programmatic enhancements. In addition, an unknown number of graduate students have completed the MEMS minor, which has hopefully proved beneficial for their research project or has been at least be enlightening about a maturing field of engineering with many applications. Lastly, 173 *undergraduate* students have completed the undergraduate MEMS course. Although some of these undergraduate students were inspired enough by this class to pursue MEMS in graduate school, it is our hope that others found at least some aspect of the broad range of course material covered useful in their engineering careers.

V. CONCLUSIONS

Although the creation of MEMS as a major field at UCLA was initially somewhat controversial, we have found it to be a successful and valuable contribution to the academic system at UCLA and beyond. Indeed, the program has now grown to over 14 courses across two departments (EE and MAE) and one interdepartmental program (BME). The MEMS courses have proven to be very popular with students from many other departments, not only within the engineering school, but from other schools as well (e.g., physical sciences, life sciences, medicine, and business). The MEMS focus of the academic core of the program and the preliminary exams insures depth and mastery of the essential MEMS knowledge. Fears that students will become overly specialized in MEMS are not realized due to the insistence that students take a strong set of electives in the application area of their research project and key related engineering fields. The opportunity for undergraduates to take an introductory MEMS-fabrication course with a hands-on laboratory, provides them with a unique experience upon which to base a graduate-school direction or their future involvement in the MEMS industry. Since we at UCLA are constantly striving to adapt our MEMS courses and MEMS curriculum to the ever-changing needs of our students and the MEMS and nanotechnology industries, we welcome comments and suggestions on how we could modify and improve our program.

VI. ACKNOWLEDGEMENTS

Some of the work presented in this paper was supported by an NSF Career Award (ECS 9876285).

VII. REFERENCES

[1] B.L. Pruitt, R. Ghodssi, J.W Judy, M,. Taher A. Saif, K.L. Turner, and M.A. Schmidt, "NSF/NASA-GSFC MEMS Education Workshop Outcomes", *Tech. Dig. Solid-State Sensor and Actuator Workshop* (Hilton Head `06), Hilton Head Island, SC (June 4-8, 2006).

[2] J.W. Judy and P.S. Motta, "Introductory Micromachining and MEMS Course for Graduate and Undergraduate Students," Tech. Dig. Solid-State Sensor and Actuator Workshop (Hilton Head `06), Hilton Head Island, SC (June 4-8, 2006).

VIII. APPENDIX

The following is a list and brief summary of each course in the UCLA MEMS major field. The common core courses and core course unique to EE and MAE are identified.

A. *Common Core Courses*

Introduction to Micromachining and MEMS
EE M150 / MAE M180 / BME M150:
Begins by introducing the field of MEMS and provides examples to demonstrate its broad utility, stimulate interest, and promote a curiosity for how they are made. After the basic concept of micromachining is introduced, the following vital micromachining processes are described on a qualitative and quantitative basis: photolithography, wet etching (isotropic and anisotropic), dry etching (vapor, plasma, RIE, ion milling), vacuum systems, physical vapor deposition (evaporation and sputtering), chemical vapor deposition, thermal oxidation, diffusion, implantation, electroplating, and design of experiments (DOE).

Introduction to Micromachining and MEMS Laboratory
EE M150L / MAE 180L / BME M150L:
A companion hands-on laboratory to the main lecture course listed above. In the past the two courses were merged one. However, to ease enrollment limitations and to provide full credit to the students and instructors, the course was split. Students may take the main lecture course above without taking the lab, but enrollment in this lab requires co-enrollment in the main lecture course. In this lab the students complete a 6-mask micromachining

process that combines surface and bulk micromachining to realize microsensors (e.g., accelerometers, pressure sensors, magnetometers), microactuators (e.g., thermal actuators, magnetostatic, lorentzian), and a variety of test structures.

MEMS Fabrication
EE M250A / MAE 280 / BME M250A:
Treatment of advanced micromachining processes and their integration into complete processes to construct MEMS. Topics covered include: thick-film lithography (SU-8, LIGA), soft lithography, DRIE, wafer bonding, electroless plating, photo-electro-chemical etching, chemical-mechanical polishing, and batch-assembly techniques. In addition, materials issues such as mechanical properties and residual/intrinsic stress are also covered.

B. Department-Specific Core Courses

MEMS Design
EE M250B / MAE 282 / BME M250B:
Introduces key design concepts, methods, and examples, such as design rules, MEMS foundries, and MEMS CAD, and basic MEMS-relevant micromechanics. Covers a wide range of transduction mechanisms, gives examples of microsensors and microactuators mechanisms, and discusses their use in MEMS designs. Design project is a major component of this course.

Microsciences
MAE 281:
Covers fundamental science issues in micro-scale domain. Topics include micro fluid science, microscale heat transfer, mechanical behavior of microstructures, as well as dynamics and control of micro devices.

C. Electives MEMS Courses

Experimental Mechanics for MEMS
MAE 283:
Methods, techniques, and philosophies being used to characterize microelectromechanical systems for engineering applications. Material characterization, mechanical/material properties, mechanical characterization. Topics include fundamentals of crystallography, anisotropic material properties, and mechanical behavior (e.g., strength/ fracture/fatigue) as they relate to microscale. Considerable emphasis on emerging experimental approaches to assess design-relevant mechanical properties.

Sensors, Actuators, and Signal Processing
MAE 284:
Principles and performance of micro transducers. Applications of using unique properties of micro transducers for distributed and real-time control of engineering problems. Associated signal processing requirements for these applications.

Interfacial Phenomena
MAE 285:
Interfacial phenomena are becoming increasingly important as the size of engineering systems decreases, which leads to and increase in surface area and energy. The fundamental concepts of interfacial phenomena are introduced including: surface tension, surfactants, interfacial thermodynamics, interfacial forces, interfacial hydrodynamics, capillarity, dynamics of the triple line and electrowetting. Various applications are presented including MEMS systems, wetting phenomena, foams and emulsions, and biological systems.

Molecular Dynamics Simulation
MAE 286:
Introduction to the basic concepts and methodologies of used to perform molecular dynamics simulation. Advantages and disadvantages of this approach for various situations will also be explored and evaluated. An emphasis will be placed on systems of engineering interest, especially microscale fluid mechanics, heat transfer, and solid-mechanics problems.

Nanoscale Fabrication, Characterization, and Biodetection Laboratory
MAE C287L:
A multidisciplinary course that introduces laboratory techniques of for specifically nanoscale fabrication, characterization, and biodetection. Topics include basic physical, chemical, and biological principles that are related to these techniques, top-down and bottom-up (self-assembly) nanofabrication, nano-characterization (AEM, SEM, etc.), and optical and electrochemical biosensors. Students are encouraged to use their own creativity and interests to self-designed experiments.

Laser Microfabrication
MAE 288:
Science and engineering of laser microfabrication of advanced materials, including semiconductors, metals, and insulators. Topics include fundamentals of laser interactions with advanced materials, transport issues in laser microfabrication (e.g., thermal, mass, chemical, carrier, etc.), state-of-the-art optics and instrumentation for laser microfabrication, applications such as rapid prototyping, surface modification (i.e., both physical and chemical), micromachines for three-dimensional MEMS and data storage, and other up-to-date research activities. Student term projects.

Nanomechanics and Micromechanics
MAE 258A:
Recent advances in analytical and computational modeling frameworks to describe the mechanics of materials at scales ranging from the atomistic, through the microstructure or transitional, and up to the continuum are covered in this course. Topics include solving the quantum-mechanics equations of motion and applying them to the mechanics of nanosystems, atomic simulation methods and their applications at the nanoscale, and the leading continuum-mechanics-based framework used today to describe the non-linear deformation behavior of materials at the local (e.g. single phase or grain level) and macroscopic (e.g., polycrystal) scales.

Nanofabrication of Biomedical Systems Using Nonconventional Materials
BME C251:
Use of nontraditional substrates and materials in the bottom-up fabrication of biomedical nanosystems. Materials and fabrication issues, post-processing integration, compatibility with standard processes, and conventional top-down fabrication environments. Packaging concerns. Imaging and diagnostics techniques. Reliability issues.

Engineering Mechanics of Motor Proteins and Cytoskeleton
BME 257:
Introduction to the physics of motor proteins and the cytoskeleton. Topics include: mass, stiffness and damping of proteins, thermal forces and diffusion, chemical forces, polymer mechanics, mechanics of the cytoskeleton, structures of cytoskeletal filaments, polymerization of cytoskeletal filaments, force generation by cytoskeletal filaments, active polymerization, motor-protein structure and operation. Emphasis on and engineering rather than a biological perspective.

MICRO AND NANOSCALE EDUCATION AT STANFORD UNIVERSITY[§]

A. Alvin Barlian[1], Roger T. Howe[2], Gregory T. A. Kovacs[2], Beth L. Pruitt[1]
[1]Department of Mechanical Engineering, [2]Department of Electrical Engineering
Stanford University, Stanford, CA 94305, USA

ABSTRACT

Stanford University is one of the pioneers in the field of micromachining as well as the early devices now classified as microelectromechanical systems (MEMS). The earliest MEMS work at Stanford was a part of the doctoral education of pioneering MEMS researchers and it is captured in several seminal papers and doctoral dissertations. MEMS research at Stanford grew from strong electrical engineering programs in integrated circuits, device physics and fabrication. Over the last two decades, research on micro- and nano-fabricated transducers and devices has become pervasive in all engineering and several science departments at Stanford. The first laboratory course on fabrication technology was offered in 1983, though Stanford's first lecture course surveying micromachined transducers was not offered until 1993, both in the electrical engineering department. Several courses in mechanical and electrical engineering departments followed, that provided further education in analysis and fabrication. More recent courses have focused on applications, such as in bioengineering, or fundamental surface science and bottom-up synthesis methods in materials science. This paper provides a brief history of MEMS at Stanford and reports on our current and planned curriculum.

INTRODUCTION

This paper provides a snapshot of Stanford's role in producing graduates trained in the field, where "the field" is rather inclusive in defining "MEMS" as micromachined, or micro/nanofabricated, and application of these techniques to any transducer. In following these criteria, we acknowledge this may have resulted in the exclusion (or inclusion) of related work. We report primarily on education activities at Stanford related to the training of graduates in "MEMS," including indicators of doctoral dissertations and course enrollments for reference. A large component of MEMS education at Stanford is on the job training through Ph.D. research. An exciting outcome of Stanford's educational activities is the large number of startup companies that grew from academic research at Stanford or from ideas of Stanford graduates. Additional research and startups in the field have also flourished because of work done at Stanford Nanofabrication Facility (SNF) [**1**] and the synergy of researchers and industry users at this Stanford facility. As one indicator of technology transfer, three of the top 35 revenue generating patents licensed from Stanford as of 2005 were for MEMS devices [**2**]. SNF was a National Science Foundation (NSF) National Nanofabrication Users Network (NNUN) site from 1994-2004 and has been an NSF National Nanotechnology Infrastructure Network (NNIN) site since 2004. From 2000-2004, the monthly average number of SNF users hovered near 200 with about 25% from industry [**3**]. In a survey of lab members in 2005, 29.3% of 140 users responding described their research as MEMS [**4**].

A recent workshop on MEMS Education in North America identified concerns from industry regarding the quantity of MEMS trained graduates at all levels and their preparedness to work in the integrated product and process development environment required for MEMS manufacturing [**5**]. Academically and industrially, there is a growing cross-disciplinary interest and need for micro-fabricated tools to interface with nanoscale devices and biological materials. The challenges for educators are in offering a curriculum which: 1) is suited to the needs of students seeking work in MEMS or to apply MEMS to new disciplines, 2) spans the broad interdisciplinary space covered by MEMS device design, 3) addresses the broad cross-disciplinary applications for micro-devices, and perhaps most important, 4) creates a technically prepared workforce at the B.S., M.S., and Ph.D. level. Historically, Stanford has performed well in producing MEMS trained graduate students, primarily Ph.D.s through research training. In the past decade, Stanford has enhanced the curriculum with courses suitable for M.S. level students, and in the last few years, with courses accessible to B.S. level students. This paper reviews MEMS education at Stanford University through the present as well as future curriculum plans.

HISTORY OF MEMS AT STANFORD

Early MEMS research at Stanford was funded by Office of Naval Research (ONR), the National Aeronautics and Space Administration (NASA), and National Institute of Health (NIH), before the term "MEMS" was coined. Stanford Professor of Electrical Engineering James Angell was a pioneer in the field; he is credited with coining the term *micromachining* in a paper presented in 1978 [**6-8**]. In the spring of 1966, Angell and his student, Kensall Wise, started work on the first microscale neural probes for surgical applications (funded by ONR); the devices were based on Angell's cutting edge work on integrated circuit (IC) fabrication. This project marked the first microfabrication (silicon micromachining) research at Stanford University. Wise then spent the summer of 1966 learning beam lead technology at Bell Labs, Murray Hill, New Jersey. This technology represents some of the earliest micromachining (for air-isolated integrated circuits) [**9**]. Wise completed his dissertation on microprobes for biopotential recording in 1969 [**10**]. The work on microprobes was followed closely by further developments from Angell's group. These included a catheter-tip integrated piezoresistive pressure sensor (Samaun, 1971 [**11**]), a full-wafer microscale gas chromatography system (Terry, 1975 [**12**]), an absolute pressure transducer (Nunn, 1977 [**13**]), and a micromachined accelerometer for biomedical applications (Roylance, 1978 [**14**]), all sponsored by NASA (NIH also co-funded Nunn's work). As an indicator of impact, at the end of 2005, there were 101 journal papers [**15**] and 103 U.S. patents [**16**] that cite Roylance's work [**14, 17**].

In 1969-1970, Vladimir Vaganov, from the Moscow Physics Engineering Institute, visited Angell's group where he "started to work in the field of sensors and micromachining" [**18**]. Vaganov returned in 1975 and worked on a piezoresistive accelerometer [**19**]. In 1968-1970, Professor Robert Newcomb of Electrical Engineering attempted to fabricate a surface electromagnetic micromotor [**20**]. However, materials incompatibility with the

---

[§] This paper is dedicated in memory of Prof. James Angell (1924 – Feb 13, 2006).

06TRF-0003/hh2006/$20©2006TRF
DOI 10.31438/trf.hh2006A.10

Stanford Microelectronics Lab's research focus on electronic devices was a major issue. After leaving Stanford for the University of Maryland, Newcomb published a proposal for resonant silicon cantilever beam high-Q MEMS filter, which acknowledges discussions with Vaganov [**21**]. In 1980, Professor James Meindl reported on a micromachined capacitive pressure sensor [**22**].

Since 1969, 135 MEMS related doctoral dissertations have been completed and many more are in progress. Figure 1 shows the number of doctoral dissertations related to MEMS from Stanford University since 1969. An advanced microfabrication projects course, EE357, was offered from 1983-1998 and taught by Professors Butrus Khuri-Yakub and David Bloom, both in the electrical engineering department [**23**]. The first lecture course surveying micromachined transducers was first offered in 1993 by Professor Gregory Kovacs in the electrical engineering department [**24**]. While the first research and courses were in the electrical engineering department, there has been an increase in the number of faculty with MEMS-related research in other departments. Figure 1 also reflects this demographic shift in MEMS doctoral graduates.

CURRICULUM AT STANFORD

There has been no school-wide coordination of the micro and nanoscale courses at Stanford. Rather, courses have "self-assembled" in departments to meet the needs of students and researchers at Stanford. MEMS, microscale, and nanoscale courses at Stanford are primarily offered as graduate-level engineering courses and thus are taken most by graduate students (~96%). Enrollment data categorized by declared major for the last 5 years show recent trends in student interest in these courses. Figure 2 provides summary statistics for course enrollment by major. Enrollment numbers reflect the number of students registered for the course. However, some courses have limited enrollments and several auditors in attendance. From anecdotal evidence, instructors believe there may be extensive uncounted use of some course materials available online. This is more difficult to track and report, but is in the spirit of the MEMS Education Workshop suggestion of creating archives of shared course materials.

Stanford is on a quarter system; most courses run 10 weeks (plus finals) in the academic year (Autumn, Winter, and Spring), with few in Summer (8 weeks + finals). MEMS related courses are offered in the bioengineering, electrical, material science, and mechanical engineering departments. Courses are loosely grouped below into those focused on design and fabrication of broad classes of devices, and those focused on more specialized device analysis. Descriptions of course content and pedagogy follow and summary syllabi for the courses are appended in Table 1. The topics covered by particular courses in the curriculum are condensed in Table 2.

Microscale and Nanoscale Design and Fabrication Courses

The following courses address how devices, products, or associated materials are made, i.e., the art, engineering, and technology of product and process at the nano- and micro- scale. Instructors are listed after the course title.

EE312 Micromachined Sensors and Actuators was the first MEMS-related lecture class at Stanford. Professor Gregory Kovacs developed this course in 1993 and taught it from 1993 to 2003. His lecture notes evolved into one of the earliest textbooks on micromachined transducers [**25**]. Professor Roger Howe recently taught it in Winter 2006 after joining Stanford in 2005. EE312 reviews microfabrication processes, introduces relative merits of different technologies, and focuses on various transduction mechanisms at the microscale through lectures/homework/term-paper format. Categories of sensors and actuators include biological, chemical, mechanical, optical, and thermal.

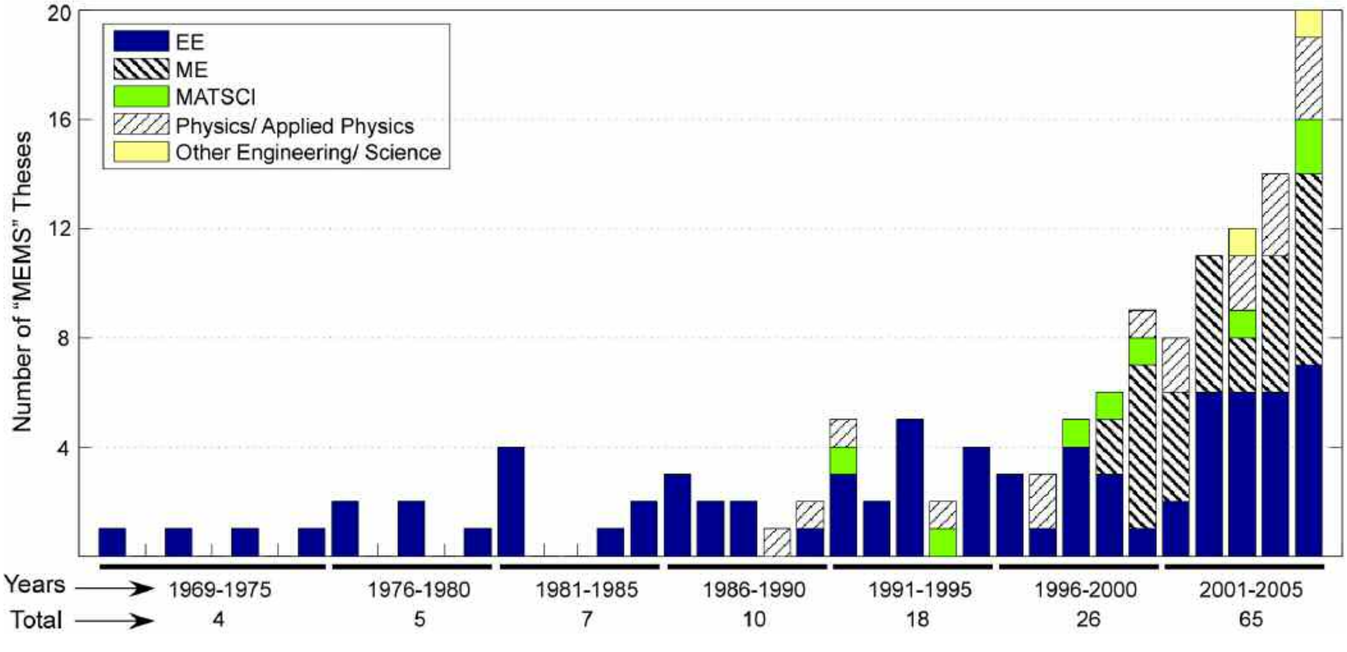


Figure 1. *Estimated count of MEMS theses from 1969 to 2005. The imprinting year of doctoral dissertation at Stanford is reported here, though demonstrations of these devices and other publications were completed earlier. The data were compiled from a search of the library archives. Dissertations were indexed 1) by advisor, for graduates advised by professors involved in MEMS research, and 2) by title for common terminology such as MEMS, micro, micromachined, microfabricated, etc. Titles and degree granting department were verified manually (abstracts were read if the title was not clear).*

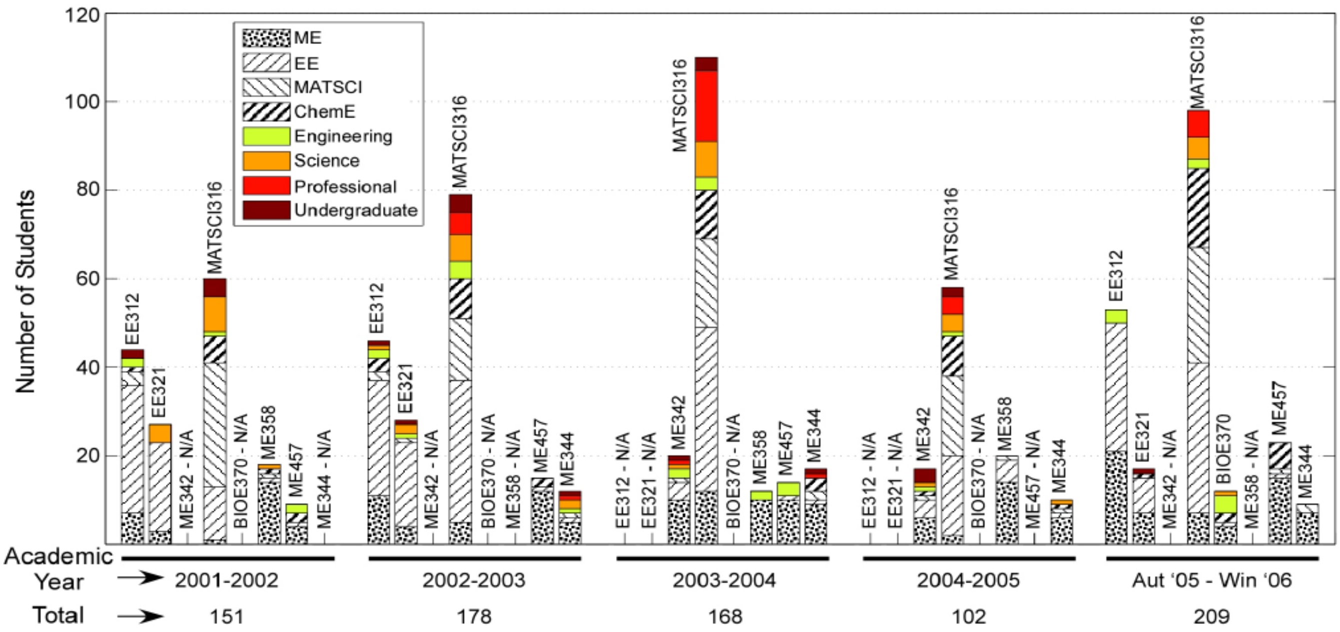


Figure 2. *Enrollment from 2001-2002 to Aut'05-Win'06 academic year for MEMS, microscale, and nanoscale courses [**26**], which are detailed in Table 1 and 2. In the legends, Engineering includes: BioE, Aero, Civil and Environmental, Management Science & Engineering, and general engineering. Science includes: Applied Physics, Physics, Chemistry, Computer Science, and Geology. Professional includes: Medicine, Business, Law, and Non-degree.*

EE321 MEMS Design (Solgaard) reviews microfabrication processes and exposes students to MEMS design rules through lectures/homework/final-project format. The emphasis is on physical understanding and elementary modeling of MEMS devices. During the course, students complete a MEMS design project including layout, evaluation strategy, and modeling. Case studies of successful MEMS devices are presented throughout the quarter.

ME342A MEMS Laboratory I (Pruitt) is a two-quarter class for all technical majors, including undergraduates. It emphasizes theory and practice of MEMS device design and fabrication. Students are introduced to fabrication facilities and basic microfabrication processes through biweekly lectures and weekly laboratories. Laboratories include photolithography, wet and dry etching, oxidation and diffusion. Transduction mechanisms and fabrication techniques are introduced. Students process wafers using pre-designed masks for piezoresistive force sensors. They also package, test and calibrate the devices. Students qualify as independent users of SNF. Students work in 3-4 person teams to design solutions for predefined challenges. These projects originate from internal research collaborations within Stanford or from industry sponsors (past affiliates include Intel, Agilent, Careside, and Fultec).

ME342B MEMS Laboratory II (Pruitt) is offered in the summer quarter. In part A, student teams collaborated with project affiliates to invent, develop, and design microfabricated solutions. In part B, functional prototypes are fabricated and tested using at least one processing approach but several design layouts on one set of masks per team. Students use fabrication facilities independently for the projects with minimal staff burden. Several ME342 projects continue beyond the course as M.S. or Ph.D. projects; those resulting in conference publications are shown in Figure 3. Enrollment is limited by laboratory constraints to 20 students in both part A and B.

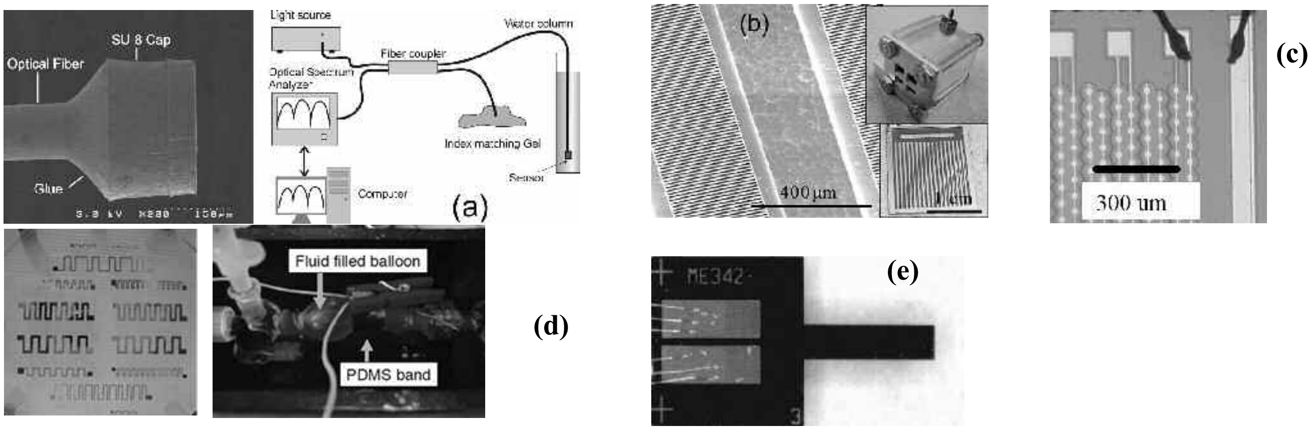


Figure 3. *Some ME342 projects that resulted in conference publications: (a) Miniature SU-8 interferometric blood pressure sensor [**27**]; (b) Electroosmotic pump integrated with miniaturized fuel cell [**28**]; (c) Biocompatible coatings for MEMS ultrasonic sensors [**29**]; (d) 100%-Radial strain gauge for monitoring aneurism formation in rat aorta [**30**]; (e) ME342 piezoresistive force sensing cantilevers and noise studies for implanted piezoresistors [**31**].*

MATSCI160 Nanomaterials Laboratory (Melosh) is designed for undergraduate students interested in nanoscience and nanotechnology and will be offered in Spring 2005/2006 for the first time. It explores synthesis and characterization techniques in nanotechnology. The labs cover several different approaches to creating nanomaterials, including syntheses of silicon nanowires, gold nanoparticles, nanorods, photonic band-gap crystals and nanopatterning surfaces using soft lithography. Students are introduced to state-of-the-art characterization equipment to analyze these samples, such as Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), and Atomic Force Microscopy (AFM).

MATSCI316 Nanoscale Science, Engineering, and Technology (McGehee) introduces students to nanofabrication techniques, such as self-assembly of amphiphilic molecules, block copolymers, organic-inorganic mesostructures, colloidal crystals, organic monolayers, proteins, DNA, and abalone shells. In addition, students are introduced to tools used for nanocharacterization of materials, nanoelectronics, nanotubes, nanowires, nanocrystals, and nanotechnology-based renewable energy. It has attracted more than 300 students from various engineering/science departments, as well as from Law, Medicine, and Business since 2002. MATSCI316 is based on lectures/homework/final-project format and offered online through Stanford Center for Professional Development (SCPD) since 2001.

BIOE370 Microfluidic Device Laboratory (Quake and Melin) covers design, fabrication, and testing of microfluidic devices for biological applications. The laboratory sessions include soft lithography (mostly PDMS) to create micromechanical valves and pumps. The emphasis of this course is on device design, fabrication, and testing of basic microfluidic chips. In the first half of the course, students are introduced to microfluidics and fabrication processes as they go through fabrication and testing of a pre-designed microfluidic chip. In the second half, students are more independent and are assigned to design their own microfluidic chips in small groups. They fabricate, and test these chips with the test apparatus provided. This course was first offered in Winter 2006 quarter and limited to 12 students. A condensed version of this course (3 days) will also be offered in July 2006.

Microscale and Nanoscale Device Analysis Courses

In addition to MEMS design and fabrication courses, Stanford offers several advanced topic microscale and nanoscale device analysis courses.

ME358 Heat Transfer in Microdevices (Goodson) introduces novel theoretical and experimental aspects of heat transfer in microdevices. Students are introduced to thermal design of electronic circuits, sensors, and actuators in microscale. The course also covers thermal property measurements for microdevices with emphasis on Si and GaAs semiconductor devices and thin films. ME358 is taught in lectures/midterm/final-project format. Final projects are based on student research interests.

ME457 Fluid Flow in Microdevices (Santiago) is an introductory course to physicochemical forces associated with fluid flow in microscale devices and emphasizes bioanalytical microfluidics system applications. The course covers creeping flow, electric double layers, and electrochemical transport. Emphasis is on bioanalytical applications in which electrophoresis, electro-osmosis, and diffusion are important. ME457 is taught in lectures/midterm/final-exam/final-project format. Final projects are based on individual student research interests.

ME344A&B Computational Nanotechnology and Nanomaterials Modeling (Cho) is a two-quarter class. In the first quarter, it introduces students to atomistic simulations as computational tools to design nano-scale materials and devices. In the second quarter, it introduces students to various techniques for atomistic simulations, such as finite difference algorithms, molecular dynamics, and Monte Carlo simulations. It offers students hands-on experience in computational design of nanomaterials and the fundamentals of simulations.

In addition to the courses mentioned above, there are other courses offered by various departments in the School of Engineering, which emphasize on characterization, modeling, and analysis of micro and nanoscale phenomena. These courses are not specific to engineering devices but provide the background necessary for more in depth study of physical phenomena important to micro/nano interfaces and design. Some examples include Elasticity in Microscopic Structures (ME), Nanophotonics (EE), Nanocharacterization of Materials, Microstructures and Mechanical Properties (MatSci), Probing the Nanoscale (AP), etc.

Faculty have also added microscale/nanoscale/MEMS as examples or modules to other courses they teach in the EE and ME undergraduate curriculum. MEMS examples are an effective means of engaging students in thinking about interdisciplinary and integrative solutions. In addition, the bioengineering department (established in 2002) also integrates lectures and materials related to MEMS and microfluidics in its graduate core curriculum through BIOE200A, B, and C (developed by Kovacs, Ku, and Sorger).

CONCLUSIONS

Stanford University has helped lay the foundation for MEMS as a field. A large component of MEMS education at Stanford is on the job training through Ph.D. research. MEMS has grown out from the electrical engineering department and has become interdisciplinary. Formal courses in various engineering departments have developed because of faculty interest in microscale/nanoscale/MEMS-related research. As the field has matured, MEMS training is becoming part of the core toolbox for many engineering students.

FUTURE PLAN

A portion of the curriculum will be revised in 2006-07 to reflect the interdepartmental nature of micro and nanoscale engineering and to provide more “MEMS trained” B.S. and M.S. graduates. Professors Howe, Pruitt, and Solgaard will replace EE321 and ME342AB with a three-quarter engineering sequence with no prerequisites and no departmental designation. It is expected that a large percentage of Stanford’s graduating M.S. students will take at least the first of these courses. The courses will be available to senior undergraduates and industry through SCPD, partially addressing concerns raised by MEMS industry participants of the 2005 MEMS Education Workshop and Survey [**5**].

ACKNOWLEDGEMENTS

The authors would like to thank Joe Mallon, Prof. Ken Wise, Dr. Kurt Peterson, Dr. Phil Barth, and Dawn Levy for helpful discussion in preparation of this manuscript. We thank the faculty for providing information on their courses: Professors Kyeongjae Cho, Kenneth Goodson, Thomas Kenny, Butrus Khuri-Yakub, Michael McGehee, Nicholas Melosh, Stephen Quake, Juan Santiago, Olav Solgaard, and Dr. Jessica Melin. We are extremely grateful for Indrani Gardella's assistance with compilation and verification of class enrollment data from the Office of the University Registrar. Special thanks to Matt Beasley, Amy Lee, and Betty Zhao for library research. Fabrication work was performed in part at the SNF (a member of the NNIN) which is supported by the NSF under Grant ECS-9731293, its lab members, and the industrial members of the Stanford Center for Integrated Systems. The authors would like to thank the SNF's staff for support in the lab. Travel support was generously provided by the Transducers Research Foundation.

Table 1. *Syllabi by week of microscale and MEMS courses at Stanford (number of prerequisites is in parenthesis)*

Week	EE312 (1)	EE321 (2)	ME342A (0)	BIOE370 (0)	MATSCI160 (0)
1	Intro, MEMS, Nano	Introduction, Fabrication	Overview, Fabrication	Introduction, Overview of Fabrication Processes	Gold Nanorod Synthesis
2	Scaling, Micromachining	Fabrication, Actuators	Implants, Transduction	Making Molds for Device Example	Transmission Electron Microscopy Characterization
3	Micromachining	Actuators	Litho, Micromachining	Making Chips for Device Example	Silicon Nanowire Synthesis
4	Micromachining, Packaging, Microelectromechanics	Accelerometers	Etching/Brainstorming	Testing of Rotary Pump	Scanning Electron Microscopy and Atomic Force Microscopy
5	Microelectromechanics	Dynamics	MEMS Reliability	Group Project - Design	Photonic Crystals
6	Microelectromechanics, Microfluidics	Stress	Mechanics	Group Project - Molds	Self-assembly and Colloidal Forces
7	Chemical, Biological Transducers	Structures	Microfluidics	Group Project - Chips	Soft Lithography
8	Magnetic Transducers, Optical MEMS	Virtual work	Packaging, Signal Conditioning	Testing of Group Device in Optical Test Setup	Contact Angles, Patterning
9	RF MEMS, Integrated MEMS	Fluids	Soft Litho/Biomedical	Testing of Group Device in Optical Test Setup	Surface Functionalization
10	Final Project Presentations	Conclusions	Projects	Group Presentation	Presentations

Week	MATSCI316 (0)	ME358 ($0^{\dagger}$)	ME457 ($0^{\dagger}$)	ME344A (1)
1	Introduction	Introduction, Thermal Modeling	Introduction, Basic Principles	Introduction
2	Self Assembly	Conduction Modeling	Transport Equation, Electrostatics	Atomic Structures of Solids
3	Colloidal Crystals, Organic Monolayers	Convection Modeling	Convective Diffusion, Taylor Dispersion	Inter-atomic Interactions
4	Biopolymers, Abalone Shells, Biomimetics	Thermometry	Uncharged Macromolecules, Brownian Motion	Atomic Structure Optimization of Nanomaterials
5	Scanning Probe Techniques	Thermal Conductivity Measurements	Introduction to Electrolytic Solutions	Molecular Dynamics
6	Synthesis of Nanocrystals, Nanowires, and Nanotubes	Radiation, Optical Devices	Charged Double Layer	Molecular Dynamics
7	Nanopatterning, Nanoelectronics	Heat Transfer in VLSI Systems	Electroosmosis	Monte Carlo Simulations
8	Organic Electronics, Molecular Electronics	Micro Sensors & Actuators	Charged Macromolecules and Particles, Electrophoresis	Monte Carlo Simulations
9	Nanowire and Nanotube Devices	Microchannel Convection	Intermediate Topics	Applications to Nanomaterials
10	Solar Cells, Hydrogen Storage, Fuel Cells	Final Project Presentations	Final Project Discussions	Applications to Nanomaterials

---

[†] with consent of instructor

Table 2. *Topical areas of microscale and MEMS courses at Stanford*

TOPICS	EE312	EE321	ME342	ME358	ME457	BIOE 370	MATSCI 316	MATSCI 160	ME344
Physics				√	√				√
Mechanics	√	√	√	√	√				√
Materials	√	√	√	√			√	√	√
Electrical	√	√	√	√	√		√		√
Biology	√	√	√		√	√	√		
Surface Chemistry/ Synthesis							√	√	
Chemistry	√	√	√				√	√	
Device Design		√	√			√			
Experiment Design			√			√			
Analysis	√	√	√	√	√			√	√
Testing			√			√		√	
Fabrication lecture	√	√	√			√	√	√	
Fabrication lab			√			√		√	

REFERENCES

[1] Stanford Nanofabrication Facility, http://snf.stanford.edu

[2] "Stanford Office of Technology Licensing Annual Report 2004-2005."

[3] Personal communication, email, P. Rissman to B. Pruitt, March 27, 2006

[4] Stanford Nanofabrication Facility Lab Members Survey, http://snf.stanford.edu/Labmembers/SurveySummary.html

[5] Report of the MEMS Education Workshop 2005, Miami, FL, http://memsed.stanford.edu/

[6] J. B. Angell, "Micromachined Silicon Transducers for Measuring Force, Pressure, and Motion," 4th European Solid-State Circuits Conference, Amsterdam, 1978.

[7] L. Rafkin, "The Founder," in *Forbes*, 2001.

[8] D. Levy, "James Angell, electrical engineer and former carillonneur, dies," in *Stanford Report*. Stanford, CA, 2006.

[9] Personal communication, email, K. Wise to A. A. Barlian, Friday, March 17, 2006

[10] K. D. Wise, "A Multielectrode Microprobe for Biopotential Recording," Ph.D. thesis in Electrical Engineering Department, Stanford University, 118, 1969

[11] Samaun, "An Integrated Circuit Piezoresistive Pressure Sensor for Biomedical Instrumentation," Ph.D. thesis in Electrical Engineering Department, Stanford University, 72, 1971

[12] S. C. Terry, "A Gas Chromatography System Fabricated on a Silicon Wafer Using Integrated Circuit Technology," Ph.D. thesis in Electrical Engineering Department, Stanford University, 146, 1975

[13] T. A. Nunn, "A Silicon Absolute Pressure Transducer for Biomedical Applications," Ph.D. thesis in Electrical Engineering Department, Stanford University, 106, 1977

[14] L. M. Roylance, "A Miniature Integrated Circuit Accelerometer for Biomedical Applications," Ph.D. thesis in Electrical Engineering Department, Stanford University, 207, 1978

[15] SciSearch® Plus at LANL, http://search.lanl.gov/

[16] L. D. Harper*, et al.*, "Fair Broker Assessment of NASA Contribution to MEMS Technology," NASA Ames Research Center 2003.

[17] L. Roylance and J. Angell, "Batch-Fabricated Silicon Accelerometer," *IEEE Transactions on Electron Devices*, vol. 26, pp. 1911-1917, 1979.

[18] V. Vaganov, "Packaging and Testing Issues in MEMS Commercialization," *SEMI Technical Paper*, 1998.

[19] Personal communication, letter, V. Vaganov to G. Kovacs, February 23, 2000

[20] K. Dutta*, et al.*, "Integrated Micromotor Concepts," International Conference on Microelectronic Circuits and System Theory, Sydney, Australia, 1970.

[21] M. F. Hribsek and R. W. Newcomb, "High-Q Selective Filters Using Mechanical Resonance of Silicon Beams," *IEEE Transactions on Circuits and Systems*, vol. CAS-25, pp. 215-222, 1978.

[22] C. Sander*, et al.*, "A Monolithic Capacitive Pressure Sensor with Pulse-Period Output," *IEEE Transactions on Electron Devices*, vol. 27, pp. 927-930, 1980.

[23] Personal communication, email, P. Khuri-Yakub to A. Barlian, March 18, 2006

[24] Personal communication, email, G. T. A. Kovacs to A. A. Barlian, March 17, 2006

[25] G. T. A. Kovacs, *Micromachined Transducers Sourcebook*, 1st ed: McGraw-Hill Science/Engineering/Math, 1998.

[26] The Office of the University Registrar, Stanford University

[27] R. Melamud*, et al.*, "Development of An SU-8 Fabry-Perot Blood Pressure Sensor," 18th IEEE International Conference on Micro Electro Mechanical Systems, Miami, Florida, USA, 2005.

[28] C. R. Buie*, et al.*, "A Microfabricated Direct Methanol Fuel Cell with Integrated Electroosmotic Pump," 19th IEEE International Conference on Micro Electro Mechanical Systems, Istanbul, Turkey, 2006.

[29] M. A. Beasley*, et al.*, "A Biocompatible Coating for CMUT," Materials Research Society Spring Meeting, San Francisco, CA, USA, 2006.

[30] E. T. Hantsoo*, et al.*, "Characterization of Modified Polymers for High Elongation Strain Sensing," Materials Research Society Spring Meeting, San Francisco, CA, USA, 2005.

[31] A. A. Davenport*, et al.*, "Noise Studies in Implanted Piezoresistors," International Mechanical Engineering Congress and Exposition, Orlando, Florida, USA, 2005.

NSF/NASA-GSFC MEMS EDUCATION WORKSHOP OUTCOMES

Beth L. Pruitt
Dept. of Mechanical Engineering
Stanford University
Stanford, CA USA, pruitt@stanford.edu

M. Taher A. Saif
Dept. of Mechanical Engineering
University of Illinois
Urbana-Champagne, IL, USA

Reza Ghodssi
Dept. of Electrical and Computer Engineering
University of Maryland
College Park, MD, USA

Kimberly L. Turner
Dept. of Mechanical Engineering
University of California
Santa Barbara, CA, USA

Jack W. Judy
Dept. of Electrical Engineering
University of California
Los Angeles, CA, USA

Martin A. Schmidt
Dept. of Electrical Engineering
Massachusetts Institute of Technology
Cambridge, MA, USA

ABSTRACT

The first North American workshop on MEMS Education was held on January 30, 2005 in Miami, Florida before the MEMS 2005 conference. The purpose of the workshop was to gather a diverse audience including MEMS academics, professionals from MEMS industry, leaders from MEMS-relevant U.S. government agencies, as well as current students. Goals included: identifying 'best practices' to share across organizations teaching MEMS courses; identifying cross-cutting issues and a set of recommendations to sponsor organizations for investment in MEMS educational development; and establishing an open dialog on these issues for continued interactions. Challenges identified include: developing a curriculum meeting needs of students seeking to be educated in this field; suitably spanning the broad interdisciplinary space covered by MEMS; and creating a technically prepared workforce.

INTRODUCTION

MEMS as a field has matured to the point where successful 'MEMS-enabled' products are on the market and require engineering support of the total product lifecycle. Universities increasingly need to consider the growing requirement for more MEMS trained students at all degree levels as well as how to prepare graduates to work in the integrated product and process development environment required for MEMS manufacturing. Academically and industrially, increasingly cross-disciplinary skills are required as are microfabricated tools to interface with nanoscale devices and biological materials. MEMS constitutes substantial research and teaching activities at universities, and the requirements for systems level integration of design, process & test offer unique educational challenges and opportunities. Challenges lie in developing curricula which are: 1) suited to the needs of students seeking to work in MEMS or to apply MEMS to new disciplines, 2) span the broad interdisciplinary space covered by MEMS device design, 3) address the broad cross-disciplinary applications for microdevices, and most importantly, 4) create a technically prepared workforce at the BS, MS, and PhD level.

This paper reports on outcomes from the first workshop on MEMS Education held in January 2005 in Miami, Fl as well as data from a set of surveys of the North American MEMS community [1]. The opportunity exists to incorporate MEMS into mainstream engineering education and to consider if it should be used as a vehicle to effect change in engineering curricula [2-3].

A small group of academics attending the Hilton Head '04 meeting met informally to discuss the educational practices at their respective universities. This group discussed common experiences, shared their problems, and observed that while most schools had developed MEMS courses, few texts existed and very little sharing between programs had occurred. The outcome of this discussion was to plan and deliver a meeting on MEMS Education. A committee comprised of the authors of this paper secured funding and organized a one day workshop following MEMS2005. The workshop was sponsored by the National Science Foundation (NSF) and the National Aeronautics and Space Administration Goddard Space Flight Center (NASA-GSFC).

The goals of the workshop were to:

- Ground participants in the history of MEMS education
- Assess the current status of MEMS Education
- Hear from industry on their educational/hiring needs
- Hear from funding agents on future areas of research funding
- Provide ample discussion time to
  - assess the current status of educational programs
  - identify what's working and what's not
  - pinpoint opportunities to develop/share/collaborate (especially items perceived as 'low hanging fruit')
- Draw conclusions and make recommendations for
  - organization of subsequent workshops/conferences
  - funding agency initiatives aimed at supporting education
  - industry groups with an interest in advocating or supporting MEMS education initiatives
- Create a web site with all materials collected before and at the workshop (http://MEMSED.stanford.edu).

PRELIMINARY SURVEYS

Prior to the workshop, the committee sought input from educators, employers and students on their perceptions of the strengths and weaknesses in MEMS education. Educators were also asked to share summaries of the courses and programs at their universities. Three separate online surveys for MEMS Education Instructors, Industry, or Students were developed and participation of the North American MEMS community was requested by

06TRF-0003/hh2006/$20©2006TRF
DOI 10.31438/trf.hh2006A.11

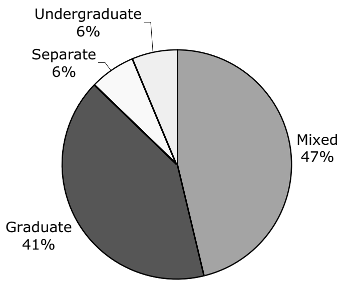
MEMS fab. lecture	MEMS fab. lab	MEMS Science	MEMS Technology	MEMS Design	Nanofab lecture	Nanofab lab	Nano-science	Micro-fluidics	Bio-MEMS	Other
67%	43%	46.8%	30%	62.5%	30%	7.8%	28%	25%	34%	43%

Table 1: *Courses offered by universities surveyed.*

emails to over 2000 previous MEMS-related conference participants.

Instructor Survey

This survey garnered 64 responses from 34 different institutions in 3 countries. Faculty were asked what types of courses are taught at their universities and at what level they are taught. The types of courses are summarized in Table 1; most universities have lecture based courses on design and fabrication and fewer than half report some kind of lab courses. The target audience of the courses is shown in Figure 1; very few institutions offer separate courses targeted to undergraduates, though most offer mixed level courses accessible to undergraduates. The average class size varied greatly, and for lab courses, the costs and difficulty of processing (gauged by number of masks) also varied significantly. All institutions with labs reported a mix of support from industry, institution and investigator sponsored research projects. From this, one may infer that institutional commitment and partnerships with industry are indicators of successful courses providing hands-on experience.



For lab courses only:
-Average # of Students: **32**
(s.d. 29, significant variation)
-Average Masks per class: **5**
(varies from 1-12)
-Average Cost per Student: $**1829**
(significant variation)
-Sponsorship: mix of Industry, Institutional, and PI support.

Figure 1. *Intended audience of courses taught.*

Mixed grad/undergrad was the most common course level. 100% of respondents have a microfab on campus, though only 69% of fabrication courses have students do their own processing, and 45% have an instructional fab.

Faculty were also asked about cooperation in teaching and developing courses. More than a quarter reported ‘a lot’ of cooperation amongst MEMS faculty at their institution, 60% felt there was some cooperation, the rest report little to no cooperation.

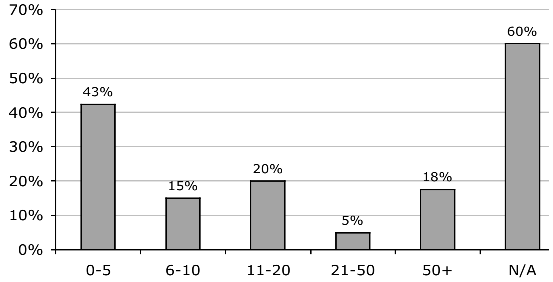


Figure 2. *MEMS PhDs granted. Faculty estimates of MEMS related PhDs graduated from their institutions in the last 10 years.*

Faculty estimated the number of PhDs specializing in MEMS graduating from their institutions, Figure 2. Only the largest estimate from each institution was used. Averaging the bins, as many as 600 MEMS trained PhDs have graduated from the responding institutions in the last 10 years. This is consistent with industry estimates of hiring.

Respondents described successful pedagogical methods; the most frequently cited included:

- Hands on Experience
- Model Based Teaching
- Physics of processes rather than recipes.
- Design Projects with hands-on component
- Deploying real problems and utilizing “coaches” from industry
- Comparing to macro-scale sensors to show benefits and drawbacks to scaling.

For practical design training and analysis, educators used a variety of software tools, including Intellisuite, SUGAR, ANSYS, Co-Solve, ADS, and FEMLAB. Several schools reported fabrication and characterization of real devices using foundries; 21% use foundry services for classes, e.g. MUMPS/CRONOS, University of Michigan, and UC Berkeley Internal.

From their educational experience, MEMS educators perceive the most important skills their students take away include: concepts of miniaturization and scaling laws; hands-on fabrication experience; and the ability to think of the big picture and be interdisciplinary. Some educators felt students need to obtain strength in fundamental areas then layer MEMS knowledge on that fundamental knowledge; two respondents felt MEMS was just a repackaging of traditional disciplines. Educators were also asked how well prepared their graduates are. With one exception, most respondents felt they were very well prepared. Educators estimated more than half their MEMS trained graduates go to Industry, while 20%-30% go to Academia including faculty & postdocs, and about 10% go to National Laboratories. This is fairly consistent with industry and student survey results.

Industry Survey

The participants of this survey included 36 industrial affiliates and 6 national laboratories. Figure 3 tabulates estimates of 76 industrial survey participants on the number of graduates with MEMS educational training hired into their organization in the past 10 years. Notably, Analog Devices, Sandia National Laboratory, Robert Bosch, and Rockwell Scientific respondents estimate they have hired more than 20 MEMS graduates at all degree levels in the last 10 years. From responses to employer surveys, one may infer that the MEMS related employers responding to the survey hired more than 60% of MEMS PhDs produced in North America over that 10 year period.

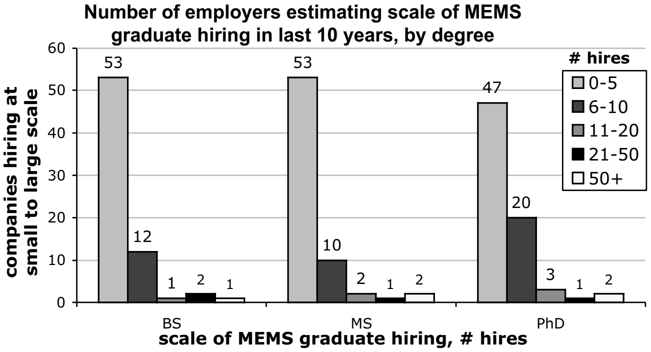


Figure 3. *Industry hiring estimates for the past 10 years, by highest degree. Averaging the bins, as many as 330 BS, 350 MS and 430 PhDs have been hired.*

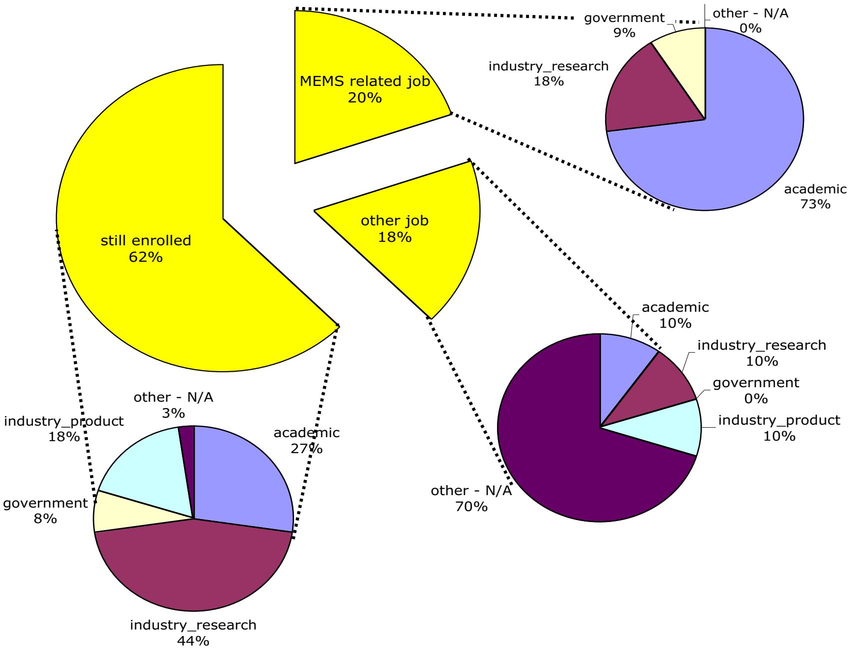


***Figure 4**. MEMS Student Employment. Of those still enrolled, most expect to do research in industry, of those already working in MEMS related jobs, most are in academics. The majority of those employed in other jobs do not report affiliation with product development or research; only two are academics in fields other than MEMS.*

Industry participants answered the question, "How well prepared to succeed were the MEMS graduates you have hired?" Overall, industry members were most pleased with the level of preparation afforded by some graduate work (Figure 5).

When asked to list the most valuable skills/assets that MEMS graduates possess, the dominant themes were the multidisciplinary background and hands-on experience with micro-fabrication and testing/characterization. Conversely, the most common missing skill/asset repeatedly emphasized was a need for a "reality check." Many respondents commented that employees were naïve regarding manufacturing, packaging and reliability concerns, and lacked a basic business understanding. Generally poor writing and communication skills were also cited numerous times. However, 74% did indicate a willingness to work with MEMS educators to ensure that MEMS graduates have an opportunity to learn these commonly missing skills.

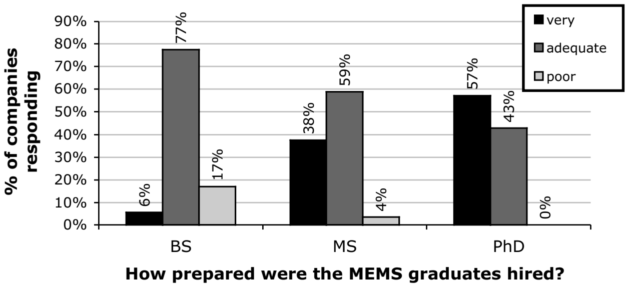


***Figure 5.** Industry assessment of the preparation of MEMS graduates hired, by degree level. Employers were generally most satisfied with preparation of PhDs hired for MEMS positions.*

Student Survey

Fifty-six current or recent students participated in this survey, most respondents were PhD candidates. Their majors were 40% Electrical Engineering, 42% Mechanical Engineering and a mix of other disciplines. Students reported on their current or expected jobs (Figure 4) and most were optimistic about obtaining research jobs in industry. About 60% of the students want industrial jobs and 30% want academic jobs after graduation. Almost 90% of students felt they would get MEMS related jobs after graduation.

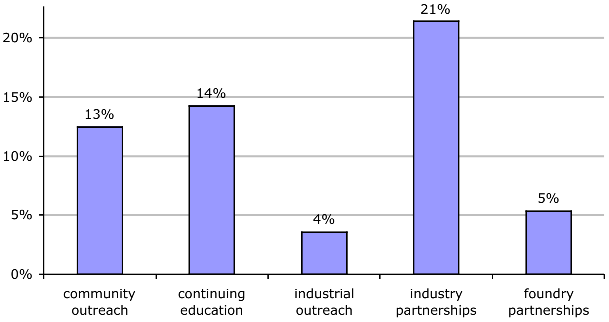


***Figure 6**. Student reported experience with forms of industrial or community outreach related to MEMS*

Most students felt they should have at least an MS degree to be successful in a MEMS related career but they perceived increased preparation with a PhD (Figure 5).

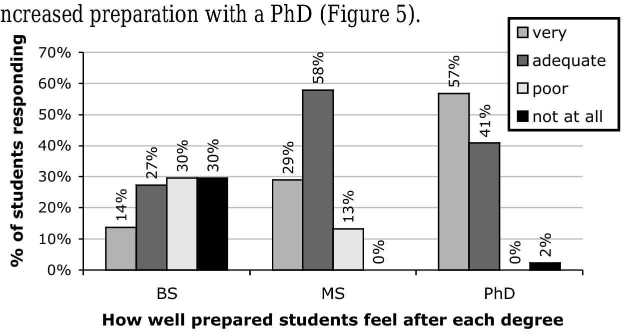


***Figure 7.** Student self-perception of preparation for MEMS careers also increases with advanced degrees.*

This is consistent with industry perceptions. Students were also asked about their involvement or collaboration with programs outside of their university. Several students reported experience with forms of industrial or community outreach related to MEMS (Figure 6); however, the exposure to non-academic partners should be higher given industry interest in improving MEMS education.

The students identified (1) hands on MEMS fabrication training, (2) broad fundamental science, and (3) MEMS design as the most important learning activities in a MEMS curriculum. Similarly, they felt that the breadth of knowledge base - fabrication, design, basic physics of MEMS, materials science of MEMS materials, and analysis techniques are the most valuable skills/assets that they will bring to their employers.

THE WORKSHOP

Common issues and themes submitted by participants in advance of the workshop centered on: interdisciplinary education; integration with the undergraduate engineering curricula; funding practical MEMS experiences; and keeping MEMS education current with industry needs. Challenges cited included:

- Today's market and product development environment require BS level graduates to think across their disciplines and have a deep appreciation of the interplay between different but concurrent physical, chemical and biological effects. How do we integrate MEMS into BS level engineering education?
- Promoting interdisciplinary education
- Challenges of making MEMS education cost effective
- Addressing the breadth and depth of current and future directions for MEMS curricula, especially as it relates to the manufacturability of MEMS devices
- Developing comprehensive programs, e.g. a series of courses with central themes rather than scattered special topics

The workshop included panel presentations by industry and funding agents, summaries of the survey results, and ample time for discussion. The content presented and generated at the workshop, as well as that submitted to the committee, and links to MEMS courses at participating universities may be found at: http://MEMSED.stanford.edu/. The final agenda and presentation slides (where available) are also included on the site.

Panel discussions

The *industry panel* (Cleo Cabuz of Honeywell and MEMS Industry Group, Richard Payne of Polychromix, and Michael Judy of Analog Devices) and associated discussion covered several major themes including the optimum curriculum balance for a MEMS engineer. Specifically, the preference for students trained in MEMS or trained in a traditional field with a focus on MEMS? Overall, the group favored the latter, but recognized that there was a challenge in teaching all the perceived important skills in a finite degree program. There was concern about certain ‘practical’ elements of MEMS being taught. These include packaging, product design, reliability, failure analysis, statistical analysis, and patents. Various panel members pointed to other fields (e.g. Aeronautics) that are successful in incorporating some of the themes. It was also pointed out that a lack of industry standards hampered this effort.

Means of engaging industry in the education process were discussed, including ‘certification’ processes for MEMS courses/degrees or continuing education certificate programs. There was also discussion of specific skills and classes. There was general recognition that fabrication classes are well done, but that as the fabrication becomes more standardized, more emphasis is needed on design and test.

The *funding agent panel* (Rajinder Khosla of NSF, Clark Nguyen of DARPA, Carl Stahle of NASA-GSFC) and the ensuing discussion focused on issues related to the types of funding and methods for collaboration and research between industry and academia. Emphasis was made that industry pursues research only to the level of solving emergent problems as they do not have the luxury of time and money to explore fundamentals beyond what their product demands. A comparison of the funding agencies and their missions highlighted that DARPA is deadline and product driven first and research programs must have benefit to DOD to be funded; NSF grants and fellowships are the most common method of supporting students and basic research and also provide the most flexibility in creativity in research while requiring evolution of education; NASA is specifically interested in building products that their enable space exploration but have found that jointly mentored student course and research projects are a good model for technology development and transfer in MEMS. On the education side, industrial/national laboratory affiliates like NASA are willing to provide real research problems with short term funding as well as student internships.

Breakout groups and discussion

In the afternoon, participants were encouraged to join one of five group discussions. The discussion groups were asked to debate recommendations which they would make to various groups having an interest in MEMS Education (Academics, Industry Groups, Funding Agents, Conference Organizers, Publishers, Media, K-12 Specialists). The specific recommendations of each group are contained in the Power Point Presentation slides collected at the meeting and are found on the workshop website.

CONCLUSIONS AND FUTURE DIRECTIONS

Several recommendations emerged from the workshop. The first two have been accomplished but require maintenance, and the profile of the remaining issues has already been elevated to discussion among faculty, in industry working groups, and at NSF.

1. Establish a web site on MEMS education with links to MEMS-education relevant sites elsewhere. The homepage for this workshop and its outcomes, as well as for shared materials from MEMS courses across North America, is maintained at: http://MEMSED.stanford.edu/
2. Encourage established MEMS conferences to incorporate MEMS education issues into the conference agendas
3. Consider holding regular workshops on MEMS education, embedded in larger conferences like the first one,
4. Address identity ‘crisis’ of MEMS versus Nano
5. Seek opportunities to integrate ‘miniaturization’ concepts and microscale examples into broader engineering education
6. Work with industry groups on defining MEMS education standards and certificate programs

ACKNOWLEDGMENTS

The committee thanks the participants of the workshop for their time and enthusiasm and also the numerous survey participants who were unable to attend but found time to share their thoughts. The committee also thanks PMMI for smooth workshop registration and management. This work was supported by the National Science Foundation under grant ECS-0503895 and NASA Goddard Space Flight Center.

REFERENCES

[1] Survey data, MEMS Education Workshop, January (2005), Miami, FL.

[2] ABET, Criteria for Accrediting Engineering Programs, Baltimore, MD.: Engineering Accreditation Commission, Nov. 11, 2003. See http://www.abet.org/criteria_eac.html.

[3] Ju, W. et al, "Project-Based Learning for Experimental Design Research," International Engineering and Product Design Education Conference, Delft, The Netherlands, 2004.

SELF-ASSEMBLY OF A BIOMEMS SYLLABUS:
TEACHING BIOMEMS THROUGH THE DEVELOPING ORGANISM

Michel M. Maharbiz
Center for Wireless Integrated MicroSystems (WIMS)
Electrical Engineering and Computer Science, University of Michigan
Ann Arbor, MI, 48109-2122, U.S.A.

ABSTRACT

This paper presents the course philosophy, syllabus, notes, and course feedback on a 'first-run' bioMEMS course offered at the University of Michigan EECS Department (*EECS 598: bioMEMS through the developing organism*) during Fall 2004. As a teaching experiment, the course explored the use of the natural hierarchy of biological organization to structure the bioMEMS material. The syllabus took a bottom-up path from gene, to protein, metabolism, signaling, tissues, and finally, to organism. Each section emphasized the engineering community's search for revolutionary technologies at that interface. The course was designed for students who had already taken the *Introduction to MEMS* course at the University of Michigan (EECS 414).

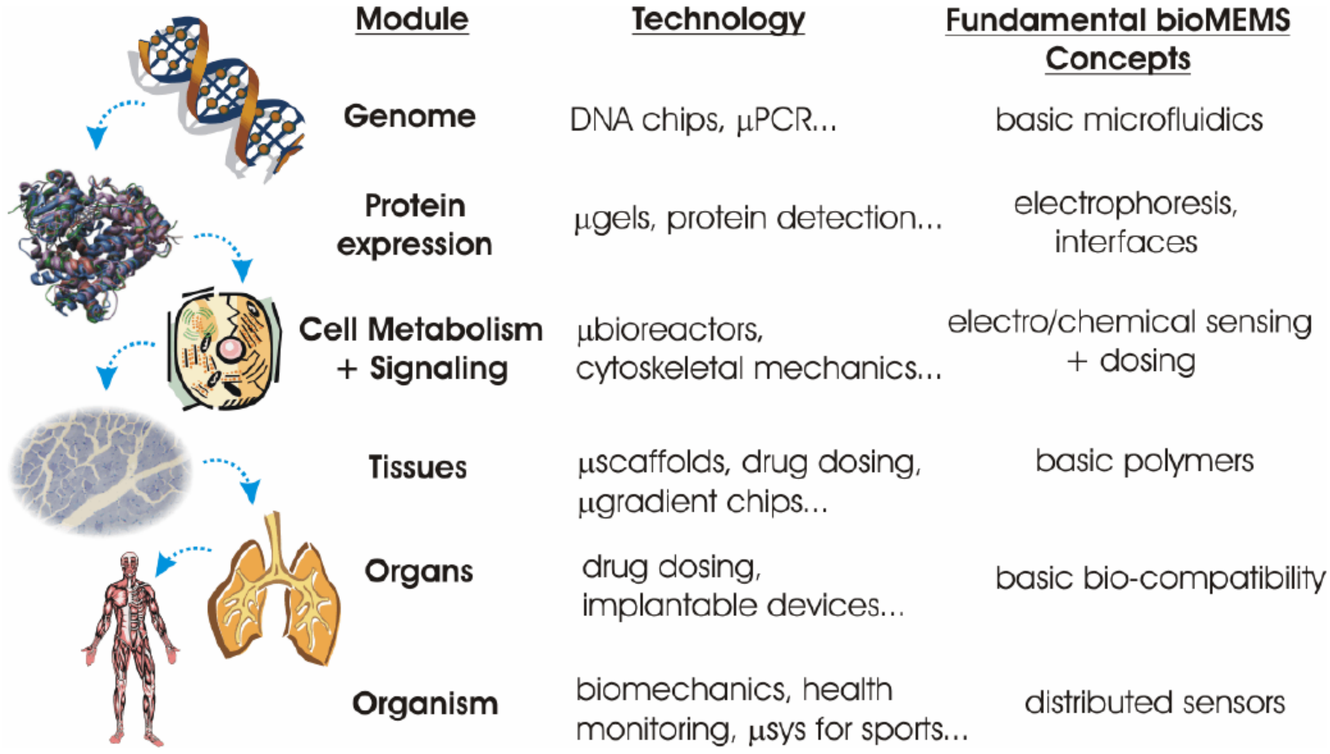
INTRODUCTION

As an emerging field, bioMEMS is often ill-defined; this makes it particularly difficult to parse and organize into a coherent system for teaching. Moreover, it is a field which, by definition, exists precisely at the interfaces between disciplines. How should a bioMEMS course be structured? How is the organization relevant to the research needs of the students and the community?

The standard organization of bioMEMS courses tends to fall into one of two categories: 1) by technological subdomain (e.g., 1 week on microfluidics, 2 weeks on solid-state chemical sensors, etc.) or 2) by application (e.g., implantable clinical devices, non-implantable point-of-care clinical devices, basic biomedical research, etc.). This paper presents the results of teaching bioMEMS through a different, third approach: bioMEMS through the biology of the developing organism.

The course uses the hierarchy of biological organization to motivate microtechnology instruction. By beginning with genes and hierarchically working upwards, students learn about both the biological problems and the technologies used to tackle these problems. This approach, moreover, focuses attention on the application space and allows for comparative evaluation of the usefulness of the microtechnologies presented (i.e., the need for miniaturization, or cost reduction, or scaling effects as technology drivers become apparent).

The course is modular: each module begins with a set of lectures on the underlying biology, followed by a review of fundamental physical science or engineering concepts employed *in the technology.* Figure 1 demonstrates the sequence of topics covered. The microtechnologies applicable to the module are then learned through two or three sessions of intensive paper reviews. The goal is for the revolutionary impact of these technologies to be obvious once the underlying biological concern is understood. The class concludes with groups of two or three students writing sample grant proposals to the NSF or the NIH (using, for example, the NIH R21 format).



Module	Technology	Fundamental bioMEMS Concepts
Genome	DNA chips, μPCR...	basic microfluidics
Protein expression	μgels, protein detection...	electrophoresis, interfaces
Cell Metabolism + Signaling	μbioreactors, cytoskeletal mechanics...	electro/chemical sensing + dosing
Tissues	μscaffolds, drug dosing, μgradient chips...	basic polymers
Organs	drug dosing, implantable devices...	basic bio-compatibility
Organism	biomechanics, health monitoring, μsys for sports...	distributed sensors

***Figure 1**. Course organization. Six sequential modules teach basic biological concepts and technologies.*

06TRF-0003/hh2006/$20©2006TRF
DOI 10.31438/trf.hh2006A.12

COURSE OFFERINGS AND ENROLLMENT

The information presented here is based on a first-run course offered during Fall 2004 (***EECS 598:*** *bioMEMS through the developing organism*). Total enrollment was 15, including 3 audits. Of those enrolled, 14 were graduate students and one was an undergraduate. The approach received substantial positive feedback (rated 4.7 / 5.0 by students; college average is 4.21 for 500-level courses). Most students benefited greatly from being forced to properly parse their interests into coherent research directions. This course will be offered as part of the core MEMS curriculum at UM starting Winter 2006 as EECS 516.

COURSE OBJECTIVES

The course is targeted at advanced undergraduates and first-year graduate students needing an introduction to the interface between microtechnologies and biomedical research. As such, it is assumed that students are at least topically familiar with *conventional* silicon microtechnologies and microfabrication techniques with EECS 414 as the prerequisite. The course has three objectives:

1) Familiarize the student with cutting edge microtechnologies in biomedical research.
2) Teach non-bioengineering students the ‘language’ used by biomedical researchers. In this context, traditional biology methods are described alongside the relevant microtechnologies so as to familiarize students with biomedical method and jargon.
3) Teach students the ‘big questions’ being asked in biology and medicine.
4) Lastly, the course is designed to provide MEMS students with a direct path into in-depth courses in specific areas (e.g. ,advanced microfluidics in the ME and BME departments, tissue engineering course in BME, etc.).

SYLLABUS

Table 1 lists the topics covered under each module. As of this writing, the class employs the instructor’s notes in lieu of a textbook. The following textbooks are provided as reference material:

- **MEMS:** Senturia **[1]**
- **Biochemistry:** Lehninger **[2]**
- **Methods:** Klipp **[3]**

(Klipp deserves special mention as it provides several outstanding introductions to biology, methodology, and mathematics intended for non-biology engineers.)

The first lecture in a module is devoted to the underlying biological principles and language. It is, of course, limited in depth, but the goal is simply to provide a springboard to further digging by the students. The relevant biology or biomedical journals in that sub-field are given at the end of the first lecture so that students know where to start their own investigations.

The goal in the second lecture is to describe existing technology not normally seen by microtechnologists. This categorization is not a question of scale or technology-type, but simply reflects the fact that workers in given sub-fields have developed ‘gold standards’ or ‘best practices’ that must be understood before microtechnologists can make an impact.

An example may be helpful. If one considers the vast realm of genetic sequencing, no intelligent discussion of microsystems for DNA sequencing can be had before students understand basic PCR, gels, high-throughout methods (such as pyrosequencing), etc. Once this is in hand, intelligent directions in miniaturization can be discerned (miniaturization of sample handling, higher throughput thermal cycling through scaling, the drive towards the $1k genome, etc.).

The third lecture is then an overview of the cutting edge microtechnologies in the field. This lecture serves as a guide and an introduction to concepts present in the critical reading. Following the third lecture, two or three sessions are devoted to ***critical*** reading and discussion of papers. Reading lists are distributed prior to the beginning of each module. Students are given a single sheet that explains how to read a paper critically; some example statements from that sheet are provided below:

- Papers should be read three times: once for familiarization, once for comprehension and the third for critique. REM sleep is encouraged between reads.
- Distrust the paper from the beginning: e.g. does Eq. 5 really follow from Eq. 4?
- There are *differences* and then there are *statistically significant differences* between data points or runs. Examine data as though your own.
- Evaluate novelty and proposed use harshly. Just because it’s neat or cool doesn’t mean it’s useful (although I love cool papers!).
- Extrapolate! By the time a paper is published, the work is anywhere from 6 – 24 months old! Where do you see this topic going next?

Below is an example of the types of papers read. The following

Module	Genes	Proteins	Signaling	Tissue	Organs	Organism
Lecture 1	*-DNA basics -transcription -hybridization -methylation*	*-protein basics -translation*	*-cell-cell signaling -mechano-transduction -morphogens*	*-tissue org. -stem cells -biocompatability*	*- devbio intro - body plans*	*-biomechanics of locomotion -health monitoring*
Lecture 2	*-genome -promoters, consensus -DNA basics*	*-hydrophobicity -trans-membr. proteins -micro patterned protein layers*	*-Dunn chambers -Boyden chambers -gels, probes, beads -optical tweezers*	*-tissue constructs -tissue scaffolds*	*- bio-telemetry -pacemakers -stents -vascular sensors*	*-sports sensors -sensor webs for the elderly*
Lecture 3	*- μ fluidics -Navier-Stokes -laminar flow -pumping -valving*	*-electrophor. -synthetic protein assembly -protein μsensors*	*-microgradient generators -μmech. sensors and actuators -chemical sensing -microbioreactors -single cell assays*	*-tissue μ fluidics -micro patterns + surfaces*	*-nano drug dosing -implantable systems and devices*	*-distributed sensor networks -integrated complex systems for biology*

Table 1. *Summary of topics covered in the course. Lecture notes available upon request.*

reference list was given to students during lecture 1 of Module 1 and discussed in sessions 4 – 7. A complete list for all modules is available by request (although no longer current).

(Sessions 4 - 7) (• mandatory, ➢ recommended)

Electrochemical detection **(Session 4)**

- **REVIEW** Kerman, K., Kobayashi, M., Tamiya, E. "Recent trends in electrochemical DNA biosensor technology," *Meas Sci Technol*, vol 15, 2004, R1 – R11.
- ➢ Robert M. Umek, Sharon W. Lin, Jost Vielmetter, Robert H. Terbrueggen, Bruce Irvine, C. J. Yu, Jon Faiz Kayyem, Handy Yowanto, Gary F. Blackburn, Daniel H. Farkas, and Yin-Peng Chen, "Electronic Detection of Nucleic Acids: A Versatile Platform for Molecular Diagnostics," *Journal of Molecular Diagnostics*, Vol. 3, No. 2, May 2001, pp. 74-84.

Pyrosequencing **(Session 5 - 6)**

- Ronaghi, M., "High-throughput pyrosequencing for analysis of single-nucleotide polymorphisms," *Proceedings of the SPIE - The International Society for Optical Engineering*, v 4626, 2002, p 316-21
- ➢ H. Andersson, W. van der Wijngaart, G. Stemme, Micromachined filter-chamber array with passive valves for biochemical assays on beads, *Electrophoresis*, vol 22 2001, pp. 249–257.

Nanopore sequencing **(Session 6 - 7)**

- Meller A, Branton D., "Single molecule measurements of DNA transport through a nanopore," *Electrophoresis*, vol 16, Aug;23, 2000, pp. 2583-91.
- Jiali Li. Stein, D., McMullan, C., Branton, D., Aziz, M.J., Golovchenko, J.A.," Ion-beam sculpting at nanometre length scales," *Nature*, v 412, n 6843, 12 July 2001, p 166-9.
- Branton, D., "Nanopore transducers: Prospects for Single Molecule Electrophoresis," *The 12th International Conference on solid-state Sensors, Actuators and Microsystems*, Boston, MA, June 8-12, 2003, pp. 210-213.

The papers are usually intended to cover a few areas in depth and the author usually played them against each other to elicit contention and heated debate (i.e. "who will win the high-throughput genome race: pyro-sequencing or nanopore sequencing?"). One review paper was used in almost all modules for breadth.

Lastly, for each module, students should be required to provide a one page technical summary (with figure references) for one reviewed paper of their choice (another way to describe this assignment is to have them generate a 'Hilton Head abstract' for the reviewed paper of their choice).

IN-CLASS TECHNICAL DEBATE

During two modules in the Fall 2004 offering, (chemical sensors and microsystems for force sensing in cell culture), students were divided into three groups of 4 and asked to give 20 minute slide presentations forcefully defending a particular technology. All groups were given competitive technologies so as to elicit debate and heated questions. While this took significant preparation on the part of instructor and students, it appeared to make a significant difference in comprehension.

For example, the chemical sensor debate asked one group to present data on sensing metabolic products with microfabricated amperometric sensors, another group defended microfabricated fluorescent sensors and a third focused on potentiometric techniques.

FINAL PROJECT

The final deliverable for the class is an NSF or NIH-style proposal. Students are encouraged to form groups of 2 or 3. Halfway through the semester, the author gives them the links to the NIH r21 guidelines and the NSF Proposal Guide. Students then schedule 20 minute meetings as a group with the instructor over the next three weeks so that they can pitch and refine their initial ideas. Five weeks before the end of final exams, each group submitted a one page summary following the standard NSF or NIH format. The instructor graded these, added hand-written notes and performed appropriate course-correction. (Budgets were, of course, completely ignored). The final deliverable was a 15 page proposal description complete with summary, figures and references.

GRADING

In its original form, class grade is based 30% on critical review participation, 30% on the one-page summaries provided after each module, and 40% on the final proposal project. The next version (offered Fall 2006) will also include 3 homework assignments and a midterm (but no final) based primarily on lecture material to test for more quantitative assessment.

CONCLUSIONS

Overall, this method for organizing the material was immensely successful. Student feedback (end-of-course surveys and verbal feedback to instructor) indicated overwhelmingly that the class filled a much sought-after need: it allowed them to understand where MEMS could make an impact in the vast spectrum of biomedical research. This, coupled with the use of the course as an intro to further biomedical engineering classes, was perhaps the primary contribution to the curriculum.

The continuing struggle of a class such as this is to provide and test for depth of understanding as well as breadth of topic. While the paper reviews certainly provide depth to some extent, homework assignments and a midterm examination are obviously necessary.

REFERENCES

---

[1] S.D. Senturia, Microsystem Design, Kluwer Academic Publishers, 2000.

[2] A. L. Lehninger, *Lehninger principles of biochemistry*, New York : W.H. Freeman, 4th ed. , eds: David L. Nelson, Michael M. Cox., 2005.

[3] E. Klipp, R. Herwig,A. Kowald, C. Wierling, H. Lehrach, *Systems Biology in Practice: Concepts, Implementation and Application*, Wiley-VCH, Weinheim, 2005.

THE 18mm^2 CLASSROOM

T. Dallas[1], R. Gale[1], and J. Berg[2]
[1] Dept. of Electrical and Computer Engineering, [2] Dept. of Mechanical Engineering, Texas Tech University
Lubbock, TX USA

ABSTRACT

We describe a MEMS course sequence based on Sandia National Laboratories' (SNL) SUMMiT V MEMS process. Over three semesters, our curriculum takes students who typically begin with no MEMS knowledge, to a level where they are capable of designing MEMS for cutting-edge research applications. The main tool is a customized AutoCAD-based MEMS layout system developed by SNL. This software incorporates the capabilities and limitations of the SUMMiT process, and includes a pre-defined library of useful and instructive components. Devices designed with this software and validated by an on-line SNL design checker may be manufactured at SNL's Albuquerque, NM facility. The SNL MESA Institute sponsors a yearly design competition for the universities in its University Alliance Program. In our first year of participation, Texas Tech student teams developed a micro X-Y stage with AFM-like cantilever probe, a microclock, a microchain and drive system, and two types of micromirrors. These devices, laid out on a 18 mm^2 (2.82 x 6.34 mm) module, were selected as the winning entry. Educational benefits for student competition participants include immersion in MEMS design and fabrication, familiarization with layout software and process and device simulation, and experience with working in tightly integrated interdisciplinary teams. Furthermore, the devices produced are themselves expected to have significant research value.

INTRODUCTION

The world of Microelectromechanical systems (MEMS) continues to expand, with increasing numbers of devices moving from the laboratory into commercial applications. Long-standing MEMS commercial success stories such as ink-jet printer heads, video displays, and accelerometers have been joined by pressure sensors and microphones in high-volume production. As the market expands, so does the demand for engineers and scientists who have the training and skills necessary to make important contributions to this burgeoning field. Accordingly, educators have the responsibility to incorporate both fundamental and advanced MEMS topics into undergraduate and graduate engineering curricula. Staying abreast of this continually advancing field without constant course overhauls is a significant task. One approach to doing so is to present students with a design challenge, based on a state-of-the-art fabrication process and incorporating current device applications. An essential component in such an approach is to select a standardized, but versatile, fabrication process with continually supported design and visualization tools.

Sandia National Laboratories has developed a polysilicon based fabrication sequence called SUMMiT V (Sandia Ultra-planar Multi-level MEMS Technology 5) that is ideally suited for this purpose. A total of five polysilicon layers are used, along with four layers of silicon dioxide used as a sacrificial layer to build complex electromechanical devices. SUMMiT V is extraordinarily capable, and has been used to construct micro engines, gears, and hinges, and many other dynamic mechanical structures [1-4]. In order to expand the usage of their MEMS foundry, Sandia has initiated a University Alliance Program which allows universities access to design and visualization software tools for a one-time fee [$5000 (2005)]. The design and visualization tools are proprietary software AutoCAD plug-ins. AutoCAD layout tools are used to construct the two-dimensional masks used in the photolithography steps of the fabrication process. The SUMMiT V process has pre-defined thicknesses for each of the polysilicon and silicon dioxide layers. Essentially, the designer chooses the X and Y dimensions and Sandia constrains the Z dimensions of each layer. Figure 1 shows a cross section of the layers that make up the SUMMiT V process. The 2-D visualization tool allows the user to cross-section a part to see how it will fabricate. The top of the screen shows each layer of the photomask cross-sections. At the bottom of the screen, the SUMMiT layers can be added, etched, and finally released, one by one. Much empirical data allows the depiction of the topology to be remarkably similar to the final fabricated result. This tool is an excellent tool for showing students how the photolithography, deposition, and etch processes affect the final MEMS structure. 3D visualization and modeler tools are also included. The 3D visualizer provides a rapid, but not overly accurate rendering of the structure. The 3-D modeler renders a detailed and accurate picture, but can take several hours for large and complex devices. These tools promote rapid assimilation into the design environment, lead to new design ideas, and highlight fabrication problems and constraints.

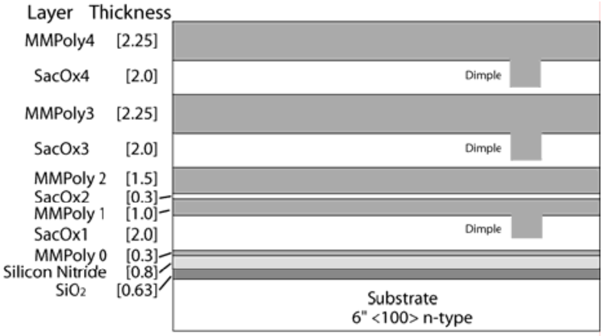


Figure 1. *Cross-section of SUMMiT V process levels. Gray shaded regions are polysilicon layers that remain after the silicon dioxide regions (white) are removed through an aqueous etch process. Approximate thicknesses of each layer are shown in microns.*

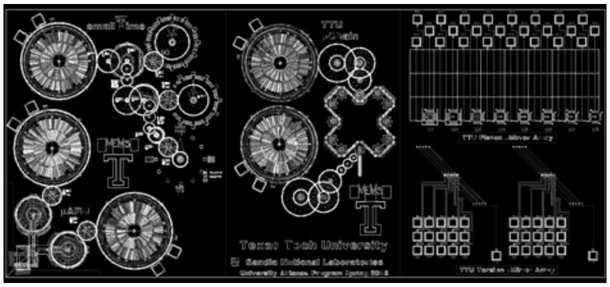


Figure 2. *TTU designed SUMMiT V module (2.82 mm x 6.34 mm); Spring 2005. From left, the module includes a microClock (top), microAFM (bottom), microChain, and two classes of micromirrors: piston (top) and torsional (bottom).*

DOI 10.31438/trf.hh2006A.13

The software tools include a library of pre-defined parts. These are primarily actuators and include a rotating drive known as a torsional ratcheting actuator (TRA) a displacement multiplier that can produce a 10X increase in motion, and a gear transmission. These and other library part can be utilized in its entirety simply by pasting it into the design area. This feature saves immense amounts of time and alleviates a designer from (sometimes literally!) reinventing the wheel when certain commonly used parts are needed. For example, instead of laboriously re-constructing a rotating drive from scratch, the designer can spend all her time designing the *device* that will utilize the circular motion. Rapid prototyping becomes much more feasible. A design rule checker is used to flag designs that do not meet minimum feature size, overlay guidelines, and other parameters. This helps prevent the most blatant mistakes, and decreases the number of design cycles needed to produce working devices.

INCORPORATION INTO TTU MEMS SEQUENCE

At Texas Tech University, we have developed a three-course sequence in microsystem design **[5,6].** Beginning in 2000, and supported by a National Science Foundation Combined Research and Curriculum Development grant, a number of faculty have contributed to developing a laboratory-based multidisciplinary curriculum. A key aspect of the course sequence is *peer-mentoring*, with senior graduate students serving as leaders of small research teams, that accomplish the design, fabrication, integration, and testing of a microsystem compliant to specifications presented by faculty "clients." We have worked to augment our laboratory-based courses with a classroom-based program offering similar characteristics and benefits, but at a lower cost. Since the fall of 2004, we have positioned our education efforts to leverage the enormous infrastructure represented by the SUMMiT design and fabrication system.

Since 2005, Sandia's MESA Institute has sponsored an annual SUMMiT MEMS design competition for member schools in their University Alliance Program **[7].** A single wafer die is segmented into eight 2.82 x 6.34 mm *modules*. Each school is allowed to submit a module, which may contain several MEMS devices. The top eight designs—as judged by a panel assembled by Sandia—are fabricated and the parts are distributed to the member schools. The criteria for winning designs include integration of multiple layers, usefulness for educational demonstrations, and uniqueness of design. Up to one-third of the module may be used for non-student designed devices. Completed devices are typically received three to four month after the designs are submitted and pass design checks. Schools receive ~50 of their own modules as well as modules designed by other schools. The fact that student-designed devices are actually available for characterization and test, using one of the most advanced MEMS fabrication processes in the world, makes SUMMiT V-based education tremendously appealing. Additional benefits are realized by creating designs that carry significant value to university research programs.

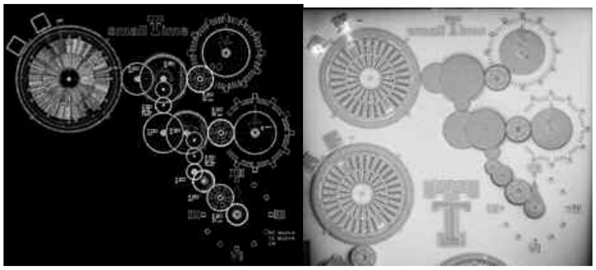


Figure 3. *AutoCAD design of microClock and SEM image of fabricated device.*

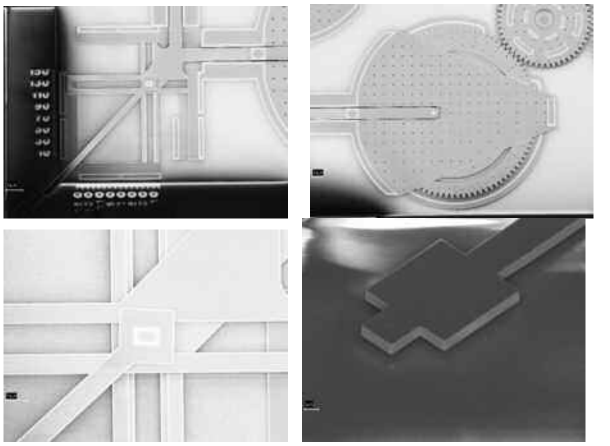


Figure 4. *(a) microAFM stage assembly, arm and scale. (b) spiral gear and cam assembly; one each for X and Y stage (c) pin assembly that allows cantilever arm to be scanned by stages(d) end of cantilever arm; a single dimple is on the underside of the tip.*

Our first semester course, Introduction to Microsystems (MEMS I), is used to give students a broad overview of microsystem technologies and covers many fabrication processes besides SUMMiT V and similar polysilicon-based technologies. However, the students are instructed on the use of the SUMMiT AutoCAD design tools and are required to complete gradually more complex designs through the course of the semester. The students are also required to carry out numerical simulation (using MATLAB or ANSYS) of a key aspect of their design. Interim and final presentations are given by the students. The most promising designs are carried forward in to the subsequent classes, Introduction to Microsystems II and III (MEMS II and III).

MEMS II is completely project based and requires individual students or small groups to design and simulate complex MEMS. In our peer-mentoring approach, Experienced MEMS III students guide the research efforts of small groups of MEMS II students. Projects are developed in conjunction with faculty and are specifically chosen to benefit real research needs. The first two iterations of the Sandia MEMS Design Competition have had submission deadlines approximately two thirds of the way through the spring semester. This timeline fits our course offering system quite well (Fall: MEMS I; Spring: MEMS II/III).

RESULTS AND DISCUSSION

In this paper, we mainly report on the results of the first year (2004-2005) that we made SUMMiT V and the Sandia Student Design Competition the focus of the curriculum. We also comment on the enhancements made in year two (2005-2006), which is still a work in progress. The majority of the work that went into the 2005 design competition module was completed in a ten week span by a class of ten students that included undergraduates and graduates. The students were tasked with developing ideas on what to design. To do this, they carried out literature searches and in some cases, contemplated the needs of their own graduate research. Prior work indicated only a limited amount of published work utilizing the SUMMiT V process. Some examples included a microfabricated chain, micromirrors, and accelerometers. The first four weeks of the semester was spent trying to narrow the list of potential projects to those that would fit in the remaining six week timeframe. Although some compelling devices resulted, more time should have been devoted to design and simulation. This is an aspect currently being addressed. Ultimately, five devices made it onto the final TTU module, shown in Figure 2.

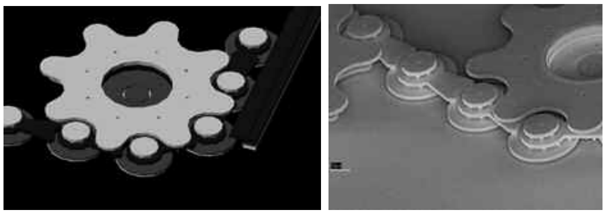


Figure 5. microChain, sprocket and guide as designed in AutoCAD and as fabricated (SEM image).

The five devices fell into two categories. First (the micro clock, micro AFM, and micro chain) are highly complex mechanical designs to mechanically involved for device-level simulation. The others (micromirrors) are relatively simple mechanical designs, and were computer simulated. A brief description of each device is given in order to demonstrate the capabilities of the technology, as well as illustrate the range of possible devices that can be fabricated on one module. The resulting designs show that highly skilled and motivated students can produce complex devices in a relatively short time frame.

The first device was a clock designed by an undergraduate student with prior AutoCAD knowledge. He designed the clock for his final project in MEMS I and made significant improvements to it for MEMS II. Being adept at AutoCAD or another CAD program greatly expedites the design process. Being able to effectively use AutoCAD is an important tool for many engineers and scientists regardless of the size of devices being designed. Therefore, we regard the acquisition of AutoCAD proficiency to have long-term benefit to the student, regardless of whether or not they continue on in the MEMS design field.

The micro clock, as shown in Figure 3, was designed to be one of the world's smallest mechanical clocks. A single TRA is geared down to run separate second, minute and hour hands. Additional levels were added to gears in order to change levels and to allow hands to be fabricated. This design was an important first step in learning how to use the design tools to construct devices. The design used mostly standard parts (gears, TRA's), but some were modified to fit this application. Students quickly gain insight into the design environment by modifying exiting designs found in the standard parts library. Occupying an area of 4 mm^2, more than fifty of these clocks will fit in the area of a penny. A single TRA is used to drive an 11 gear drive system with 3 additional gears used to rotate the second, minute, and hour hands. Compound gears were specially designed to accomplish significant ratio changes. The device design allowed room for artistic embellishes, such as TTU's "Gun's Up" hand gesture used on the clock's second hand. Effective MEMS design requires large amounts of creativity and we encourage students to develop designs that are first and foremost functional, but incorporate aesthetic elements that enhance human interaction with the devices.

The Atomic Force Microscope (AFM) has become a ubiquitous characterization tool for measuring topology and other surface phenomena. An atomically sharp tip is scanned across the surface of a sample. Interactions between the tip and the surface are measured allowing quantification of many surface properties. This analytical tool served as the inspiration for the device shown in Figure 4. A student designed an X-Y stage, driven by two TRAs, which can be used to position/scan a pseudo-AFM cantilever arm which included a 1.5 µm x 1.5 µm polysilicon dimple (tip) at the end and on the underside of the arm. These dimple elements are typically used as anti-stiction structures and are available for incorporation on three of the polysilicon levels. The cantilevered arm is connected to a flanged pin held between slots in the X and Y stages. The travel is 110 µm in both X and Y. The layout allowed the arm to be extended off the edge of the chip, possibly to access an external Z-stage where a sample could be placed. Due to TRA limitations (i.e., uni-directional rotation), the arm cannot be retracted at this juncture. During operation, the TRAs are used to drive a gear with a spiral slot etched into it. A flanged pin that is positioned in the slot is connected to the X or Y stage and is pushed away from the center as the gear turns. The AFM arm is connected to a central pin that is held between the X and Y stages. A scale is used to indicate arm position.

Figure 6. SEM images of (a) Torsion micromirror (b) piston micromirror.

The basis of the mechanical design had its origins in a macroscale mechanical system that took rotational motion and converted into linear motion **[8].** With some modification and allowing for the limit on the number of polysilicon levels, a microscale analog was designed that allows for precise X and Y motion. Although an AFM-like arm was attached, the motion generating part of the design could be attached to a stage or some other structure where X and Y motion would be needed.

A 60 link micro chain, tensioner, and drive system was also included on the module. The chain is composed of 50 µm links giving an overall chain length of 3 mm and a width of 20 µm. Figure 5 shows the 3D AutoCAD design as well as an SEM of the fabricated structure. The fidelity between the AutoCAD 3D rendering and the actual device is quite good and get be analyzed by the students to gain further insight into the realities of the fabrication process. A torsional ratcheting actuator (TRA) is connected to a drive sprocket by a gear train and is designed to drive the chain along a path delineated by ten custom idler sprockets in addition to the single drive sprocket and a linear tensioner. The linear tensioner is designed to remove slack from the released chain and force contact with the drive system. A second TRA is implemented with a rack and pinion system to move the tensioner and provide the ability to remove up to 200 µm of slack. The entire device occupies a surface area of under 4 mm^2 including the relatively large TRA's. A previous SUMMiT chain was unable to be driven due to low power and high mechanical resistance. The students' design reduces the contact area inside the link hub and therefore, potentially reduces friction and stiction. This system was designed by finding alternatives to the pin joint undercut used in most SUMMiT hub designs. In addition, the design incorporated an actuator with more power than the previous system. An automated tensioner is included that improves upon the previous device that had to be tensioned by hand, using a probe.

Two micromirror arrays were designed to meet research needs of students participating in the class. Their designs were guided by systems that the MEMS devices would be integrated with. The first type of micromirror is a linear, array of electrostatically actuated torsion micromirrors that incorporate multiple electrodes for static feedback control. A number of preliminary designs were simulated using a Finite Element Modeling software package (ANSYS 8.0) to determine a suitable design for the fabrication process. The mirrors were designed to produce both translational and torsional analog motion. The pitch of the array was chosen to correspond to the mean distance between two consecutive waveguides of a reflective folded arrayed waveguide grating multiplexer (32 microns). Each mirror, fabricated at the poly3 level of SUMMiT, is 25 µm x 25 µm and is supported by 400 µm long springs to allow relatively low actuation voltages. To prevent excessive translational motion, two stops are built below the springs using poly1 and poly2 at a distance of 20 µm from the end of the mirror. The mirror will translate vertically and then rotate once the springs land on the stops. A total of four bond pads are used to form electrical contacts to each mirror. One pad is used for each of the two driving electrodes and one is connected to the sensing electrodes. A common bond pad is connected to all the mirrors. Thus, the translational motion is achieved by activating both drive electrodes while rotational motion is achieved by activating one drive electrode. The voltage at the driving electrodes will be varied analogically depending on the feedback signal from sensing electrodes, given the position of the mirror at the previous state.

Analog amplitude modulation of light can be used to make a variable optical attenuator and add-drop multiplexer using the Mach-Zehnder interferometer principle. For this principle to apply, it is necessary to precisely control the optical-path lengths of the two interferometer arms. Thus, the exact control of the movement of the translational micro mirrors which vary the optical-path lengths is required. The mirror is required to translate by ¼ of the wavelength of the light used; in this case, 1.55 µm. Therefore, the mirror translation movement needs to be 0.5 µm to ensure controllability over the required range. The mirrors were designed to have a control voltage below 50 volts. The pitch of the mirrors was set to 250 µm to match the pitch of the optical device it will be coupled with. Based on these requirements, the students designed an 84 µm square micro mirror with serpentine support springs. Various electrode designs have been incorporated to test different structural support geometries. ANSYS simulations were used to explore the mirror design space and electrode functionality.

During the spring 2006 semester, MEMS II students have been working to assemble testing systems for these devices. Due to a small, but important design error, the TRA's were shorted on the original module preventing electrical actuation of the devices. Sandia has re-manufactured the devices with a correction and the new parts will be received later in the spring semester. Where possible, a sharp probe has been used to manipulate the various mechanical structures to test some aspects of functionality. The microchain slides very easily over the surface and moves in an analogous manner to macroscale chains. The piston micromirrors are being tested using an interferometric microscope and probe station. Students will be able to compare the design goals with the actual performance of the mirrors. Testing modules designed by previous classes is a critical aspect of this work that allows students to gets hands-on experience with real devices, and allows critical analysis of prior work. Testing actual devices can give important insight to current design projects.

CONCLUSIONS AND FUTURE WORK

We have successfully transitioned our MEMS course sequence to incorporate the design, fabrication and testing of SUMMiT MEMS devices. We believe we have developed a productive teaching cycle in which students first understand and reverse engineer existing student-designed devices, then develop and design their own. This approach builds student confidence, and allows accumulation of expertise and design of devices of increasing sophistication and research value. This work illustrates an exciting avenue for giving students an in-depth educational and research experience on complex microscale systems. In addition, it demonstrates the relatively rapid MEMS prototyping capabilities of the SUMMiT fabrication system. Further benefits of this educational activity include nurturing of student creativity and exploration of projects of personal interest, learning about semiconductor and MEMS processing steps and constraints, utilizing 3D CAD tools, utilizing software simulation tools, and building devices to support the research of individual students. The design competition aspect fosters excitement and imposes hard deadlines—both aid in motivating the class. The students involved in the first iteration received significant publicity for winning the Sandia competition, which will continue to spur future classes to match or surpass their accomplishments. The inherent research value of many of the devices also leads to student co-authorship on archival journal papers.

One of the main educational paradigms that we developed during the previous iteration of the MEMS course sequence was the forum for interdisciplinary student training using peer mentoring and a "client"-driven project model. In the second year of the SUMMiT-based courses, we are developing devices for specific applications that meet the needs of "client" research endeavors. Although the scope is limited to a few devices on the current module, we will use the lessons learned through this process to increase this number in subsequent years.

A group of students is currently designing microcantilever arrays that can be functionalized through wet chemistry techniques and utilized in standard sensing configurations using an optoelectronic system. This project requires significant interaction with researchers in chemical engineering and chemistry. Projects like this draw in MEMS students outside the typical electrical and mechanical engineering disciplines, by solving real problems using micro and nano technologies.

ACKNOWLEDGEMENTS

This work supported in part by: National Science Foundation grants EEC-0087902 and ECS-0218245, TTU's Teaching Learning and Technology Center, Maddox Endowment at TTU. We thank Sandia's MESA Institute for fabrication of this module.

REFERENCES

[1] G. E. Vernon, Sr., *Surface-Micromachined Chain for use in Microelectromechanical Structures*, US Patent #6,328,903 (2001).

[2] D. Hah, S. T. Y. Huang, J. C. Tsai, H. Toshiyoshi, M. C. Wu, "Low-voltage, large-scan angle MEMS analog micromirror arrays with hidden vertical comb-drive actuators," *Journal of Microelectromechanical Systems* 13, pp. 279-289 (2004).

[3] A. A. Seshia, M. Palaniapan, T. A. Roessig, R. T. Howe, R. W. Gooch, T. R. Schimert, and S. Montague, "A vacuum packaged surface micromachined resonant accelerometer," *Journal of Microelectromechanical Systems* 11, pp. 784-793 (2002).

[4] J. Li, Z. Cui, and M. A. Baker, "A study of the surface chemistry, morphology and wear of silicon based MEMS," *Surface and Interface Analysis* 36, pp. 1254-1258 (2004).

[5] J. M. Berg, M. Holtz, Y. Su, R. Bunuam, J. Wilhelm, T. Dallas, R. Gale, L. Gollahon, S. Gangopadhyay, and H. Temkin, "Towards Integrating Graduate Research and Education with 'Internal Internships': Experiences and Assessment," Innovations 2004, World Innovations in Engineering Education and Research, Editors: W. Aung, R. Altenkirch, T. Cermak, R. King, L. M. S. Ruiz, iNEER. Arlington VA, 2004, pp. 291 – 301.

[6] T. Dallas, J. Berg, M. Holtz, S. Gangopadhyay, & H. Temkin, "Developing "Internal Internships" for a Microsystems Engineering Curriculum," INNOVATIONS 2003: World Innovations in Engineering Education and Research; Eds: W. Aung, M. Hoffmann, N. W. Jern, R. W. King, L. M. S. Ruiz, iNEER/Bergell House, 2003 p. 319-330, ISBN 0-9741252-0-2

[7] http://www.sandia.gov/mstc/education/alliance/

[8] R. O. Parmley, *Illustrated Sourcebook of Mechanical Components*, McGraw-Hill, pp. 22-58, (2000).

WHAT SHOULD A FIRST COLLEGE COURSE ON MEMS BE?

Khalil Najafi and Michel Maharbiz

Center for Wireless Integrated Microsystems (WIMS)
University of Michigan, Ann Arbor, MI, 48109-2122, USA

ABSTRACT

This paper reviews the course entitled ”Introduction to MEMS”, which is offered at the University of Michigan and is available to students at other schools through the web. The course is the first in a series of courses in the MEMS/Microsystems curriculum developed at the University of Michigan during the past 5 years. It is intended mainly for undergraduate students with a science or engineering background who do not have any prior experience in microfabrication or MEMS and who want to learn the introductory material that could provide them with an overview of this field, and be the basis for future courses. The course covers basic microfabrication and planar semiconductor processes, micromachining and MEMS technologies, and capacitive, piezoresistive, and thermal transducers. In all of these areas, the basic theory and fundamental concepts are first discussed, followed by a review of how these concepts are applied to actual devices and applications. Coventorware and ANSYS are used as the CAD tools using which students simulate and model several simple structures in their homework problems. The course is offered through the web to several institutions and is available to others who are interested in offering this material to their students.

INTRODUCTION

The past few decades have seen the tremendous growth of the field we know as MEMS, Microsystems, or Micromachines. Whatever its name, the field deals with the development of miniature systems that are capable of handling, manipulating, or processing signals and information in other than electrical and optical domains that are typically handled by microelectronics systems. The field utilizes microfabrication and semiconductor processing, and sometimes traditional machining technologies, for the fabrication of a variety of devices and systems that have found widespread use. Although research, development, and commercialization of these devices have seen impressive progress during the past few decades, educational programs that can support the training of students with a diverse set of skills have been rather limited in scope and size. More recently, many schools and programs have started offering specific courses on these topics. These courses have been received well by students and have continued to evolve and mature.

One of the main challenges in MEMS education has been teaching the ***first*** course to novice ***undergraduate*** students. Several questions immediately arise as one begins to prepare such a course. Who is taking the course and what backgrounds do they have? What should, if any, be the prerequisites, do we make this first course available to most engineering students, or do we limit access by adding one or several prerequisites? When is the right time to take this course? What should be taught in the course, what should be the balance between theory and practice/technology, and what is the objective? Should it have a lab component, should it have a major design project, or should it have several projects? Should design and software tools be covered in the course? How can both undergraduate and graduate students be accommodated in a single course, or should they be? What does industry like to see in this course? Is one course sufficient to prepare students for practicing MEMS in industry? Undoubtedly many institutions, which have attempted to prepare such a course, have faced these and other questions.

In this paper we will first review the contents and the course coverage for EECS 414, the “Introduction to MEMS” course offered at the University of Michigan. Then, we will attempt to answer some of the above questions by presenting the philosophy and experience gathered at the University of Michigan over the past five years since we first taught the course and have made it available to practically all engineering and science students with an interest in learning about MEMS.

MICHIGAN’S “INTRODUCTION TO MEMS” COURSE DESCRIPTION

Figure 1 shows the structure of the MEMS curriculum at the University of Michigan, where the “Introduction to MEMS” is the first course and the only prerequisite needed for follow-on courses. This first course is open to all students irrespective of their discipline. Only basic math, physics and chemistry, as typically offered in most engineering/science curricula, are required. It serves as a prerequisite for all the other courses, and is offered as a senior-level undergraduate course.

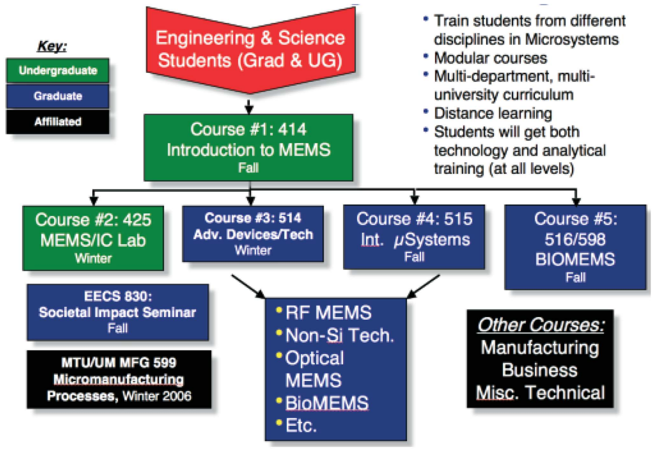


Figure 1. *MEMS Curriculum at the University of Michigan*

Because the students taking this course have had only the basic electricity and mechanics topics covered in typical physics courses, the course had to be designed to ensure that these students with this limited background are taught enough of the background material in technology and fabrication. In addition, since the course is also taken by many first year graduate students who have had other courses covering semiconductor processing, electronics devices, circuits, and basic mechanics, the course had to cover the materials in sufficient depth to maintain the interest of these graduate students. Indeed, one of the most challenging aspects of teaching this introductory course is maintaining the delicate balance between breadth and depth, and keeping the course interesting to all who take it.

06TRF-0003/hh2006/$20©2006TRF
DOI 10.31438/trf.hh2006A.14

Solid-State Sensors, Actuators, and Microsystems Workshop
Hilton Head Island, South Carolina, June 4-8, 2006

The course is divided into two parts, the first deals with teaching all of the basic microfabrication and micromachining technologies, and the second deals with teaching three of the most common transductions techniques.

Since micromachining technology affects all aspects of MEMS, the course starts with a detailed coverage of microfabrication and micromachining. Note that in this first course, only planar, thin-film based technologies that have been developed for semiconductor manufacturing are covered. This is because MEMS and Microsystems are still mostly fabricated using these standard thin film materials and technologies, and because students who only want to take one course in this field need to know this basic silicon based micromachining more than any of the other technologies. The technology and fabrication topics covered in the first part of the course and the approximate amount of time spent on each topic are summarized below:

1) **Review of standard semiconductor planar processing technologies (~6 hours)**
    - a) Review of basic semiconductor physics and electronics
    - b) Review of thin-film materials and their composition
    - c) Silicon as an electronic and mechanical material
    - d) Basic technologies and processes
        - i) Photolithography
        - ii) Silicon oxidation: wet and dry
        - iii) Doping: ion implantation, diffusion
        - iv) Deposition: CVD, PECVD, LPCVD, evaporation, sputtering
        - v) Etching: wet and dry

2) **Review of specific micromachining technologies (~9 hours)**
    - a) Silicon etching: wet (isotropic, anisotropic), dry
    - b) Wafer bonding (anodic, fusion, eutectic, polymer)
    - c) Etch stops: concentration dependent, electrochemical, dielectric
    - d) Review of common micromachining technologies:
        - i) Silicon bulk micromachining: wet and dry
        - ii) Surface (sacrificial) micromachining: polysilicon, metals, polymers, etc.
        - iii) Molding: electroplating
    - e) Review of MEMS-IC integration techniques and issues

Following the coverage of fabrication technologies, and before teaching transduction methods, the course covers signal/energy domains, material properties, mechanical structures, and mechanical analysis techniques. It is noted here that a review of electrical circuits is not done as an essential part of the course since most engineering and science disciplines cover some electrical circuits and circuit techniques. Instead of formally covering this topic as part of the regular lectures, taped modules and appropriate handouts are made available to students. The topics covered during this section of the course are summarized below:

3) **Signal/Energy Domains, and basic mechanical structures and analysis techniques (~6 hours)**
    - a) Lumped modeling with circuit elements
        - i) Review of basic circuit elements and analysis
            - (1) Electrostatics, RLC circuits and analysis, first and second order linear systems
        - ii) Review of basic mechanics (force, pressure, moment, static relationships)
    - b) Elasticity (basic definitions of stress, strain, etc.)
    - c) Mechanical structures, and mechanical analysis techniques
        - i) Bending of beams
        - ii) Bending of plates
    - d) Materials and material properties

At this point in the course, the students know the technologies, materials and their properties, and basic mechanical structures and how to analyze them for simple force/pressure vs. deflection characteristics. They are then introduced to the second part of the course, which deals with different transduction methods. Transducers are introduced as devices which convert signals from one energy domain to another, with a focus on energy conversion of all the non-electrical signals to electrical signals. In this course, only three of the many different transduction techniques are covered. These are capacitive, piezoresistive, and thermal. The rationale behind this selection is that these three basic transduction techniques cover a very wide spectrum of devices and applications and are those which will be most likely used by students who decide to go directly from this course into industry. These are the three transduction techniques we want our students to know if they are only going to take one course in MEMS. Of course other techniques are covered in other courses. In addition, by knowing these transduction techniques, a student can take the laboratory course of our MEMS curriculum (EECS 425) [1] and be able to design, fabricate, and test a sensor/actuator easily using the knowledge learned in EECS 414.

Of these three basic transduction techniques, capacitive is by far the most common. It is easy to understand, is most compatible with standard microfabrication techniques, and there are numerous examples of actual devices to show students. Therefore, it is taught first. The basic topics covered here include:

4) **Capacitive Transducers (~8 hours)**
    - a) Capacitor structure
        - i) Energy storage in a capacitor
        - ii) Capacitor as an electro-mechanical device
    - b) Capacitive sensors
        - i) Varying gap and varying overlap area sensing
        - ii) The electromechanical capacitive sensor
        - iii) Examples of sensors: accelerometers, pressure sensors, humidity sensors
    - c) Capacitive actuators
        - i) Parallel-plate actuator, pull-in voltage
        - ii) Varying overlap area actuator, comb-drive actuator
        - iii) The electromechanical capacitive actuator
        - iv) Examples of capacitive actuators: lateral and vertical comb-drive actuators, acoustic actuators

Piezoresistive sensors are discussed next, because this sensing mechanism is the most widely used technique in many commercial devices. The basic principles of piezoresistive sensing using both metal and semiconductor gauges are first introduced, followed by a detailed review of piezoresistive sensors for measuring pressure and acceleration:

5) **Piezoresistive Sensors (~5 hours)**
    - a) The metal strain gauge
    - b) The piezoresistance effect
        - i) Introduction to basic semiconductor properties
        - ii) Piezoresistive effect and coefficients in silicon
    - c) Piezoresistive sensors
        - i) Bridge configuration, and sensing structure
        - ii) Examples: pressure and acceleration sensors

Finally, the course ends with a review of thermal transducers. First, basic heat transfer and electro-thermal modeling is presented, followed by examples of thermally-based sensors, including temperature sensors, flow sensors, infra-red imagers, and other sensors such as accelerometers and pressure sensors. Finally, thermal actuators are presented, by first reviewing resistive Joule heating and its use in a variety of actuator structures such as bimorphs:

6) Thermal transducers (~7 hours)
  a) Fundamentals of heat transfer and thermal material properties
  b) Electro-thermal modeling
  c) Thermal sensors: thermistors, thermocouples and thermopiles, IR imagers, flow, pressure, and acceleration
  d) Thermal actuators, Joule heating, bimorphs, actuators based on expansion of solids and gases.

Because of their multi-domain nature, and due to their three-dimensional structure, design and analysis of MEMS is often complicated and requires the use of modeling and simulation tools. Coventorware and ANSYS are introduced and used to model and simulate some simple structures and compare the simulated results with simple analytical equations. Because of lack of time, it is not possible to extensively use these tools in the course. The main goal is to introduce students to these tools so they can use them in future courses. These tools are used in some homework problems and in limited computer assignments that either accompany the homework or are given as mini-projects. Homework assignments are distributed on a weekly basis resulting in a total of 11 homework sets during the semester. Two midterm exams and a comprehensive final exam are given in the course.

During its first offering in Fall Term 2001, the textbook *Microsystem Design* [2] by S. Senturia was designated as a textbook. After that term, the reading materials have been course notes and PowerPoint slides, as well as designated journal and conference papers, since these better match the content and flow of the course. The fact that a single textbook is not used in the course is a major shortcoming and often cited by students as a major handicap. Clearly, there is a need for more MEMS/Microsystems textbooks that can serve undergraduate students.

COURSE STATISTICS AND DELIVERY FORMATS

This course was offered for the first time in Fall 2001 and has been offered on a regular basis since then. It consists of two 1.5-hour lectures and a one-hour discussion session. All of the lectures are taped and made available through the web within two hours of when they are given. All course materials, including lecture notes, homework problems, and any other handouts are also available on the course website. The course has been taken by several institutions through the web, including Michigan State, Western Michigan, Michigan Tech, Howard, University of Lille in France, the Middle East Technical University in Turkey, and the University of Puerto Rico in Mayaguez. Each institution has a local instructor whose primary responsibility is to hold office hours and answer student questions. Figure 2 shows the enrollment in the course (at all institutions), and Figure 3 shows the enrollment and the breakdown of undergraduate and graduate students taking the course at the University of Michigan for the past five years. Although the course was at first taken mostly by graduates with a 2:1 ratio, it now has a 2:1 ratio of undergraduates to graduates. This trend clearly indicates the growing interest in MEMS as a discipline often required by industry. The course is available and open to any other institutions interested in using it through the web.

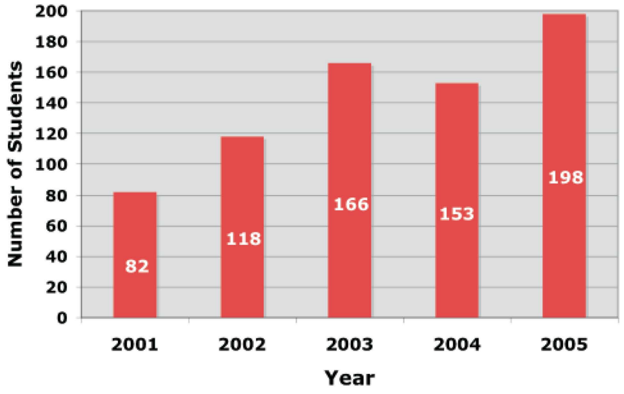


Figure 2. *Total enrollment for the "Introduction to MEMS" course, EECS 414, by all schools taking the course through Distance Learning.*

Figure 3. *Enrollment history for the "Introduction to MEMS" course, EECS 414, at the University of Michigan.*

DISCUSSION

In the introduction, we posed a number of questions that are often faced when teaching a first course in MEMS. Here, we will review some of these issues and discuss our experience at Michigan. The main challenge of this first course in MEMS is determining what it should contain, and of course this is decided by many factors, most important of which is the intended audience.

Course Attendees/Audience:

We believe the first course in MEMS should be made available to students from all engineering and science disciplines. MEMS is a multi-disciplinary field, both in terms of the science and engineering that supports it, and the application areas that use it. Therefore, it is critical that any educational programs developed are made available to as broad a set of students as possible. While it is possible to develop individual courses in individual departments, the amount of effort needed to support multiple courses is significant and not necessary. Offering a single course that serves many groups of students is challenging and may sacrifice material coverage in either breadth or depth. But the advantage of having a single course that all students can take and that all can use as a single prerequisite for many other courses is quite appealing. As with anything else, a single course cannot be everything to everybody, but using today's teaching tools and the availability of many forms of media, one can more effectively teach or convey difficult topics to a broader set of students. In addition to students from different disciplines, the first course also needs to serve both undergraduate and graduate students. We believe that the first course in MEMS should be an undergraduate course, otherwise, the topic of MEMS will never become a widely accepted discipline in our curricula. In addition, it should also be offered such that it is a useful course for first year graduate students who want to start their graduate studies in this field.

Course Pre-requisites:

In order to make this course widely available to all students, the pre-requisites have to be as few as possible. Therefore, only basic math, physics, and chemistry are required for the Michigan course, in addition to a junior or senior standing. Familiarity with semiconductor devices, mechanics, or microfabrication technologies is not required since many of these topics are discipline specific and as soon as any of them is made a requirement, students who are not from that particular discipline will have a hard time taking the course. Making the prerequisite set as small as this certainly complicates teaching the course, but we believe that the price we pay is well worth the benefits gained. As mentioned above, one of the prerequisites for the course at Michigan is a junior or senior standing. This requirement will provide undergraduate students with a little more maturity and experience that will be required to handle the rather heavy load of taking this course and learning a broad set of topics in a short period of time. Without that experience, these students will have a much harder time. The best time for an undergraduate student to take this course is during the second semester of the junior year or the first semester of the senior year.

Course Content, Lab, Design Projects:

The topics that should be covered in this course were reviewed in the previous section. First, a detailed coverage of micromachining and microfabrication technologies is critical since this field was created and is enabled primarily by the underlying technologies that are used to make relevant devices. Second, teaching the basics of signal transduction, and the basic idea of devices that operate on a number of different signal types and in different energy domains are important core issues for MEMS and Microsystems.

Although it is very desirable to have a lab accompanying the course, given the amount of material that needs to be covered in this first course, and given the time that it sometimes takes for students to become comfortable working in different signal/energy domains, we believe that it is more efficient to provide the laboratory experience in a separate course offered in a later semester. Many courses these days have a major design project or design component. Again, we believe that due to the rather heavy load of this first course, incorporating major design projects is not practical. The important topics, even when design experience is needed, can be covered through homework problems and mini-projects that are assigned as part of a homework set.

Software and CAD Tools:

Because of the key role that CAD tools play in all engineering disciplines, but particularly because of their importance in MEMS, being a multi-domain field, we believe that it is very important that students taking a first course in MEMS get some introduction to CAD and simulation tools and their use in design and modeling of some basic MEMS devices. Obviously, becoming good at using any CAD tool takes a substantial amount of time and effort, but any exposure to these tools provides the students with valuable experience and enables them to visualize and simulate the operation of these rather complex 3D MEMS devices, and see how process and material properties influence the performance of even the most basic structures. Although in our course we use Coventorware, which is provided to our program at a very deep discount by Coventor Inc., and ANSYS, which is available in most colleges and universities, there are also other software packages that are available either at very low costs or for free for those institutions which cannot afford the fees required by some vendors.

Is One Course Enough for Industry:

Obviously one course is not enough to prepare students at a sufficient level for industrial jobs. There are simply too many topics to cover and not enough time to do so in a single course. However, we believe that the course described above provides students, who want to take only one course in this field, sufficient knowledge in microfabrication, transducers, and applications to make them understand the principles and to allow them to become more specialized by taking follow-on courses or even short courses through their companies. Perhaps the main item missing from this course that industry would want to see is more hands on experience, design experience, and more in depth understanding of some of the topics. It is not possible to do these things in a single course that is made available to all engineering/science students.

CONCLUSIONS

Teaching the ***first*** course to novice ***undergraduate*** students coming from a broad set of disciplines is not easy, but could be very rewarding for our discipline and for those who take it. MEMS/Microsystems is a field that plays and will continue to play a central role in the development of many future applications, including telecommunication, health care, environmental monitoring, pharmaceuticals, simple consumer appliances. The main goal of this first course should, therefore, be to make it attractive for those students who have only heard of MEMS but do not know what it is, no matter what disciplines they come from. The more of our engineering and science students we can train in multi-disciplinary topics, and the more they get exposed to complex systems that require knowledge of several areas, the more these students realize that the face of engineering has changed and will continue to change for the next few decades. Engineering disciplines should no longer be defined by what they are and what others are not, but rather by how they fit in a big system that requires multiple capabilities and disciplines. The field of MEMS provides an opportunity to teach rather interesting and important topics to students through many applications and examples that they can immediately relate to and get interested in. Therefore, the sooner we can get undergraduate students through to this first MEMS course, the better off these students will be.

ACKNOWLEGEMENTS

The development of the courses and the educational programs in MEMS and Microsystems at the University of Michigan was supported by the Engineering Research Centers Program of the National Science Foundation under Award Number EEC-9986866.

REFERENCES

[1] L.C. McAfee, K. Najafi, Y.B. Gianchandani, K. D. Wise, And M. M. Maharbiz, D.M. Aslam, P.L. Bergstrom, C.R. Friedrich, “A MEMS/Microsystem Curriculum With International Dissemination,” *Digest, Hilton Head Solid-State Sensor, Actuator, And Microsystems Workshop*, Hilton Head, Sc, June 2006

[2] Stephen D. Senturia, *Microsystem Design*, Kluwer Academic Publishers, 2000.