Curriculum Development in Microelectromechanical Systems in Mechanical Engineering

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***Abstract*—Curriculum development in microelectromechanical systems (MEMS) in the Mechanical Engineering and Applied Mechanics (MEAM) Department at the University of Michigan is presented. A course curriculum structure that integrates both mechanical and electrical engineering courses is proposed for mechanical engineering students. The proposed curriculum starts from undergraduate study and finishes at the Ph.D. level. Two new graduate-level MEMS courses are proposed: "Introduction to MEMS" for senior undergraduate students and entry-level graduate students and "Advanced MEMS" for graduate students. The first course has been experimentally taught at the University of Michigan for three years and the class assessments are summarized and analyzed in this paper. It is clear from the student responses that they are interested in taking courses in emerging technologies such as MEMS and more courses in the MEMS area should be offered. Future MEMS curriculum development and a new MEMS course for undergraduate-level students in the college of engineering are discussed.**

***Index Terms*—Curriculum, microelectromechanical systems (MEMS, mechanical engineering, microelectromechanical systems, microsystem.**

I. Introduction

MICROELECTROMECHANICAL systems (MEMS) is an emerging field that utilizes IC (Integrated Circuit) or precision mechanical machining to fabricate microsensors and microactuators [1]. Researchers in electrical engineering have pioneered the MEMS research that dates back to the early 1970s. In recent years, MEMS research has also focused on mechanical issues such as solid mechanics, fluidics, and thermal sciences, dynamic systems and control at the micro scale [2]. As a result, more mechanical engineers have participated in MEMS research. The movement of mechanical engineers into MEMS research is in line with the demands of 21st century engineers [3]–[5]. These include versatility; strong fundamental knowledge in mathematics, and the physical and engineering sciences; and hands-on design and laboratory experience.

The rapid growth of MEMS also presents a big challenge in education. Previously, MEMS curriculum development has been proposed by electrical engineers [6], [7] and the curriculum development in the mechanical engineering side has lagged behind. However, the nature of MEMS requires the integration of different disciplines such as electrical, mechanical, chemical, biological, etc. In fact, many of today's machines and processes are of an electromechanical nature while the application areas are broad and diversified. Therefore, any curriculum development in MEMS requires contributions from both electrical engineering and mechanical engineering.

The proposed education development is motivated by the need for a systematic MEMS educational curriculum for mechanical engineers. Currently, students in mechanical engineering have little exposure to microelectronics or MEMS-related research. For example, the University of Michigan has been known to have a very strong MEMS research program. However, there was only one Ph.D. level MEMS course in the area of integrated sensors and sensing systems in the EECS department. Both undergraduate or entry-level graduate MEMS courses are missing. This paper presents MEMS curriculum development in the Mechanical Engineering and Applied Mechanics Department at the University of Michigan. The primary objectives of the present effort are to integrate cross-disciplinary areas; to incorporate MEMS research results into the curriculum development; and to shorten the time required to develop a MEMS researcher.

II. Curriculum Structure

The essence of this curriculum development in mechanical engineering is to integrate basic courses in both the mechanical and electrical engineering departments and to introduce new MEMS courses. The current course structure at the University of Michigan is adopted as an example and the overall MEMS course curriculum is shown in Fig. 1. These courses are listed in a chronological manner from freshman to Ph.D. levels. Conventional and fundamental courses in mechanical engineering such as design and manufacturing, materials and solid mechanics, fluids and thermal sciences, dynamic systems and control have been included in this curriculum. These are important areas of knowledge that the mechanical engineering student should obtain for various MEMS applications.

On the other hand, fundamental electrical engineering courses are included because they offer indispensable knowledge in MEMS research. These are Electrical Engineering I for basic foundations in electrical engineering; Circuit Analysis and Semiconductor Device Theory for the theoretical background in integrated circuits; and Circuit Analysis Lab and Solid-State Device Lab for practical experience in semiconductor manufacturing and testing. This course structure is designed and based on the current courses offered at the University of Michigan. In addition to these existing courses, the two new courses as illustrated in the shaded areas, "Introduction to MEMS" and "Advanced MEMS," are to be developed. Furthermore,

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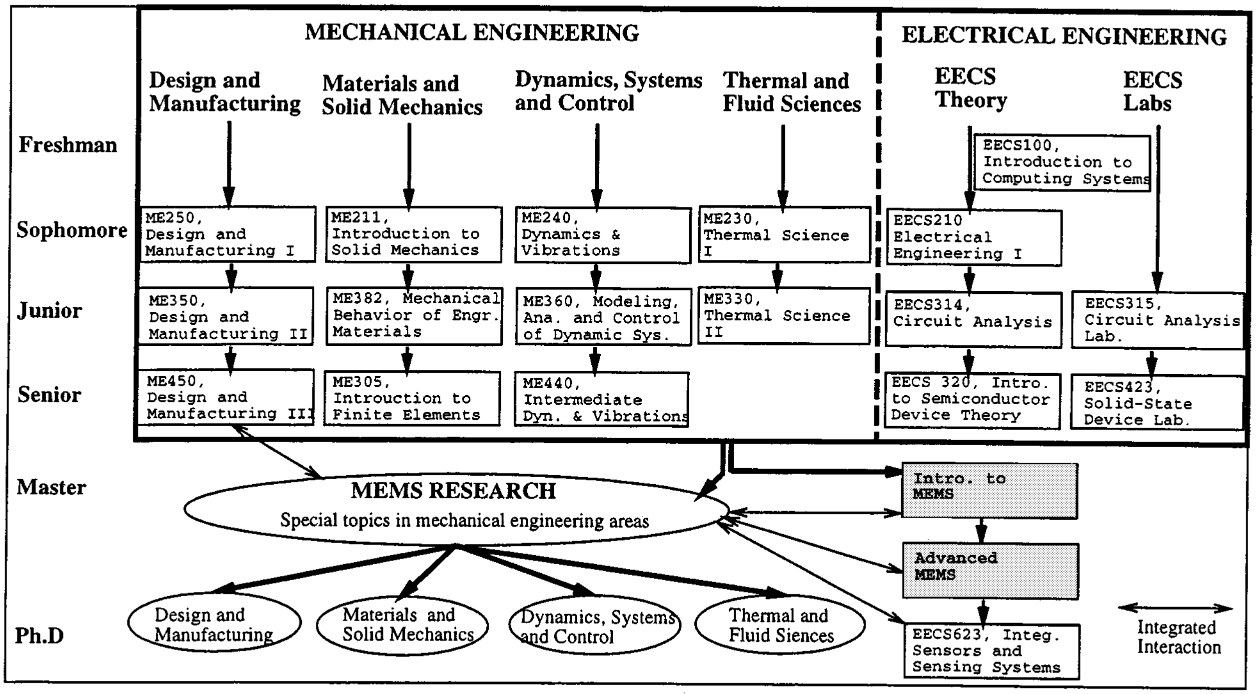

Fig. 1. MEMS curriculum in mechanical engineering introduced at the University of Michigan.

MEMS research is integrated with the course structure with designed interactions between several courses. It is paramount for the nation's leading universities in MEMS research to take a leadership position in building up this educational curriculum and disseminating the knowledge through education at both the undergraduate and graduate level nationally and internationally.

The MEMS curriculum for undergraduate students is proposed in Table I. According to the new "Curriculum 2000" set up by the Mechanical Engineering and Applied Mechanics department at the University of Michigan [8], students have to take at least 128 units of total course credits in order to graduate. Among them, 83 units are from fixed courses as specified by the MEAM department (with $*$ signs in Table I), 16 other units are electives from humanities/social science and the rest of the units can be taken from other electives. The MEMS program has recommended 27 units of courses as technical electives from the MEAM and EECS departments. These courses cover a wide-range knowledge that will be useful for MEMS research. On the other hand, they fill up most of the technical electives and give very specific guidelines on when and what are the courses students who are interested in MEMS can take.

III. New Course Development

Two new MEMS courses are proposed to complete the course structure. The development of these courses is closely linked with the MEMS research in both Electrical and Mechanical Engineering disciplines.

A. Introduction to MEMS

This course is designed for senior-undergraduate and graduate students. It is motivated by the need for an entry level MEMS course in the Mechanical Engineering Department as well as in other departments for students who are interested in MEMS research. Previously, only one Ph.D.-level course was offered at the EECS department at the University of Michigan and it focused on integrated sensors and sensing systems. There is a strong demand for an entry-level MEMS course not only for the students from the mechanical engineering department but also for students from other departments. Therefore, the objective of this course is to introduce MEMS research in an effort to train MEMS researchers at the entry-level.

The course is structured as a design-oriented one and no prerequisite is required for senior/graduate students who have the knowledge of junior-level ME courses, including ME382 and ME360. Both IC fabrication and micromachining technologies are covered in parallel in this class as shown in the details of weekly topics as listed in Table II. After finishing this course, students are expected to have a basic understanding of IC and MEMS processes. Technologies including analysis, design, simulation and manufacturing of MEMS are introduced. The first part of the course focuses on IC fabrication processes including thin film deposition, lithography and etching. The second part of the course deals with micromachining processes including surface-, bulk-micromachining, LIGA and others. This course consists of weekly, three-hour lectures; homework; paper reading; one midterm and one final project. The major components of the course are as follows:

1) basic IC fabrication technologies;
2) basic micromachining technologies;
3) CAD layout tools for MEMS design;
4) weekly internet readings;
5) Cronos MUMP's [9] as a design project;
6) weekly paper readings.

TABLE I
MEMS PROGRAM IN MECHANICAL ENGINEERING

MEMS Program in Mechanical Engineering		**128 Units**
Freshman Year	*Fall*	*Spring*
Mathematics 115 & 116, Calculus I & II*	4	4
Engineering 100, Introduction to Engineering*	4	
Chemistry 125, Collaborative Investigations in General Chemistry*	3	
Chemistry 130, General Chemistry*		2
Physics 140 & 141, General Physics I and Elementary Laboratory I*	5	
Physics 240 & 241, General Physics II and Elementary Laboratory II*		5
EECS100, Introduction to Computing Systems*		4
Electives		3
Total	**16**	**18**
Sophomore Year		
Mathematics 215, Calculus III*	4	
Mathematics 216, Introduction to Differential Equations*		4
ME211, Introduction to Solid Mechanics*	4	
ME240, Dynamics and Vibrations*		4
ME230, Thermal Science I*	4	
ME250, Design and Manufacturing I*		4
EECS210, Electrical Engineering I	4	
Electives		4
Total	**16**	**16**
Junior Year		
ME350, Design and Manufacturing II*		4
ME382, Mechanical Behavior of Engineering Materials*	4	
ME330, Thermal Science II*	4	
ME360, Modeling, Analysis and Control of Dynamic Systems*	4	
EECS314 & 315, Circuit Analysis and Electronics Laboratory		4
ME395, Laboratory I*		4
Electives	4	4
Total	**16**	**16**
Senior Year		
ME450, Design and Manufacturing III*		4
ME305, Introduction to Finite Elements	3	
ME440, Intermediate Dynamics and Vibration	4	
ME495, Laboratory II*		4
EECS320, Introduction to Semiconductor Device Theory	4	
EECS425, Integrated Circuit Laboratory		3
ME553, Introduction to MEMS		4
Electives	4	
Total	**15**	**15**

* required courses for "Curriculum 2000"

Weekly internet and paper readings are integral parts of the course for students to gain knowledge outside of the lectures and the up-to-date information can be found from the class homepage [10]. In addition, students are asked to summarize the internet and paper readings periodically and to make short presentations during the class. Depending on the enrollment of the class, each student makes about three to four times of short technical presentations during one semester. Furthermore, students design their own micro devices by using the standard micromachining process.

The manufacturing process is to be done via a foundry service, MUMP's (Multi-User MEMS Processes) by Cronos Inc., North Carolina. Students use IC layout software such as CADENCE, KIC, MAGIC, LEDIT, or others to draw their microstructures. An area of 1000 μm $\times$1000 μm is allocated to each student. The instructor will assemble all the student designs and put them into a 1 cm $\times$ 1 cm area and send the file to the foundry. A typical class design layout is shown in Fig. 2 that also includes many of the research projects from the instructor's research group. It takes about ten weeks for Cronos Inc. to finish the manufacturing process when the semester has already ended. However, students are invited to examine their microstructures under an optical microscope and the testing of their microstructures can be arranged. For example, Fig. 3 shows a fabricated specimen for MEMS fatigue and fracture tests from one of the class projects. The comb shape resonator [11] uses an area of only about 300 μm $\times$ 300 μm. Fig. 4 is another class project with a beam-shaped microstructure for the creep testing in the micro scale. The results were published in a solid-state sensors and actuator conference [12].

TABLE II
WEEKLY COURSE TOPICS FOR "INTRODUCTION TO MEMS"

Week	Topics in IC Fabrication	Topics in MEMS Technologies	Internet Material
1	Introduction	MEMS Overview	Cronos-MEMS
2	Lithography & Oxidation	Surface-Micromachining Process	MUMPs Process
3	Oxidation	Micro Mechanisms	CaMEL
4	Diffusion	Micro Resonators	CaMEL
5	Diffusion	Issues of Residual Stress	Design Rules
6	Thin Film Deposition	Hinged Microstructures	Sandia MEMS
7	Thin Film Deposition	Heactuators and other Actuators	SmartMUMPs
8	Ion Implantation	Silicon Anisotropic Etching	i-MEMS
9	Interconnect & Contact	Bulk-Micromachining Processes	Microsystems
10	Packaging & BJT Process	Silicon as a Mechanical Material	Clearing House
11	MOS Process	MEMS Device Examples	MOSIS
12	Semiconductor Physics	MEMS Device Examples	UW-MEMS
13	Scaling Rules	LIGA Process	LIGA
14	Presentation	Other Micromachining Processes	LIGA-MUMPs
15	Presentation		

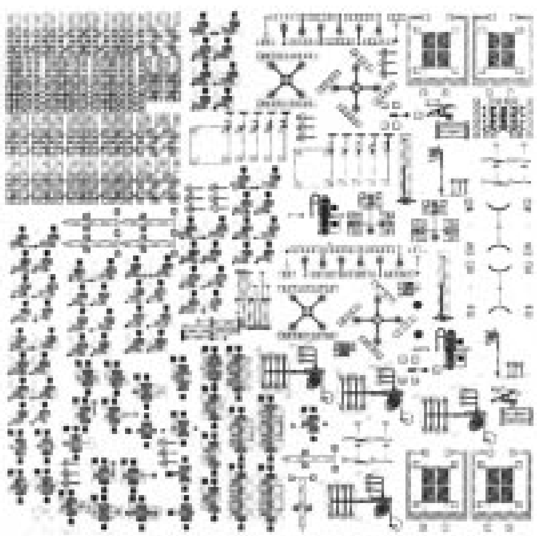

Fig. 2. A design layout example from the MEMS class projects. The total area is 1 cm × 1 cm and it can accommodate 100 design projects with individual area of 1000 μm × 1000 μm.

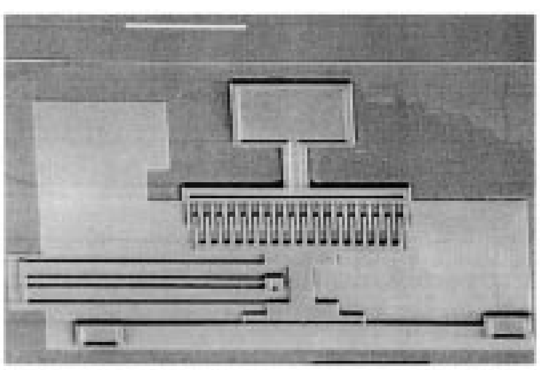

Fig. 3. A fabricated, fatigue test-structure under SEM (Scanning Electron Microscope) as an example from the MEMS class. The overall size is 300 μm × 300 μm.

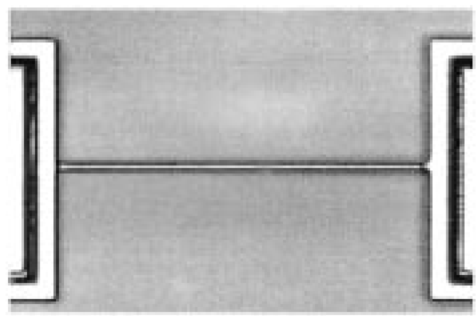

Fig. 4. A beam shape microstructure for the characterization of creep behavior of polysilicon in the micro scale. The side of the beam is $2 \times 2 \times 100$ μm^3.

B. Advanced MEMS

The second course is called "Advanced MEMS" for graduate students. This course is motivated by the need for training MEMS engineers in hands-on processing and testing. In addition to the regular lectures that detail the advanced MEMS topics, hands-on type laboratories will be incorporated into this course. Currently, there are very few hands-on types of MEMS courses. The primary reason is the lack of a suitable facility for microfabrication. Major universities generally have designated teaching clean-room laboratories in the Electrical Engineering Department. With proper coordination, these laboratories can be utilized for this new course.

This course will target graduate students who are interested in MEMS research such that advanced materials in MEMS will be introduced. There are three parts in this course, including topics in advanced and newly developed MEMS, hands-on MEMS processing laboratory, and MEMS testing laboratory. The most recent research results from MEMS conferences will be introduced as special topics in this course. A final MEMS project including design, process and testing of a fabricated MEMS device is expected. Although these special topics may change over time, the major components of the course, including examples, are the following.

1) **Special topics in MEMS devices.** Examples of the advanced MEMS devices include micro gyroscope [13], microelectromechanical filters for signal processing [14], IC-processed microneedles [15], micro optoelectromechanical device [16], lab-on-a-chip devices [17] and other interesting new micro sensors and actuators.
2) **Special topics in MEMS fabrication.** Examples of the advanced fabrication topics include laser micromachining, photoelectrochemical etching [18], DRIE processes [19], the SCREAM process [20], the HEXSIL process [21] and other newly developed processes.
3) **MEMS process laboratory.** Examples of MEMS process laboratory include various bulk-micromachining and surface-micromachining processes. A six-mask process for micromachined pressure sensor [22] is proposed as the standard MEMS process to be conducted by student groups (two students in each group) during the class.
4) **MEMS testing laboratory.** Examples of MEMS testing laboratory include basic training on the usage of a probe station, spectrum measurements of micro comb-shape resonator [11], micro pressure sensor characterization experiments [22], and micro accelerometer qualification measurements. The testing devices can be readily prepared by using various foundry services as well as the devices made in the first MEMS class, "Introduction to MEMS," or the MEMS process laboratory in this class.

Students are expected to conduct MEMS research independently at the end of this course and may elect to take further related classes (such as EECS623 in the specific area of integrated sensors and sensing systems at the University of Michigan).

IV. Course Assessements

The author has experimentally taught the first course, "Introduction to MEMS," in the Mechanical Engineering and Applied Mechanics Department at the University of Michigan in the spring semester, 1997. The class attracted students from various departments, including 50% from ME, 30% from EE and 20% from other departments such as bioengineering and chemical engineering. The responses from students were extremely positive. The official feedback conducted and collected from the Center for Research on Learning and Teaching (CRLT) at the University of Michigan reveals that:

1) Student presentation of papers helps reinforce topics and gives good training in formal presentations.
2) The project associated with the course (real-time) is very helpful.
3) The course content is very interesting with cutting-edge technology introduced.
4) More courses in this area should be offered with units—one semester part I, next semester part II, third semester part III, etc.
5) We would like to have some lab sessions for the course (could be related to the above sequence—could be part II.)

Other typical student inputs are "more in-depth coverage on micro mechanics along with the principles of electrostatic, magnetic and other actuation mechanisms," "more discussions on various MEMS device examples and their uses," and "more introductions on MEMS structures that are simple for us to emulate and modify." These evaluation and assessment are valuable feedback from students and will be used to improve the contents, depth, and effectiveness of this course. Moreover, the student opinions clearly indicate that more MEMS-related courses should be offered and they enjoy taking these courses sequentially. As a result, the Mechanical Engineering and Applied Mechanics Department at the University of Michigan has officially listed this course as MEAM 553 in the regular curriculum. The EECS department has also listed this course for students majoring in Circuits and Microsystems. Enrollment in this course has been steadily increasing from 15 (1997) to 22 (1998), and further to 34 (1999) with students from MEAM, EECS, ChE, AE, IOE, and BME departments.

V. Future Development

The future of the MEMS curriculum development looks encouraging not only in the mechanical engineering department but also within the college of engineering. Several universities that have active MEMS research programs are in the process of developing such a MEMS curriculum in the college of engineering such as UC-Berkeley, University of Michigan, MIT, UCLA and University of Illinois at Chicago.

One key element that has been intensively discussed is a new undergraduate-level, college-wide MEMS course. Ideally, this course will be open to students having different backgrounds from various departments. This course may cover engineering principles in the microscale such as engineering mechanics (solid, fluid, dynamics), engineering physics (electrical laws, electromagnetics, physics), scaling laws, materials, basic design and manufacturing of microsystems. The major deficiencies for this basic course are the lack of a good textbook that details the general knowledge of micromanufacturing in microsystems.

VI. Conclusion

A MEMS curriculum for mechanical engineering students has been proposed together with two new graduate-level, MEMS courses. The introductory MEMS course has been taught in the Mechanical Engineering and Applied Mechanics Department at the University of Michigan from 1997 to 1999. It is clear from the student responses that more MEMS courses should be offered. Moreover, it is the national and international trend that MEMS curriculum should be constructed from the undergraduate level and a new undergraduate MEMS course should be developed.

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Dr. Lin is the recipient of the 1998 NSF CAREER Award for research in MEMS Packaging and the 1999 ASME Journal of Heat Transfer best paper award for his work on micro scale bubble formation. He led the effort in establishing the MEMS subdivision in ASME and is currently serving as the Vice Chairman of the Executive Committee for the MEMS subdivision.