WHAT SHOULD A FIRST COLLEGE COURSE ON MEMS BE?

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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.

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.

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