

## An Undergraduate MEMS Course for Everyone

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### Abstract

Miniaturization is becoming a dominant theme in a large variety of technologies. With this increased miniaturization comes the need to familiarize undergraduate students from a variety of science and engineering students with such technology. Unfortunately, most courses currently offered in micro electrical mechanical systems (MEMS) target graduate-level students or senior-level students with highly specialized backgrounds. Recently, eight faculty members from five different academic departments at Rose-Hulman Institute of Technology collaborated to develop an introductory course in MEMS open to all science and engineering majors of junior standing. This course was team-taught and included a laboratory component, giving students hands-on experience with the processes involved in the fabrication of MEMS devices. This paper presents the results to date of this multidisciplinary faculty team's efforts to make MEMS more accessible to a larger audience. In particular, the paper documents the development of the new course and its content, as well as the continuing evolution of its implementation.

### I. Introduction

Starting out as the realm of solid-state physicists and electrical engineers, the silicon revolution quickly found its way into things non-electrical, such as miniaturized accelerometers and pressure sensors. This marriage of transistor technology with moving parts on the silicon wafer eventually became something much larger. Thus was born the field of Micro-Electrical Mechanical Systems, or MEMS, to which it is most commonly referred today. By 1996 an estimated MEMS product volume of US\$2.28 billion existed. In recent years this may have grown to as much as US\$9.03 billion with growth expected to continue, much of it in the area of optical communications, wireless communications and biotechnology.<sup>1,2</sup> Today's MEMS also cover a wide array of applications including microscale gyroscopes, mass flow sensors, optical switches and displays, cell phone components, relays and ink-jet printer heads.

Despite this recent boom in MEMS and the fact that the field has actually been around for some twenty-odd years reaching a state of maturity in its own right, engineering institutions have only recently begun to teach it as a distinct field. More often than not, these courses have targeted graduate students or senior-level students with existing knowledge of solid-state physics and/or integrated circuit (IC) technology. The courses therefore tend to impart an extra degree of specialization to a set of students who otherwise have a rudimentary skill set in the field anyway. With miniaturization no longer restricted to IC technology, but reaching critical levels in seemingly disparate fields such as mechanical engineering, biomedical engineering, chemical

engineering, chemistry and optics, such an approach will no longer suffice. Existing MEMS courses need to be complemented by MEMS courses that target a larger audience, namely, the undergraduate technical major in general.

Engineering professionals increasingly find themselves required to acquire proficiency in fields outside their core disciplines.<sup>3</sup> Such a multidisciplinary approach to engineering is an outright necessity in MEMS, especially considering that miniaturization is becoming a dominant theme in most technical disciplines. An effective MEMS course, therefore, should include a wide variety of applications from many fields, as well as instruction from multiple vantage points. The consequence of limiting the instruction of MEMS only to a student's supposed field is to pigeon-hole the student into fecklessness.

This paper outlines the efforts of eight faculty members from five different academic departments at Rose-Hulman Institute of Technology and their collaboration in creating an introductory MEMS course open to all technical majors of junior standing. The development of the ten-week, four-hour course and its lab component is described in detail, as are its continued evolution and the lessons learned from its first two installments.

## II. The Players

Since 1999 Rose-Hulman has offered a certificate program in semiconductor materials. Thirty-seven students representing six different major areas have graduated with the certificate as of 2003. Rose-Hulman's MEMS program grew from this semiconductor certificate program, much as the field of MEMS itself grew from an existing semiconductor industry. Two professors involved in the semiconductor certificate program led the effort to create a center for MEMS education at Rose-Hulman by first assembling a multidisciplinary team of faculty from five academic departments. Both engineering and pure science departments were represented. Azad Siahmakoun and Jerome Wagner joined fellow Physics and Applied Optics professor Michael McInerney, Tina Hudson and Ed Wheeler from the Department of Electrical and Computer Engineering, Jameel Ahmed from the Department of Applied Biology and Biomedical Engineering, Dan Morris from the Department of Chemistry and the author from the Department of Mechanical Engineering for the task.

The newly formed MEMS group submitted a successful proposal to the Keck Foundation to fund the MEMS center. During the 2001-2002 academic year, the MEMS group designed an introductory course in MEMS and an associated laboratory. The first installment of the course was taught in the spring quarter of 2002 without a lab component. Construction of a new MEMS fabrication laboratory began soon thereafter and was completed in time for the second installment of the course in the spring of 2003.

By design the faculty members which make up the MEMS group represent a wide array of expertise. Siahmakoun brought expertise in semiconductor materials and optics, Wagner in optics and photolithography, McInerney in packaging, Adams in heat transfer and fluid flow, Hudson in integrated circuitry and solid state electronics, Wheeler in electromagnetics, Ahmed in biosensors, and Morris in microfluidics and chemical analysis. All these topics and more play vital roles in MEMS and require attention in an introductory MEMS course. As such, the faculty members comprising the MEMS group have team-taught both the course's lecture and laboratory

components. Such an approach has the added benefit of forcing students and faculty alike to acknowledge the often differing vantage points of scientists and engineers in various fields.

### III. The Course

The breadth of knowledge required to understand fully the fabrication and modeling of even a single MEMS device is vast. As an example consider what has become the poster child for MEMS, a capacitive accelerometer. The deployment of air bags in almost all currently manufactured automobiles is governed by such MEMS devices. Such an accelerometer often consists of a series of stationary and moveable parallel plates collectively known as a “comb drive.” When the plates comprising a comb drive are electrically charged, a capacitor of changeable capacitance results. At a critical vehicle deceleration rate, the motion of the moveable plates or “proof mass” of the accelerometer consequently changes its capacitance. This change in capacitance is sensed by surrounding electronics which in turn signal the airbag to deploy.

Understanding the operation of a comb drive alone requires elements of dynamics, electrostatics, electrical circuits, and dynamic systems modeling. What’s more, the changing capacitance of a comb drive results in non-linear dynamic system behavior, a topic beyond the scope of most introductory circuits and dynamics courses.

Modeling a device without knowledge or concern for its fabrication is always poor engineering practice. This is even more the case in MEMS, as the very design of many microdevices is largely dictated by the ability (or lack thereof) to fabricate them. Indeed, microfabrication techniques often bear little resemblance to processes or equipment in other areas.<sup>4</sup> In the case of our MEMS accelerometer, the fabrication process relies heavily on techniques borrowed from the IC industry. The fabrication process includes producing photolithography masks on silicon substrates, chemical etching, process flow design, and electrical interfacing to name a few. Thus, topics ranging from solid state physics, optics, chemistry, solid mechanics and materials engineering must be considered in any treatment of MEMS fabrication. Recently, the options for possible MEMS fabrication techniques have grown well beyond their IC roots.<sup>5</sup> If these are included as well, the topic list becomes even lengthier.

A survey of MEMS, then, encompasses elements from the entire curricula of virtually any science and engineering field – and then some. And this doesn’t even mention the art of packaging, which makes up anywhere from 30-70% of a MEMS device’s cost. Considering this vast amount of material required in a survey course in MEMS, Rose-Hulman’s MEMS group faced an ambitious task.

The first course taught in MEMS went by the title “Introduction to MEMS: Fabrication and Applications.” The MEMS group designed the course to be a ten-week long, four-hour course consisting of forty one-hour lectures. Cross listed in the departments of Chemistry, Physics and Optical Engineering, Biomedical Engineering, Chemical Engineering, Electrical and Computer Engineering and Mechanical Engineering, the course had but one prerequisite – junior class standing. As such, the students’ assumed background included no more than a working knowledge of calculus, differential equations, freshman level chemistry and physics, and

competence in written and graphical communication. No background in solid state physics, integrated circuit fabrication, systems modeling or any other specialized area was assumed or required. This made the endeavor all the more ambitious.

Eleven students representing six majors including applied optics, physics, biomedical engineering, computer engineering, electrical engineering, and mechanical engineering enrolled in the course. With eight instructors, this made for a friendly instructor-to-student ratio. An existing MEMS textbook intended for a senior or graduate level engineering audience was used. Table 1 gives a breakdown of the topics covered in the course.

**Table 1:** Topic Coverage for “Introduction to MEMS: Fabrication and Applications”, Spring 2002

Week	Topic	Instructor
1	Intro. to MEMS & Microfabrication Wafer-Level Processes	Siahmakoun
2	Surface and Bulk Micromachining, Thin-film deposition, Etching	Siahmakoun
3	Photolithography	Wagner
4	Process Integration	Hudson
5	Lumped Modeling, Energy Conserving Transducers	Wheeler
6	Dynamics	Wheeler
	Elasticity	Adams
7	Structures, Dissipation of Thermal Energy	Adams
8	Microfluidic Systems	Morris
9	MEMS Packaging	McInerney
10	MEMS Applications: Capacitive accelerometer Electrostatic projection display DNA amplification	Hudson Ahmed

The sequence of the course topics was chosen to walk the students through the process of fabricating a MEMS device and the modeling and packaging of such a device, followed by case studies whereby the fundamental material encountered earlier in the course could be synthesized.

Each of the instructors gave approximately five lectures on material within their expertise during the course. Many of these instructors also gave lectures on material outside their respective areas. For example, the author, a heat transfer and energy systems engineering specialist, also gave lectures on solid mechanics. Dr. Ahmed, a biomedical engineer, was in charge of a case study on electrostatic projection displays. As a result, the faculty learned alongside the students.

Rose-Hulman's Office of Assessment worked with the faculty in the course in designing an assessment plan to measure the effect the course had on students' perceptions of their knowledge and competence levels in MEMS. In this effort, a *MEMS Course Survey* was developed and administered the first day of the course and again the last week of the term. A detailed statistical analysis was performed on the collected data, detailed results of which will be presented elsewhere. Traditional course evaluation surveys were also administered at the end of the course.

The assessment revealed that student reaction to the course was generally favorably, although mixed. Many students felt overwhelmed by the amount of material covered in the course and the textbook as well. The large number of instructors resulted mainly in a student sense of discontinuity rather than an appreciation of the multidisciplinary aspect of MEMS as was intended. Nonetheless, the assessment clearly showed that the course substantially improved students' knowledge of and their competence in their ability to apply MEMS concepts. In short, the course showed that undergraduates with only fundamentals courses such as freshmen calculus and physics can indeed learn about MEMS. Furthermore, students' performance showed no correlation to major area of study.

In the spring of 2003, the course was offered for the second time, this time with a lab component. Originally, one section of the course was offered. Such a large number of students signed up for the course, however, that another section was consequently offered. A total of fifty-five students representing ten different majors took the revamped course consisting of thirty one-hour lectures and seven three-hour labs. A break down of topics in the second installment of the course is given in Table 2.

**Table 2:** Topic Coverage for “Introduction to MEMS: Fabrication and Applications”, Spring 2003

<b>Week</b>	<b>Topic</b>	<b>Lab</b>	<b>Instructor</b>
1	Intro. to MEMS & Microfabrication, Photolithography		Wagner
2	Lithography, Pattern Transfer		Wagner, Siahmakoun
3	Chemical and Physical Vapor Deposition	Orientation, safety	Siahmakoun
4	Materials Issues	Micromanipulator	Wagner, Adams
5	Materials Issues, Chemical Etching	Oxidation	Adams, Morris
6	Chemical Etching, Solid Mechanics	Photolithography	Morris, Adams
7	Surface Micromachining	Bulk Micromachining, Isotropic Etching	Siahmakoun
8	Scaling, Electric and Magnetic Actuators	Bulk Micromachining, Anisotropic Etching	Wheeler
9	Heat Transfer, Thermal Actuators	Anodic Bonding	Adams
10	MEMS Applications: Capacitive accelerometer Electrostatic projection display DNA amplification		Hudson Ahmed

In hindsight the instructors agreed with the students’ comments regarding the original course’s topic density. Due to this insight, as well as the fact that the addition of a weekly lab reduced the number of lectures by twenty-five percent, several topics were removed from the course to be covered in an extended fashion in a second, advanced MEMS course. These topics included microfluidics, packaging, and portions of the modeling.<sup>6</sup> A new textbook emphasizing MEMS fabrication and basic modeling replaced the first.

The most notable distinction between the first and second version of the course was the addition of a lab. The lab took place in Rose-Hulman’s new microfabrication facility consisting of class 10,000 and class 1000 clean spaces, which required students to don gowns and masks. Students gained hands-on experience with many of the standard MEMS fabrication techniques including wafer oxidation, creating photolithography masks, chemical etching and anodic bonding. Students used such equipment as an oxidation furnace, micromanipulator station including electronics and video capture equipment, a Micralign projection mask aligner, an e-beam evaporation system and a dual cathode sputtering system. Funding for the \$500,000 facility came from the Keck grant, Rose-Hulman and donations from On Semiconductor.

Each instructor in the course was in charge of one lab. As was the case with the lectures, instructors sometimes championed material outside their area of expertise. In addition, Rose-Hulman's microfabrication facility can only accommodate 6-10 students at a time, requiring multiple iterations of the same lab. This resulted in as many as twenty-five contact hours some weeks of the quarter for instructors, a daunting schedule considering that most instructors involved taught the course *pro bono*.

Student reaction to this second version of course was also favorable but mixed. Again, students felt the course was material dense, the textbook was cryptic and that multiple instructors constituted a distraction. Student reaction to the lab component, however, tended to be fairly upbeat. Students enjoyed the experience of wearing clean room attire as well as gaining experience with microfabrication processes. As was the case with the first iteration of the course, students' performance showed that they can indeed learn about MEMS with a modicum of fundamental math, physics and chemistry. Again, that performance showed no correlation to major area of study.

#### IV. Lessons Learned

Considering the large number of students interested in learning about MEMS and the enthusiasm of Rose-Hulman's MEMS group, we had hoped for stellar student response to this course. Though such a response was not the case, the student reaction was indeed favorable and on par with those for new courses in general. From that vantage point alone, the course has been a success.

To address the common student comment concerning the large amount of material covered in a short time, the instructors created two MEMS courses instead of one. The first course covers fundamentals of MEMS fabrication and modeling with an associated lab. The second covers more sophisticated modeling techniques, and advanced topics such as microfluidics and packaging. (The associated lab for the second course is project based, and requires students to design and create an actual working MEMS device.) Even with this reduction in topic coverage, however, student comments about material density continued.

The reason for the perception of too large a topic coverage stems mainly from the multidisciplinary aspect of the course. The instructors in the course had a tendency to remind students that they were presenting them with a "crash course" in this or that area before relating it to MEMS. With eight instructors, then, the students no doubt felt that they were taking eight courses. This perception can easily be remedied by a change in approach.

Any emerging field is a synthesis of prior knowledge and therefore requires some familiarity with other fields. Complete mastery of those fields, however, is not only unreasonable but impossible. The topic of heat transfer, for example, requires elements of both thermodynamics and fluid mechanics. Heat transfer texts rarely speak about the Maxwell relations or vorticity dynamics, however, but focus only on those aspects of thermodynamics and fluid mechanics required to understand the heat transfer topic at hand. Likewise, MEMS courses need not develop the entire field of chemistry, solid state physics and materials engineering, but just those

aspects relevant to an understanding of MEMS. Upon reflection, this is exactly what the instructors did in this course. The difference lies in how instructors present the material. Rather than presenting the student with “Everything about Solid Mechanics” followed by “Solid Mechanics Issues in MEMS,” the instructor can simply present “Stress and Strain in MEMS Devices.” Slight changes in semantics can go a long way in student perception.

Many of the comments about the texts used in the courses echoed those about the course in general. As an emerging field, many existing MEMS textbooks take the “crash course” vantage point. Furthermore, the texts used in the course described here were geared towards the more usual student audience consisting of seniors or graduate students with something of a specialized background. As such, the texts sometimes contained too much detail on some topics but not nearly enough on others.

The instructors chose to remedy the textbook issue by writing one in-house. The new book incorporates the appropriate point of view for this new MEMS student, making it a unique text. It will be used for the first time in the spring of the 2003-2004 academic year.

Though the students’ performance in the course as a whole showed no correlation to major, there was no doubt that some material came more easily to some student majors than to others. For example, mechanical engineering majors felt relatively comfortable with the solid mechanics topics but struggled with the photolithography topics. Physics majors reacted in exactly the opposite way.

Recognition of this fact provides tremendous opportunity for student cooperative learning, the efficacy for which is well known.<sup>7</sup> The instructors created a heterogeneity of majors within lab groups with this very purpose in mind. The student response to the lab component shows this to be largely successful. In fact, having multiple student majors in the course proved to be a more effective mechanism for imparting an appreciation for multidisciplinary endeavors than the use of multiple instructors. Other ways of exploiting cooperative learning opportunities in the course are currently being explored.

## V. Conclusion

The miniaturization of technology continues relentlessly in most fields of engineering at an accelerated rate. With such miniaturization comes the need to educate all engineers in the field of microtechnology. A laboratory-based introductory course in MEMS designed specifically for this purpose was described here in detail. The course is unique in that it has no prerequisites other than junior class standing in a technical major. Assessment of the students’ knowledge and competence levels shows that undergraduates can indeed learn about MEMS, regardless of their major field of study.

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