An Introductory Multi-disciplinary, Design Course in MEMS

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Introduction

Microelectromechanical systems (MEMS) will likely be one of the 21st century's engineering design achievements. Integration of sensors and actuators with associated electronics on a single platform has added a new dimension to the design of engineering solutions. MEMS devices have already made significant commercial impact in such diverse applications as airbag deployment sensors, inkjet printer cartridges, vaccine delivery systems, digital light projectors and optical switches. With an ever increasing number of applications in automotive, aerospace, medical and other industries, projections have the MEMS market growing to $12 billion in 2002[1] and experts envision that MEMS will soon be as ubiquitous as microcircuits. As such, educating undergraduate as well as graduate students in this important developing area is no longer an interesting experiment in education but a necessary fact.

In this paper, the results of an introductory multi-disciplinary, project-oriented course in MEMS are presented. The course is team-taught at Tennessee Technological University (TTU) by faculty from chemical (CHE), electrical (ECE) and mechanical (ME) engineering to a mix of undergraduate and graduate students from these three disciplines. The authors will discuss the format for this course including content, structure and student projects. These results, including lessons learned, are from two offerings of the course, Spring 2000 and Spring 2001. MEMS by nature are interdisciplinary systems and thus this topic is not only appropriate for accomplishing ABET goals of providing interdisciplinary team experience, but also the course material exposes undergraduates to a field of study not typically offered in most undergraduate engineering curricula.

Course Content and Structure

Tennessee Technological University is predominately an undergraduate institution, thus the authors have geared this introductory MEMS course at the senior/first-year graduate level. Other universities offer undergraduate MEMS courses but often they are off shoots of on-campus semiconductor activities and thus focus on device fabrication[2, 3]. In addition, these courses tend to be departmentalized. TTU, however, does not have a fabrication facility nor does it have a faculty member with MEMS-specific expertise and thus a different approach has been taken. Building upon the various strengths of faculty throughout the College of Engineering, this cross-listed course emphasizes system level issues associated with developing MEMS devices as opposed to providing students with hands-on fabrication experience. The course addresses topics relevant to the design, fabrication and assessment as indicated in Table 1. Emphasis is placed on design rules for basic phenomena such as turbulence, stiction, electrical breakdown, etc. The contrast in behavior of classical "macro" devices versus MEMS "micro" devices makes teaching design a challenging task. A faculty member from CHE, ECE or ME addresses each concept in a three-week block. A fourth faculty member utilizes an additional three-week block for instruction on the IntelliSuite CAD for MEMS[4] software package. The students use this software for the design, simulation and layout of their projects. The remaining lectures are allotted for guest presentations from various research organizations (e.g., Oak Ridge National Labs, NSF and DARPA) and for student presentations.

Table 1. Topics Covered in Course

Design Issues	Fabrication	Performance Assessment
▪ What are MEMS? ▪ Interdisciplinary nature ▪ Design issues ▪ Electronic components ▪ Mechanical components ▪ Process components ▪ Integration ▪ Layout ▪ Nano-scale structures	▪ Fabrication issues ▪ Micro-scale structure ▪ Photolithography ▪ Thin film deposition ▪ Bulk etching ▪ Surface micromachining ▪ Diffusion and ion implantation ▪ Annealing and gettering	▪ Performance issues ▪ Electrostatic properties ▪ Micromechanical properties ▪ Electromechanical properties ▪ Microfluidic phenomena ▪ Device simulation and analysis ▪ Physical characterization

During the first two offerings, finding suitable course material was somewhat difficult. While there is a huge amount of technical publications in the area of MEMS, up until recently, this information has not been synthesized into teaching materials. The *Micromachined Transducers Sourcebook* by Kovacs[5] was used as a primary source/text in Spring 2000 and 2001 and was supplemented with material from a three-day MEMS short course[6]. Since then several new teaching texts have been introduced including *MEMS and Microsystems: Design and Manufacture* by Hsu[7], which was adopted for Spring 2002. Other lecture materials are largely developed from the research literature.

Student Projects

The main vehicle, however, for learning in this course is the student design project. To accomplish this task, students work in teams that are diversified in terms of both discipline and experience (i.e., a mix of seniors and first-year graduate students). As such, the course addresses ABET 2000's Criterion 3d, that *students will demonstrate the ability to work in interdisciplinary teams*[8] in addition to satisfying TTU's major design requirement. The authors feel that MEMS are a particularly suitable topic for interdisciplinary teamwork for two reasons. First, the instructional material is founded in physics more than any of the specific engineering disciplines. Second, and perhaps most important, is that all students coming in the class have **no** experience in the subject matter and thus all students operate on a equal playing field. The course enrollment by discipline is given in Table 2. This enrollment is out of a present total of approximately 640 undergraduate and 140 graduate students in the three departments.

Table 2. Student Enrollment by Discipline

	Undergraduate			Graduate			
Semester	CHE	ECE	ME	CHE	ECE	ME	Total
SP 2000	0	0	0	4	0	10	14
SP 2001	0	3	0	6	3	5	17
SP 2002	1	7	7	6	3	3	27

Working as a team, the students choose a problem for which they will design a MEMS device to monitor or manipulate some phenomena. Typically these projects are associated with the research topic of a graduate student team member. This vertical integration of teams provides TTU undergraduates with a glimpse of graduate studies. The teams perform background research on their problem and early in the semester present design concepts. Each team is then paired with a faculty member who mentors the teams during the rest of the semester. Thus, there is a distinct advantage to having numerous faculty involved; by splitting the teams among the faculty, each team receives more in-depth mentoring. In addition, projects have also been associated with the mentor's area of interest and so it is also a winning situation for the faculty.

The faculty mentor guides the team's progress through the rest of the design that consists of device analysis, simulation and developing fabrication files. The faculty assess the quality of these intermediate tasks. The team's final design is presented in a written paper and oral presentation targeted to a conference audience. Students assist in evaluating their peers' designs. In addition, students evaluate their own and their team member's contribution to their project. Students are also assessed individually through exams on the presented material and individual software design and simulation assignments.

At the end of the semester the fabrication files have thus far been submitted to Cronus Integrated Microsystems for three-layer, surface micromachining fabrication using the Multi-User MEMS Process (MUMPS)[9]. The fabricated devices are later tested and characterized at TTU by students with continuing interest in this area. Note that while the MUMPS process is a cost-effective means of fabricating student designs, the course itself is not specifically tied to any single fabrication method. In fact, projects for the Spring 2002 course will address a microfluidics problem for which a bulk etching method is more appropriate.

An example of a fabricated student project is the micro-hinge shown in Figure 1. This design was unique not only in that it enabled a floating hinge using only a three-layer fabrication process[10] but also that it was designed by an undergraduate EE, a graduate ME and a graduate CHE student as part of a single semester course. In addition to this project, several other student projects have lead to conference publications[11,12] and M.S. theses[13,14]. More remarkably though is the number of students who first learned about MEMS through this course who have now continued graduate studies in this area. Of the 30 students enrolled in the first two course offerings, six (6) have pursued a M.S. in the area of MEMS and two (2) are pursuing a Ph.D. in this area. Furthermore, subsequent to taking this course, five (5) of the students have worked with MEMS researchers at Oak Ridge National Labs (ORNL).

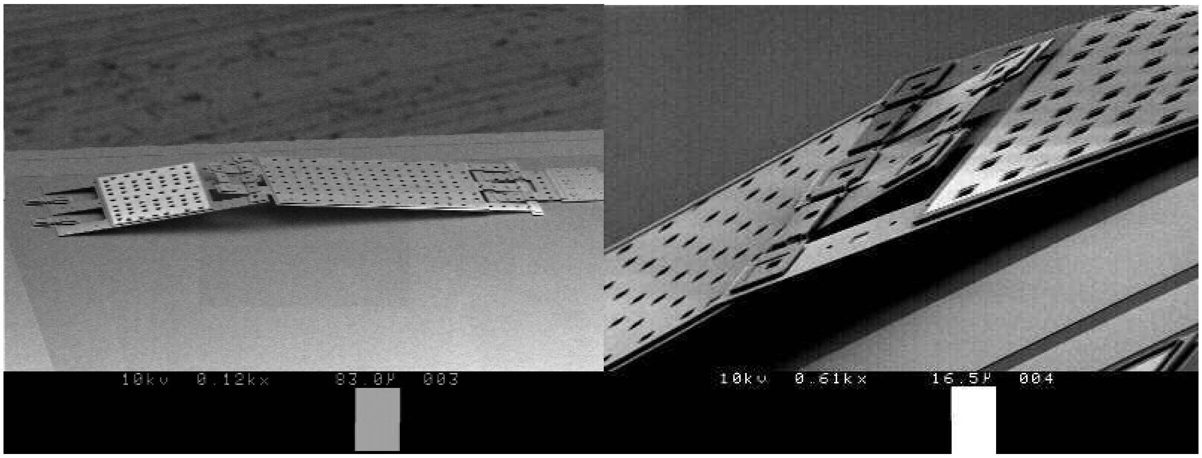

Figure 1. Fabricated Micro-Hinge

Lessons Learned and Future Improvements

Perhaps the greatest lesson learned from a pedagogical perspective was in regards to the formation of teams. In the course's first offering, the faculty had three main objectives in forming teams and assigning projects: (1) maximize student diversity, (2) each team would have a student who was to begin working at ORNL the following summer and (3) have projects guided by ORNL researchers. The faculty thought associating with outside experts would result in better projects. However, in the end, the non-ORNL students never accepted ownership of their team's design and the ORNL students claimed too much ownership. The results were that the projects were not of good quality (as noted in that few of the fabricated devices actually functioned). Furthermore, students made their frustration known in the severely harsh course review.

For the second offering, the faculty explained to the students their previous failure and indicated that the goal is still to have the most diverse team as possible in terms of discipline mix and having undergraduates work with graduate students. The students were allowed to organize themselves and surprisingly came up with very diverse teams. In addition, the students were also allowed to choose their own course project. The end results were that the projects were far superior with three out of the five resulting in a publication [10,11,12]. In short, the authors believe that student teams can be self-selected as long as the desired outcome is clearly established. This in conjunction with choosing their own projects resulted in greater ownership and in an overall superior experience (based on course reviews and resulting publications). The former contradicts common practice[15] for team forming, but does confirm that maximizing ownership through self-assessment produces better results[16].

Organization of the course material was also a learning process. In the first course offering, the faculty rotated lecture by lecture the conceptual material. The rationale was that students would grow expertise uniformly in the key areas throughout the course (i.e., a parallel approach). However, students found this approach less than satisfactory and thus the material has been re-organized to present three-week conceptual blocks (i.e., a serial approach). The exam scores in the second course suggest that the latter approach is superior and in addition this method received no negative comments.

Conclusion

This paper presents an interdisciplinary, design-based approach to an introductory course in the area of MEMS. Using team-based designs as a focus, students become familiar with various aspects of MEMS design, fabrication and performance assessment. The authors have found that course objectives were best met when students were allowed to maximize the ownership of their designs projects. By addressing the lessons learned, this course has improved dramatically in terms of quality of projects and course reviews. Finally, this course has excited many students to pursue further studies and careers in this area of increasing importance.

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