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A Three-semester Interdisciplinary Educational Program in Microsystems Engineering

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Abstract

Motivated by an NSF IGERT grant in the general area of microfluidics, a sequence of three interdisciplinary technical courses has been developed in the emerging area of microsystems engineering. Designed as a sequence, these courses provide students, both graduate and upper-level undergraduates from multiple disciplines, who have virtually no knowledge of the microscale and nanoscale engineering and science field, with the ability to design and fabricate complete microscale and nanoscale systems.

I. Introduction

The development of a formalized educational program in microsystems engineering at the University of Utah was motivated by an NSF Integrative Graduate Educational and Research Traineeship (IGERT) grant in the general area of microsystems engineering with a focus on thermal fluid systems and phenomena. A required sequence of three interdisciplinary technical courses has been developed for the formalized educational component of the traineeship program. Designed to be taken in series, these courses provide both graduate and upper-level undergraduate students from diverse disciplines with the ability to design and fabricate complete microscale and nanoscale systems.

The first course in the sequence, Fundamentals of Microscale Engineering, provides an overview of the important technologies from a fundamental point of view through a lecture-only format. Topics include scaling, microfabrication technologies, microscale and nanoscale phenomena, and microfluidic applications. The second course, Fundamentals of Micromachining Processes, is lab intensive and concentrates on the most frequently used microfabrication technologies, such as wet bulk micromachining and surface micromachining. Hands-on experience and instruction is provided for key fabrication and characterization equipment such as pattern generators, evaporators, sputterers, chemical vapor deposition systems, an SEM, and a surface profilometer. The third course, Design and Characterization of Microsystems, is project driven and generalizes microsystems design considerations with practical emphasis on MEMS and IC characterization, and physical analysis. The class team projects emphasize ongoing dissertation research, which produces an additional benefit for some students of significant progress on their individual projects. In some cases, project final reports have been in publishable form and have been subsequently submitted for inclusion in either conference proceedings or archival journals [1].

One of the goals of this course sequence is to prepare students in the fundamental microfabrication technologies so that these may be implemented in their research. Data indicate that this goal is being achieved and that the students are much better prepared to design and fabricate microsystems for their individual research projects. This paper presents details on the design of each course, and on the implementation challenges related to the interdisciplinary nature of microsystems, the diverse background of the students, and the integration of each course in the sequence. Assessment and course enrollment data indicate that the courses have been well received by the intended audience but that there remain a number of areas that need to be addressed to further improve the entire course sequence.

The goals of the course sequence are 1) to provide a basic educational foundation in microsystems engineering emphasizing thermal fluid systems, 2) to provide education and training in fundamental microfabrication technologies, and 3) to provide experience in microsystem design issues and characterization practices. The design of the course sequence was constrained by a number of factors related to the institution, lab facilities, and personnel. Each course was designed so that both upper-level undergraduates and graduate students could participate. The intent of this decision was to provide the education and training for the graduate students but also to attract interested undergraduates into the microsystems field with the hope that they would continue on to graduate school with a microsystems research emphasis.

The University of Utah is on the semester system and the College of Engineering traditionally offers courses at the graduate level that contain three semester credit hours of content. Thus, all of the new courses were designed to be delivered on a semester calendar and to contain material that is consistent with three semester credit hours (an additional one credit hour may be added for a course including a lab). In addition to providing the education and training for students in the IGERT program, it was decided to create the courses so that they could also be used as technical electives for non-IGERT students with an interest in the microsystems area. This had an impact in terms of course content for all three courses. Rather than design the courses such that they only had technical content that was consistent with the goals of the IGERT program, with its emphasis on microfluidic systems, course content was necessarily broadened to include the more traditional microelectromechanical systems (MEMS) area and, in some cases, microelectronics topics were included. Undergraduate students in Electrical Engineering are required to take a course in microfabrication if they specialize in VLSI. Given this condition, Course 2 of the sequence, which emphasizes fundamental microfabrication technologies, had to be designed to accommodate those students without the prerequisite of Course 1. As a result, Course 1 has become an introduction to microsystems engineering that serves two purposes: to prepare students for the following two courses and to introduce students, who have no intention of continuing, to the possibilities and opportunities in the microsystems field.

Microfluidic systems are fabricated using a fairly new and unique set of microfabrication technologies such as photolithography, surface micromachining, silicon bulk micromachining, and LIGA. In order to fully appreciate these technologies and to gain experience with the most fundamental ones, students must be given hands-on opportunities. Thus, lab exercises had to be included in the course sequence. It was decided that the latter two courses should both include a lab section for this purpose. Thus, Course 1 evolved to include microsystem science topics as well as an introduction to basic microfabrication technologies without an accompanying lab. Course 2, with its emphasis on microfabrication was designed to have a weekly lab that was directly coupled to the lectures. Course 3, with its emphasis on characterization, was designed to include lab exercises that demonstrate and provide exposure to fundamental characterization technologies and practices. Certainly another constraint in developing lab activities is the physical resources of the microsystems laboratory. The lab facility has many of the more common processes used in microfabrication and, as a result, lab activities are based around those common processes.

Given the nature of the microsystems area, each course was designed to be multidisciplinary and to be open to students from all areas of engineering and the basic sciences. Thus, the background of the students is quite diverse which leads to compromises in how material is delivered. For instance, students from Electrical Engineering, Bioengineering, and Physics most likely do not have much educational background in fluid mechanics. Thus, topics related to fluid dynamics at the microscale, such as slip flow, have to be presented in a way that is understandable to all students, even if they have not previously taken a fluid mechanics course. The multidisciplinary makeup of the student population in the courses is challenging for all of the instructors. Lectures must always be tailored so that all students have the ability to understand the majority of the technical content.

All of the constraints mentioned above have had an impact on the final form of each individual course as well as on the sequence as a whole. Thus the courses described in the following section do not represent the ideal three course sequence with which to introduce students to microsystems engineering, rather they represent our best design given the constraints related to resources (both financial and in personnel), the requirements of the IGERT grant, and the local administration.

II. Courses

All three courses are described in this section. The catalog description is included for each along with the motivation, objectives, course structure, and principle activities associated with each course. A brief syllabus of all three courses that lists topics covered in lectures and labs is included in the Appendix.

Course 1 – Fundamentals of Microscale Engineering

Catalog Description: **ME EN 6620** Fundamentals of Microscale Engineering (3 credits).
Prerequisite: Graduate status in engineering. Taught Fall.
Introduction to microscale and nanoscale engineering. Topics include scaling laws, metrology methods, and microfabrication technologies such as photolithography, sputtering, ion-beam etching, chemical vapor deposition, bulk micromachining, surface micromachining, LIGA, laser ablation, and micromilling. Microscale thermal fluid phenomena, such as slip flow, temperature jump, viscosity variation, surface tension effects, and conduction in thin films, are introduced.

MEMS and microfluidic applications, such as sensors, actuators, micro total analysis systems, and electronic cooling are presented. Meets with ME EN 5620.

Textbook: Madou, M., *Fundamentals of Microfabrication- The Science of Miniaturization, 2nd Ed.*, CRC Press, Boca Raton, FL, 2002.

Structure: Lecture (80 minutes – 2 times/week)

The first course in the sequence is designed to both prepare students for the following two courses in the sequence and also to serve as a reasonably comprehensive overview or survey of the microsystems field. Since the latter two courses emphasize microfabrication through considerable lab activities, the first course was designed to be a lecture-only course. The course emphasizes microsystems science and is divided into four components. The first portion of the course emphasizes scaling issues, introducing phenomena that may be beneficial with down sizing as well as those that are disadvantageous at the microscale. These scaling arguments are solely based on traditional theory and correlations. The second segment of the course emphasizes microfabrication technologies such as photolithography, dry etching techniques (sputtering, ion-beam etching), additive techniques (chemical vapor deposition, epitaxy, physical vapor deposition), bulk micromachining, surface micromachining, LIGA, laser ablation, laser photopolymerization, and micromilling. Since these technologies are at the core of microsystems development, they are introduced so that all students, even those not continuing on to Course 2, have some familiarity with the processes and language of the field. The third portion of the course introduces phenomena not typically significant at the macroscale but which become more important at the microscale. Given the nature of the IGERT program, thermal fluid phenomena are emphasized. Topics include slip and free molecular flow, temperature jump at solid boundaries, micropolar fluid theory, viscosity variation, and scale effects on thermal properties.

The last portion of the course is dedicated to student presentations of their literature research findings. This individual project involves an investigation of the state of knowledge in a particular technical area associated with microsystems technology. The topic area may be related to fabrication issues, assembly, packaging, applications, fundamental theory, or any specific issue that is related to microscale systems. The specific area selected for the project should be relatively focused so that the project is manageable. The focus should be on depth rather than breadth. It is acceptable that the topic be directly related to students' research work, either planned or underway. A minimum of seven papers taken from the literature constitutes the material to be reviewed. Both an oral and written report of the student's findings are required. The written report is constructed such that the paper could be used for the literature survey chapter (or section) of the student's thesis or dissertation. An oral presentation of the topic area covered in the review article must also be presented to the class. This presentation is intended to be informational such that all students may become more aware of the work that has been done in the topic area. With the time constraints (approximately 15 minutes), it is not possible to convey very many details. In most cases, some additional background information needs to be conveyed so the audience has a good idea of the overall scope of the research area. Visual aids (transparencies, slides, PowerPoint presentation, etc.) must be used in the presentation. The oral presentation is viewed as a technical presentation, similar to the type of talk given at a professional conference. A listing of all topics covered in the lectures is given in Table 2 in the Appendix.

The textbook for this course is primarily used for the section on microfabrication. A number of textbooks have been considered for this course [2 – 7]; however, no text has been found to have the rigor, content, and focus required for this course. A variety of sources have been used to create the lectures not drawn from the textbook. Homework problems and solutions have also been created to support the learning process. A number of publications from the literature are introduced to support the lecture material. These include historical papers [8], as well as papers on heat transfer regimes [9] and microscale fluid dynamic characteristics [10].

Feedback provided through student evaluations has been utilized for course improvement. The coverage on microfabrication has been reduced since similar coverage is provided in Course 2. Time spent on scaling issues, emphasizing the impact on system design, has been increased. Coverage of microsystem design, modeling, and physics has also been increased, as students seem to quite interested in understanding the microscale and nanoscale phenomena that are new to them. It has been suggested that a new textbook be selected. As mentioned above, however, a suitable replacement has yet to be identified. Students also requested that more coverage be given to topics related to microscale biological systems (BioMEMS) since many of the microfluidic applications are in the biological field. With the reduction in microfabrication coverage, all topics that students indicated should receive more attention have been given more coverage in the most recent version of the course.

Student evaluation data are available for the first two times the course was offered. These data indicate that students feel they "learned a great deal in the course", with 84% responding that they agree or strongly agree with the statement. The majority of students also feel that "overall, the course was effective", with approximately 72% of the students responding that they either agree or strongly agree with the statement. The numerical data for both these questions are above the Department of Mechanical Engineering average. Thus, it appears that the course has been well received by students, although it is certainly understood that improvements must continued to be made.

Course 2 – Fundamentals of Micromachining Processes

Catalog Description: **ME EN 6050** Fundamentals of Micromachining Processes (3 credits) Cross-listed with BIOEN 6421, ECE 6221, and MSE 6421. Prerequisite: graduate engineering status or instructor consent. Taught Spring.
Introduction to the principles of micromachining technologies. Topics include photolithography, silicon etching, thin film deposition and etching, electroplating, polymer micromachining, and bonding techniques. A weekly lab and a review of micromachining applications are included. Meets with ME EN 5050 and ECE 5221.

Textbook: Madou, M., *Fundamentals of Microfabrication- The Science of Miniaturization, 2nd Ed.*, CRC Press, Boca Raton, FL, 2002.

Structure: Lecture (1 hour – 2 times/week) and lab (3 hours – 1 time/week)

The Fundamentals of Micromachining Processes course, the second in the series, has been taught in its revised configuration for the past two years. The course is comprised of two hours of lecture each week along with a three-hour lab where practical microfabrication is taught and a hands-on experience is available. The laboratory experience mirrors the lecture topics and allows students the opportunity to immediately implement their theoretical understanding of the material.

The objective of this course is to provide students with the tools to design and fabricate MEMS and microfluidic devices, especially in a research environment. Accordingly, a significant portion of the course is spent in teaching microfabrication techniques to provide a strong foundation and fundamental understanding of the strengths and weaknesses of potential methods available to microscale engineers. The last few weeks of the course focus on implementing microfabrication techniques in practical environments. Thus, microsystem design is taught by reviewing case studies of microfabricated devices, both successful and unsuccessful, and delivering an overview of the challenges associated with working at the microscale in the various disciplines. Therefore, the course does not focus on one type of microscale device, but provides understanding regarding a wide range of devices including: mechanical, electrical, RF, optical, magnetic, chemical, biological, and microfluidic. The course topics for each lecture and the associated labs are given in Table 3 in the Appendix.

In addition to the lectures and labs, each student in the course must complete a design project and a lab module. The topic of each design project is chosen by the individual student, who is then required to generate a microfabricated system. All topics are required to be approved by the instructor. The design projects are to be completed using Intellisense software (or similar) and should simulate all of the processes involved in the design and development of the microfabricated system. The results of the design projects have been presented at a poster session near the last day of class as part of Engineering Day at the University of Utah. The project and poster are expected to include sections addressing: problem definition, literature search, motivation or rationale, implementation methods considered (brainstorming), "customer" requirements, functional specifications, modeling and scaling effects, fabrication methodology, mask layout, packaging, "real world" testing methodology, simulation results, conclusions, and references.

The first year the course was taught, we attempted to allow each student to build some facet of their design project during the last 3 or 4 weeks of the lab, but we found that the logistics of this effort made for a poor experience for everyone. Thus, in the most recent configuration we provided 3 modules that student groups could choose from. These modules included a range of MEMS devices that we had already proven could be built in the lab. The use of modules allowed students to complete a device of their own and to test its function when the fabrication was complete. The use of modules proved much more successful from both an administrative and learning perspective.

The poster session at the conclusion of the course has often been the highlight of the class and has received praise from not only the students, but also from the professors and broader campus community that attended. The posters have consisted of the student's design projects and allowed them the opportunity to publicly explain and defend their work. In general, professors that attended the poster session have been impressed by the high quality of work that was presented and the innovative ideas generated by the students. The students benefited significantly by receiving feedback not just from the instructor and other students in the class, but also from the professors that attended. Several new ideas for research projects were generated by the session and new collaborations were forged during the activity. The experience for the students was very similar to that at major conferences and gave them all the opportunity to develop a greater understanding of the interactions and activities that go on in the research arena. The most recent poster session was also attended by a group of junior high school students, a number of which expressed significant interest in the topics presented.

Homework problems were not required the first year the course was taught and a number of students felt that they were unprepared when exams were administered. Homework problems from the textbook were added the second year the course was taught, but it was found that the homework questions from the book were not well suited to the class, poorly written, inconsistent with the textbook itself, and structured inconsistently such that it was challenging for students to feel comfortable with the questions. Thus, during upcoming classes, the instructor has determined to write his own homework problems to complement the text, lectures, and labs. During the last three weeks of the course, design problems were assigned that allowed the students to integrate all of their learning to date, instead of homework from the text. The design problems proved to generate a number of very creative solutions. They were also excellent preparation for the final exam, which involved a design problem as well.

The wide range of students who have taken the course has necessitated the course breadth. Students have enrolled in the course from nearly every area of engineering (electrical, mechanical, chemical, biomedical, computer, and materials) as well as chemistry and physics, and each student therefore has unique expectations of the course. Over the past three years, average enrollment in the course has been about 40 students with about half coming from electrical engineering, one-third from mechanical engineering, and the remainder from the other engineering disciplines (see Table 1). The primary limitation on enrollment has been laboratory space. Since microfabrication is time intensive, serial in nature, and more conducive to individual rather than group labs, the lab sizes have been limited to 6 students to help optimize the learning experience in the labs. Unfortunately, this also limits the number of students who can participate due to the expense of setting up multiple laboratories.

Another challenge associated with this course is that, while this course is the second in a series for students in the NSF IGERT program, the first course is not a prerequisite for this course. Thus, a number of students have a good introduction to microscale phenomena while others who enroll have had little or none. This disparity does end up being reflected in grades at the end of the term, even though the two IGERT classes do not directly overlap.

Student evaluation data are available for the first two times the course was offered. These data indicate that students feel they "learned a great deal in the course", with 66% responding that they agree or strongly agree with the statement. The majority of students also feel that "overall, the course was effective", with approximately 72% of the students responding that they either agree or strongly agree with the statement. For both questions, the scores the second year were significantly higher than for the first year as logistical problems in the lab were corrected. The numerical data for both these questions are now above the Department of Mechanical Engineering average. Thus, it appears that the course has been well received by students, with some students remarking it was their most enjoyable course at the university, yet there are still areas for improvement.

Course 3 – Design and Characterization of Microsystems

Catalog Description: **ME EN 6060** Design and Characterization of Microsystems (3 credits). Prerequisite: ME EN 6050 or similar course.
Third in a 3-course series on Microsystems Engineering. This course generalizes microsystems design considerations with practical emphasis on MEMS and IC characterization/physical analysis. Two lectures, one lab per week, plus 1/2 - hour lab lecture. Students will complete a design/build/characterization project as part of a multidisciplinary team, outside of lab. Must also register for ME EN 6056 (lab).
Course meets with MEEN 5055, BIO EN 6421, ECE 5225/6225, MetE 5055/6055, MSE 5055/6055, ChFE 5659/6659.

Textbook: None required (lecture notes and miscellaneous readings on e-reserve)

Structure: Lecture (1 hour – 2 times/week), lab (3 hours – 1 time/week), lab lecture (1/2 hour – 1 time/week)

Being the last course in the sequence, one of the objectives of this course is to transition students from the academic environment to their professional career after degree completion. One aspect of this transition is to get students out of a lab-report mentality, and into an "engineering recommendation" mentality that includes data-driven decision making, and effective engineering communication. A second objective is to provide exposure to principal tools of day-to-day microsystems engineering including: resource allocation (including project planning and budgeting), engineering ethics, microsystems application to concurrent engineering, experimental design, reliability engineering, statistical process control and reduction of variability, failure analysis methodology, construction analysis techniques (sample preparation and use of SEM), and an overview of characterization techniques. A third objective is to facilitate multidisciplinary team building where teams are based on diverse skills and backgrounds necessary to integrate problem solving.

Students are encouraged to have previously taken either the microsystems (Course 1 and 2) or integrated circuit (IC) processing series, but not necessarily as pre-requisites. Good success has been achieved with Metallurgical Engineering and Chemical and Fuels Engineering students without that particular background, since the course is not based on *a specific* body of prior knowledge, but is rather *process-based*: the goal being how one thinks, not so much on what one knows. A programmatic decision has been made to encourage participation of students from many departments, which adds diversity of skill and perspective. A direct result of this interaction is the ability students gain to learn the language of other disciplines, and not to be discouraged when they are outside their direct major. The course has been designed to be project-based, with projects directly associated with student's research topics, when possible.

Projects are conducted by teams, with team leaders expected to gain direct experience in distributing responsibilities and managing progress. Seventy percent of the course grade is directly dependent upon the students' ability to work effectively as a team. Most of the assessment of team productivity is based on group reports with the residual coming from peer review techniques similar to those used in industry. For instance, the mid-term exam comprises students' review of team members and team leader performance, as well as an evaluation of each team's project, as referenced against the principles taught in class.

Communications activities have been integrated throughout the course. Consistent with this focus, all reports are first evaluated in draft form. Grades are then based upon how well instructor feedback was incorporated into the final copy. This format was implemented for the project proposal, three lab reports, and the final project report. A teaching assistant from the Department of Communications was contracted to assist in the development and evaluation of language, report, and presentation skills. The guidance provided by the communications TA was found to be especially useful for students for whom English is a second language

Guest lecturers with industry or hands-on processing and/or characterization experience were utilized for a number of topics. Topics covered by the guest lecturers include: 1) design for manufacturability (case study), 2) analytical simulation techniques, 3) gage capability studies, 4) residual stress test structures, 5) alignment test structures, 6) design of experiments, 7) sources of variability in photoresist processing, 8) transmission electron microscopy (TEM), 9) surface analysis techniques, and 10) statistical process control. Given the lab and project emphasis in the course, grades are based on 50% lab effort (understanding converted to engineering reports), 35% on project management, and 15% on homework and exams. A complete listing of lecture topics and lab exercises is given in Table 4 in the Appendix.

A half-day local fieldtrip to Fairchild Semiconductor included a tour of wafer fabrication facilities, guided by engineers specializing in etch, PVD, photolithography, and diffusion processes. Discussions were held with production operators, process engineers and supervisors on the topic of what makes a good process engineer. Discussions were also held with company personnel on device engineering, describing what device engineering is from the industrial standpoint and indicating why is it important. Integration engineering was also addressed through discussions regarding students' construction analysis of Fairchild devices.

Another unique feature of this course is the final exam format. Students are allowed a single page of notes for the exam. Exam questions are presented in slide form accompanied by instructor explanation of context, in a format similar to lectures. Students are given a fixed time to answer each question. Questions come from both the primary and guest lectures, with emphasis on principles taught in labs, as well as the Fairchild plant visit.

This course has been taught two times and a number of useful observations have been made that impact the course design and delivery. These issues are presented below.

- No single text exists to adequately cover the broad topic range for this course. A combination of lecture notes, case studies, electronic reserve (.pdf downloads), and outside expertise forms the content.

- The multidisciplinary barrier has proven to be challenging. It is manifest both institutionally (departments are reluctant to make it easier for students to diversify their curriculum necessitating extensive cross-listing), and psychologically (students expressing reluctance to understand topics they feel are "outside" their discipline).

- Many aspects of the course are unusual for the student accustomed to memorizing facts and phenomena, deriving equations, and other academic pursuits. The applied nature of the course, with emphasis on case studies and learning through hands-on personal experience, personal failure, and feedback other than letter grades, requires a rapid maturation process. Many students pass through the entire course and never quite understand this alternative educational and assessment format.

- Unlike the academic environment, it is often the case in industry that an engineer's output is directly dependent upon the engineer's ability to work with others, and the results often reflect a group, rather than an individual effort. This industrial approach is emphasized in the class and some students have difficulty adopting this different assessment strategy.

- Grading is complex, with 70 percent of the grade dependent upon team efforts (e.g., combined group reports); yet, students are not given a final grade relative to each other, but relative to the standard of possible points. The outcome standard is set by the students in their project proposal. In the event of unforeseen equipment unavailability, the standard is adjusted to the student's ability to adapt, learn from their efforts, and make solid engineering recommendations for future work. Maximum grades are not given unless the output standard is achieved, but failing grades are not given as long as a minimum standard of effort is expended.

- Student evaluation data from the two semesters indicate that students feel they "learned a great deal in the course", with 73-74% responding that they agree or strongly agree with the statement. Only 50-65% of the students responded that they either agree or strongly agree with the statement: "Overall, this was an effective course." Interpreting these results relative to observations of interactions during lectures and performance on assignments and exams, we take it to mean that it was a very unusual course relative to the rest of the student's academic experience. Some students adapted well, and others did not.

- The first year of the course, students adapted very well to the unexpected issues associated with equipment and process problems typical in microfabrication labs, and were generally rewarded with good grades. In the second year of the course, the grade distribution was substantially different. The difference between the first year and the second year outcomes may be a direct result of decreased supervision (TA and instructor) during the second year. The higher level of maturity required for the course may not arise without sufficient coaching, guidance, and instructor interaction. Structurally, the first year course had four paid TAs, and an undistracted instructor. The second year saw an effort to use volunteer TAs (IGERT graduates from the first year class) coupled with permanent staff. In addition, the instructor was also saddled with managing the renovation and operation of the microfabrication lab. However, certain activities were relatively constant (in terms of content and instructor interaction) between the first and second years including the four-week set in construction analysis, and the final exam format and content. The performance of the second versus first year student populations in both these activities was decidedly inferior during the second year.

Based on the experiences gained (reflected in the above list of observations) during the two times the course has been taught, several changes will be implemented in future offerings. These modifications are described below.

- Student feedback indicates a portion of the grade should be based on attendance, especially at labs. It is important to be careful with this, since the grade-based approach removes responsibility of team leaders and team members to work out their team building by themselves. It is preferred that the group independently come to an understanding of the need for them to work together effectively, and hence pull together, rather than have the instructor use punitive actions (lower grades) to motivate team building.

- Another aspect of professionalism needing to be reinforced in the future is that group reports with multiple author names must reflect contributions of each signatory. This aspect should be accomplished by requiring that group reports be circulated for member proofreading and signature. Team leaders need to be held accountable for ensuring that each team member is involved, and each team member needs to be accountable for holding the group output to their own individual standard of perfection.

- The slide lecture format makes note taking difficult, especially going back to review the lectures. In the future, the students will be encouraged to download the lectures in advance with associated e-reserve readings, and take notes real-time on a per-slide basis.

- Team building needs a more pro-active approach, emphasizing direct problem solving. The role of the instructor as coach to mediate specific interaction problems should be clearly defined. For example, the midterm peer review asks how team members performed against expectations they set and commitments they made, then asks if the reviewer has either discussed any criticisms directly with the person complaining or with the team leader. What needs to be reinforced is that once a direct interaction fails to produce positive results, the worst thing is to proceed without doing anything further. The instructor needs to reinforce his own role as a coach and mediator to resolve team conflicts and get the team back on track.

III. Observations and Future Developments

Institutional constraints have impacted the course implementation. Currently, no provision is made to offer courses that are truly multidisciplinary without a department designation. So instead of designating a course as a College of Engineering course, each course is required to have a home department designation, such as Mechanical Engineering, and be cross-listed with other departments (up to six, in one case). As with most new courses, all of the microsystems courses had to be originally designated as a Special Topics course. After at least offering the course two times and with confirmation that enrollments are reasonable and expected to continue, a Special Topics course can be converted to a permanent course by receiving department approval (again, multiple department must approve) and Curriculum Committee approval at the College level. Thus, the lack of a common course designation for the College has made permanent course adoption more difficult than for most single discipline courses. Financial resources for the teaching assistants required for the two labs have also been problematic. As these are new labs, new sources of funds had to be identified. Currently, the IGERT grant provides most of the required funds. When the IGERT program terminates, permanent ongoing funding sources will need to be identified. Once again, since the course enrollment cuts across the entire College, it is expected that multiple departments will have to commit to support the course. Since the lab exercises are highly dependent on the fabrication equipment available in the microfabrication laboratory, finding experienced teaching assistants has also been difficult. Most students that have the highly specialized expertise are typically research assistants and are not available to serve as teaching assistants.

The three new courses represent additions to the course offerings of the College. With no new faculty, these courses must be taught by the current faculty, representing an overload for those involved. Another administrative concern is the allocation of student credit hours for each class. With students from several different departments, and classes being cross-listed with many of the same departments, allocation of the student credit hours (used for department productivity analysis) is problematic. After much discussion at the College administrative level, it was determined that student credit hours should be assigned only to the home department of the instructor.

As noted previously, all courses were designed so that students with diverse educational backgrounds could be accommodated. The entire sequence was also designed so that both graduate students and upper level undergraduate students could participate. In addition, the courses were specifically designed to support the IGERT educational program, and all IGERT students are required to complete the entire sequence of courses. Enrollment data for all course offerings during the first three years of their existence are provided in Table 1.

The course developers have been pleasantly surprised by the reception the courses have had by non-IGERT students (IGERT students are required to take the courses). Approximately 2/3 of the enrolled students have taken the courses as technical electives. The total enrollments have been reasonably large when compared to other engineering graduate courses. Students have been primarily from Mechanical Engineering and Electrical Engineering (approximately 83%), although students from eight separate departments in engineering and science have participated. In order to attract a more diverse student group, additional advertising of the course offerings must be made in the College of Engineering and the College of Science. The Number of undergraduates taking the courses also has been less than expected. Only about 12% of all students have been undergraduates. A better effort has to be made to inform undergraduates of the opportunities that exist in the microsystems field and to allay any fears they may have of taking classes that are predominately populated by graduate students.

IGERT students who have taken the entire sequence of courses were surveyed to get their impressions of the overall impact of the courses. The majority of respondents felt that the courses were adequately linked together and the courses represented a fairly cohesive package. Some students felt that a single project could be undertaken throughout the entire sequence, thus insuring strong linkages between courses. Suggestions for improving the course sequence also included the addition of more case studies, an increased emphasis on microfluidic fundamentals and applications, and less repetition of topics (primarily microfabrication) in the latter two courses. Each respondent typically had a unique opinion of the topics that deserved to have more emphasis, suggesting that the microsystems field is indeed very diverse and that there are many important topics of interest. All of these suggestions have been implemented in some fashion into the current versions of the courses to try to improve the overall impact of the sequence.

The creators of the course sequence are now actively engaged in combining these courses with others related to specific disciplines to create a multidisciplinary certificate program in the microsystems area. A project in the microsystems area will also be required. For students planning to complete the microsystems certificate from the beginning of their studies, the project can be completed during the sequence of three classes. Thus, students who complete the courses along with at least two electives specific to their discipline will receive a certificate upon graduation indicating their proficiency in the microsystems area.

Table 1. Enrollment data for the initial three-year period

	Course 1			Course 2		Course 3		Totals	%
Students	Fall '01	Fall '02	Fall '03	Spr '02	Spr '03	Fall '02	Fall '03		
IGERT	11	7	12	11	7	13	4	65	32.7
Non-IGERT	10	16	13	34	29	14	18	134	67.3
Subtotal	21	23	25	45	36	27	22	199	
Mechanical Eng	15	13	13	18	17	12	9	97	48.7
Electrical Eng	1	9	3	24	15	9	7	68	34.2
Bioengineering	3	0	8	2	2	2	0	17	8.5
Material Science	0	1		0	1	3	2	7	3.5
Metallurgical E	1	0		0	1	1	2	5	2.5
Chemical Eng	0	0	1	1	0	0	1	3	1.5
Mining Eng	1	0		0	0	0	0	1	0.5
Physics	0	0		0	0	0	1	1	0.5
Subtotal	21	23	25	45	36	27	22	199	
Graduate	21	18	23	39	29	24	21	175	87.9
Undergraduate	0	5	2	6	7	3	1	24	12.1

IV. Summary and Conclusions

A three-semester sequence of courses has been developed to introduce upper level undergraduate and graduate students in engineering and science to the field of microfluidics. The courses have been designed so that the learning experience is maximized when courses are taken in series, although the first course is not a prerequisite for subsequent courses. Student feedback has been utilized for course improvement and the current versions of the courses have been deemed effective by the vast majority of students. Students enrolled in the courses to date have diverse backgrounds, with students from eight separate departments participating. In the future, more attention should be placed on attracting students from departments other than the two largest departments in the College of Engineering. The courses were created in response to the educational need of graduate students participating in an NSF IGERT program that emphasizes microfluidic systems. The authors feel that the sequence of courses is providing the required core educational background necessary for all IGERT students to be successful in their research. In addition, traditional graduate students are also finding that the course sequence is an effective means of gaining knowledge of the microsystems and MEMS field. It should also be noted that the IGERT program has served as a seedbed for a variety of other programs, activities, and infrastructure improvements [11].

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VI. References

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Biographies

TIM AMEEL received B.S. (1975) and M.S. (1977) degrees in Mechanical Engineering from Montana State University and the Ph.D. (1991) degree from Arizona State University. He was an Assistant Professor at Louisiana Tech University for four years where he was affiliated with the Institute for Micromanufacturing. Currently, Professor Ameel is an Associate Professor and Director of Graduate Studies in the Department of Mechanical Engineering at the University of Utah. His research interests focus on the thermal fluid phenomena associated with microscale convection and internal flows.

BRUCE GALE received his B.S. in Mechanical Engineering from Brigham Young University in 1995 and a Ph.D. in Bioengineering from the University of Utah in 1999. He spent over two years as an Assistant Professor of Biomedical Engineering at Louisiana Tech University and the Institute for Micromanufacturing. In December of 2001 he joined the Department of Mechanical Engineering at the University of Utah. His interests include medical and biological based applications of microfluidics and micromachining and his work has recently involved micromachined particle separation systems and detectors, MEMS for tissue engineering applications, and sensors related to these applications.

IAN HARVEY received his BS and MS degrees from the University of Utah in Materials Science and Metallurgy, respectively. He took his Ph.D. (Materials Science) at the Colorado School of Mines in 1990 while doing an internship at IBM-Boulder. Ian worked at VLSI Technology in San Jose for seven years in IC failure analysis, focused ion beam prototype repair, and advanced process development (plasma etch of dielectrics). Joining Bourns in 1997, Ian has worked in thin film magnetic inductor development and in chip scale package development. Ian Joined the University of Utah in 2001 as a Research Associate Professor, where he is manager of the Utah Microfabrication Lab. Ian has jointly authored over sixteen publications and holds twenty-two U.S. patents.

Appendix

Table 2. Fall 2003 Schedule for Fundamentals of Microscale Engineering

Class	Topics
1	Microintuition, scaling in nature
2	Scaling in electrostatics, micromotors
3	Scaling in fluids
4	Scaling in conduction
5	Scaling in convection, radiation
6	Lithography, photolithography
7	Photolithography
8	Dry etching
9	Dry etching, additive techniques
10	Additive techniques
11	Bulk micromachining
12	Surface micromachining
13	Surface micromachining, micromirrors, and microchannel fab.
14	LIGA
15	LIGA, laser micromachining, micromilling
16	Test 1 (through class 13)
17	Packaging
18	Packaging, Metrology (profilometer)
19	Heat transfer regimes
20	Heat transfer regimes, microchannel flow
21	Slip flow modeling – fluid dynamics
22	Slip flow modeling – convection heat transfer
23	Electrophoresis microfluidics
24	BioMEMS
25 - 29	Student Presentations
30	Student Presentations, course wrap-up
31	Test 2 (Class 15 – 30)

Note: each lecture is 80 minutes in length.

Table 3. Spring 2003 Schedule for Fundamentals of Micromachining Processes

Class	Topic	Weekly Lab
1	Introduction to MEMS; Preview of Course, Course Policies	Lab Safety and Facilities Tour
2	Chemicals, Clean Rooms & Vacuum Systems in MEMS	
3	Basic Lithography	Cleaning and Photolithography;
4	Advanced Lithography Techniques; Mask Layout & Design	
5	Project Guidelines and Design Process	Intellisuite Lab Tutorial
6	Materials Science for MEMS, Crystallography	Mask layout and generation
7	CVD Processes and Thermal Oxidation and Diffusion	
8	Dry Etching	Oxidation and Diffusion
9	Wet Etching and Bulk Micromachining	
10	Physical Vapor Deposition: Sputtering, Evaporation,	CVD and Dry Etching
11	LIGA	
12	Electroplating and Micromolding	Metallization and Electroplating
13	Beam Processing, Mechanical Micromachining and Other Techniques	Laser Micromachining
14	Plastic Molding Processes: Hot Embossing, Injection Molding, PDMS	
15	Wafer Bonding and Basic MEMS Packaging	Wet Etching and Soft Lithography
16	Midterm Exam Lectures 1-16	
17	Integration with Microelectronics; Packaging of Optical and Fluidic Systems	Intellisuite Lab Tutorial
18	MEMS CAD and Simulation Programs	
19	Basic Measurement and Characterization of MEMS systems	Wafer Dicing, Polishing, Packaging
20	Basic Design of Microsystems	
21	Case Study: Optical Microsystems	Characterization and Metrology
22	Case Study: Electrical and Magnetic Microsystems	
23	Case Study: Mechanical Microsystems	Modules
24	Case Study: Chemical Microsystems	
25	Case Study: Microfluidic Systems	Modules
26	Case Study: Biomedical Microsystems	
27	Poster Presentation of Design Projects	Modules
28	Introduction to Nanotechnology	
29	**Final Exam Comprehensive**	

Note: Lectures and labs are 80 and 180 minutes in length, respectively.

Table 4. Fall 2003 Schedule for Design and Characterization of Microsystems

Class	Topic	Weekly Lab
1	Class overview. Definition of class projects.	
2	Microsystems Design Philosophy	Facilities tour / Lab Safety requirements and quiz / student project coordination.
3	Basic Design Principles / Guest on Design for manufacturability	
4	Guest Lecturer—Design Simulation	Demonstration -CAD layout ==> Intellisuite
5	Process capability corr. w/ design architecture / design rules	
6	System integration	Lab: Design==>Model==>Mask (CADE Lab)
7	Reduction of Variability	
8	William Wulf Lecture: President of the National Academy of Engineering	Hands-on Engineering Optimization Lab CAD==>Laser micromachining (MicroFab): Classical Engineering Process Optimization
9	Project Planning	
10	Critical performance attributes / "Burn-in" Thermo-mechanical testing / Weibull analysis	Laser lab II: Statistical Experimental Design / factorial design
11	Test design for performance characterization	
12	Student oral reports on PROJECT status Peer review.	
13	Fairchild Guest Lecturer, Jim Pugmire: DOE ("Design of Experiments")	Demonstration Statistical Design of Experiments : response surface designs
14	Jim Pugmire: Use of Screening Experiments	Lab times combine to either of two H session
15	Gage Capability (GR&R) measurement variation Nephi Harvey	Tencor measurement Gage capability study
16	Case Study: Chip Scale Package Development reliability engineering, and failure analysis	
17	Failure Analysis philosophy / Diagnostic Engineering	Case study: CSP Weibull analysis of cyclic bend testing
18	NDE / acoustic tomography, X-radiography	
19	Construction analysis / Cross-sectioning DMOS	Lab: IC construction analysis part I: X-sec
20	Deprocessing Techniques (wet / dry / mech.)	
21	Guest Lecture: Jeff Griffin, AZ Clariant on Photolithography Process Engineering	Lab: IC construction analysis part II: LV-SEM
22	Defect site identification/ EmMi, LC, CIVA, EBIC	
23	SEM / EDS overview / SEM tricks of the trade	Lab: IC construction analysis part III: Parallel Lapping deprocessing
24	Specialized techniques: TEM / guest lecturer	
25	Specialized techniques: Auger / SIMS / XPS guest lecturer	Differential Surface Discharge (SEM Demonstration / Passivation verification)
26	FIB as characterization tool / proto development	
27	Feedback loop/Scaling/optimization for manufacturability	No lab; Turn in 1st draft project report
28	SPC: Jim Pugmire / Fairchild 3:00-5:00	No lab; reports returned with feedback
29	Live final presentation / Poster Session / U of U	Lab notebooks due
30	Tour / Poster session at Fairchild	Tour/Fairchild Semiconductor
31	Final Exam	

Note: Lectures and labs are 80 and 180 minutes in length, respectively.