The Science and Technology of Micro-machines: Development of An Undergraduate Course

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Abstract-The technological foundations of microelectronics provide the basis for the emerging science and technology of micro-machines. Most instruction in micro-machines has occurred at the graduate level, leaving a relative void in the undergraduate curriculum. With industrial and governmental support, we have incorporated hands-on fabrication and foundry-based device design into a comprehensive undergraduate course.

I. Introduction

The microelectronics industry has created a tremendous technological foundation over the past fifty years. Its foundation is commonly thought to rest on three principle components: microfabrication process engineering; electronic device physics; and circuit design [1].

The advent of micro-machines, as an analogous endeavor to microelectronics, can arguably be said to have begun with Petersen's summative article on the micro-mechanical behavior of silicon [2]. With this change in perspective, the technological accomplishments of microelectronics found new applications in a much broader design space [3]. The possibilities presented by this new technology were detailed by a seminal workshop in the mid-1980's [4].

As with microelectronics, initial progress in micro-machine technology has been led by industrial and graduate-level university researchers. In microelectronics, eventually the technologies of process engineering, device physics, and circuit design entered the undergraduate curriculum [5]. The same technology transfer of micro-machine technology to the undergraduate curriculum began with a course on process engineering at MIT, reported at this Symposium [6]. Other efforts have begun during 1995. In this paper, we describe our undergraduate curricular changes, which establish and emphasize principles of micro-machine device *design*, while preserving important aspects of their process engineering [7].

II. Local Context

Undergraduate science majors at Dartmouth College receive A.B. degrees at the end of the usual four-year course of study. Out of 35 required courses, students majoring in engineering sciences take eight required prerequisites, six core courses in the major, and a minimum of two elective courses. The core classes are interdisciplinary in nature, and include: engineering design; systems (dynamics); solid mechanics (statics); science of materials; thermodynamics; and fields.

Entering classes at Dartmouth number 1100 students. Of these, approximately ninety major in engineering sciences, making it the largest science major on campus. Half of these students fulfill the requirements of the B.E. degree, a fifth-year program which follows the A.B. An additional ten courses in engineering sciences is required to fulfill the B.E. requirements.

Our course in micro-machines attracts students from both the upper-level A.B., and B.E., courses of study. Students are presumed to have thorough, introductory backgrounds in design, statics, dynamics, materials, mathematics, and physics. Most also have taken the courses in fields, and in thermodynamics. In addition, B.E. students frequently have taken other, microelectronics related courses relevant to the study of micro-machines.

Since Dartmouth students take only three classes each quarter, the work load in each class is greater than a semester class more customary at other institutions. The equivalent number of semester hours for our course is, roughly, five or six.

III. Facilities Description

A. Microfabrication Facilities

Our general program in undergraduate micro-fabrication, including a facilities description, has been described in detail elsewhere [8].

The Solid State MicroEngineering Laboratory is a cleanroom laboratory with 250 square feet of class 100 lithography processing space and 600 square feet of class 1000 general processing space (Fig. 1). Capabilities include *photolithography* (resist spinner, mask aligner, and bake ovens); *e-beam lithography* (direct write SEM); *physical vapor deposition* (e-beam, laser ablation, and thermal evaporation); *wet chemical processing* (laminar flow fume hoods); *thermal processing* (diffusion furnaces and rapid thermal processing); *reactive ion etching*; *ellipsometry* (dual wavelength); *surface profilometry* (AFM, Electrostatic Force Microscope, alpha-step); *structure analysis and testing* (SEM with x-ray EDS micro-analysis, and microprobe stations including low temperature station).

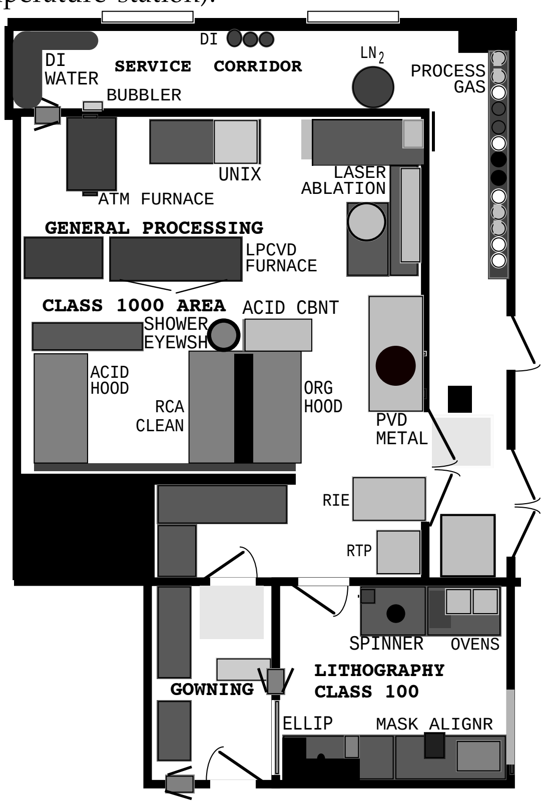

Fig. 1: The Solid State Microengineering Lab at Dartmouth

B. Computation Facilities

Dartmouth is fortunate to have a powerful and well networked computing environment. High end UNIX workstations are readily available to undergraduates; these were utilized in this course for simulation (SUPREM-IV from Stanford U. and FLOOPS from the U. of Florida), and design layout (Tanner Research's L-Edit and MCNC's Consolidated Micromechanical Element Library). L-Edit was also available in a keyserved Macintosh environment. Over 95% of the Dartmouth undergraduates own Apple Macintosh computers. We have keyserver license agreements which make a wealth of software available to students using any Macintosh on the campus network, including L-Edit and other CAD software. An email environment which supports enclosures adds to the power of this keyserved software. Work begun in a dorm room can be mailed to other students for further work on a Macintosh or UNIX workstation elsewhere on campus, and homework layout and technology files can be distributed and turned in by email.

Because of L-Edit's difficulty in providing crucial cross-sectional views and derived layers of structures designed using arcs or circles, we also developed a program (called CircCIF) to allow easy construction of circular and annular structures using right-angle polygons, from which L-Edit can construct cross-sectional views.

IV. Course Conception

In conceiving our course, we chose to combine traditional lectures on the scientific concepts related to micro-machines, with hands-on fabrication of simple micro-machines, and with the design of more complicated structures which would be fabricated using a foundry service. We felt the combination of theory, experiment, and a culminating design project, would provide a comprehensive and compelling experience for our students, whether their post-graduate steps lead to graduate school, or careers in industry or government.

A. Lectures and Syllabus

Lectures emphasize a generalized non-silicon specific approach to the physical and chemical phenomena and tasks related to micro-fabrication. Frequent guest speakers from academe, government, and industry provide relevant, global perspectives. Lectures for the course last two hours on Tuesdays and Thursdays. An additional hour is available on Wednesdays.

There are four parallel themes for the first half of the course. Theme 1, on Tuesdays, covers the Science and Technology of Microfabrication. Structure control is the first topic, which breaks down into discussions of photolithography, thin film deposition, and etching. Defect control is the second topic, breaking down into discussions of diffusion, ion implantation, gettering, and annealing. Structure and defects combine to dictate the properties of micro-machines.

Theme 2, on Thursdays, covers the Science of Micro-machines. This thread starts with materials properties relevant to micro-machines: mechanical, chemical, thermal, and electrical. Subsequently, analysis of the behavior of specific instances of micro-machines is presented, in the context of these material properties.

Theme 3, held on Wednesdays, is a practicum covering computer-aided design tools. It builds a base of experience in various tools of interest to micro-fabrication in general, and micro-machines in particular. These include: Mosaic and Netscape; SUPREM-IV and FLOOPS; and L-Edit.

Theme 4 is held one afternoon each week. It covers practical aspects of microfabrication. Lab safety is emphasized. Two specific types of micro-machines are built and characterized: a micro-cantilever; and a micro-diaphragm.

In the second half of the course, these four themes are utilized in a practical sense, through the design project. They are amplified in the formal or academic sense through presentation and discussion of more complex micro-machines and their fabrication processes.

A syllabus for the course is shown in Table I.

TABLE I.
Course Syllabus

DATE	TOPIC
Wednesday, January 4	Org. Mtg. Overview. Videos.
Thursday, January 5	Review chemistry, diffusion.
Tuesday, January 10	Structure Control: Litho (Optics and Photoresist)
Wednesday, January 11	Sim. workshop (WWW)
LAB: Safety; Micro-cantilever Part One	
Thursday, January 12	Properties of materials I
Tuesday, January 17	Structure Control: Thin Films (VPE; oxidation; nitridation)
Wednesday, January 18	Sim. wkshop (SUPREM-IV)
LAB: Micro-cantilever Part Two	
Thursday, January 19	Properties of materials II
Tuesday, January 24	Structure Control: Thin Films (SiO2, Si3N4, poly, metal)
Wednesday, January 25	Sim. workshop (L-Edit)
LAB: Micro-diaphragm, Part One	
Thursday, January 26	Micromech. Device Behavior
Tuesday, January 31	Structure Control: Etching
Wednesday, February 1	The essentials of design
LAB: Micro-diaphragm, Part Two	
Thursday, February 2	Microsensor Device Behavior
Tuesday, February 7	Defect Control: Simple Diffusion, Ion Implantation Solid, Liquid Source Doping
Wednesday, February 8	1:1 Group project meetings
LAB: CAD: Begin Design of projects	
Thursday, February 9	MCNC MEMS fabrication process and examples
Tuesday, February 14	Case studies: Sensors
Wednesday, February 15	One-on-one Group meetings
LAB: CAD: Design of projects	
Thursday, February 16	Case studies: Actuators
Tuesday, February 21	Case studies: Transducers
Wednesday, February 22	One-on-one Group meetings
LAB: CAD: Design of projects	
Thursday, February 23	Case studies: Device integ.
Monday, February 27	SHIP DESIGNS TO MCNC
Tuesday, February 28	Characterization and testing
LAB: Characterization Techniques	
Thursday, March 2	Review. Future Prospects
Tuesday, March 7	Project Presentations
Wednesday, March 8	Project Presentations
Saturday, March 11	Pick up take-home final.
Wednesday, March 15	Last day to turn in final.

B. Homework Exercises

Homework problems focus on lecture material, and exercise basic skills and understanding of process science and technology. Design problems of increasing complexity are included, which couple to both the on-site labs, and the MCNC-based design project. For instance, one homework assignment requires students to create a simple mask for a cantilever or mechanical resonance structure of their own design. This structure is layed out at a fairly large scale and compiled with other student structures. Using a mask created using 3386dpi laser printing techniques and low-cost chrome-coated glass, these designs are reduced to practice in the surface micro-machine lab. Students then have the positive experience of building and characterizing their own designs.

C. Final Exam

An example final exam is shown in Table II. The example is drawn from [9]. The exam is a take-home, and is intended to test mastery of micro-machine science, and student ability to use tools of the trade. It also offers students, through a problem of relatively short duration, the opportunity to express their creative skills in design.

TABLE II
Sample Final Exam

PROBLEM ONE: (50 points) Design a process which can be used to fabricate a micro-lamp, or micro-light bulb. Detail each process step, using the (simplest) means we have discussed in class. Specifications are: a) Each lamp element should generate 5 mW of light in an area no bigger than 100 µm by 25 µm. b) 'Light' is taken to mean total spectral output, not simply visible light. That is, you will have to use the black body radiation curve, and integrate over all wavelengths, in order to find the total spectral output. You may assume your light-emitting filament to be an ideal blackbody. c) The lamp element cannot be operated in air, due to degradation (oxidation) of the light emitting element. You will therefore need to devise a means to seal the filament hermetically. **PROBLEM TWO:** (50 points) Design a light bulb based on your proposed process. That is: using L-Edit, layout your device in preparation (after the exam is over!) for fabricating it. In order to complete this problem, you will need to: a) Devise a technology file for your process. b) Devise design rules for your process. Focus only on critical design rules. Justify your choices and specifications. c) Layout your device.

D. Laboratory Exercises

Two extended laboratories during the first half of the course reinforce lectures by emphasizing the basics of micro-fabrication technology: film *deposition* (including physical and chemical deposition processes); *diffusion* (including film growth, anneal, and solid or fluid source doping); *etch* (including wet and dry processes); optical *exposure*; ion *implantation*; and materials and device *characterization* and evaluation. Hands-on demonstration of these basic techniques involves, in the first lab, **surface micro-machined devices** (such as cantilevers and resonators); in the second lab, **bulk micro-machined devices** (such as pressure sensors) are constructed. Both labs use prepared masks and the facilities of the Solid State Microfabrication Laboratory.

At the end of the quarter, after the submission of design projects, students complete their hands-on laboratories by characterizing their devices. This activity 'closes the loop' on these labs, and prepares them for the characterization work once their design projects are returned from the foundry. Characterization includes SEM analysis. Students are encouraged to submit their work in HTML format, so that results can be archived for Internet access.

i. Surface Micro-machining

Table III shows the fabrication sequence for the surface micro-machining process used in the labs. One structure fabricated is the micro-cantilever. An example cantilever is shown in cross-section and plan view in Fig. 2.

TABLE III
Surface Micro-machining Fabrication Sequence

General Step	*Specific Step*	*Monitor/Measure*
1. Initialization:	Starting material 75mm <100> Si	Four-point probe/Resistivity
2. Etch:	RCA Clean	
3. Diffusion:	Wet Oxidation (sacrificial)	Ellipsometer/Film thickness
4.	Photolithography	
4a. Deposit:	Spin on photoresist	Ellips/Film thick; Microsc. inspection
4b. Diffusion:	Pre-exposure bake photoresist	Time, Temperature
4c. Exposure:	Anchor Hole Defin.	Time, Light Intens.
4d. Etch:	Develop photores.	Microsc. inspection
4e. Diffusion:	Post-bake photores	Time, Temperature
5. Etch:	Anchor Hole Cut	Time, Temperature; Microsc.inspection
6. Etch:	Photoresist strip	Time, Temperature; Microsc. inspection
7. Deposition:	Polysilicon Deposition	Ellips/Film thick; Microsc. inspection
8a. Diffusion:	Polysilicon Anneal	Time, Temperature; Microsc. inspection
8b. Diffusion:	Dry Oxidation (hard mask)	Time, Temperature; Microsc. inspection
9.	Photolithography	
9a. Deposition:	Spin on photoresist	Ellips/Film thick; Microsc. inspection
9b. Diffusion:	Pre-bake photores	Time, Temperature
9c. Exposure:	Cantilever Defin.	Time, Light Intens.
9d. Etch:	Develop photores	Microsc. inspection
9e. Diffusion:	Post-bake photores	Time, Temperature
10. Etch:	Oxide mask etch	Time, Temperature; Microsc.inspection
11. Etch:	Photoresist strip	Time, Temperature; Microsc.inspection
12. Etch:	Polysilicon etch	Time, Temperature; Microsc.inspection
13. Etch:	Oxide Release	Time, Temperature; Microsc. inspection

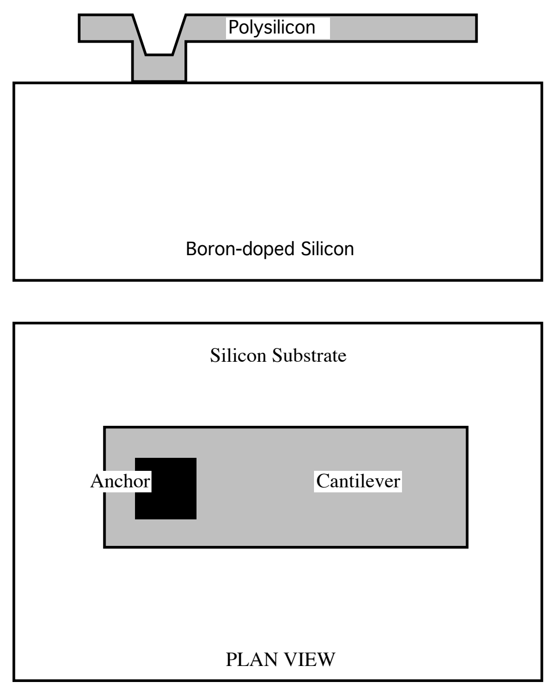

Fig. 2: Cross section and plan views of micro-cantilever

ii. Bulk Micro-machining

A similar process to that given in Table III is used in the bulk micro-machining lab. A schematic of the final cross-section and plan view of a simple diaphragm is shown in Fig. 3.

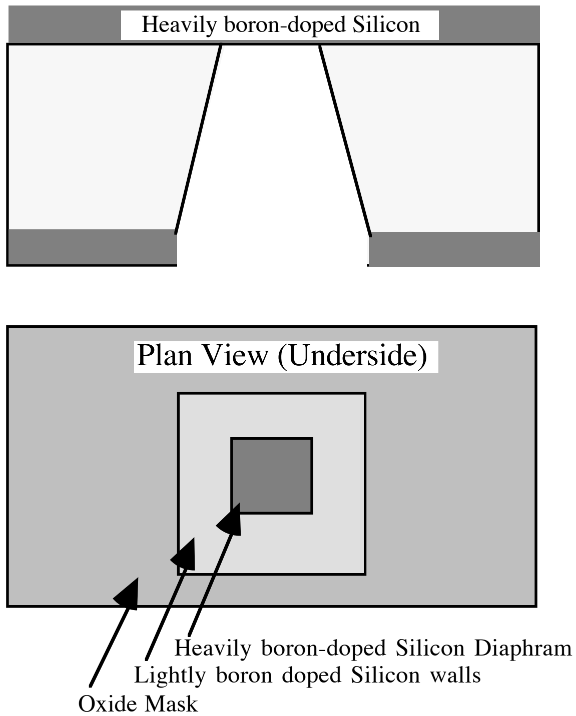

Fig. 3: Cross section and plan views of micro-diaphragm

E. Student Design Projects

In the latter half of the course, a group design project is required, wherein students in small groups create their own micro-machines using available CAD tools (principally L-Edit, and SUPREM-IV). Designs are subsequently sent to the Microelectronics Center of North Carolina (MCNC), an ARPA-funded foundry service for fabrication. Upon return from MCNC, students test and evaluate their designs using characterization facilities at Dartmouth. Grades are not reported until this task is completed.

We considered three possible foundry sources for student projects. We were sensitive to choosing appropriate fabrication technology, commensurate with our students' experience. We were also sensitive to choosing a design tool, consistent with the computing environment at Dartmouth, and the particular fabrication technology.

Besides MCNC, we considered using the MOSIS foundry service commonly used in VLSI design courses, with an additional micro-mechanical release step added at the end of the process [10]. We also considered using the surface micro-machining process made available by Analog Devices to the public, under a grant from ARPA. Ultimately, we chose the MCNC process because we wished to place less emphasis on the microelectronic aspects of device fabrication, and more emphasis on non-microelectronic aspects. The MCNC MUMPs process, with two mechanical polysilicon layers, was most attractive from this perspective.

We had determined to offer the course during the winter quarter. The selection of MCNC reinforced this choice. Since students must measure and characterize their design projects prior to receiving a grade, it was imperative the finished wafers be returned from the foundry prior to the end of the academic year. MCNC's project receipt deadline, and fabrication schedule, matched the end of our winter quarter (mid-March), and end of our spring quarter (early June), respectively.

In terms of software design tools, we considered *magic* and L-Edit. Cadence was briefly considered, but its cost was prohibitive, and most users reported it to be unwieldy, especially in an academic environment. L-Edit has the advantages of an intuitive user interface and running across platforms (UNIX/Macintosh/PC).

Each group was given a 1 cm^2 area to execute their projects. Students were encouraged to define their own design projects, based on response to case studies presented in class, and their own interdisciplinary engineering experience at Dartmouth. Since all students had completed the introductory design course during their freshman or sophomore years, we were able to draw on the principles of this class [10] in encouraging students to envision and develop their own designs. Some examples of these are given in Table IV.

TABLE IV
Student Projects

Project	Device	Description
Micro-fluidics		Exploration of passive and active devices for amplification and control of fluids
	Passive Amplifier	Pressure transducer with gain
	Active Amplifier	Pressure transducer with electrically controllable throat size
Biological cell resistivity		Exploration of methods to hold cells, and measure their temperature-dependent resistivity. Devices have embedded thermocouples and resistive heaters
	'Waffle iron'	Cells sit atop an electrode. The second electrode is hinged, and placed mechanically atop the cell
	'Accordion'	Both electrodes are hinged, and hold the test cell between them laterally
Micro-antennas		Devices to measure electromagnetic fields at small size scales
	Electrical antenna	Single-pole antennas, some shielded, some not; some with ground planes, some without; of various lengths

	Magnetic antenna	Micro-solenoids for measurement of magnetic flux
Micro-counters		Geared counters of vibrational or rotational motion. Some have built-in electrostatic actuators for test
Micro-mirrors		A variety of electrostatically controlled devices with large deflection angles to explore high-contrast, digitally activated mirrors

F. *Textbook*

No appropriate text was available in time for this course. Our own course notes, and original source material from the periodical literature, was utilized.

V. Institutional Relationships

A. *Relationship to Government*

The National Science Foundation provided original and crucial support for the course development.

B. *Relationships to Industry*

Industrial relationships have been important to the development of the course, and the facilities it calls upon. Analog Devices in Wilmington, MA provided financial support during the start-up phase of the Solid State Microstructures Lab, and has continued to provide occasional and graduate research support. IBM in Essex Junction, VT has provided equipment, materials, and occasional materials analysis. Most recently, IBM provided the boron solid diffusion source disks used in our micro-diaphragm laboratory.

The AT&T Foundation has provided financial support for the summer workshop on micro-machines, for students stipends.

C. *Relationship to Organizations*

MCNC has provided staff support for student micro-machine designs, submitted as part of their ARPA-funded MUMPs (Multi-Use MEMS Process) foundry service. Their cell libraries have been valuable as a source for examples and templates of MEMS devices. Their yearly users' workshop, last held in October, 1994, has been an important venue for information exchange, with professionals from government, industry, and academe, concerning MEMS research and teaching, at both the graduate and undergraduate levels.

D. *Relationships to Other Universities*

MIT's Microsystems Technology Lab (MTL) has provided a venue for testing MEMS-related research ideas at the graduate level, beyond those available through MCNC. Faculty and staff at MTL have offered important advice which benefitted this course.

Spelman College and Morehouse College in Atlanta are partners with Dartmouth in a related project (also funded by NSF, and by the AT&T Foundation), a summer workshop for minority students in science and engineering covering the same topics addressed in the course described here.

VIII. Evaluation and Dissemination

A. *Student Feedback*

Following completion of the course, students feedback was solicited, and is summarized here. Their comments have merit for any undergraduate course in micro-machines.

Presentation of process science should focus on the basics of: diffusion; chemistry; oxidation; ion implantation; photolithography; mask-making. For instance, we attempted to introduce point defect theories of diffusion; students felt this was unnecessary.

Increased emphasis should be placed on mechanical behavior, the relationship of mechanical behavior to material properties, and dynamic response of mechanical systems.

Students sought more visualization. For instance, they expressed a desire to see examples of MCNC MUMPs-based devices, especially SEM pictures of such devices, earlier on in the course. Side-by-side comparison of L-Edit layouts and SEMs of final devices was also suggested strongly.

Students emphasized that design rule checks should be done during the entire design process, and not reserved for the final few days. Also, they suggested setting a design deadline several days prior to the actual MCNC deadline, to allow slack for correction of errors after final design reviews.

Students suggested projects be smaller in size, to allow greated focus on a smaller number of devices. Also, they desired the opportunity to express both individual, as well as the required group, designs.

The PME and CaMEL libraries were regarded highly. Mechanisms to create even broader design and cell libraries, both on-campus and across the Internet, were strongly encouraged.

B. *World-Wide Web*

A full description of the course and related materials can be found at the URL http://hypatia.dartmouth.edu/courses/es65/es65.html, in order to promote the widest dissemination of course developments. In the near future, access will also be provided via the Semiconductor Subway (http://www-mtl.mit.edu/subway.html), and the MEMS Information Clearinghouse (http://mems.isi.edu/mems).

We utilize the Web for information dissemination in the Solid State Microfabrication Lab. This includes lab procedures on individual equipment, description of lab exercises, and safety information. Following completion of the course, students post information on their design projects on the Web.

X. Conclusions

We have developed an undergraduate course in micro-machine science and technology. The course emphasizes the science of micro-fabrication and micro-machine behavior through classroom lectures, homework assignments, and exams. Hands-on instruction in the practice of micro-machine fabrication, emphasizing both surface and bulk micro-machining techniques, are taught on-site in a small cleanroom. Principles of design, similar to those encountered by many undergraduates in VLSI design courses, are emphasized in a culminating design project. The foundry facilities of MCNC are used to execute the designs.

Acknowledgments

The staff at MCNC (Karen Markus, Dave Koester, and Allen Cowen) has provided invaluable help throughout the project phase of the course. Jack Judy of the University of California, Leslie Field of HP, and Richie Payne of Analog Devices have provided videos of MEMS devices for illustration and instruction. Financial support from the National Science Foundation (Grant DUE-9354726) and the AT&T Foundation is acknowledged with gratitude. Consultations with Marty Schmidt at MIT-MTL were greatly appreciated. Continuing support and encouragement from Analog Devices, especially Richie Payne and Dennis Buss, has been crucial to our efforts.

References

[1] No slight is intended for the contributions and importance of manufacturing, reliability, packaging, test, and other important endeavors.

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[3] The technology of micro-machines is taken to include microelectromechanical systems (MEMS), micro-sensors, micro-actuators, micro-transducers – any device, in short, manufactured using micro-fabrication techniques, which is not purely microelectronic.

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[7] Our work is funded by the National Science Foundation's Division of Undergraduate Education, under Grant DUE-9354726. Our related micro-machine summer workshop for minority students in science and engineering has received additional funding from the AT&T Foundation. Other institutions working on micro-machine curriculum development include: the U. of Minnesota (NSF Grant ENG-9212159, W. P. Robbins, *et al.*, PI); UCLA (K. Pister); Cal Tech (Y.-C. Tai); and U. Illinois-Chicago (NSF Grant ENG-9315420, G. Maclay, PI).

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