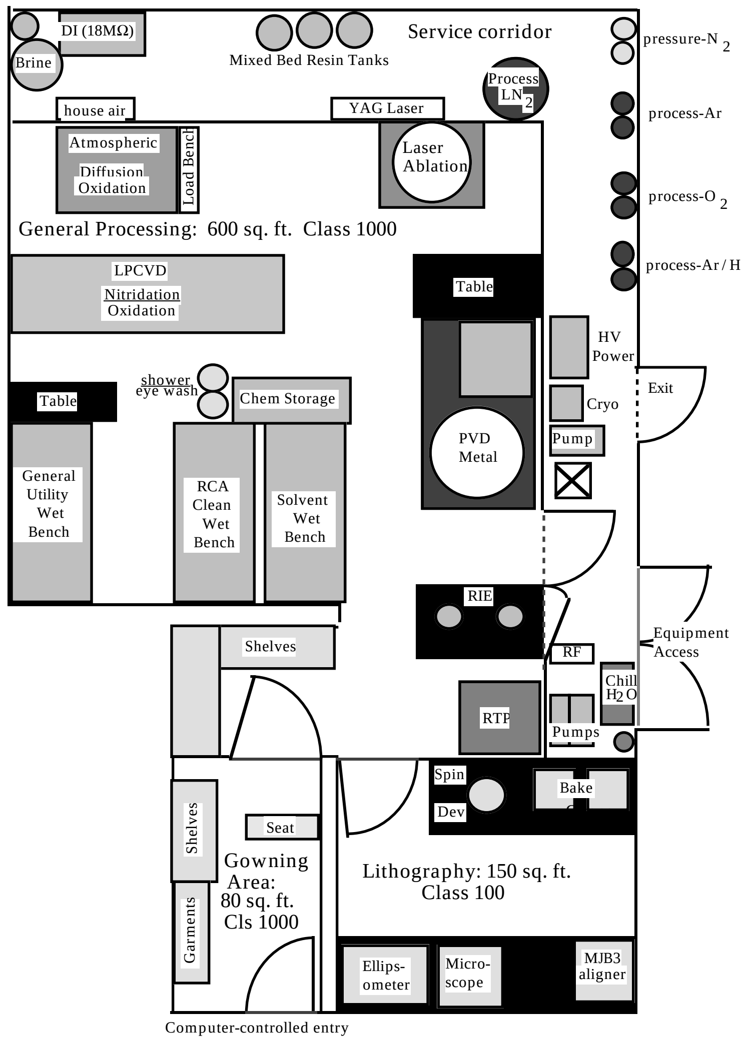

Figure One: Floor plan of the Solid State Microstructures Laboratory (SSL)

21. “Capacitance measurements in thin-film high-T_c superconducting capacitors.” Sanjeev Dugar A.B. ’93. Supported by NSF-DMR REU grant, Winter 1992.

22. “Fabrication of a laminar fluidic amplifier on silicon.” Wayne Bantner A.B. ’92. Senior honors thesis advisor. Elected to Sigma Xi. Now employed by Motorola, Inc., Libertyville, IL.

23. “Fabrication of micron size Rayleigh jets through micro-machining.” Nicholas Mourlas A.B. ’92. Senior honors thesis advisor. Elected to Sigma Xi. Now employed by Reliable Power Products, Franklin Park, IL.

24. “Switchable thermocouple array.” Todd Cook A.B. ’93. Senior honors thesis advisor. Research assistant, Summer 1992, supported under Analog Devices Career Development Professorship. Winner of Colligan Award as outstanding student in materials science.

25. “Design, construction, and characterization of a liquid phase oxide deposition system.” Ian Czaja ’94 (A.B. candidate and Presidential Scholar), Summer 1992. Work-study support (Fall 1992) through faculty discretionary account.

26. “Growth and measurement of thin oxides.” Noble Ekajeh ’94 (A.B. candidate). Supported Summer and Fall 1992 by E.E. Just Undergraduate Research Program.

27. “High-T_c devices and film deposition.” Jing Yan, Yale B.S. ’93. Supported Summer 1992 under NECUSE program.

28. “Studies of silicon wafer bonding.” April Whitescarver ‘96 (A.B. candidate). Supported Winter ’93-Spring ’93 under NSF-sponsored Women in Science Project internship program.

29. “Two-dimensional measurement of dopant density and thin-film stress with 50nm lateral resolution using scanning Kelvin probe microscopy.” Geoff Zawtocki ‘94 (A.B. candidate). Supported Winter ’94-Spring ’94 using Analog Device grant funds.

30. “Direct write electron beam control: Conversion from rastor to vector scanning”. Joseph Dadzie ‘95 (A.B. candidate). Support Summer '93 by E.E. Just Undergraduate Research Program and Winter ‘94 using Analog Device grant funds.

31. “Characterization of process for electron beam resist exposure and development” Christine Chen ‘97 (A.B. candidate). Supported Winter ’94 - Spring ’94 under NSF-sponsored Women in Science Project internship program.

32. “Laser ablation and optical properties of ferroelectric PLZT on $LaAlO_3$ and YBCO” David Moore, Middlebury College B.A. ’93. Supported Summer 1992 under NECUSE program and NSF-DMR (REU) grant.

33. “Laser Ablation Deposition of Superconducting $YBa_2Cu_3O_x$ for use in Optical Studies”. Daniel G. Crosby A. B. ‘90. Senior honors thesis. Now employed by Tracer Technologies, Sommerville, MA.

34. “Techniques for Modulated Optical Studies of $YBa_2Cu_3O_{7-\delta}$”. David Handron, A. B. ‘90. Senior honors thesis. Now studying physics in graduate school at Cambridge University, England.

term-long laboratories through Engineering Sciences 63 (Science of Materials), are given great responsibility. They must make basic decisions about how their experiments are to be designed, what resources are required to execute them, and how the experiments will proceed. Of course, this approach, at the undergraduate level, requires increased supervision and personal feedback, compared to conventional lab experiences.

ACKNOWLEDGMENTS

Portions of student research described in this paper have been supported by equipment grants from NSF (through the ILI program, Grant DMR-8951673; and through the EREG program, Grant MSS-9010482), IBM (through Project NORTHSTAR, the IBM Technical Gifts Program), Analog Devices, Inc., and the Hewlett-Packard Foundation. Direct research support has come from NSF (Grant DMR-8914240, including Research Experiences for Undergraduates Program supplements), Analog Devices, Inc. (through a Career Development Professorship granted to AKH), the Office of Naval Research, and the New England Consortium for Undergraduate Science Education (NECUSE).

APPENDIX

Impacts Of The Curriculum On Undergraduate Research And Individual Students

1. "Semiconductor measurement software." Andrew Wells A.B. '89. Supported Spring 1988 under Dartmouth Work-Study and Analog Devices Career Development Professorship programs. Now a Ph.D. student at the California Institute of Technology.

2. "Capacitance measurement software", and "Linear voltage ramp hardware for quasi-static capacitance measurements." Jian-Qi Tan A.B. '90. Supported Winter-Spring 1989 under Dartmouth Work-Study and Analog Devices Career Development Professorship programs. This work encouraged him to complete an M.S. degree at Dartmouth, studying high-temperature superconducting micro-fabricated devices.

3. "Raster scanning electronics for laser ablation of high-T_c thin films", and "SiGe Poisson-Schrödinger numerical equation solver." James Di Carlo A.B. '91 (Presidential Scholar and independent study/senior honors project). Winner of Colligan Award as outstanding student in materials science. Now a Ph.D. student at Stanford University in Applied Physics.

4. "Raster scanning electronics for laser ablation of high-T_c thin films." Edward Truex A.B. '91 (Presidential Scholar). Subsequently completed an M.S. degree at Dartmouth. Now employed by Digital Equipment Corporation, Hudson, MA.

5. "Lock and entry accounting system for Solid State Laboratory." Rachel Batto A.B. '90. Supported Winter 1990 under Dartmouth Work-Study and Analog Devices Career Development Professorship programs. Subsequently completed M.S. degree in micro-structure of ice and related materials at Dartmouth.

6. "Parallel architectures and Monte Carlo simulation of electron flow in silicon." Arif Irfanullah A.B. '91. Supported Summer 1990 under Analog Devices Career Development Professorship. Now a M.S. student at Stanford.

7. "Design and construction of a resist spinner for photolithography." Herbert Anderson A.B. '91. Supported Summer 1990 under Solid State Lab budget and Dartmouth Work-Study Program. Now employed by McLean-Fogg Co. near Chicago, IL.

8. "High-temperature superconducting thin-film deposition and characterization." Adam Payne, Yale B.S. '91. Supported Summer 1990 under NECUSE program and NSF-DMR grant. Completed his A.B. degree in Applied Physics at Yale, including development of a direct-write, scanning electron beam system for fabrication of nano-structures in Prof. Mark Reed's laboratory. Subsequently received a Fulbright scholarship for study in Germany.

9. "Parallel architectures and convolution simulation of electron flow in silicon." Steve Kovacs A.B. '92. Supported Fall 1990 under Analog Devices Career Development Professorship. Now a M.S. student at UCLA.

10. "Carousel target holder for in situ multi-layer deposition of thin-film high-temperature superconductor, and characterization of films using SEM." Karen Daniels '94 (A.B. candidate). Supported Fall 1990-Winter 1991-Spring 1991 under NSF-sponsored Women in Science Project internship program. Majored in Physics.

11. "Substrate temperature control with feedback for high-temperature superconductor deposition system." Rebecca Grube '94 (A.B. candidate). Supported Fall 1990-Winter 1991-Spring 1991 under NSF-sponsored Women in Science Project internship program. Majored in Physics.

12. "Examination of fluid flow in micro-channels." Luis Paz-Galindo A.B. '93. Now completing his B.E. degree at Dartmouth.

13. "Computer modeling of fluid flow through microchannels." Mulumba Kiwanuka-Natigo A.B. '92. Supported Summer 1991 and AY 1992 (work-study) under Analog Devices Career Development Professorship. Supported Summer 1992 by E.E. Just Undergraduate Research Program. Now employed by Logica UK, Ltd., in England.

14. "Modifications and characterization of a vacuum leak detector." Sohan de Mel, exchange student, Vassar College. Supported Summer 1991 under Analog Devices Career Development Professorship. Completed his B.E. degree at Thayer School, 1992.

15. "IEEE-488 bus and instrument control for capacitance vs. voltage measurements." Navaid Farooqi, exchange student, Vassar College. Supported Summer 1991 under Analog Devices Career Development Professorship. Completed his B.E. degree at Thayer School, 1992.

16. "Continuation work on the laser ablation temperature monitor program." Michelle Maurer, Smith College A.B. '93. Exchange student, Summer 1991, through the Liberal Arts Connection program. Supported in part by NSF-DMR (REU) grant..

17. "Automated resistance vs. temperature measurement" (project 1) and "Improvements to laser ablation raster control" (project 2). Alison Spencer, Amherst College B.S. '92. Supported Summer 1991 under NECUSE program and NSF-DMR (REU) grant.

18. "Studies of thin-film, high-temperature superconductors." Teressa Trusty '95 (A.B. candidate; subsequently transferred to Stanford). Supported Winter '92 under NSF-sponsored Women in Science Project internship program.

19. "Closed-loop substrate temperature control for a high-temperature superconductor deposition system." R. Jed Buchanan A.B. '93 (Presidential Scholar). Winter 1992. Now applying to E.E. graduate programs.

20. "Capacitance measurements in thin-film high-T_c superconducting capacitors." Joseph Lin A.B. '93 (Presidential Scholar). Winter 1992.

program has impact, not only on the students, but on the institutions where they next carry their interests.

Our program has also attracted students from regional liberal arts colleges lacking programs in engineering. These students have enrolled in a 3-2 program leading to simultaneous science and engineering degrees, from their home institutions and Dartmouth, respectively. A number of them have been engaged in MFST projects. Also, a number of students have been supported in summer MFST research work through New England Consortium for Undergraduate Science Education.

In conjunction with Engineering Sciences 65, we are developing a Summer Workshop for students from, initially, Spelman and Morehouse Colleges. Students will come to Dartmouth for the summer, on paid fellowships, to learn the principles of MFST as applied to MEMS. The intention is to increase the number of minority undergraduates with expertise and interest in MEMS, and encourage them to enter industry and/or graduate school, and engage themselves in lifelong careers in this field. The Workshop has received grant support from NSF's Division of Undergraduate Education.[10]

Impacts on Industry

Our students have taken their micro-fabrication expertise and interests into industry, as well. Here, the impacts are perhaps less direct. Their micro-fabrication experience becomes less a skill used and enhanced on a day-to-day basis, and more a part of the context of experience in which they can place and understand their every-day work.

Local industry has worked with our undergraduates, mentoring them in research projects related to their own interests in MFST. Three companies in particular -- Creare, Dean Technologies, and Spectra -- have created micro-structures of interest using the SSL, and/or written collaborative SBIR research proposals with SSL students, faculty, and staff. One SBIR proposal has received funding, involving deposition of high-temperature superconducting materials. Our portion of the contract explicitly involves undergraduate students in the execution of the specified tasks, and provides an excellent venue for undergraduates to experience contract engineering development activities, beyond academic and industrial research.

Impacts on the Undergraduate Curriculum, and Opportunities for Minorities in Engineering

The success of the programs revolving around the SSL -- as well as the success of other programs, such as the NSF-funded Women in Science Project[11], which seeks to support and maintain interest in the sciences among undergraduate women through financial support and faculty mentoring of first-year research projects -- have resulted in attraction of further outside funding. For instance, NSF's Course and Curriculum Development Program in the Division of Undergraduate Education, has funded our proposal to develop a new, upper-level undergraduate course in Micro-machining.[10] In order to expand the impact of the course beyond Dartmouth, a summer workshop for minority students is an integral part of this project. The workshop seeks to inspire these students, with an interest in science and technology in general, and not necessarily, specifically in micro-machining, through hands-on experiments, seminars taught by leaders in the field from academia, industry, and government, and visits to industrial micro-fabrication facilities. The track record of support for undergraduate research in micro-fabrication through the SSL facilities is a key component of these proposals.

Impacts of the Curriculum on Undergraduate Research and Individual Students

Beyond the direct curriculum impacts of our program. individual students have both made contributions to the program, as well as drawn experience from it. Specific details are provided in the Appendix. Generally, however, each individual has engaged in a research project, with a faculty mentor. The students are encouraged to act independently, by maintaining lab notebooks, managing portions of budget, and of course designing, executing, and analyzing experiment. A written report is required of each student upon completion of the research project. These reports are archived, and frequently become the starting point for later students picking up a particular research thread.

To date, twenty-five men and eight women have undertaken individual research projects in MFST-related areas. Seven seniors, seventeen juniors, four sophomores, and five freshmen have participated. Seven of the thirty-three have been from institutions other than Dartmouth. Taken another way, the group is comprised of three Blacks, seven Asians, one Hispanic, and twenty-two Caucasians.

CONCLUSIONS

We believe our program in MFST is making significant impacts at Dartmouth and beyond. From our description, however, it is clear that the program, as envisioned and executed at Dartmouth, requires a considerable investment in time, capital equipment, and personal commitment on behalf of faculty and staff. Replication of this program at other institutions will likely take other forms.

We emphasize that, while other institutions today have undergraduates involved in upper-level microelectronics laboratory courses and senior thesis projects, it is unusual to involve them earlier on in their courses of study. Undergraduate participants in our program include first-year women (through the Women in Science Project), and many second and third year students. These students receive hands-on exposure and experience with sophisticated lab equipment in a research environment, rather than in a student lab station environment. Even those first-year women involved in the MFST program, and those students participating in

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[11]K. E. Wetterhahn and C. B. Muller, "Women in Science Project". Awarded National Science Foundation funding 1 Sept 1991. Grant #DUE-9153478.

ink-jet printers, devised a fabrication method for sub-50µm nozzle orifices. He measured the behavior of these nozzles experimentally, and compared the results to theory. Incidentally, he discovered a novel technique to bond silicon wafers together, which is now the subject of another undergraduate research project, as well as a pending research proposal. The student presented his work at the annual Sigma Xi seminar series at Dartmouth, and received second prize for his efforts. Subsequently, he took a development engineer position with Reliable Products in the Chicago area, and has applied his knowledge of micro-characterization techniques to debug materials- and process-related problems in that company's fabrication sequence. He has been accepted in the Ph.D. program at Carnegie-Mellon University, where he intends to explore the use of micro-fabricated electrode arrays to interface with nerve cells.

Studies Of Silicon Wafer Bonding

The undergraduate mentioned in the preceding paragraph discovered a new method to bond two silicon wafers together, during the course of his senior thesis research work. This work was picked up, first, by a M.E. student for a course project, and subsequently by a freshman involved in the Women in Science Project[10] The latter student attempted, during her first year, to demonstrate silicon wafer bonding using nickel silicide, at temperatures down to 300°C. After an initial learning period, she designed her own experiments, designed and built necessary 'jigs' and holders in the School's machine shop, executed her experiments, analyzed the results, and made recommendations concerning possible improvements based on her observations. Following a summer internship with an oil and gas exploration firm in Texas, she is currently a sophomore, planning to major in engineering.

High-Temperature Superconducting Device Materials and Fabrication

A grant from the NSF Division of Materials Research was used to design and built a pulsed laser ablation system for deposition of high-temperature superconducting materials. Twelve different undergraduates participated in the evolution of this system, and its use in thin-film and microelectronic device research. The individual contributions are described subsequent to this section. The success of their contributions to the development of this system can be measured, in part, by its ability to attract further research funding. Most recently, a Dept. of Defense Small Business Innovation Research grant was made to a local company, Creare, Inc., on which Thayer School is a prime sub-contractor due to this system.

OUTCOMES

Impacts on the Engineering Curriculum at Dartmouth

Undergraduates are encouraged to learn and use the facilities of the SSL through three specific, *existing courses*.

Engineering Sciences 63 (Science of Materials), is a core course in the Engineering Sciences major. It requires the completion of a significant laboratory project. Roughly twenty-five percent of engineering majors over the past four years have completed this requirement through experiments conducted in the SSL. Examples include: design, fabrication, and characterization of MOS capacitors and p-n junction diodes; deposition and characterization of thin metal films, including patterning of these films into narrow wires using photolithography and etching; studies of oxide growth; and characterization of grain growth in thin metal films, crucial to the understanding of electromigration phenomena in integrated circuit technologies.

Engineering Sciences 184 (Semiconductor Theory and Devices), utilizes devices built in the SSL to demonstrate the relation between semiconductor device theory, and actual measurements. Devices measured include those fabricated in ENGS63, resulting in a synergy between courses. This is particularly important in ENGS184, since it is comprised of roughly one-half junior- and senior-level undergraduates, and one-half graduate students in engineering and physics.

Engineering Sciences 194 (Physics and Chemistry of Semiconductor Device Fabrication), is also a 'swing' course, including advanced undergraduates as well as graduate students. It engages students through, especially, a hands-on, term-long laboratory project in the SSL, where complete MOSFETs are built and tested. This project experience was made possible by the MFST program described here.

New courses are also under development, to increase the impacts of MFST on the undergraduate curriculum.

Engineering Sciences 73 (Electronic Materials), is targeted for upper-level undergraduates, and intended to cover in depth the nature, structure, and properties of important electronic materials. By need and design, this course will include a laboratory component utilizing the facilities of our MFST program.

Engineering Sciences 65 (Science and Technology of Micro-machines), will be principally an undergraduate course, though interested graduate students will also be encouraged to enroll. The focus will be on the application of MFST to MEMS. Again, a quarter-long lab project will be undertaken, wherein students will design MEMS devices for fabrication. Students will have the choice to emphasize process design, or device design. Those choosing process design as their emphasis will fabricate their projects at Dartmouth, while those choosing the alternative path will have the option to fabricate their structures through the new MEMS foundry service available through the Microelectronics Center of North Carolina.

Impacts on Other Academic Institutions

Many of our undergraduates have gone on to graduate study in fields utilizing micro-fabrication techniques. The section 'Impacts on Individual Students' identifies where these students have gone to further their interests. So, our

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[10] A. K. Henning, "Undergraduate Curriculum Development in Micro-machine Science and Fabrication Technology". Awarded National Science Foundation funding 1 April 1994. Grant #DUE-9354726.

making (*kic* and *magic*, applications developed by the University of California at Berkeley), process simulation (FEDSS from IBM, and Suprem-III and Suprem-IV from Stanford University), and device simulation (FIELDAY from IBM, and Pisces from Stanford).

The resulting *Solid-State Microstructures Laboratory* (SSL) serves the College community, as well as local industry, as the focal point for a program in micro-fabrication-related teaching and research. The SSL layout, including major equipment footprints, is shown in **Figure One**.

Expenditures for the SSL itself totaled $750,000, which was paid out of the Department of Commerce grant. These expenditures included architectural and general contracting fees, as well as design and HVAC engineering assistance. Capital equipment was obtained using external grants from Analog Devices, IBM, the National Science Foundation, and Hewlett-Packard. Direct outlays from Thayer School budgets for capital equipment totaled approximately $100,000, and were primarily applied toward matching requirements from external grants.

During the start-up phase, a single faculty member (AKH) had responsibility for all aspects of lab and equipment design, operation, and maintenance. At present, a full-time, permanent staff member (CGL) is responsible for the day-to-day operation of the SSL. Salary support for this person is derived, half-and-half, from Thayer School and external research contracts and grants. Safety orientation and instruction for use of the lab is handled by the authors, and Dartmouth's Office of Biosafety. Maintenance for the SSL is handled by students, SSL staff, and the regular building maintenance crew. Operating budget for consumables is $6,000 per year. Estimated electrical cost is $12,000 per year, primarily used for the air handling and high-temperature diffusion furnace tasks[7].

GOALS

The goals of our program in MFST are (not necessarily in order of priority):

•Establish a strong program of micro-fabrication-related research and teaching at Dartmouth College;

•Incorporate micro-fabrication theory and experiments into the existing undergraduate and graduate curriculum, and create new undergraduate and graduate courses founded on MFST;

•Be a recognized leader in focused, selected research areas of micro-fabrication-related science and technology;

•Be a recognized leader in undergraduate MFST, consistent with the capabilities of the SSL. Leadership is measured by the extent to which we encourage undergraduates to pursue graduate study and industrial careers in MFST, through:
>>high-quality teaching
>>state-of-the-art research opportunities
>>encouragement to present and publish their work
>>faculty-industrial employer contacts
>>faculty-faculty contacts between Dartmouth and graduate schools offering program in MFST

•Facilitate the university-industry interface, through invitation of external research leaders in MFST to speak at seminars, give guest lectures, mentor undergraduate research projects, support research financially, and recruit students for post-graduation work;

•Use the SSL as a tool to assist local industry in new product development, including winning SBIR contracts.

[7]A premium was spent during design and construction of the lab, on a two-speed air handling unit, so that the electrical costs could be minimized during off-hour operation by cycling the air flow to a lower speed.

RESEARCH EXAMPLES

The undergraduate research goals have, in many ways, been met and exceeded. The first, functional metal-oxide-semiconductor capacitors and transistors were both fabricated first by *undergraduate* research assistants in the SSL. We offer several specific examples of research work by our undergraduates.

Thermocouple Transistor Design, Fabrication, and Characterization

Following the conception of the use of MOSFET structures as addressable thermocouple junctions on the micro-scale, an undergraduate shouldered the research responsibility for initial device and process design and development. This resulted in the fabrication of the first functioning transistors using the SSL. The devices are central to our research applications[8], and a successful patent application[9]. They also form the basis of a research contract with the Office of Naval Research to use the devices as a means to measure temperature at the micro-scale in thin films of tribological importance. The student, whose A.B. degree was conferred *summa cum laude* in 1993, is now completing a B.E. degree, and plans to go on with further, M.S.-level studies in this field. The M.S. student presently carrying out research on the ONR project was 'turned-on' to micro-fabrication through the undergraduate Science of Materials course (described below), and has been successful in continuing this work as a graduate student at Dartmouth.

Micro-Fluidic Jet Nozzle Design, Fabrication, and Characterization

Three students, in 1992, engaged in projects related to micro-fluidic nozzles and devices based on scaling Rayleigh's theory of fluid flow through orifices to the micron scale. One student, in conjunction with Spectra, a local company engaged in development of low-cost color

[8]X. Tian, F. E. Kennedy, Jr., J. J. Deacutis, and A. K. Henning, "The development and use of thin film thermocouples for contact temperature measurement." *Tribology Transactions* **35**, pp. 491-499 (1992).

[9]J. J. Deacutis and A. K. Henning, "Switchable Thermoelectric Element and Array". U.S. Patent No. 5,261,747, granted November, 1993.

satellite to the graduate-level educational thrust. To our knowledge, however, no institution in the U.S. has yet attempted to bring MFST, with emphasis on micro-machines as well as microelectronics, so deeply into the undergraduate experience. Nor has this been undertaken at an institution whose principal mission is undergraduate teaching and research.

INSTITUTIONAL BACKGROUND

Thayer School of Engineering was founded in the 1860's by Sylvanus Thayer (who had earlier revitalized the engineering program at West Point). Thayer's goal was to enhance the level of engineering expertise outside the military, by educating professional engineers, who would make lifelong practice of the engineering arts and sciences. A strong, interdisciplinary character was manifested in the curriculum early on, through courses emphasizing broad-based fundamentals and scientific flexibility. The School has no formal departments, which further encourages interdisciplinary activity in teaching and research.

In the 1950's, Thayer School assumed responsibility for undergraduate instruction in the Engineering Science major at Dartmouth. As expected from the conjunction of an interdisciplinary-oriented graduate school with a liberal studies undergraduate college, broad-based learning which seeks to cross the boundaries between traditional disciplines, was and is one of the major goals of the engineering faculty.

In the mid-1980's, the School's Board of Overseers determined to expand the size of the faculty, physical plant, and undergraduate and graduate student enrollment. Utilizing funds raised from private sources, as well as a $15M grant from the U.S. Department of Commerce, this expansion began in 1986, and was substantially completed by 1991.

The School currently has 27 tenure-line faculty, four research professors, and 34 adjunct professors. Approximately 120 graduate students pursue M.E., thesis M.S., and Ph.D. degrees. An additional 35 students participate in the fifth-year, ABET-accredited Bachelor of Engineering degree program. Undergraduate enrollment in the Engineering Sciences major, leading to the A.B. degree, numbers between 80 and 90 students in each class. External research funds reached $6M in 1992-3.

MICRO-FABRICATION INFRASTRUCTURE DEVELOPMENT

The expansion allowed several new areas of research and teaching to be targeted for inclusion into Thayer School. One of these areas was in MFST. The Dept. of Commerce grant contributed, beginning in 1987, approximately $750,000 to the design and construction of a small (1000 sq. ft.) **clean room**, with both Class 100 space for lithography, and Class 1000 space for general microfabrication processes. This phase of the lab development covered de-ionized water, house vacuum and compressed air, specialty (including toxic) gas plumbing, a separate HVAC system dedicated to the lab, furniture, two bake ovens for lithography, and three laminar flow/exhaust hoods for wet chemical processing.

Processing equipment became next in priority for lab development. Due to the high cost of semiconductor processing tools, most equipment purchased during this phase was used or re-furbished. Using some additional funds directly from Thayer School, a contact lithography system (Karl Suss MJB3-UV400) was purchased, as was an AG410 rapid thermal oxidation and anneal furnace. As part of an undergraduate research project, a photoresist spinner was created using a mask cleaning system donated by IBM in Essex Junction, VT. An oxidation and diffusion furnace system donated by General Electric contributed virtually new mass flow controllers. These became part of a student project, to design and build mass flow controls for three used and re-built Thermo Mini-Brute atmospheric diffusion-oxidation furnaces. A production-quality, three-furnace LPCVD deposition system for oxide, nitride, and polysilicon deposition was donated by Analog Devices. Funds from an NSF-EREG grant, along with matching funds from Dartmouth, were used to purchase a scanning electron microscope (Zeiss DSM 962), with direct-write-on-wafer and mask-making lithographic capabilities. A reactive ion etch system was built in-house, using undergraduate and graduate student labor, and components scavenged from a radio-frequency plasma barrel etcher system (donated by IBM-Essex Junction). A physical vapor deposition (electron beam) system was obtained from U.S. government surplus, for aluminum and other thin-film metallization. A pulsed laser ablation system, for high-temperature superconductor thin-film deposition, was built through combined undergraduate and graduate student efforts, using funds from an NSF-DMR grant.

Test and measurement equipment was the remaining priority from the perspective of equipment outfitting. An NSF-ILI grant allowed purchase of a Gaertner L104 SA two-wavelength ellipsometer for thin film materials measurements. Corporate donations from IBM-Essex Junction and the Eaton Corporation brought a Nanospec critical dimension measurement system, and a four-point probe resistivity measurement system. Funds from Analog Devices, the NSF-ILI grant, and two Hewlett-Packard Foundation grants allowed purchase of electrical equipment related to semiconductor device analysis and materials measurement[6].

Software for mask-making and process simulation were also important considerations. Donation of high-speed engineering workstations by IBM (RS6000), Sun (Sparc I), and Hewlett-Packard (HP9000 Series 715 and 735) created the necessary hardware environment. Software was obtained through low-cost academic pricing, research grant, by donation, or freely over InterNet, for carrying out mask-

[6]HP 4142 DC Source Monitor, HP 4284A LCR meter, HP 4140 Picoammeter and Source, HP 51540A 100MHz oscilloscopes, Tek AFG 5101 Programmable Pulse Generator, HP 9000-340M workstations for IEEE-488 instrument control and data acquisition, HP 8753C 3 GHz spectrum analyzer, MMR Technologies Low-Temperature Microprobe, Rucker & Kolls auto-step probe station, Micromanipulator probe stations

Undergraduate Research in Micro-Fabrication Science and Technology at Dartmouth College

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ABSTRACT

If the delivery of engineering education is taken to include both teaching and research, then it is imperative that research activities for undergraduates be fostered and supported. Further, interplay between teaching and research must also be encouraged, so that these two activities reinforce each other, with the boundaries between them easily bridged.

As applications of micro-fabrication science and technology spread beyond the realm of microelectronics, it becomes increasingly important to incorporate micro-fabrication into undergraduate education. This paper describes the undergraduate research activities at Dartmouth related to micro-fabrication, and their relationship with the undergraduate engineering curriculum.

INTRODUCTION

Our program in micro-fabrication science and technology (MFST), and our emphasis on **undergraduate** participation and leadership in this field, stem from a national need, and a local reality.

The national need is two-fold. It is based on the mature industry of *microelectronics*, and the emerging field of micro-electrical mechanical systems, or *MEMS*. The former is well-known. There are still lifelong career opportunities for undergraduates to enter industrial jobs, or graduate schools, which emphasize microelectronic fabrication. The industry is in a mature phase, however, and the long-term prospects for careers in microelectronics have clouded. The case for MEMS, on the other hand, is best described in the NSF publication, entitled "Small Machines, Large Opportunities"[1]. While some would still argue that MEMS are 'solutions in search of problems', recent products (such as a low-cost accelerometer for automobile air-bag deployment[2]) prove the worth of this emerging technology. We believe this application for MFST presents at once the greatest breadth and depth of opportunities for our students. This belief has been a major driving force behind the development of our MFST program.

The local reality is that Dartmouth College is a small university. Undergraduate education remains its emphasis, though there is significant graduate-level research activity. In this context, Thayer School offers unique opportunities to bring advanced technology into the academic life and experience of undergraduates.

Microfabrication laboratories, courses, and projects emphasizing microelectronics are familiar to the undergraduate curriculum[3]. Similar laboratories, dedicated to research and teaching centered on MEMS at the graduate level, are becoming more commonplace, with seminal work coming mainly from the U.C.-Berkeley Sensors and Actuators Center, the Microsystems Technology Laboratory at MIT, the microfabrication lab at the University of Michigan, and somewhat smaller efforts at a handful of other large universities. MIT began development of an undergraduate MEMS fabrication course in 1991[4], and the University of Minnesota recently received NSF funding to coordinate instructional development with research in MEMS.[5] In both cases, the undergraduate component is a

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[1] "Small Machines, Large Opportunities: A Report of the Emerging Field of Microdynamics". Report of the Workshop of Microelectromechanical Systems Research (1987). Published by AT&T Bell Laboratories and the National Science Foundation (W. Trimmer, editor).

[2] F. Goodenough, "Airbags boom when IC accelerometer sees 50 g". *Electronic Design* **39**, p.45 (8 Aug 1991).

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