

Integration of Microscale Fabrication in an Undergraduate Manufacturing Elective*

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This work describes the introduction of microscale manufacturing education into the mechanical engineering curriculum at the Purdue University. Lectures and laboratories on microscale manufacturing are integrated into an undergraduate technical elective course, Principles and Practices of Manufacturing Processes. Three one-hour lectures introduce fundamental microfabrication processes with a focus on soft lithography. Two microfabrication laboratories have been designed, developed, and implemented using a newly developed pilot facility within Purdue's Multiscale Manufacturing Center (MMC). Through the laboratories, students gain hands-on microfabrication experience and achieve devices with features as small as 10 μm . We expect this work will serve as a model to establish similar manufacturing educational laboratories at other institutions.

INTRODUCTION

THE IMPORTANCE of the manufacturing enterprise and the need for improved manufacturing education are becoming increasingly recognized by higher educational institutions across the world. Surveys of American industry have revealed that the number of manufacturing education programs in the United States is growing substantially [1]. Moon [2] recently reported on a manufacturing education model that includes the establishment of a new manufacturing engineering curriculum. Similar curriculum reforms that focus on manufacturing education have also been reported [3,4]. An outline of the major forces that shaped the development of manufacturing enterprises in the United Kingdom and how these have changed over time was presented by Burns [5]. Brennan [6] described recent curriculum reforms in manufacturing education toward the satisfaction of academic requirements for professional engineering registration in Canada. Collectively, these studies and initiatives demonstrate significant activity in reforming manufacturing education toward the evolving needs of global industries.

Today, microfabrication plays an important role in many promising interdisciplinary areas of science and engineering, including studies at the atomic and bio-molecular levels that employ micro-electro-mechanical systems (MEMs). To equip the next generation of engineers, a foundational understanding of microfabrication is needed, and a growing demand exists for integrating

microfabrication into existing courses on manufacturing [7]. However, microfabrication education that emphasizes hands-on laboratory experience is often limited to the graduate level because of the expense and complexity of microfabrication laboratory procedures. For instance, a typical chrome mask made by e-beam lithography is very expensive, and it is often impractical for each student in a course to fabricate an individual mask. Common procedures require the use of dangerous chemicals, such as those used in etching processes, that require specialized training and safety certification. On the other hand, soft lithography is a recently developed microfabrication technique based on printing and molding of 'soft' materials [8] that involves many of the basic microfabrication processes such as photomask production, spin coating, and photolithography. Unlike silicon-based microfabrication, inexpensive masks and non-toxic chemicals are used in these procedures. Consequently, soft lithography minimizes the need for specialized equipment and training, and microfabrication laboratory modules based on soft lithography are quite practical for introduction at the undergraduate level.

This paper describes the development of a laboratory facility and its use in a course-based laboratory module employing soft lithography to introduce microfabrication principles. The module includes three lectures and two laboratories and has been integrated into an undergraduate manufacturing course. The objective is to offer the students fundamental knowledge and hands-on experience in microfabrication. The new laboratory facility in Purdue's School of Mechanical

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Engineering represents an extension of a well established student machine shop for traditional manufacturing instruction to include basic micro- and nano-scale manufacturing processes. Collectively, we refer to these facilities as the Multiscale Manufacturing Center (MMC). The new pilot facility emphasizes soft lithography processes that are now commonly used to create microfluidic devices. Through this laboratory improvement effort, six modules have been developed for six different courses [9]. Here, the manufacturing course has been selected to illustrate the logistics of module implementation and to highlight the importance of improving manufacturing-related education in engineering curricula.

The following section introduces the basic principles of soft lithography, and the subsequent section describes the MMC pilot facility's equipment and capabilities. Next, the integration of the microfabrication laboratory module into a manufacturing course is discussed, followed by results from a student survey.

SOFT LITHOGRAPHY

Recent advances in micrometer-scale patterning and molding of 'soft' materials, typically polymers, have allowed the efficient and inexpensive production of intricate microstructures with feature sizes of approximately 10 micrometers [10]. At this size scale, many useful features can be incorporated into prototypes for microfluidic elements and other MEMs structures. The distinguishing feature of a soft lithography manufacturing system is the replacement of expensive and complex sub-micron lithography and etching processes, which are necessary for solid-state electronic devices, with vastly simplified and time-saving processes that involve the use of standard office printers and 35 mm photography for the production of lithographic masks. These masks, which can be produced in a matter of minutes, are used to

pattern photoresist materials, which become relief masters for the creation of molded MEMs structures and devices. We note that these processes avoid the use of highly toxic chemical etchants and are therefore substantially safer for students than many microelectronics fabrication lab processes.

Soft lithography offers the opportunity for time savings and related pedagogical efficiency as compared to traditional, silicon-based microfabrication lab courses. In a typical soft lithography lab module, students actively experience all major fabrication processes in two lab periods and are closely involved in every process step, from computer-aided design to prototype molding.

DESCRIPTION OF LABORATORY AND EQUIPMENT

The MMC pilot facility was borne out of the vision of a group of eight mechanical engineering faculty members at Purdue. In the Fall 2002 semester, the College of Engineering provided funding to enhance the facility with the purchase of a lithographic mask aligner and an atomic force microscope, as well as several smaller pieces of equipment. Construction of the lab began in Fall 2002 with the purchase of a 144 sq.ft., class 10,000 modular clean room. The current facility layout is shown in Fig. 1. The following paragraphs describe the primary features of the equipment.

Bio/fume hood area

The lab contains a class-10 bio/fume hood (NuAire NU430 Class II B2) encompassing a solvent processing area, two programmable spin coaters (Suss Delta 10BM), and a sonicator (Branson 3500). The hood provides 1100 scfm of exhausted air flow, and in situ particle measurements have confirmed the class 10 categorization. The spin coaters are capable of handling wafers up to six inches in diameter and are fully programmable for all industry specifications. The sonicator

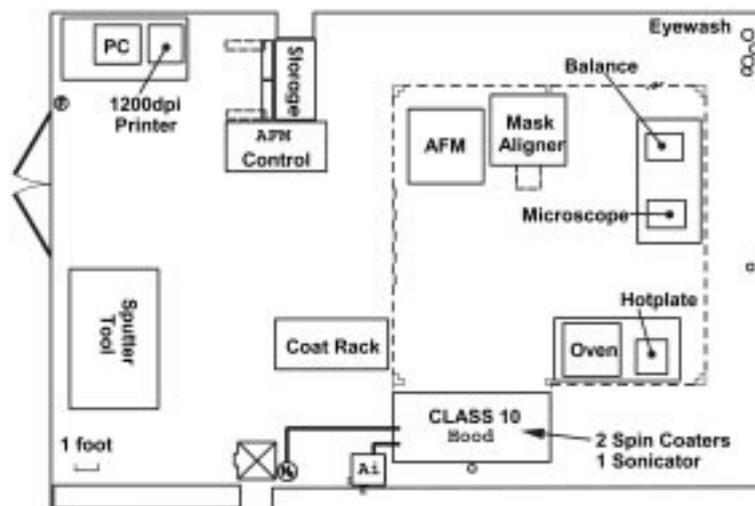


Fig. 1. Layout of the MMC pilot facility.

enables cleaning and abrasion of substrates for a variety of purposes.

Mask aligner

The Suss Microtech model MA1006 mask aligner can handle wafers of two, four, and six inches in proximity, soft contact and hard contact modes. Three, five, and seven inch masks can be used and aligned with features on the front of the substrate by reflected light microscopy as well as the back side by transmitted infrared (IR) energy. The IR backside alignment feature enables the processing of layered MEMs and micro-fluidic devices in which layers are aligned to each other and to through-holes located on the substrate. The 350 W Hg lamp and related optics deliver UV light between 350 and 450 nm wavelengths and provide an exposure resolution of approximately $3\ \mu\text{m}$.

This mask aligner model offers very little automation; thus, student users must understand in detail the operation of the machine and its capabilities. The aligner is typically used to expose SU-8 photoepoxy with patterns created by the students and printed on high-contrast black-and-white slide film.

Atomic force microscope (AFM)

The Digital Instruments Dimension 3100 atomic force microscope is used to image and measure a variety of small-scale structures created by the students. The AFM can handle samples up to eight inches in air or fluids. A variety of scanning techniques are available for the imaging of different samples. For micro-patterns in SU-8 photoresist and polydimethylsiloxane (PDMS), contact and tapping modes are most commonly used [11]. The AFM can measure features up to $\sim 6\ \mu\text{m}$ in height with a background noise of less than 0.05 nm. The positioning stage can scan an area of $125 \times 100\ \text{mm}$ with $2\ \mu\text{m}$ resolution and approximately 20 nm accuracy.

Lightbox/photographic mask-making

The tools for photographic mask making include a computer, a high-resolution (1200 dpi) laser printer, two 35 mm SLR cameras, a tripod, an $8' \times 4'$ lightbox, and a darkroom. Students design mask patterns on the computer and print them to single or multiple transparencies. Printing the patterns at a larger scale minimizes the printer requirements and also enables a level of quality control difficult to achieve when printing on a transparency at 1:1 scale. The transparencies are then mounted on the lightbox, and a 35 mm camera (Nikon FM3A with Nikkor 105 mm Macro lens or Olympus OM10 with 50 mm lens) is positioned on a tripod at a distance from the lightbox that corresponds to the reduction ratio needed to achieve the desired feature size. The 105 mm Nikkor Macro lens is designed for flatfield photography and will image the center and edge of the lightbox without distortion. The 50 mm Olympus lens is used when a higher reduction ratio is

necessary and produces images that compare favorably to the Nikon's. Each pattern can be exposed at a variety of settings to allow for variations in lighting and to guarantee that an optimal image can be chosen from the film roll. Each roll of film can hold multiple patterns and is developed in a darkroom. After drying, the negatives are cut into individual slides, the best exposure is evaluated, and the slide is mounted on a glass mask made specifically for the $24 \times 36\ \text{mm}$ image size of the slide.

Oven/hotplate

A Cole Palmer digital hotplate and Lindberg/Blue mechanical convection oven are used for soft- and hard-baking of photoresist and photoepoxy. Both are located within the cleanroom and can be set up with nitrogen environments to minimize oxidation and contamination. Both units have digital temperature control units that allow temperature settings of $40\text{--}325^\circ\text{C}$ and $40\text{--}300^\circ\text{C}$ for the hotplate and convection oven, respectively.

Other equipment

The bench at the top right of the clean room diagram (see Fig. 1) includes an analytic balance (Ainsworth M2200) for precise mass measurements of fluids and solids. The bench also contains an upright microscope (Leitz SM-LUX HL) for optical characterization of surfaces. The microscope includes a digital camera (PULNIX) for image recording. The bench also includes a jar desiccator for degassing of polymeric mold materials (e.g., PDMS). In addition, a sputter deposition tool (PE 2400-8J) is being installed outside the clean room. This tool provides three-target sputtering capability for thin-film deposition of a variety of metals, semiconductors, and insulators.

MICROFABRICATION LABORATORY MODULE DEVELOPMENT

ME363, *Principles and Practices of Manufacturing Processes*, is an undergraduate course developed by Professor Yung Shin over the past ten years. The objective of this manufacturing course is to give juniors and seniors in mechanical engineering a basic understanding of manufacturing processes that involve deformation and joining. The main topics of the course are (a) metrology, (b) material properties and testing, (c) introduction of machine tools and mechanics of metal cutting, (d) materials, geometry, life and wear of cutting tools and machinability, (e) computer numerical control, (f) forming processes, including composite and ceramics, and (g) non-traditional processes.

In the Fall 2004 semester, a new topic on microfabrication was added to the course. Three one-hour lectures and two laboratory sessions were offered to help students understand and practice the basic elements of microfabrication. The two laboratories were performed in the

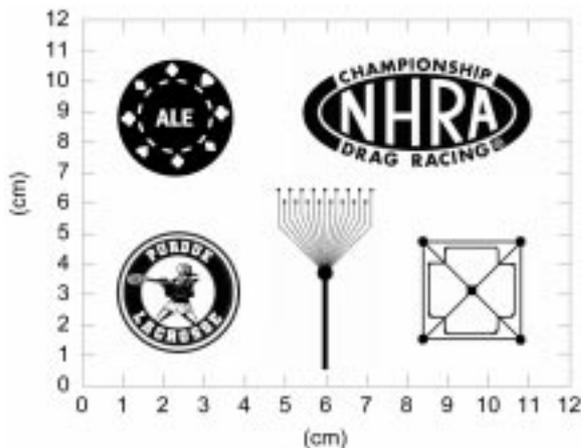


Fig. 2. Soft lithography patterns designed by students in ME363 course.

MMC pilot facility with the guidance of the facility's postdoctoral supervisor. The laboratories serve the dual purpose of introducing students to soft lithography procedures while training them to use microfabrication equipment, such as photoresist spin coaters, mask aligners, and other equipment described above. In the first lab session, students designed masks and calculated optical reduction factors necessary to achieve final mask dimensions with the subsequent photography module. Students then printed their final designs on transparencies and brought them to a photography area to be placed on a light box, where a standard 35 mm camera captured the images on high-contrast 35 mm film (Kodak, F-4016). Example masks designed by students are shown in Fig. 2.

Between the first and second lab sessions, the lab supervisor developed the students' film. At the beginning of the second lab session, students adhered the photographic film on a standard 5 inch glass wafer and used it as the photomask. They then coated SU-8 photoepoxy on silicon wafers at a specified thickness (nominally $25\ \mu\text{m}$) according to the manufacturer's specifications for spin rate and duration. Silicon wafers coated with SU-8 were placed on the hot plate for soft baking, which evaporates the solvent and densifies the SU-8 film. Students then patterned the photoresist using the mask aligner's projection mode, hard-baked the photoepoxy, and developed the patterned photoresist in SU-8 developer to create a relief master.

Molded microscale devices were then created using PDMS. First, students mixed the PDMS resin with hardener (resin 20 ml: hardener 2 ml = 10:1) and poured the mixture onto the wafer that contained the relief patterns and waited for most bubbles to disappear. After the PDMS mold was cured, it was released from the master and then either bonded to a standard glass slide to create a functional device or used independently as a micro-contact printing stamp. The

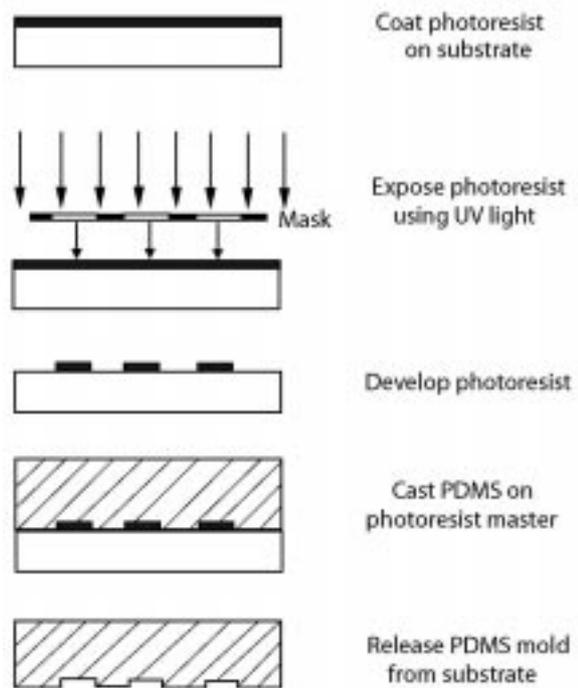


Fig. 3. The procedure of soft lithography in the second laboratory.

process flow for the second lab session is illustrated in Fig. 3. The two sessions described above have been well documented and posted to the lab's website (<http://widget.ecn.purdue.edu/~mmcenter>).

In only two laboratory sessions, all students successfully completed the microfabrication lab and produced unique microscale patterns in PDMS. By comparison, the production of functional devices in silicon-based microfabrication laboratory courses often requires five or more sessions. Further, the concepts of mask design and production, spin coating, photolithography, and photoresist development are common to both types of microfabrication processes.

Figure 4 shows microscale patterns fabricated on a silicon wafer by students. Four different student-generated patterns shared a 4 inch silicon wafer to improve the time efficiency of the exercise. Students adhered their photographic films to a common glass mask and fabricated masters on the wafer in a single exposure. After this process, the wafer was diced to separate the four designs. Alternatively, the entire wafer could have been molded, and then each mold could be separated by cutting the PDMS with a knife.

STUDENT SURVEY RESULTS

In order to examine student comprehension in the course and to improve our teaching, a simple survey was conducted. The survey was given to all students in the class both at the beginning and

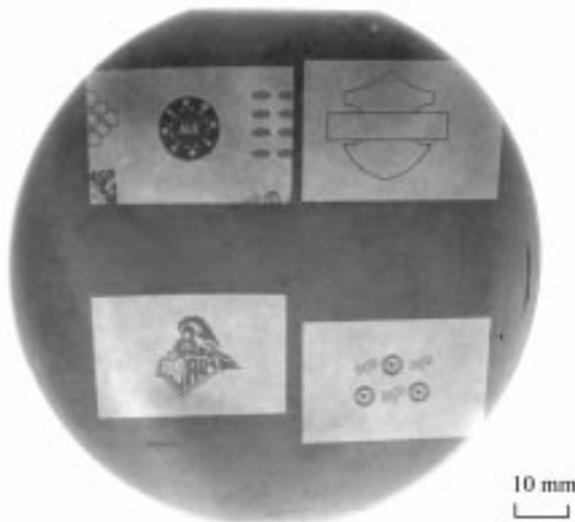


Fig. 4. Patterns microfabricated on a 4" silicon wafer by lithography.

end of the module. The survey included four multiple-choice problems and a written question as shown in Table 1.

Results from the survey's multiple-choice problems are summarized in Fig. 5. This non-scientific survey suggests that the students gained some understanding of microfabrication after two lectures and laboratories. Responses to the written question show that all students enjoyed the lectures and laboratories and found them to be very useful.

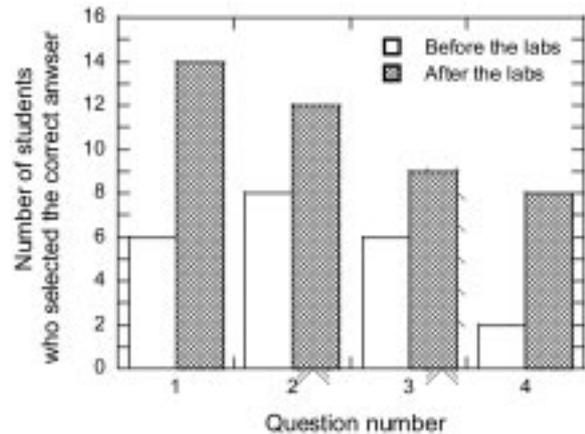


Fig. 5. Survey results from all students in the course (16 respondents).

SUMMARY AND CONCLUSIONS

Microfabrication education has been integrated into a manufacturing course, *Principles and Practices of Manufacturing Processes* at Purdue's School of Mechanical Engineering. The microfabrication laboratories are performed at the Multiple Manufacturing Center, which is equipped with pilot facilities capable of addressing basic microfabrication processes. Students gained a realistic, hands-on microfabrication experience through the execution of soft lithography processes. The modification to the existing manufacturing course appears to be successful and appreciated by the

Table 1. Student survey conducted both at the beginning and end of the course module.

ME363 Survey Before/After Microfabrication Labs

- Select ALL materials that you think are possible to be used as the active region of a semiconductor logic transistor (i.e., the part that switches on and off)?
 - Germanium
 - Au
 - Silver
 - Silicon
 - Copper
 - Gallium Arsenide
- What is the highest resolution of photolithography? Please circle only ONE of the following:
 - 1 mm
 - 10 μm
 - 1 μm
 - less than 1 μm
 - less than 1 nm
- In our lab we use SU-8 photoresist, which is a negative photoresist. Which of the following statements about negative photoresists are true? (May be more than one)
 - Negative photoresist contains negative charges
 - Negative photoresist will be photopolymerized when exposed
 - After exposure, the negative photoresist in the exposed area will be dissolved by the developer solution
 - After exposure, the negative photoresist in the exposed area will be insoluble to the developer solution and therefore remain on the substrate
- Why is the word 'soft' included in the phrase 'soft lithography'?
 - A soft substrate instead of a silicon wafer is used
 - A part made of an elastic polymer material is created
 - A special soft photoresist is used
 - A special soft baking procedure is included

Written question:

BEFORE LAB: What do you expect to learn from microfabrication lectures? AFTER LAB: Did the experience meet your expectations? Were the lectures and labs on microfabrication useful to you, both with regard to basics and applications, in terms of your expected future study or work?

students based in a course survey. This effort should have significant impact, both at the Purdue University and elsewhere. This seed effort will begin the initial phase of a planned reformation of the ME curriculum in manufacturing at Purdue. At the national scale, we expect that the work will serve as a model for establishment of multiscale manufacturing educational laboratories at other institutions. Recognizing a common inertia among engineering departments in implementing lab-based curriculum reforms, we anticipate

that the free dissemination of laboratory manuals, guides, and brochures, presentations at workshops and conferences will facilitate adoption, either fully or partially, of the products of this research.

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