Hands-On MEMS

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Abstract-- We have developed an innovative MEMS education program that combines virtual fabrication with actual testing of classic MEMS devices. This approach is suitable both for large classes and in university environments that do not have access to large fabrication facilities. Under NSF funding, we are currently refining the curriculum to allow the course to be easily adopted by other schools.

1. INTRODUCTION

Microelectromechanical systems (MEMS) are becoming increasingly common in applications ranging from car air-bag accelerometers and inkjet printer heads to actuators for telecommunications and chips for chemical analysis or biomedical testing. While their growing prevalence has generated strong interest among students from a wide range of majors, and a concomitant demand by potential employers for graduates with MEMS experience, only a handful of university departments offer MEMS courses with a laboratory component that provides practical instruction. These tend to be schools with strong nationally funded research programs. Most other institutions lack the infrastructure for fabricating and testing MEMS devices. During the past several years, faculty at NJIT, Columbia and Lehigh have joined forces to develop a MEMS course component that addresses this educational need.

The aim of our "Hands-On MEMS" program is to expose students, particularly those without easy access to cleanroom facilities, to design, simulation, microfabrication, and testing of MEMS devices in a one semester introductory course. We accomplish this by combining simulated fabrication using a virtual reality software tool with hands-on mounting, characterization and study of actual, classic MEMS devices. Through a recently established NSF grant, we are refining our approach at our three universities and other beta sites for ultimate national dissemination. We envision development of a student kit that includes the virtual fabrication tool, a variety of MEMS chips for testing, straightforward packaging materials, and a complete set of supporting documentation. In this paper we describe our "prototype" course, with particular emphasis on the hands-on components.

2. THE PROTOTYPE COURSE

The course was initiated three years ago as part of the education activities funded through the NJ MEMS Initiative, a research and development excellence program supported by the NJ Commission on Science and Technology.[1] This is a program that emphasizes industrial interaction, and the education component was developed in response to the need conveyed to us by area industrial partners who interact with the Initiative program, including larger companies, military suppliers and labs, and smaller start-ups. In our discussions with these companies, we have found that the MEMS industry is frustrated by a shortage of graduates with the appropriate training for joining the workforce, training that ranges from engineering conceptualization, through hands-on MEMS device experience, to market research and commercialization. This situation is exacerbated by the industry's rapid growth. The shortage in the workforce must be addressed by university programs that provide graduates with the appropriate diverse skill set.

The first semester, in Spring 2000, the prototype course was offered only at NJIT as a rework of an existing microelectronics course, Physics 482. Because of its intended breadth of coverage, the course was opened as an elective to upper division undergraduates in all science and engineering majors. Eight students from five departments, applied physics, mechanical engineering, materials science, electrical engineering and computer engineering, completed the course. One of those students was hired after graduation by a leading MEMS company, and she was considered to be exceptionally well prepared for work in the MEMS field. Because of demand, the course was expanded the second and third years, and was co-developed and co-taught at Columbia University's Mechanical Engineering Department. To date, over 130 students have taken evolving versions of the course. While course enrollment has been limited at each school to keep the class size manageable, demand has outpaced space. The following description is excerpted from the Spring 2001 course syllabus:

> <u>Course Description</u>: This course will combine lecture and laboratory work to provide students with a practical, hands-on introduction to MEMS. About one-third of the class time will be devoted to the lecture portion of the course, and will cover mainly the material found in an assigned textbook, with supplementation where necessary from other sources. The goals of the lectures are to provide an introduction and overview of 1) MEMS markets and applications, 2) MEMS materials and fabrication methods, with emphasis on silicon micromachining,

3) basic MEMS device concepts including pressure, acceleration, rotation and flow sensors, as well as more advanced devices, systems and applications, 4) MEMS device design and simulation tools, 5) MEMS device measurement and characterization principles and techniques, and 6) MEMS packaging concepts. About two-thirds of the class time will be devoted to the laboratory portion of the course, and will comprise 1) an introduction to cleanroom safety and protocol, 2) hands-on fabrication of MEMS device structures including pressure sensors, accelerometers, gyros, flow sensors, and actuators and 3) packaging and testing fabricated devices.

It is important to note that the prototype course initially took advantage of the excellent fabrication facilities at NJIT to offer students hands-on participation in the fabrication steps of their test wafers. We found that this was not especially practical given the large number of students participating in the course, and this activity became more of a demonstration rather than participation component of the lab. In the third year of the prototype, Spring 2002, we eliminated the hands-on fabrication component in favor of process development and simulation activities using ICLAB, a virtual reality tool developed recently at Lehigh University[2]. As described in more detail below, ICLAB was intended to illustrate and teach microelectronics device design and fabrication. However, we found that it could also be used to teach aspects of MEMS device fabrication. We supplemented this software tool with ACES shareware, an anisotropic silicon etch simulation program, and with video demonstrations of cleanroom processing. We believe that this combination of resources, coupled with hands-on testing of actual devices has led to an educational product that is accessible to the widest institutional audience with a minimum required setup investment.

3. VIRTUAL FABRICATION SOFTWARE

ICLAB is a powerful "virtual laboratory." Created as a tool for teaching process integration, it teaches by allowing students to make the same decisions that have to be made in a real device manufacturing facility but without the expense and risk involved with such laboratories. Figure 1 shows what a student might see after completing one side of a simulated, single resistor, piezoresistive pressure sensor with aluminum contact pads.

A student using the simulation starts with a blank wafer. He or she then lays out the needed photolithography masks using the built in CAD program. From here, the student begins processing the wafer. Individual processes are conducted, one at a time, until the wafer is completed. For example, an oxidation may be needed. For this operation the student must select the correct ambient, temperature and oxidation time to get the correct oxide thickness. All the variables are entered into the program using an interface that simulates the actual process. Students set the temperature of the furnace, provide the correct ambient and start and stop the oxidation. Figure 2 shows a virtual sputtering system used to etch various films on the wafer. When this system is used, the student not only has to set gas flow, etch power and time, he or she must also operate the vacuum system. Pumps are turned on and valves opened or closed as needed to achieve the correct pressure for etching.

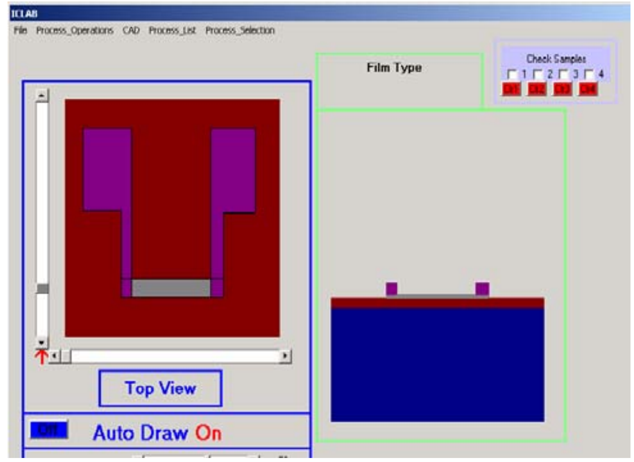

Figure 1 Top and cross sectional views of polycrystalline silicon piezoresistor with aluminum leads on top of an oxidized silicon wafer.

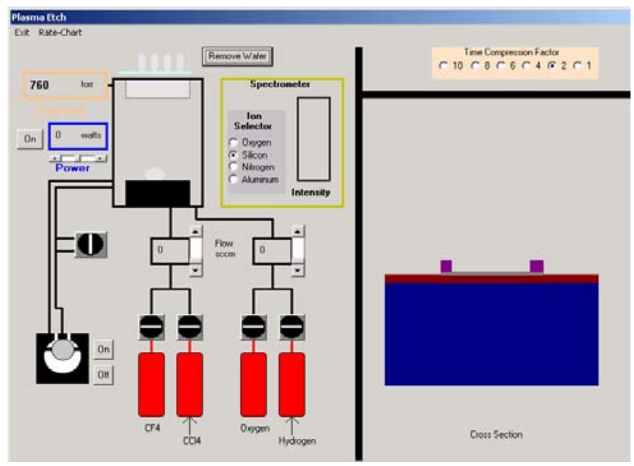

Figure 2 Virtual plasma etch system.

In all processing two things are available to students using the simulation that are not available in a real laboratory: time compression and a real-time cross sectional view of the wafer in process. Time compression allows the student to speed up the simulation so that a process that might take hours or even days in the lab, takes only a few minutes in the simulation. The cross sectional view of the wafer is available both during and after all processes. When etching, for example, the student can watch as films are removed, forming steps at the edge of mask features.

While the current version of ICLAB works well for teaching semiconductor processing, it was not originally written with MEMS in mind. With faculty and student feedback as guides, this tool is currently being adapted to be more useful for simulated MEMS fabrication.

4. MEMS DEVICES

The anchor activity of the "prototype" course development has been the design and fabrication of sets of MEMS devices for the students to test. Over the past several years we have developed two complete, straightforward processes for the fabrication of MEMS structures to be used in the course. The first is a bulk micromachining process for constructing a variety of pressure, flow, acceleration and rotation sensors using a single four mask set. These devices are interrogated using standard polycrystalline silicon resistors in stand-alone and Wheatstone bridge configurations. The second process is a hybrid wafer bonding and deep reactive ion etching sequence to produce a variety of electrostatically actuated micromirrors and other structures. This technology is currently at the forefront of the optical telecommunications revolution, yet is easily adapted for classroom use. We refer to these processes as "straightforward," because the fact is they are now easily carried out at NJIT after numerous improvements and refinements over the years. We have chosen these two device types, bulk micromachined piezoresistive sensors and hybrid micromachined single crystal silicon electrostatic actuators because they are traditional device structures of classic design, which clearly illustrate the basic principles of MEMS. For example, first principles beam equations can be used to calculate the deflection of the cantilever used as a flow sensor. These results can then be used to predict the resistance change of piezoresistors strategically placed on the beam. Measured results can easily be compared with predicted performance. Similarly, first principle calculations can be used to predict the performance of the actuator structure, including static and dynamic behavior, which again can be compared to measured results. Fabricated flow and micromirror structures are shown in Figures 3 and 4, respectively. Many 1 cm^2 chips from a single multi-sensor wafer are shown in Figure 5.

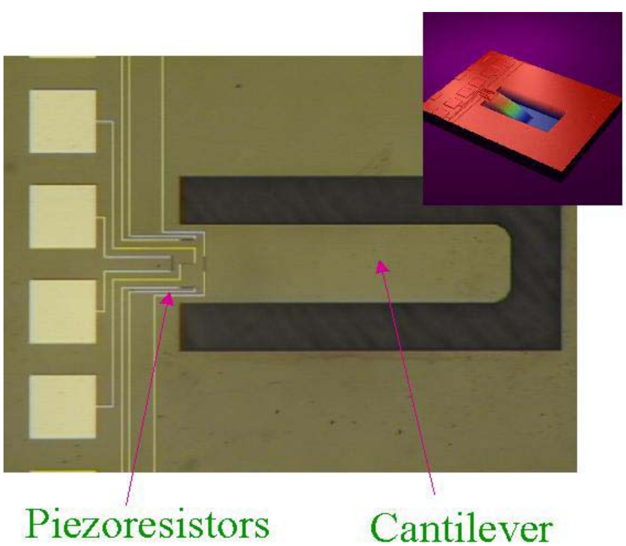

Figure 3 Microscope and WYKO (inset) images of flow sensor. Resistors are 10 µm wide by 200 µm long.

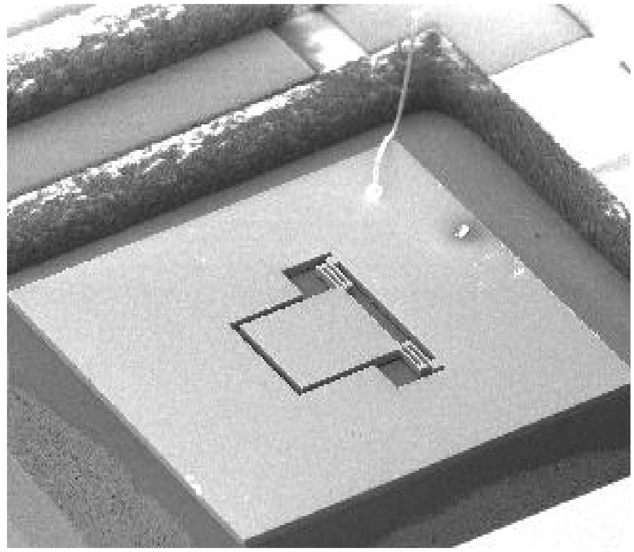

Figure 4 SEM image of micro-actuator. The mirror plate is 0.7 mm on each side.

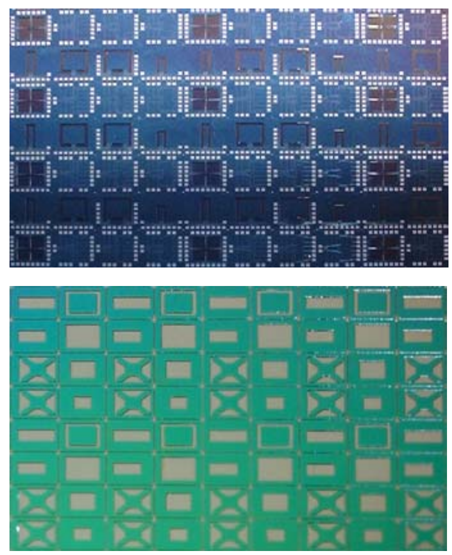

Figure 5 Front and back of multi-device wafer.

5. TEST APPARATUS

As part of the "prototype" course development, we have established test stations for a number of the device types, including the pressure and flow sensors, the accelerometer and the electrostatic actuator. The actuator is investigated by shining a laser pointer beam onto the micromirror surface and measuring its deflection as a function of applied actuation voltage, AC or DC. The bulk micromachined sensors are packaged in simple, homemade chip holders and interfaced with the appropriate environment, an oscillating mass/spring system for acceleration, or a nozzle connected to a regulated flow or pressure source for the flow and pressure sensors. Individual resistors can be interrogated using a straightforward current/voltage circuit connected to an oscilloscope. In preparing for beta testing, we have developed a more versatile, "recommended" interrogation setup consisting of a power supply, a scanning multimeter and software for serial port data acquisition and analysis using a PC, but for all of our devices, we have tried to develop laboratory activities where the required test apparatus is minimal, and readily available in most labs.

6. LABORATORY OVERVIEW

A key aspect of the laboratory portion of the course involved studying a classic MEMS device. While traditional individual preparation and assessment was employed in the lecture and safety portions of the course in order to assure adequate individual readiness for processing activities, group learning and evaluation was emphasized in the laboratory. Students were assigned to groups of three or four, and chose among three device testing activities. The following description is excerpted from the 2003 laboratory manual.

> The goal of the laboratory is to expose students to the equipment and fabrication processes used to construct their MEMS devices, and to provide an introduction to MEMS device testing and characterization. During the laboratory, each student is expected to keep a notebook, journaling their processing experience and detailing their device testing procedures and measurements. At the conclusion of the laboratory session, each student is expected to compile a report that describes their laboratory experience, including an overview of the design of the device they tested, the fabrication steps needed to construct their device, an outline of the procedure and methods they used to test their device, a presentation of their measurement results, and most importantly, a discussion and interpretation of their results compared to what they expected to observe. The students will also propose a new device using the same fabrication approach as the existing structure.

The laboratory manual then went on to provide detailed experimental procedures for each device. For example, in the actuator lab, students were asked to measure deflection versus voltage for negative and positive bias to the moveable plate, to look for hysteresis, to look for and explain the pull-in instability, to measure and explain dynamic behavior in response to an AC bias of increasing frequency, and in all cases to compare measured data to first principles calculations. The design component of the lab served to integrate all aspects of the course, including device modeling, mask design and wafer fabrication.

7. COURSE EVALUATION

Assessment of the quality of the course was performed using mandatory confidential surveys. In discussing the strengths and weaknesses of the course, the students appreciated that they had been exposed to an emerging field with broad applications. One student wrote that the course "covered a wide range of backgrounds, eg., electrical and mechanical engineering, chemistry and physics. Not everyone was familiar with the different subjects, but the lectures, handouts and lab were helpful in absorbing the new material." Another student added, "The relevance of the course to the outside world is the most appreciable strength." One student noted the value of the lab by writing, "Classroom topics are shown in the laboratory. It makes the theory/design practices more real." The value of the virtual reality process simulation tool introduced in 2002 was underscored by the comment, "Simulation helps a lot in order to have a feel how to micromachine." One very prevalent comment, appearing on more than half of the evaluations in 2002, was a desire to design and fabricate new MEMS devices, building on the foundation provided in this course, a strong indication that we were successful in stimulating excitement for the field. One student wrote, "If given the chance I would dive into MEMS directly head on," and another actually wrote, "This course is the best that I have ever taken."

8. CONCLUSION

We have developed an innovative MEMS education program that combines virtual fabrication with actual testing of classic MEMS devices. This approach is suitable both for large classes and in university environments that do not have access to large fabrication facilities. Under NSF funding, we are currently refining the curriculum to allow the course to be easily adopted by other schools.

ACKNOWLEDGMENTS

This work was supported through the National Science Foundation, award DUE-0230556, and the NJ Commission on Science and Technology through the NJ MEMS Initiative.

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