INTRODUCTION TO MICROMACHINING AND MEMS:

A LECTURE AND HANDS-ON LABORATORY COURSE FOR UNDERGRADUATE AND GRADUATE STUDENTS FROM ALL BACKGROUNDS

Jack W. Judy and Paulo S. Motta

Electrical Engineering Department, University of California, Los Angeles

Abstract *— A 10-week course on micromachining and microelectromechanical systems (MEMS) technologies has been designed and taught that incorporates both a lecture component (3 hours/week) and a hands-on laboratory component (4 hours/week). By completing this course the students gain an understanding and hands-on experience with photolithography, isotropic and anisotropic wet etching, dry etching, physical and chemical vapor deposition, electroplating, metrology, statistical design of experiments, MEMS release etching, stiction, and MEMS device testing. The layout of the course chip enables students to produce over 100 different devices using both bulk micromachining and surface micromachining. The layout of the chip includes microsensors (accelerometers, pressure sensor, resonant magnetometers), microactuators (torsional magnetic microactuators, optical switches, thermal microactuators), and microstructures (cantilever beams, bridges, neural probes, needles, thin-film stress test structures, bulk micromachining test structures, electrical test structures). This course prepares students to be active participants in the growing MEMS and microsystems industry.*

Index Terms — microelectromechanical systems, MEMS, microfabrication, microsensors and microactuators.

INTRODUCTION AND MOTIVATION

The economic significance of microelectromechanical systems (MEMS) to the world economy is increasing rapidly. Market surveys predict that MEMS revenues may exceed $50 billion in the year 2005 [1]. The drive behind this industry is the reduction of the cost, size, weight, and power consumption of the sensors, actuators, and systems we use to monitor and control our surroundings. This is to be done while simultaneously increasing their capabilities and compatibility with existing information and control systems. In fact, as the performance of our computing resources continues to grow, our ability to manage complex systems with many sensors and actuators has also been growing. The limiting factor has been the lack of affordable and compatible sensors, actuators, and systems. As the MEMS industry continues to grow, another consideration will be the supply of skilled people of all levels (particularly at the B.S. and M.S. level), who are familiar with MEMS and skilled at micromachining.

It is well known that providing hands-on learning experiences is one of the most effective ways of teaching. This is particularly true when there are many details that are important, yet can easily be passed over in lecture or are quickly forgotten. Good examples of material like this are micromachining processes and MEMS. Describing a micromachining process or, for example, the stiction problem in MEMS, and actually experiencing them are two very different things. Clearly the hands-on lesson will be longer lasting and is also likely to provide additional unexpectedly valuable lessons.

Another important issue in the teaching of micromachining and MEMS is the reality that the students taking the course will have very different backgrounds. It is common for graduate students in mechanical engineering to have no knowledge or experience with IC fabrication and other micromachining techniques. Students from outside of engineering, say in the life sciences or medicine, will lack much of the engineering background that is taken for granted, and thus will also struggle in graduate-level micromachining and MEMS classes. This is most unfortunate, since the field of MEMS gains tremendously by the involvement of people from diverse backgrounds, because of the unique needs, applications, and abilities of their field.

An undergraduate course on micromachining and MEMS would be an excellent instrument for addressing these issues. The level of the course will make it much easier to cover sufficient background material, which will enable students with no knowledge of micromachining or MEMS to participate. Adding a laboratory component will facilitate the solidification of this first-time learning experience. After taking this course, students from almost any background will be able to go on to the graduate-level courses in MEMS with confidence.

The corresponding author is Jack W. Judy, who can be reach at the following address: 6731E Boelter Hall, 420 Westwood Plaza, University of California Los Angeles, Los Angeles, CA 90095 and by email at: jjudy@ee.ucla.edu. The co-author is Paulo S. Motta and can be reached by email at: pmotta@ee.ucla.edu. This work is supported by the Henry Samueli School of Engineering and Applied Science, UCLA and a special Intel Corporation Grant to support the development of MEMS Laboratory Courses.

COURSE STRUCTURE AND DESIGN

The course described in detail here is an undergraduate course on micromachining and MEMS, which also has an accompanying laboratory in which the students make a variety of MEMS, thus putting their lessons to practice. This course is intentionally designed for students with almost any background (prerequisites include a nominal exposure to college-level chemistry, calculus, and physics). The intent is to allow students without the background in micromachining or MEMS to learn the basics and to get hands-on experience, before taking graduate-level MEMS courses. The 10-week course is divided into two parts: the lecture component (3 hours/week) and the laboratory component (4 hours/week). Each component is described in detail in the following two sub-sections.

Textbook

There is no single textbook that is optimal for this undergraduate micromachining and MEMS course. Currently chapters from multiple texts [2-6] are being compiled with selected conference and journal papers into a single course reader.

Lecture Component

The purpose of the lecture is to provide both the broad perspective of the field in general and to instruct the students on the fundaments and theory involved in each of the major micromachining process technologies. Weekly homework assignments are used to allow students to practice the lessons taught in lecture. A week-by-week breakdown of the material covered in the lecture component is given below in Table I.

TABLE I

OUTLINE OF THE LECTURE COMPONENT OF THE COURSE

Week	Lecture Material
1a	Welcome and Administration, Introduction and Overview
1b	Process Flow, Crystallography
2a	History of MEMS, Scaling Issues
2b	Clean Rooms and Cleaning Procedures
3a	Mask Making, Layout, Photolithography Basics
3b	Photolithography Tools
4a	Wet Etching (Isotropic, Anisotropic)
4b	Wet Etching (Anisotropic)
5a	Vacuum Systems
5b	Plasmas and Dry Etching (Plasma Etching)
6a	Dry Etching (RIE, Sputter Etching, Ion Milling)
6b	Physical Vapor Deposition (Evaporation, Sputtering)
7a	*No Class (U.S. Holiday)*
7b	Midterm Exam (covers week 1 through week 4)
8a	Diffusion
8b	Ion Implantation
9a	Thermal Oxidation
9b	Chemical Vapor Deposition (LPCVD, PECVD)
10a	Design of Experiments (Statistical Process Control)
10b	Process Integration

A 10-week quarter is not long enough to include a thorough discussion of advanced microfabrication processes, thin-film material properties, and MEMS design issues. Instead, in each lecture the relevance of the material covered is briefly related to MEMS by the inclusion of a pertinent example taken from the MEMS literature. Furthermore, a follow-on graduate course on MEMS fabrication covers many of these topics (e.g., foundries, DRIE, wafer bonding, thick-film lithography, LIGA, advanced lithography, soft lithography, electrochemical deposition and etching, stiction and release techniques, the mechanical properties of thin-films, and process integration) and another on MEMS design covers the rest.

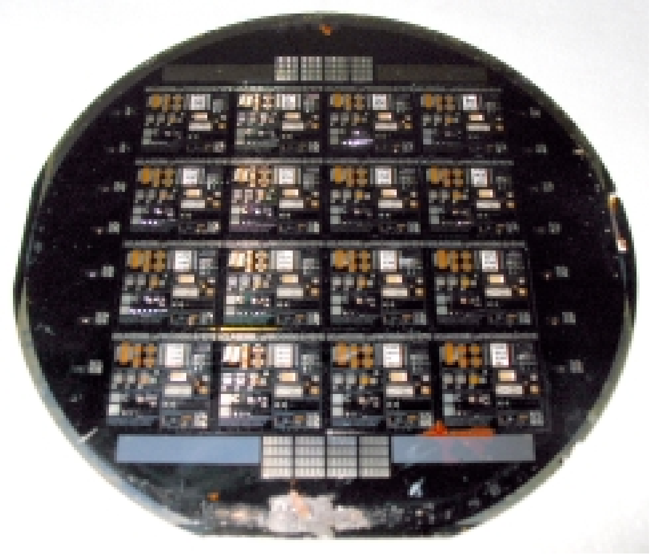

FIGURE. 1

PICTURE OF A WAFER FABRICATED BY THE 2001 CLASS.

Laboratory Component

The purpose of the laboratory is to provide hands-on experience fabricating MEMS that compliments the lecture-based instruction. Specifically, the student gains hands-on experience in photolithography, etching (wet and dry surface and bulk micromachining), metal deposition (evaporation, sputtering, and electrodeposition), and several metrology tools (microscope, profilometer, probe station, four-point probe, and spectrometer). The devices to be fabricated are: accelerometers, thermal micoractuators, magnetic microactuators [7] and microsensors, fiber optic switches, neural probes, and pressure sensors. The laboratory portion of this course is taught in the instructional wing of the UCLA Nanoelectronics Research Facility, known as the *UCLA Microlab*, which is discussed in more detail below. A week-by-week breakdown of the material covered in the laboratory component is given below in Table II.

TABLE II
OUTLINE OF THE LABORATORY COMPONENT OF THE COURSE

Week	Laboratory Material
1	Walk-Through and Safety Exam
2	LPCVD, Photolithography and Dry Etching
3	LPCVD, Photolithography and Dry Etching
4	Backside Photolithography
5	Physical Vapor Deposition (Metal Evaporation)
6	Electrodeposition
7	Bulk Micromachining
8	Device Testing and Characterization
9	Device Testing and Characterization
10	Device Testing and Characterization

The flowchart in Figure 3 illustrates our approach to teaching microfabrication in a weekly laboratory. First, students are required to read pre-assigned pages in a laboratory manual that explains the processes that will be applied during the next laboratory session and how those processes will affect the final outcome of the MEMS devices. Second, in a brief lecture the teaching assistant (TA) summarizes the theory and processes that the students have just read in the laboratory manual. Following the TA lecture, the students take a weekly quiz of the processes that are to be performed in the current week's laboratory session. Once the students finish the quiz, the examination is corrected and any misunderstandings are addressed immediately and the students have a third opportunity to clarify any question they may have. Following the quiz, the students perform the fabrication steps and can ask more question during their execution. Finally, at the end of the quarter, the students have to turn in a laboratory report showing that they have indeed mastered the topics and techniques covered in the laboratory section.

Student Demographics

The course was taught for the first time in the winter quarter of 1998 on an experimental basis, and a majority of the 12 enrolled students were not from electrical engineering (primarily mechanical engineering and chemical engineering). Figure 1 shows how the enrollment in the course has doubled each year it was taught until it was over subscribed in 2001 and the enrollment was capped at 64 students for laboratory safety reasons. In addition, Figure 1 illustrates how the diverse background of the students in the class has evolved from over time. Although students from chemical engineering (ChemE), civil engineering (CivE), computer science (CS), materials science (MatSci), and even neuroscience and medicine (MD) have taken the course, the majority of the students are in mechanical and aerospace engineering (MAE), electrical engineering (EE), and biomedical engineering (BME).

Figure 2 shows how the level of student in the class has changed over the four years it has been offered. Although it is an undergraduate course, it is clearly very popular with graduate students, as they have consistently made up the majority of the class.

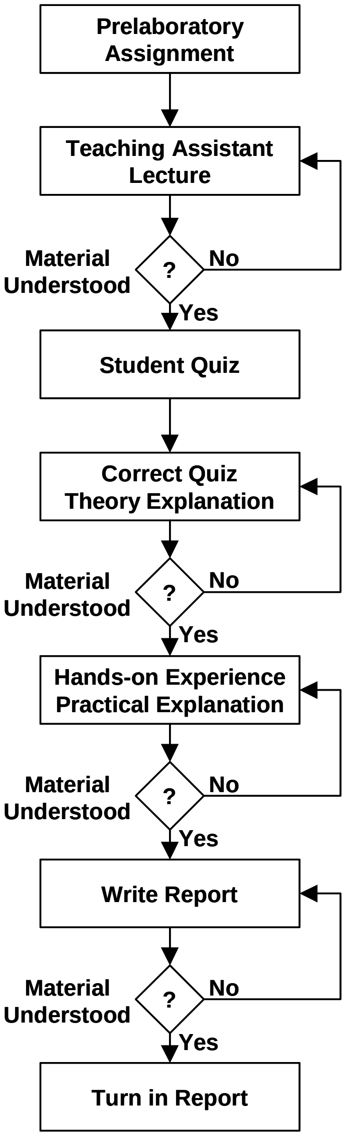

FIGURE. 2
FLOWCHART DESCRIBING THE WEEKLY TEACHING STRATEGY FOR THE LABORATORY SECTION OF THE COURSE.

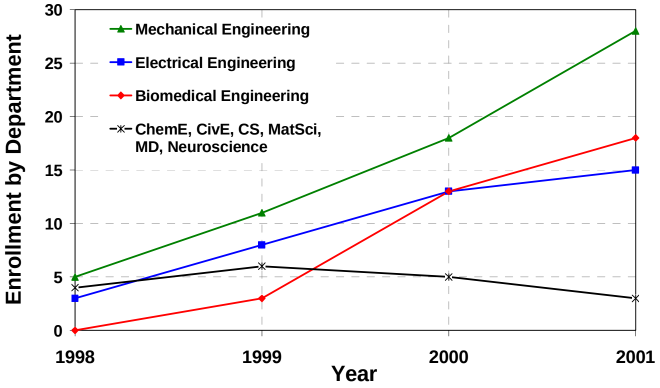

FIGURE. 3
GRAPH OF ENROLLED STUDENT DEPARTMENTAL AFFILIATION DURING THE FOUR YEARS THE COURSE HAS BEEN OFFERED.

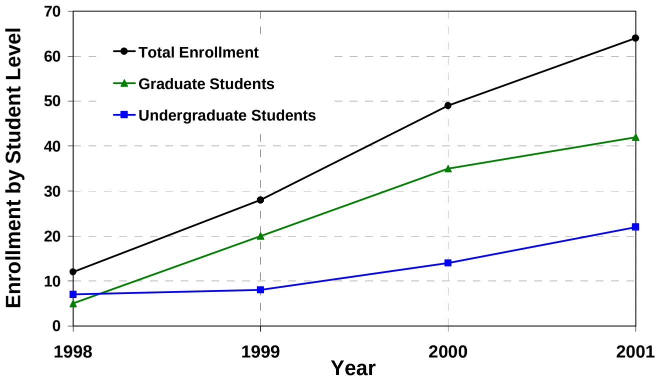

FIGURE. 4
GRAPH OF ENROLLED STUDENT LEVEL (GRADUATE AND UNDERGRADUATE) DURING THE FOUR YEARS THE COURSE HAS BEEN OFFERED.

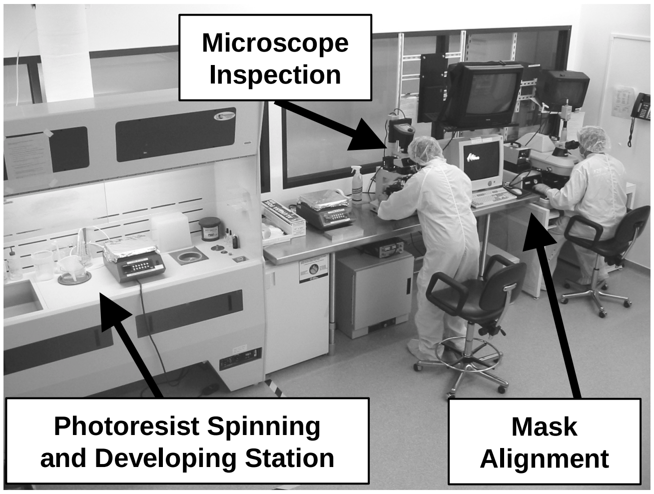

FIGURE. 5
STUDENTS WORKING AT ONE OF THE TWO PHOTOLITHOGRAPHY LINES AT THE UCLA MICROFABRICATION INSTRUCTIONAL FACILITY.

MICROFABRICATION LABORATORY

The Microlab instructional facility is a 306-m^2 (3300 ft^2) class-1000 cleanroom capable of processing 100-mm (4") wafers. It consists of a temperature-controlled and humidity-controlled laboratory with integrated photolithography, wet etching, measurement, and lecture rooms. The lecture room is where students are instructed and quizzed about the microfabrication processes they perform. It also contains four probe stations with characterization equipment for device testing. The photolithography room (Figure 5) contains two parallel processing lines for maximum throughput. Each processing line contains a wafer spinner, a Quintel mask aligner for UV exposure, a developing station and sink, and a microscope for inspection. The etching room consist of two wet benches for wet etching processes. In addition, it contains a programmable spin dryer with 50-wafer capacity, and a Tegal oxygen plasma etching tool. The measurement room contains a Dektak profilometer and a Nanospec spectrometer. The microlab has a capability of teaching 200 students per year (i.e., ~64 students/quarter).

MICROFABRICATION PROCESS FLOW

The objective of the design of the MEMS chip (Figure 6) is to enable the demonstration of the fabrication of various MEMS microsensors and microactuators using a single fabrication process that takes 7 weeks to complete. The fabrication process consists of 7 photolithography steps, 6 etching steps, and 6 deposition steps. There are 16 chips per wafer, and in each chip contains over 100 devices: microsensors (accelerometers, pressure sensor, resonant magnetometers), microactuators (torsional magnetic microactuator [7], thermal microactuator), and microstructures (neural probe, stress test structures, bulk micromachining test structures).

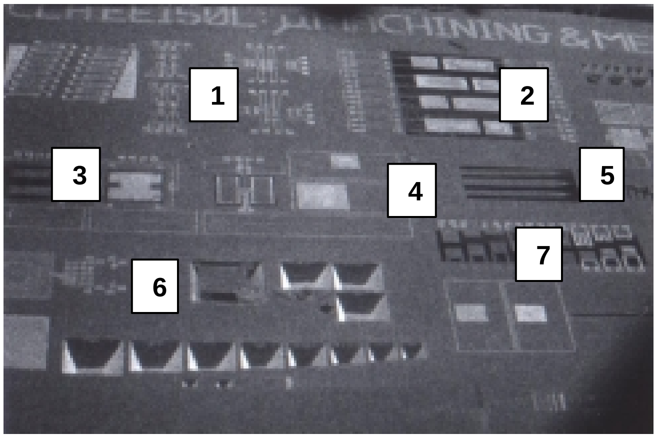

FIGURE. 6
SCANNING ELECTRON MICROGRAPH (SEM) OF MEMS CHIP SHOWING (1) PRESSURE SENSORS, (2) ACCELEROMETERS, (3) MAGNETIC SENSORS, (4) MAGNETIC ACTUATORS, (5) NEURAL PROBES, (6) TEST STRUCTURES, AND (7) THERMAL ACTUATORS.

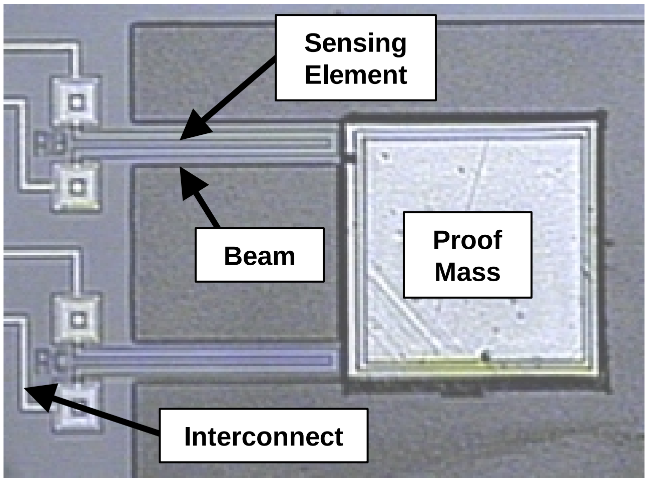

FIGURE. 7
TOP VIEW OF ACCELEROMETER.

Starting with a single-side polished, <100>-oriented, p-type, 500-µm-thick silicon wafer, a 2-µm-thick low-stress silicon nitride is deposited using a low-pressure chemical vapor chamber (LPCVD). Silicon nitride serves as both an insulator and as the mechanical layer. Next, a 1-µm-thick layer of LPCVD polycrystalline silicon (poly) is deposited and doped with boron. Polysilicon was chosen because it is piezoresistive (i.e., its resistance changes as a function of stress) and it is used as the sensing element in various devices on the chip. Polysilicon is also used as a sacrificial layer for other devices that are produced by surface micromachining. Once the polysilicon layer is patterned, the wafer is covered with another 1-µm-thick layer of low-stress silicon nitride. This layer also serves as a mechanical layer for surface micromachined structures and as the encapsulation to protect the resistors from the release etch. To enable the creation of bulk micromachined devices, openings are created on the backside of the wafer that are aligned to features on the front side. This is accomplished by using a front-to-backside alignment tool (Karl Suss MA-6). Once an opening is created in the upper nitride layer to reveal the polysilicon layer, electrical connection is made to the piezoresistors. A 0.1-µm-thick Cr/Ni layer is then deposited by evaporation to form the seed layer for electrodeposition. Next a 5-µm-thick layer of low-stress nickel is electroplated to form the electrical interconnects. Since some devices require a large volume of metal to serve as the proof mass and as the magnetic torque element, another 25 µm of electroplated nickel are deposited in specific regions. The release of the device is accomplished by etching exposed single-crystal silicon and polycrystalline silicon with potassium hydroxide (KOH).

TESTING

Once released, the chips are separated from the wafer (i.e., V-grooves on the wafer allow it to be broken into chips without using a diamond saw – the standard method) to test the chips in probe stations. Students test all devices, but for breiviety, only the accelerometer testing (Figure 9) will be described here.

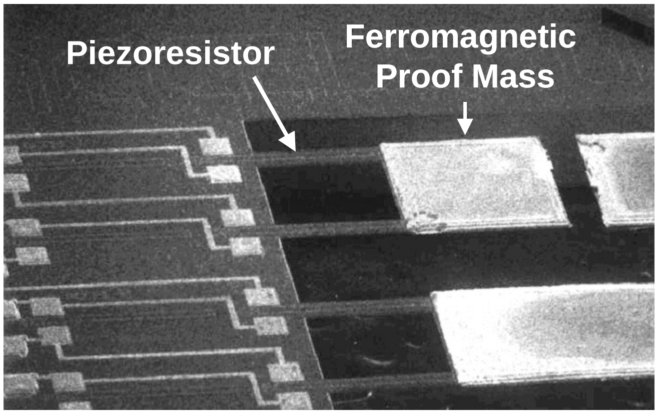

FIGURE. 8
SEM OF ACCELEROMETER.

The sensing in the accelerometer is done via doped polysilicon piezoresistors laid out on the beams that support the proof mass and are integrated into a Wheatstone bridge circuit. To simulate acceleration, a magnetic field is applied to generate a magnetic torque on the ferromagnetic proof mass, as shown in the setup of Figure 10. The torque due to the magnetic field can then be related to the measured voltage across the Wheatstone bridge. By knowing the beam deflection, geometry, and material properies the effective acceleration can be computed.

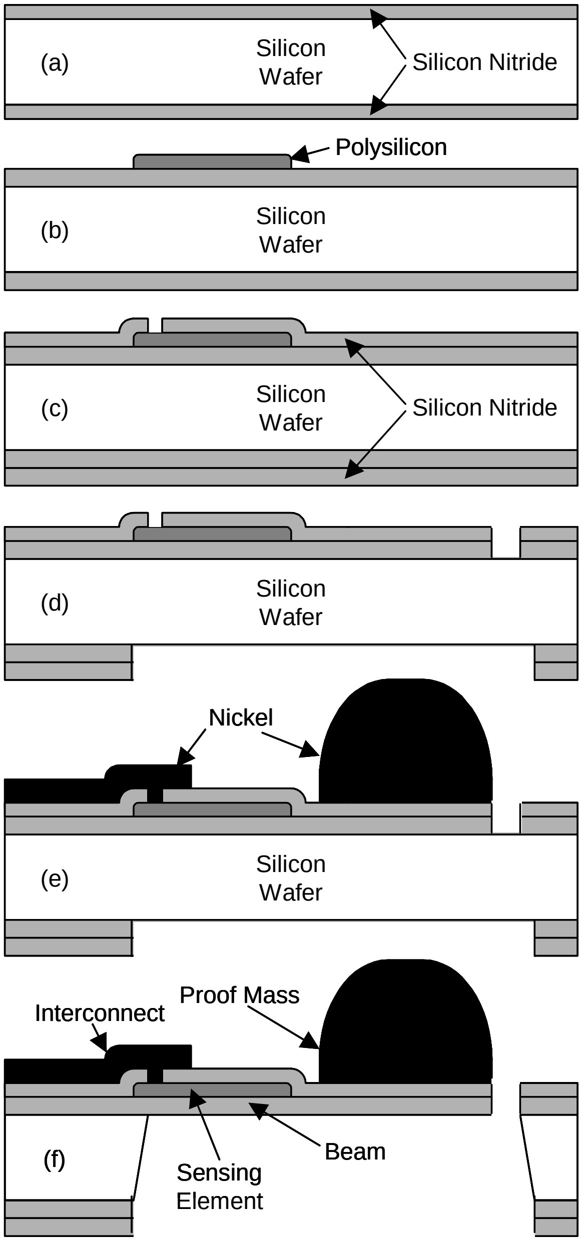

FIGURE. 9
PROCESS FLOW SHOWING (A) NITRIDE STRUCTURAL LAYER, (B) POLYSILICON SENSING ELEMENT, (C) NITRIDE INSULATION AND STRUCTURAL LAYER, (D) PATTERNING THE STRUCTURAL LAYER AND THE BACKSIDE OPENINGS, (E) ELECTRODEPOSITION OF NICKEL INTERCONNECT AND PROOF MASS, AND (F) RELEASED ACCELEROMETER.

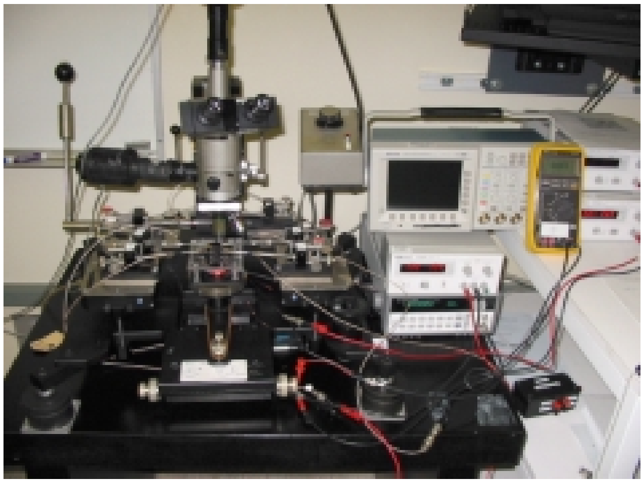

FIGURE. 10

TESTING SETUP FOR MEASURING ACCELEROMETER DEFLECTION.

A plot of the deflection of the tip of the beam versus applied magnetic field is shown in Figure 11. The error bars are due to experimental error, non-uniform electroplating of the proof mass, non-uniform applied magnetic field, etc. Despite the modest processing variability inevitable in any undergraduate laboratory, good device yield is obtained. The students are amazed, thrilled, and relieved that their hard work all term long has yielded functional devices.

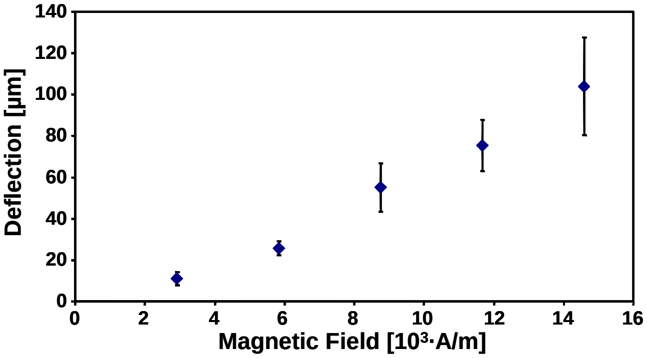

FIGURE. 11

PLOT OF DEFLECTION VERSUS MAGNETIC FIELD APPLIED SHOW LINEAR RESPONSE.

CONCLUSIONS

A 10-week course on micromachining and MEMS technologies has been designed that incorporates both a lecture component (3 hours/week) and a hands-on laboratory component (4 hours/week). It has been taught once a year year since 1998 and the enrollment has grown from 12 to 64 students. Although most of the students are from electrical, mechanical, and biomedical engineering, students from many other disciplines, some even outside of engienering (e.g., neuroscience and medicine) have completed and benefited from the course. Despite being an undergradate-level course, it is very popular with graduate students (66% grads, 34% undergrads). By completing this course the students gain an understanding and hands-on experience with photolithography, isotropic and anisotropic wet etching, dry etching, physical and chemical vapor deposition, electroplating, MEMS release etching, stiction, and MEMS device testing. This course prepares students to be active participants in the growing MEMS and microsystems industry.

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