Capstone Design Project on Optical MEMS: A Vehicle for Interdisciplinary Research and Learning

Eniko T. Enikov and Stanley Pau[1]
University of Arizona, 1130 N Mountain, Tucson, AZ 85721
e-mail Enikov@engr.arizona.edu

***Abstract* - The objective of this senior capstone design project is to develop a low-cost optical bench and micro-mechanical (MEMS) cantilever gas sensor. The integrated system will be used in the micro-technology curriculum at The University of Arizona. This presentation describes the experience of the authors in supervising a highly interdisciplinary project between the Aerospace and Mechanical Engineering Department and the College of Optical Sciences at the University of Arizona. The challenges of teaching students with different backgrounds are highlighted through examples from our mentoring sessions. The resulting compendium of lessons and technical knowledge include mechanical vibration, energy dissipation and noise analysis, optical design, surface chemistry, instrumentation, and computer programming. Also included is a technical specification of the designed system with a suggested method for dissemination at other institutions.**

Index Terms – Cantilever-Sensor, Capstone-Design, Micro-Technology, Optical MEMS.

I. INTRODUCTION

Hands-on laboratories have been an integral part of the engineering curriculum since its inception [1]. Their importance has been recognized by the Accreditation Board of Engineering Education (ABET) and its predecessors by creating criteria requiring adequate laboratory practice for students [2-6]. During the last three decades, engineering laboratories have become more complex, including simulation tools and computer-controlled test and measurement equipments [7-8]. This increase in sophistication has also led to increase in cost, particularly to more expensive equipment. The inclusion of such laboratory courses in the undergraduate curriculum is challenging due to the large number of students and the increased demand for instruction and equipment time. Hands-on experience, on the other hand, is invaluable for active and sensory learning styles, which are the predominant types of learning styles used by undergraduate students [9].

In this paper we describe our effort to incorporate a hands-on laboratory experience with elements of engineering research through the use of Micro-Electromechanical Systems (MEMS) in the context of the senior engineering capstone design course. MEMS have acquired a history of over 30 years of development. Many successful commercial applications have emerged, such as switches, display, pressure sensors, accelerometers, gyroscopes, inkjet printer heads and lab-on-a-chip chemical detection systems. These success-stories inspired not only the industrial world, but also sparked interest among academic institutions in incorporating MEMS into their curriculum. Many institutions now offer degrees with specialization in the field of micro- and nanotechnology. A distinguishing feature of educational programs focused on MEMS is their interdisciplinary nature stemming from the need to design and integrate electrical, mechanical, optical, or chemical sub-systems into a functional MEMS device. Therefore, MEMS is an inherently interdisciplinary field and provides excellent opportunities to foster team- and problem-based learning techniques in the curriculum. However, developing MEMS-based curriculum at the undergraduate level remains challenging, as most programs are limited to 128 credit hours, committed to what is considered classical and therefore, required courses in traditional engineering disciplines such as mechanical, electrical, or chemical engineering. This paper reports an alternative to a specialized undergraduate curriculum in MEMS through the use of the ABET-mandated capstone design course. The recognized benefits of interdisciplinary team-based design have enticed many engineering colleges to offer inter-departmental capstone design projects at the senior level; therefore, it is a natural candidate for introducing MEMS. Here we report our experience from one such project focused on the design and testing of an optical gas sensor. The project was developed in collaboration between the Mechanical and Aerospace Engineering Department and the College of Optical Sciences at The University of Arizona.

II. PROJECT DESCRIPTION AND DESIGN OBJECTIVES

Microfabricated cantilever sensors are one of the earliest examples of the use of mechanical structures for chemical detection. The early sensor examples were based on mass-induced mechanical resonance shift [10]. However, due to relatively complicated detection scheme and the need for external excitation, these did not result in a wide-spread use. An alternative detection mode is the surface stress based detection scheme, which uses the optical lever technique to amplify the cantilever displacement [11]. The first such demonstration was pioneered by a research group at IBM in Zurich, who demonstrated that a change in a single base-pare (bp) in a 12-bp sequence can be detected with chemically functionalized cantilevers [12]. Since then, a broad effort emerged to develop other sensors using similar technique including metal ion detectors (Hg, Cu, As) [13] and organic molecules [14]. The student design project described here is based on the preliminary work by [11], which demonstrated

[1] Stanley Pau, University of Arizona, e-mail stanpau@optics.arizona.edu

sensitivity of alkenethiols using a commercial atomic force microscope (AFM) scan head and Au-coated cantilevers. The experimental setup is shown in Figure 1. A fixed volume chamber is used to expose the Au-coated cantilevers to the vapors of alkenethiols, during which, a well-known reaction between organic thiol groups and the Au-coated surface results in a densely packed layer of self-assembled alkanethiol molecules (SAM). Functionalized SAMs are formed from alkanethiolates with the structure $HS(CH_2)_nX$, where n = 16-18 and X is a non-polar, organic functional group. Using various X groups, one could impart selectivity of the sensor to a variety of substrates [11]. The resulting surface stress, $\Delta\sigma$, produces a cantilever curvature R, given by the Stoney equation

$$\frac{1}{R} = \frac{6(1-\nu)}{Et^2}(\Delta\sigma), \qquad (1)$$

where E, t, and ν are the Young's modulus, the thickness, and the Poisson ratio of the cantilever, respectively. Assuming constant curvature, the deflection angle $\Delta\theta$ at a distance L from the base of the cantilever is

$$\Delta\theta = \frac{L}{R}. \qquad (2)$$

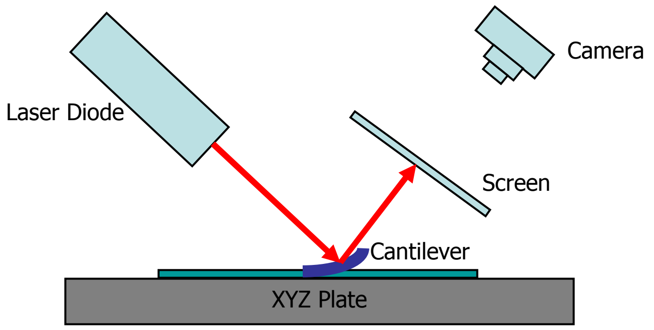


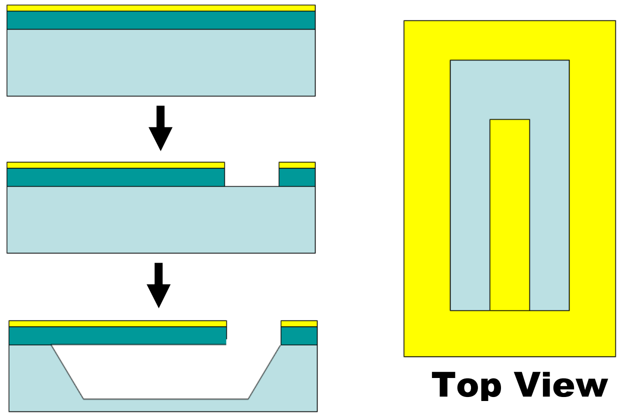
FIGURE 1
SCHEMATIC OF MICRO-CANTILEVER SENSOR EXPERIMENT

The deflection angle is then amplified using the "optical lever" technique, i.e. by monitoring the position of the reflected laser beam illuminating a position sensitive detector at a distance d from the cantilever

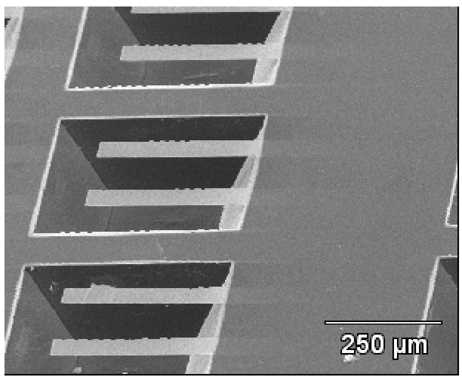
$$\Delta x = 2d\,\Delta\theta = \frac{12dL\Delta\sigma(1-\nu)}{Et^2}. \qquad (3)$$

Therefore, by monitoring the deflection of the reflected beam, one can determine the surface stress, provided that the elastic and geometric constants of the cantilever are known.

The capstone design project also included the design and fabrication of the micro-cantilevers. Students were presented with a process outlined in Figure 2a [15], which is based on a single photolithographic step, followed be dry etching of the Si_3N_4 (the material of the cantilever) and subsequent wet etching of the substrate (Si) underneath it. The resulting array of cantilevers is shown in Figure 2b. The main objective of the design project however, is to design an optical detection system comprised of a diode laser, focusing optics, positioning stages, and a position sensitive detector (PSD). The student team was presented with available research literature, design formulas, and was asked to design and produce a system capable of detecting the presence of alkenethiols in a gas phase.



(A) FABRICATION SEQUENCE



(B) FABRICATED CANTILEVERS

FIGURE 2
CANTILEVER FABRICATION PROCESS RESULTING CANTILEVERS

III. STUDENT POPULATION AND TECHNICAL CONTENT

III.1 Student Teams

The described project was developed over two years. The first cohort of students was recruited from three departments: Aerospace and Mechanical Engineering, Agricultural and Biosystems Engineering Department, and Electrical Engineering Department . These students enrolled in a 3-credit senior level course on micro- and nanotechnology, which also had a laboratory component. The second group of students was recruited from the college-wide engineering capstone design class (ENGR 498), which is open to all engineering majors. This group was comprised of students with major in Optical Sciences (3 students) and Material Science (2 students). Since the second group did not have prior training in micro-technology, these students were provided with research papers, attended mini-lectures given by the two authors in a bi-weekly advising sessions. Additionally, they participated in a hands-on demonstration of photolithographic pattern formation in the University of Arizona's clean room. The following tasks were presented to both groups as appropriate:

- Design an array of cantilevers taking into account the fabrication process and the limitations it imposes on the size/geometry of the cantilevers;
- Design an optical interrogation system and estimate the resolution of the complete sensor (offered to the students with optical engineering background);
- Design and build the integrated system with commercially available parts (only for participants in the capstone design project).
- Generate as diverse as possible uses of the cantilever-based sensing using data from research papers (offered to student teams with biosystems engineering background).

For both groups, the sensor was fabricated by the research associate assigned to the project. Both student groups elected members responsible for the individual tasks. Highlights of the team's design work are presented next.

III.2 Learning Objectives

The project was designed to stimulate the technical interests of diverse mix of students. With each group of students, the focus could be placed on a different aspect of the project, thus allowing the students to pursue their own scientific interests.

III.2a Cantilever Theory for Chemo-Mechanical Transducers

Because of the central role of the micro-cantilever as a transducer, all students were asked to design an array of cantilevers by applying the Euler-Bernoulli beam theory [16] and predicting the deflection angle according to (1)-(3). To stimulate the confidence in their analysis, the students were presented with experimental data from cantilever deflection using simple bi-layered cantilevers comprised of 300 nm SiO_2 and 200 nm of Si_3N_4. Using published values of the coefficient of thermal expansion of these materials, the students were asked to predict the cantilever deflection due to exposure to a 100 °C hot air.

An important aspect of the design included a discussion on the limitation of the length of the cantilevers due to the surface tension caused by water during the rinsing and drying steps. Students were presented with a research paper containing a model of the "releasable length" [17], and were asked to apply the model to their designs. The design required a trade-off between the stiffness/length of the cantilever and its sensitivity. A stiffer cantilever will be less prone to substrate adhesion and will exhibit smaller thermally induced vibrations; however it will also undergo smaller deflections upon application of surface stress.

III.2b Optical Design

The performance of the micro-cantilevers as chemical detectors is a strong function of the sensitivity of the optical interrogation system. The second group of students was asked to design an optical beam shaping system, select a laser source and photodetector and estimate the sensitivity of the system. During this step, students used Gaussian beam propagation theory [18] and analysis software (Code V, Optical Research Associates, Inc., CA) to analyze the performance of the optical system. The final design developed by the team included a laser diode/lens assembly operating at 635 nm and producing a collimated Gaussian beam. One concave and one convex lenses were used to re-shape and focus the beam onto the cantilever as is shown in ray trace diagram in Figure 3. The resulting parameters are listed in Table I.

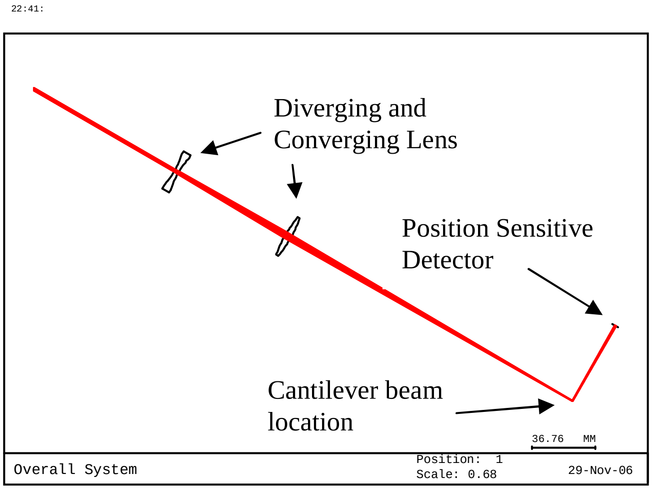


FIGURE 3
BEAM SHAPING OPTICS WITH RAYTRACE DIAGRAM

TABLE I
GEOMETRIC DISTANCES BETWEEN OPTICAL ELEMENTS AND BEAM CHARACTERISTICS

	Propagation Distance to Next Surface	Beam Radius on Surface		Waist Radius Before Refraction	
Surface	--	x	y	x	y
Laser	50.000	0.810	0.810	0.810	0.810
Lens 1	2.500	0.810	0.810	0.810	0.810
	71.780	0.823	0.823	0.025	0.025
Lens 2	0.000	1.983	1.983	0.013	0.013
	189.027	1.983	1.983	0.071	0.071
Cantilever		0.019	0.019	0.019	0.019
Wavelength 635nm		Dimensions in mm			

The students were also asked to identify the resolution-setting component in their design by comparing the detection limit of the PSD with the amplitude of thermally excited random vibrations of the micro-cantilevers. The latter was determined through an application of the energy equipartition theorem to the vibrational degrees of freedom of the cantilever beam [9]. For the first mode of vibration, it is easy to show that this amplitude is

$$\Delta z = \sqrt{\frac{4kT}{3K}}, \quad (4)$$

where k is the Boltzmann constant, T is the temperature, and K is the spring constant given by

$$K = \frac{Ewt^3}{4L^3}. \qquad (5)$$

The resulting change in curvature and deflection can be obtained through

$$\Delta R = \frac{(z \pm \Delta z)^2 + L^2}{2(z \pm \Delta z)}, \quad \Delta x = \frac{2Ld}{\Delta R}, \qquad (6)$$

respectively.

III .2c Cantilever (Chemical) Modification

Micro-cantilever sensors are being explored as a detection technology for a variety of compounds. Therefore, the research literature is abundant with examples that could be explored by the students. The objective of this design task was to stimulate creativity by asking the students to identify different analytes to be used with the current sensor. The teams then presented their concepts to the rest of the class and were asked to defend their choices in front of their peers. Examples of concepts that were presented included lactic acid sensor, metastatic cancer-cell detector, and Escherichia Coli detector. Expectably, most of the student teams selected a project related to their research interests, regardless of the fact that some of the proposed solutions were impractical and required the use of non-optical detection methods.

III.3 System Integration and Testing

The completed demonstration system consists of 635 nm laser diode with beam shaping optics (Edmund Optics NT59-080), a *x*- *y*- and θ positioning stage with sample holder, a post with the position sensitive detector (Hamamatsu S5990-01), and a syringe for dispensing the alkenethiols (see Figure 4).

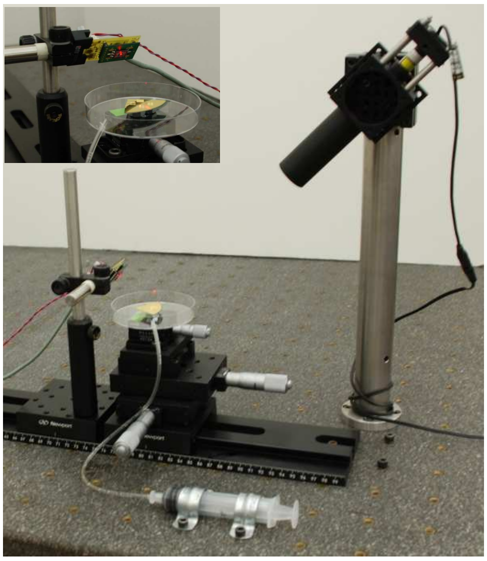


FIGURE 4
EXPERIMENTAL SETUP: LASER DIODE WITH OPTICS (RIGHT); SAMPLE HOLDER WITH ORIENTATION CONTROL(CENTER); PSD DETECTOR (LEFT)

The micro-cantilevers are fabricated using conventional microfabrication techniques. Figure 2a shows the simple process for producing gold-coated silicon nitride cantilevers for alkanethiol self-assembled monolayers (SAM). First, a silicon nitride layer is deposited by low-pressure chemical vapor deposition (LPCVD) on silicon wafer. A thin gold layer is then deposited using an e-beam evaporator, and the surface is patterned by photolithography followed by reactive ion etching. The cantilever itself is formed by wet etching with alkaline etchant, such as CsOH, or KOH. The large lateral etch rate of convex corners results in undercutting and produces a freestanding cantilevers, shown in Figure 2b. While the actual fabrication was conducted by the graduate research assistant assigned to the project, the students from the capstone design course were asked to participate in a hands-on demonstration of photolithography and etching. A covered Petri dish containing Au-coated silicon nitride cantilevers was used to expose them to a solution of dodecanethiol (2 ml) using a medical syringe. The cantilever deflection was then recorded and converted to surface stress values using (1-3). Figure 5 shows typical experimental data.

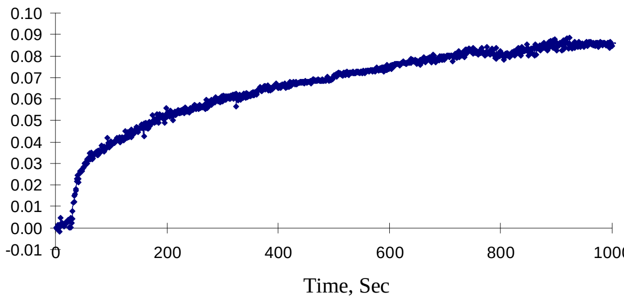


FIGURE 5
MEASURED SURFACE STRESS (N/m) AS A FUNCTION OF TIME

IV. OBSERVATIONS

Interdisciplinary teams provide a unique educational opportunity. Stemming from their varying educational background, students from different majors had different approach and different behavior during the recitation sessions. While the engineering students showed confidence in applying mathematical models, their peers from the optical and natural sciences were more skeptical about the validity of the Euler-Bernoulli theory when applied to micro-cantilevers. Preliminary data from the previous course offerings proved invaluable as an illustration of the predictions of the model and in convincing the students in the validity of the model. Conversely, the students from the natural sciences departments were more accustomed to new concepts from the field of statistical mechanics, as opposed to their engineering counterparts. In both cases, a 50-minute lecture was sufficient to introduce and illustrate the concept and instill confidence in the students.

Another objective of the present project was to evaluate the feasibility of incorporating micro- and nano-technology based projects into the traditional curriculum (the capstone design project) of students with no prior training in this area. Several factors contributed to the successful completion of the project by the student design team. These include:

- Availability of MEMS samples and reports from previous groups that could be used as an illustration of the device concept;
- Ability to tailor the scope of the project to the technical ability of the team, e.g. when the team was mainly comprised of optical engineering students, the project was focused on the optical design, while the research assistant fabricated micro-devices and assisted with testing;
- Higher motivation due to self-selection of team members. Exit surveys of the lecture-based introductory course on micro- and nanotechnology showed that students in that class were more interested in as many topics as possible and were, therefore, less interested in a prescribed design project;
- Finally, the time limitation of a one-semester course is simply prohibitively short to complete an open-ended design project, since there is not sufficient time for design iteration and revision.

Further comparison between the two groups showed that the students from the optical and material sciences departments had sufficient training in physics to allow them to quickly understand and learn the specifics of MEMS. Peer-to-peer teaching and learning was also present as the team quickly identified and appointed “experts” in each of the technical areas of the project. Conversely, the group participating in the lecture/lab course was more dependent on the instructor and the teaching assistant of the cours in making design decissins. Informal feedback from the students from both groups indicated sustained interest in pursuing further studies in nanotechnology at the graduate level, which was one of the objectives of the project.

V SUGGESTED MODE OF DISSEMINATION AT OTHER INSTITUTIONS

The described project could be conveniently adapted and implemented at other institutions, because most components are commercially available. The fabrication of Au-coated Si_3N_4 cantilevers is straightforward; however, a more economical way of producing them might include the usage of a pre-coated Si- Si_3N_4-Au substrate. In this case, the only in-house fabrication processes are pattern formation and release of the cantilevers. Institutions without access to a cleanroom facility could also utilize the many available foundry services offered by academic institutions.

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