MICROFLUIDICS @ THE BEACH: 
Introduction of Microfluidics Technology to the ChE Curriculum at Cal State Long Beach

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Microfluidics involves the study of the behavior of fluids at microscale, fluid manipulations, and the design of the devices that can effectively perform such manipulations. It has been widely applied to the miniaturization of analytical methods and chemical and biological processes because of its many advantages, such as significant reduction in analysis time, much lower sample and reagent consumption (in the nanoliter range or less), and enhanced system performance and functionality by integrating different components onto microfluidic devices.[1, 2] These applications are usually called micro total analysis systems (μTAS) or lab on a chip (LOC).[3, 4] Since its debut in the 90s,[5–7] microfluidics has made significant progress and gradually moved from pure research projects to commercialized products, such as Agilent Technologies’ 2100 Bioanalyzer for biomolecule analysis, PerkinElmer Inc.’s LabChip systems for biomolecule analysis and drug discovery, and Fluidigm Corporation’s BioMark system for real-time PCR.

Microfluidics is an interdisciplinary area that incorporates various technical branches, such as biochemistry, biology, chemistry, physics, and engineering.[8] As microfluidics finds increasing new applications, there is a strong need for general awareness and in-depth understanding in this growing area, especially for science and engineering education. Although some undergraduate courses exist, most microfluidics courses are offered to graduate students. They are mostly lecture-based and do not have hands-on sessions for students to put in action right away what they see/learn from class lectures. The major barrier to integrating hands-on sessions with lectures in microfluidics courses is the need for access to equipment in cleanroom facilities and the associated costs for supplies, such as silicon wafers and polydimethylsiloxane (PDMS), to
fabricate microfluidic devices for educational purposes. As a result, these resources are generally available for research personnel only. In addition, fabrication of microfluidic devices requires specific training to enable each individual to reliably make working devices, which is not feasible for a typical class of 20 to 30 students. To provide students with hands-on experiences in microfluidics, there have been efforts on developing more accessible systems and educational modules, e.g., LabSmith’s commercial SVM340 microscope,[16] shrink-film microfluidic devices by Nguyen, et al.[17] Jell-O chips by Yang, et al.[18] SmartBuild by Yuen,[19] and several reported chemical engineering laboratories.[20-23] These efforts have lowered the barrier to such integration.

In the past few years, we have seen an increase in job opportunities for engineers with skills relevant to microfluidics, such as microfluidic chip design, microfabrication, optical imaging, and programming languages for instrument control and data analysis. For such opportunities, we believe that chemical engineers need to bridge the gap from theory to practice by actually performing them and revising the protocol to fit ongoing research projects into the ones suitable for teaching. For such opportunities, we believe that chemical engineers need to bridge the gap from theory to practice by actually performing them and revising the protocol to fit ongoing research projects into the ones suitable for teaching.

We seek to address this gap by initiating a course development project for two courses: Microfabrication and Microfluidics Technology and Its Applications, along with corresponding hands-on laboratory sessions. In this project, both undergraduate and graduate students were involved in the design of the laboratory sessions. They helped to convert some projects in our ongoing research projects into the ones suitable for teaching by actually performing them and revising the protocol to fit our class needs.

In this paper, we present the contents and student feedback of the first course, Microfabrication and Microfluidics Technology, which was offered for the first time in the Spring 2013 semester as a cross-listed course for both undergraduate and graduate students.

### FACILITIES AND RELEVANT COURSES AVAILABLE

California State University, Long Beach (CSULB; The Beach) is predominantly an undergraduate institution. We have been seeking to include microfluidics technology in the chemical engineering curriculum at the senior and first-year graduate level. Currently in the CSULB College of Engineering, there are several courses covering some relevant topics in microfluidics technology offered in the Department of Electrical Engineering (EE 435 Microelectronics, EE 436/536 Microfabrication and Nanotechnology, and EE 437 Multidisciplinary Nano-Science and Engineering).

### COURSE CONTENTS

In this course, we introduce fundamental concepts involved in the design, construction, and operation of microelectromechanical systems (MEMS)-based devices and provide students with working knowledge to get involved in this area of growing importance through both class lectures and related reading materials. In the laboratory sessions, our students get hands-on experience by fabricating chips and conducting experiments on flow in the channel. The topics covered are summarized in Table 1.

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However, these courses focus on the device fabrication, material characterization, and the standard photolithographic techniques used in the microelectronics industry. In addition, these courses do not come with laboratory sessions, because CSULB had neither a fabrication facility nor faculty members with microfluidics expertise before 2009. To initiate our research program and this course development project, we have established the Microfabrication Laboratory, a Class 10,000 cleanroom, capable of fabricating polydimethylsiloxane (PDMS) and thin-film-based microfluidic chips using soft lithographic techniques[24] and the Analytical Instrumentation Laboratory capable of fluorescence microscopy and image processing for microfluidics applications. They have been fully functional since Summer 2010, and our students have presented their work from these two laboratories at various conferences, such as Southern California Conferences for Undergraduate Research (SCCUR), ASEE, and AICHE annual meetings.

### MATERIALS

PDMS (poly(dimethylsiloxane)) is a very popular material used to construct microfluidic devices and other components for applications in biology, chemistry, and engineering because of its great properties, such as optical transparency, biocompatibility, and ability to control flow, and a simple fabrication process (“soft lithography”).[25] However, fabrication of PDMS devices is not suitable for a teaching lab because of the cost of mold making and toxicity of the monomer and curing agent.

With low-cost, non-toxic materials, this session was intended to familiarize our students with the typical soft lithographic process. A collection of chip designs was drafted with an open-source vector graphics editor (<http://www.inkscape.org>) and was printed on copy paper using an office laser printer (<http://www.inkjet.com/>). The gelatin solution was prepared by dissolving 40 grams of the powder in 1 liter of boiling water and was later treated with activated filter carbon to produce a clear solution. To cast hollow channels, 50 mL of the clear gelatin solution was poured into each Petri dish with the designed mold with care to avoid any bubbles, and the whole assembly was allowed to set in the refrigerator. Access holes were punched on the hollow channels with coffee stirrers before they were reversibly sealed onto Petri dish covers to form working chips.

### LABORATORY DESCRIPTION

To enhance the learning experience through teamwork, students were required to work on lab assignments in groups of two. As described below, the lab sessions were held over four weeks after all the lectures had been completed.

#### Week 1: Soft lithography

PDMS is a flexible material used to construct microfluidic devices and other components for applications in biology, chemistry, and engineering because of its great properties, such as optical transparency, biocompatibility, and ability to control flow, and a simple fabrication process (“soft lithography”).[25] However, fabrication of PDMS devices is not suitable for a teaching lab because of the cost of mold making and toxicity of the monomer and curing agent.

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fluids in channels on their gelatin chips. With this configuration, our students could directly visualize the laminar flow profile within the channels without using a microscope, as shown in Figure 2. They could see the formation of an interface between two colored fluids (red and blue) and mixing taking place along the channel length. To enhance our students’ understanding of the flow profile, we asked them to calculate the Reynolds number (Re), the ratio of inertial forces to viscous forces, to confirm the laminar flow profile is the one they should see in such a configuration.

\[
Re = \frac{\rho U_0 l_0}{\eta}
\]

where \(\rho\) is the fluid density, \(U_0\) is the characteristic velocity, \(l_0\) is the characteristic length, and \(\eta\) is the shear viscosity of the fluid, respectively.\(^{[18]}\) Given our channel dimensions (3 mm x 2 mm in cross section), water-based working fluids (\(\rho = 1.0 \text{ g/cm}^3\); \(\eta = 1.0 \times 10^{-3} \text{ g/cm s}\)), and a characteristic velocity of 1.0 cm/s, the Reynolds number was determined to be 24. This indicated that the viscous forces were dominant and the flow was within the laminar regime (\(Re << 2300\)) on our chips.

In addition to the Reynolds number to confirm the flow regime, we also asked students to identify the dominating mechanism for fluid mixing on their gelatin chips by calculating the Péclet number (Pe), which is the ratio of convective mass transport to diffusive mass transport.

\[
Pe = \frac{U_0 l_0}{D}
\]

where \(D\) is the diffusion coefficient. Given the average diffusion coefficients of food dyes (2.33 x 10^{-7} m^2/s),\(^{[18]}\) the Péclet number was determined to be 103,004. This indicated that convective mass transport was the dominating mechanism for fluid mixing and the diffusive mass transport is negligible along the characteristic length (the hydraulic diameter of the channel) on the gelatin chips. As the channel width decreases, the effect of diffusive mass transport becomes more pronounced. Through calculations of these dimensionless numbers, our student could identify the dominating mechanism and mass transport on a fluidic chip and thus could design microfluidic devices according to desired applications by identifying the dominating mechanism and changing parameters, such as characteristic length and velocity.

**Week 3: Homemade pH sensors**

To fabricate homemade pH sensors, pH paper strips were imbedded into chip channels before sealing onto Petri dish covers. Two syringes were used to load the acid and base, 0.1 M HCl and 0.1 M NaOH, into the channel. As indicated in Figure 2, the pH paper strips turned red in contact with the acid and purple in contact with the base, respectively. Through this lab, our students could see how to construct a simple device for chemical analysis. Another concept demonstrated here was parallelization, an important feature of microfluidics technology, because multiple reactions/assays could run simultaneously in different channels on a single chip. Herein, we introduced to our students the idea of "lab on a chip," which allows integrating multiple steps onto a single microfluidic device, ranging from sample pretreatment to final readout. In this case, both acid and base could be detected at the same time on a single gelatin chip, and the results could be read by color changes.

**Week 4: Pattern fabrication onto copper-coated slides**

Electrodes have been integrated onto microfluidic chips for various applications, such as electrochemical detection and electrokinetic manipulations of molecules for reactions/assays. For etching experiments, desired patterns were drawn on copper-coated slides with a permanent marker. With the ink serving as the resist, all excess copper was etched away with a 3:1 mixture of 3% H2O2 and 10 M HCl (Thermo Fisher Scientific, Inc., Waltham, MA, USA). The final copper pattern was revealed by washing away the permanent marker ink with acetone, as shown in Figure 4. Through this lab, students could learn the basic techniques of fabricating metal electrodes on a substrate.

**COURSE ASSESSMENT**

Besides the regular CSULB Student Perceptions of Teaching (SPOT) questionnaire, this course was also evaluated by...
an additional outcome survey at the end of the semester. We used a course outcome assessment survey form on a five-point Likert scale with 5 being Strongly Agree and 1 being Strongly disagree. The criteria of each expected course outcome was included, and students could rate how successfully they reached the goal as described by the criteria (Table 2). The survey results are summarized in Figure 5. In general, our students responded very positively and were confident in what they had learned from this class, as supported by average scores ranging from 4.00 to 4.69 (out of 5.00). They were glad to be able to take the gelatin chips home as souvenirs and knew that they could make new ones easily to showcase what they learned using materials readily available around the corner.

After looking into individual criteria, the results indicated that our students felt less confident in Outcomes 3 and 4, as reflected in the scores of 4.06 and 4.00, respectively. From their comments, our students suggested that an adjustment in the topic coverage and labs would help them better understand the materials presented in this course. To address these comments, we aim to improve this course, we will prepare more detailed lecture slides to help walk our students through the topics presented in the textbook and focus on those more directly related to microfluidics technology. We will also increase the coverage of the device design and introduce more experiments demonstrating actual applications of the microfluidic devices in the field, such as sample separation and detection of biological/chemical agents.

**CONCLUSION**

We present in this paper our efforts and current progress to introduce microfluidics technology to the chemical engineering curriculum at CSULB. Although the first course offering was successful, there is still room for improvement. We have recently started in our department an instrumentation development project that employs 3D printing and open-source electronics to design and construct portable systems for chemical and biological analytics. We plan to include the results from this project in the next course offering. A sequential course, Microfluidics Technology and Its Applications, is currently under development. It will focus more on theoretical aspects of microfluidics technology and its applications.

These two elective courses are intended to expose our senior and first-year graduate students at CSULB to this exciting field of study and to provide them with working knowledge to get involved in this area. They will be first offered to students in our department as a pilot program and will later be offered to all science and engineering majors at CSULB after revising the course contents according to the feedback from our students and faculty. Throughout these courses, our students will obtain not only the working knowledge of microfluidics technology, but also the written skills required for effective technical information exchange. We hope that in the future these two courses may excite more students to pursue advanced studies and careers in this area of growing importance.

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**REFERENCES**