Graduate-level hands-on laboratory practices of microdevices for microooptic and biosensor applications

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Abstract

We present our experience in graduate-level, small enrollment size, hands-on laboratory instruction of microoptic and biosensor microdevices. Inherently, instructing the two microdevices types can be largely benefited by linking with microfabrication laboratory practices to design, fabricate and characterize these devices in class. Based on the knowledge base of microfabrication instructions, two experimental courses emphasizing each device category were offered by Department of Electrical & Computer Engineering at Missouri University of Science & Technology. All laboratory experiences were team-based and many laboratory project topics were proposed by the students themselves. Cost-effective microfabrication and characterization facilities were utilized to conduct the lab projects. The preliminary assessments indicate that students prefer significant laboratory experience and that learning of lecture concepts of the two types of devices is enhanced. Several key issues need to be further investigated and improved for this type of experimental laboratory courses to be more effective learning experience. These include the selection of appropriate project topics, the structure of the course contents related with laboratory and lectures, and the enhancement of the laboratory infrastructure for higher flexibility in process practices and higher enrollment.

Introduction

The area of integrated optical devices in microscale, including passive microoptical components and solid-state photonic devices, has already emerged as a substantial area within the broad scope of the various engineering disciplines. The need of enriching curricula in this area has long been the subject of matters [1]. Also, developing affordable teaching laboratory in this area to support accompanying lectures is becoming important with the constraints of academic teaching budgets [2].

The subject of biosensor technology is also becoming an increasingly important area to educate future workforce as large demands are expected for the coming decades. Furthermore there has been a huge impact on this subject recently from the incorporation of microfabrication technology, thus creating an emerging area of biological micro-electro-mechanical systems (bio-MEMS). Education in this area requires a great level of interdisciplinary activities and the need of laboratory exercises on this subject is rapidly growing [3,4].

Based on the nature of the two microdevice categories mentioned above, one common aspect of the two subject areas is that linking the laboratory practices of microfabrication process with these areas can enhance the students understanding. Implementing laboratory instructions on the microfabrication processes for traditional solid-state microelectronic devices or micro-electro-mechanical systems (MEMS) has been reported by many educators [5 - 9]. Based on this knowledge base, two experimental courses emphasizing each device category were offered by Department of Electrical & Computer Engineering at Missouri University of Science & Technology (formerly the University of Missouri-Rolla) in the spring semesters of 2007 and 2008. This report describes how the microfabrication instructions were implemented for accommodating the two important subject areas utilizing a cost-effective microfabrication facility. The main educational aims of laboratory instructions were to enable students to reinforce their understanding and knowledge of microoptics and biosensors and to gain practical experience for designing, fabricating, and characterizing the two types of microdevices.

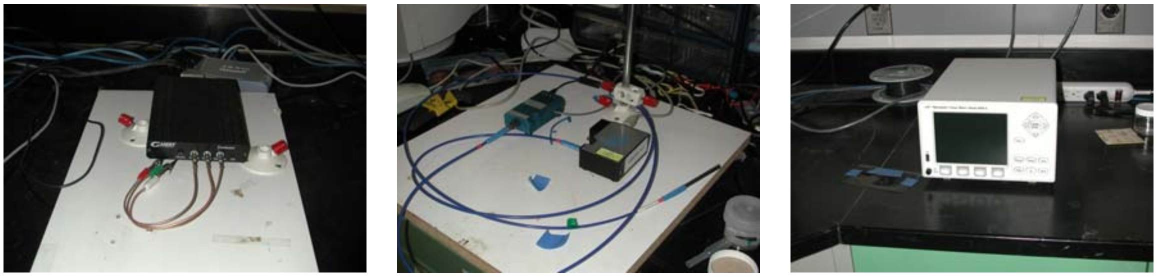
Course implementation

I. Laboratory equipment

All laboratory experiences utilized cost-effective microfabrication facility initially prepared for laboratory instruction of general micromachining technology and micro-electro-mechanical systems (MEMS) [10]. As shown in Figure 1 and 2, the major equipment routinely used includes; an aligner/exposure system and a spin coater for photolithography, a metal sputter coater for thin film deposition, a current-voltage source-measure unit for electrochemical measurements, a spectrophotometer and an optical power meter for optical measurements (about $50,000 total). A custom 2-cathode sputter deposition machine was used as needed to form bilayer metal films (e.g. Pt/Ti layer). For insulator films (e.g. silicon oxide layer), the wafers with pre-deposited films were purchased. The photomasks for lithographic patterning processes were printed in a local office supplier that provides printing service on mylar sheets. The cost for these flexible photomasks with reliable 200 um linewidth resolution was about $10 per printing. The laboratory supplies and chemicals cost between $200-$600 per each project.

(a) (b) (c)

Figure 1. Major process equipment routinely used in the class. (a) UV-exposure system (Cobilt, refurbished CA800, $10,000), (b) Spin coater (Laurel, WB-400B-6NPP-LITE, $6,000), (c) Metal thin film coater (Bio-Rad, refurbished E-6175, $6,000).



(a) (b) (c)

Figure 2. Major characterization instruments routinely used in the class. (a) Electrochemical workstation (Gamry, FAS-1, $15,000), (b) Spectrophotometer (Ocean Optics, USB2000-FLG, $6,000), (c) Optical power meter (Newport, 2936-C, $5,000).

II. Microoptic devices course

A graduate-level experimental course on integrated optical devices, EE 401 Advanced Optics & Devices: Microoptic Devices (lecture 1.5-hr / laboratory 1.5-hr), was offered in 2007 spring semester. The course contents composed of an 8-week lecture session and a 7-week hands-on laboratory session as in Table 1. Major lecture topics included; (1) a brief review of microfabrication technology, photonic devices and guided optics, (2) basic structures of integrated optical components, such as solid-state photodetectors and emitters, passive components especially waveguides and couplers, and (3) micro-opto-electro-mechanical systems (MOEMS), especially focused on microsensors and microactuators for optical applications. General optics theories were not covered in this class, since we already have well-established optics courses available in the departments of Electrical & Computer Engineering and Physics, including Classical Optics, Fiber & Integrated Optics, and Electromagnetic Optics.

The laboratory session consisted of two phases. The Phase-I period of about 3.5-weeks was devoted to feasibility tests for new designs of individual integrated components or to practice samples using selected fabrication processes, while the Phase-II period involved the preparation and characterization of simple microdevices incorporating selected components. The students were teamed in groups of two or three members and each group attended 3-hour laboratory sessions two times per week during the 7-week laboratory session. Every student attended all three presentations including project planning, Phase-I wrap-up and final presentations to monitor the progress of other groups' projects and learn from each other. All groups were required to turn in 1-page laboratory report every week.

III. Biosensors course

In 2008 spring semester, another experimental course, EE 401 Biosensors & Bioelectrodes (lecture 1.5-hr / laboratory 1.5-hr), was offered emphasizing bioelectronic devices of microscale or mesoscale. Similarly with the microoptic class, the course composed of an 8-week lecture session and a 7-week hands-on laboratory session as in Table 1. Major lecture topics included;

(1) a brief review of microfabrication technology, (2) basic concepts of applied electrochemistry and photochemistry, (3) review of electroanalytical and photometric methods, (4) structures and principles of electrochemical biosensors and (5) structures and principles of optical biosensors.

The laboratory session was implemented the same way as the microoptic class, except the main theme was the biosensor devices. Since the subject of biosensors is a highly interdisciplinary area, this time the laboratory activity was more focused on interdisciplinary content, especially identifying appropriate laboratory project topics that were amenable to both chemical/biological engineering students and electrical engineering students.

Table 1. Overall schedule of the Microoptic devices course offered in 2007 spring semester.

Weeks	Sessions	Contents	Assignments
1	Microfabrication review (lecture)	Introduction, thin film deposition, photolithography	
2		Etching, doping, oxidation	Homework problems
3	Photonics review (lecture)	Photodiodes	
4		LED	Homework problems
5		Laser diodes	
6	Microoptic devices and MOEMS review (lecture)	Thin film waveguides, chip-scale couplers	Homework problems
7		Optical microsensors	Test
8		Optical microactuators	Project proposal
9	Phase-I laboratory session	Phase-I	Planning presentation
10		Phase-I	
11		Phase-I	
12		Phase-I	Phase-I wrap-up presentation
13	Phase-II laboratory session	Phase-II	
14		Phase-II	
15		Phase-II	
16		Final week	Final presentation and term paper

Table 2. Overall schedule of the Biosensors course offered in 2008 spring semester.

Weeks	Sessions	Contents	Assignments
1	Microfabrication review (lecture)	Introduction, thin film deposition, photolithography	
2		Etching, doping, oxidation	Homework
3	Electrochemical biosensors (lecture)	Electrochemical cells review	
4		Electroanalytical methods review	Homework

5		Electrochemical biosensors case study	
6	Optical biosensors (lecture)	Photochemistry review	Homework
7		Photometric methods review	Test
8		Optical biosensors case study	Project proposal
9	Phase-I laboratory session	Phase-I	Planning presentation
10		Phase-I	
11		Phase-I	
12		Phase-I	Phase-I wrap-up presentation
13	Phase-II laboratory session	Phase-II	
14		Phase-II	
15		Phase-II	
16		Final week	Final presentation and term paper

Laboratory practices and outcomes

I. Microoptic devices course

The enrollment in this class was eight students, seven from electrical engineering and one from mechanical engineering. As an experimental course, the prerequisite of the first offering was graduate standing and consent of instructor. Four students had already taken classes related to microfabrication technology, two students had prior backgrounds in photonic devices, and five students had a general optics background. Only one of these students had a background in all three subjects and one student had a background in none of the subjects. Therefore, the students were grouped by the instructor depending on their background. The criteria for group formation were that the group members can learn from each other and complement each others expertise.

As can be noticed in the Table 3, all laboratory projects were related with MOEMS type devices such as passive components or microsensors rather than the traditional solid-state photonic devices. Implementing hands-on laboratory sessions to fabricate such traditional photodetectors or emitters made with silicon or compound materials are very challenging with limited budget and equipment. Some project topics were proposed by students themselves after literature search related with the lecture contents, while some topics were suggested by the instructor and chosen by the students.

II. Biosensors course

As with the microoptic class, the prerequisite of the first offering was graduate standing and consent of instructor. Four students of the total enrollment of five graduate students were from the Department of Chemical & Biological Engineering and only one was from electrical engineering. Although all students had general knowledge of college-level chemistry courses, none of them had in-depth knowledge on analytical sciences which is essential in biosensor engineering. Only one student had a physical chemistry background that covers some portions of analytical chemistry. Compared to the microoptic course, this class emphasized more on the interdisciplinary activity. The instructor, an electrical engineer with expertise in biomedical engineering by training, and the one electrical engineering student worked closely with them to identify and formulate appropriate topics content and topic scope.

Table 3. List of the laboratory projects of the two courses and technical issues that required students' major efforts to conduct the projects.

Courses	Project titles	Major laboratory issues
Microoptic devices	Coupling between long period fiber grating (LPFG) and SU-8 waveguide	Fiber-to-chip coupling, grating couplers, propagation loss, thin film waveguides, etc.
	Integrated optical oxygen sensor chip	Fluorescence oxygen membrane, microfluidic channels, fluorescence intensity measurements, etc.
	Development of a vertical waveguide imaging system	Thin film waveguides, photopolymer refractive index, transmittance measurements, etc.
Biosensors	2-D dissolved oxygen control and monitoring using hydrogel microarray sensor	Photopatternable hydrogel membrane, colorimetric analysis, microelectrodes fabrication, etc.
	An amperometric glucose biosensor based on gold-polyaniline nanocomposites	Nanocomposite material synthesis, thin film adhesion, device packaging, etc.
	Hydrogen peroxide sensor membrane using europium tetracycline	Fluorophore immobilization, sensor stability, thin membrane film formation, etc.

III. Preliminary assessment result and discussion

Although there is limited quantitative assessment data after only one offering of each experimental course, several important observations were made. A survey was conducted after the course including the following questions:

1. The laboratory session helped me to understand the lecture materials better.
2. The lecture session provided enough background knowledge to practice the laboratory session.
3. I feel that my theoretical knowledge (e.g. theory of the device that you design, theory of fabrication processes that you practice, etc.) was improved after the laboratory session.
4. I feel that my practical skills (e.g. instruments, laboratory practice, etc.) were improved after the laboratory session.
5. I feel that I experienced an interdisciplinary team activity (e.g. collaborative work between electrical engineering and chemical engineering).

6. I would recommend this course to other students.

Figure 3 shows a preliminary result which indicates that the benefits of laboratory sessions are substantial in general. Also, student feedback has been very positive and student responses to the course, especially the effectiveness of the laboratory session, were highly favorable. It is considered that the rather low score of question #5 is because of the similar disciplinary background of the majority of students. The role of instructor is very important because some project topics needs to be developed carefully by the instructor with consideration for the background and research interests of the student team. For small enrollments, each student team can have an independent project to stimulate the students' creativity. Larger enrollments can require more uniformity in the project topics for each team.

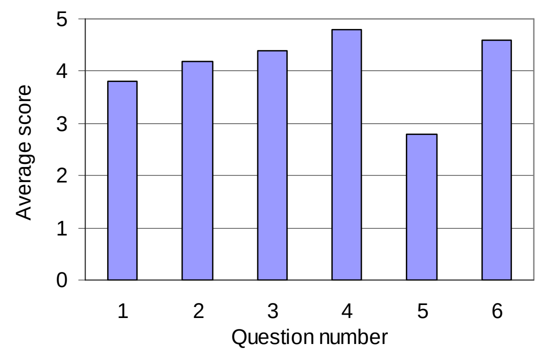


Figure 3. Preliminary survey results after the Biosensor course (5 = strongly agree, 1 = Strongly disagree, n=5).

It is necessary to relate the lecture materials with laboratory projects more closely to allow the students to gain more hands-on experiences directly related with theories covered in lectures. As evidenced by the slightly low scores of questions #1 and #2, there is a certain limitation of process capability due to the constraint of budget and equipment to cover the lecture materials with laboratory projects. The cost of the laboratory equipment and the consumables places limitations on developing more advanced projects with a higher degree of project complexity. This fact also prevents us from increasing the class enrollment size to benefit more students.

Also there is significant room for improvement of the courses in other aspects. The limited time in a single-semester experience requires that the tasks and scope of the projects be well defined and matched to the lecture materials and available equipment. Also, a balance of prescribed and project-based assignments [10] are useful because the structure of this type of courses must provide a sufficient theoretical background for the laboratory work and adequate training in needed fabrication operations.

Conclusion

We presented graduate-level, small enrollment size, hands-on laboratory practices of designing, fabricating and characterizing microdevices for microoptics and biosensors. Laboratory and project experiences are particularly important for interdisciplinary areas, such as microoptic and biosensor microdevices applications. In job settings, students will need to be able to learn outside of their expertise areas and to be able to interact with specialists in other areas [11]. The implementation of this type of courses that emphasize laboratory work poses challenges. Key issues are the selection of project topics, the structure of the laboratory course content, and the cost of laboratory infrastructure. If the project topics and equipment are well matched to the students and the lecture material and its pedagogical structure provides an adequate support for the performance of the project, the laboratory can provide an effective learning experience.

The preliminary assessments indicate that students prefer significant laboratory experience and that learning of selected lecture concepts is enhanced through an interactive environment. Also the feedback from students revealed that the course was delivered effectively and presumably achieved its aims well to enhance the student learning in applying the microfabrication technology to microoptics and biosensor applications. We plan to address the aforementioned key issues by adjusting lecture materials to be able to provide more background for potential laboratory projects in the next course offering. Further details of class assessment results will be reported after continuous offering of these experimental courses.

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Bibliography

1. Palais, J. C., N. C. Gallagher, H. Stark, "Photonics enrichment of the EE curriculum", IEEE Transactions on Education, Vol. 35, No. 2, 1992, pp. 103-108.
2. Johnstone, W., B. Culshaw, D. Walsh, D. Moodie, I. Mauchline, "Photonics laboratory experiments for modern technology-based courses", Proceedings of IEEE, Vol. 88, No. 1, 2000, pp. 41-54.
3. Gale, B., "BioMEMS education at Louisiana Tech University", Biomedical Microdevices, Vol. 4, No. 3, 2000, pp. 223-230.
4. Papautsky, I., E. T. K. Peterson, "An introductory course to biomedical microsystems", Biomedical Microdevices, Vol. 10, No. 3, 2008, pp. 375-378.
5. Gowzdz, P., "NSF microfabrication workshops", IEEE Transactions on Education, Vol. 39, No. 2, 1996, pp. 211-216.
6. Cirstea, M., "Problem-based learning (PBL) in microelectronics", International Journal of Engineering Education, Vol. 19, No. 5, 2003, pp. 738-741.
7. Muscat, A., E. Allen, E. Green, L. Vanasupa, "Interdisciplinary teaching and learning in a semiconductor processing course", Journal of Engineering Education, Vol. 87, 1998, pp. 413-421.
8. Allen, E., S. Gleixner, G. Young, D. Parent, Y. Dessouky, et al., "Microelectronics process engineering at San Jose State University: a manufacturing-oriented interdisciplinary degree program", International Journal of Engineering Education, Vol. 18, No. 5, 2002, pp. 519-525.
9. Lin, L., "Curriculum development in microelectromechanical systems in mechanical engineering", IEEE Transactions on Education, Vol. 44, No. 1, 2001, pp. 61-66.
10. Kim, C-S., S. E. Watkins, "Work in progress – Balancing prescribed and project-based experiences in microfabrication laboratories", The 38th Annual Frontiers in Education Conference (FIE), Saratoga Springs, NY, Oct 22-25, 2008, Abstract # 1250, accepted.

11. Watkins, S. E., V. M. Eller, Josh Corra, Martha J. Molander, Bethany Konz, R. H. Hall, K. Chandrashekhara, and Abdeldjelil Belarbi, "Interdisciplinary Graduate Experience: Lessons Learned," *Proceedings of the 2002 ASEE Annual Conference*, 16-19 June 2002, Montreal, Quebec.

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