3D Printing as an Effective Educational Tool for MEMS Design and Fabrication

Reena Dahle, *Member, IEEE*, Rafiul Rasel, *Student Member, IEEE*

***Abstract*—This paper presents a series of course modules developed as a high-impact and cost-effective learning tool for modeling and simulating the microfabrication process and design of MEMS devices using three-dimensional (3D) printing. Microfabrication technology is an established fabrication technique for small and high precision MEMS devices; these processes typically take place in a cleanroom with the use of expensive high vacuum equipment. These course modules were developed to provide engineering educators a more affordable and effective method for teaching MEMS modeling in settings without a cleanroom, as is the case in many undergraduate institutions. Feedback from student evaluations as well as course grades all support the efficacy of these course modules. In these hands-on modules, by designing and building the MEMS prototypes, the students learn by experiencing the process of building a MEMS device from the specifications given. The results are also compared to similar assessments made in the course before the introduction of these course modules to verify success. The detailed description of the modules, the evaluation methodologies adopted, and reflections on the implementation are discussed.**

***Index Terms*—Electrical engineering education, fabrication, micro-electromechanical devices (MEMS), printing.**

I. Introduction

New and exciting products created as a result of 3D printing include such as extreme new sneaker designs and incredibly light prosthetic limbs. 3D printing is a multi-billion dollar business that is revolutionizing the world around us [1]. Today the demand for 3D printing in education is growing rapidly, and it has been incorporated into the study of the molecular structure of chemical compounds and other microscopic components that are otherwise difficult to conceptualize and understand. Several papers have reported on the use of 3D printing for education and the advantages of using a hands-on approach in electrical engineering education [2]-[4].

MEMS are integrated devices that contain extremely small mechanical elements and are fabricated using standard integrated circuit (IC) processes. With the advancement of the Internet of Things (IOT) and the rising requirement for miniaturization and environmental sensing and monitoring, MEMS are increasingly being embedded in many of the electronics used daily. Companies around the world are progressively more involved in MEMS-related design and fabrication. Therefore, it is essential that universities meet the rising demand in industry for highly qualified MEMS engineers by educating students on the critical skills required in design and manufacturing. Moreover, for a thorough understanding of MEMS fabrication processes, working in a MEMS cleanroom is one of the very first requirements. However, cleanrooms and cleanroom equipment can be very costly and most campuses have limited access to such facilities. With the availability of 3D printing, it is very easy to emulate the fabrication process of MEMS devices and gain a better understanding of this field without investing a significant amount of time and money in a cleanroom. A 3D printed design and simulation helps the student better visualize and understand the multilayer MEMS fabrication process while also allowing them to physically examine the final product. Given the lack of access to cleanroom equipment, MEMS courses currently offered typically only examine the theory of fabrication processes. Students focus more on memorizing the processes rather than gaining a conceptual understanding of how these devices are fabricated. In an attempt to provide students with a more meaningful experience and enhance their knowledge of the process of design and fabrication of MEMS, the course ‘Introduction to MEMS’ was redesigned so that students are required to generate 3D prototypes of MEMS devices using the processes and fundamentals they learn in class.

This paper describes a one-semester course that includes assignments and project modules, aimed at producing skilled, innovative and career-ready engineers who have a deep understanding of the fabrication and modeling process of MEMS components. In the first assignment, students individually use SolidWorks [8] and their understanding of Miller indices to generate 3D print models for the crystalline planes of [100]-oriented and [110]-oriented wafers with [100]-aligned mask features. In the second assignment students then apply their understanding of the properties of materials and the basics of microfabrication wet etching techniques on silicon wafers by creating the 3D profiles of an isotropic and anisotropic etch, given a specific mask outline. Finally, a semester-long project is assigned in which students, in pairs, design, build and print the step-by-step model of a capacitive MEMS switch or MEMS inductor scaled to a larger size. Each step used in the cleanroom fabrication process is replicated using a Stratasys Dimension 1200es 3D printer [9]. This course has multiple goals and benefits. It covers the design,

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R. Dahle is with the Division of Engineering Programs, State University of New York (SUNY) New Paltz, New Paltz, NY 12561 USA. (e-mail: dahler@newpaltz.edu).

R. Rasel is with the Division of Engineering Programs, State University of New York New Paltz, New Paltz, NY 12561 USA. (e-mail: n02062595@hawkmail.newpaltz.edu).

modeling and manufacturing aspect of MEMS engineering where the students are able to replicate the fabrication process without the use cleanroom equipment.

A number of papers have discussed improving the MEMS educational process [5]-[7]; their focus, however, has been on developing lab modules with the assumption that there is access to cleanrooms. This paper presented here is unique in that to the authors' knowledge, no papers in the literature apply the use of 3D printing to emulate the fabrication and design process of MEMS devices. The following sections present the structure of the course modules, the teaching goals, student comments about the course, and the subsequent changes and improvements to the course.

II. Motivations, Structure and Learning Outcomes

A. Motivations

The motivation behind developing these MEMS assignments and lab modules was to supplement and strengthen the traditional approaches to teaching MEMS classes to electrical engineering and computer engineering (ECE) students without access to cleanrooms and laboratory equipment. Typical MEMS classes taught without access of a cleanroom lab have a lecture format presented by the instructor, where MEMS fabrication processes are demonstrated with the use of lecture notes and animated videos. This approach fails to motivate and engage the student.

B. Module Structure and Schedule

This semester-long MEMS course is typically offered to senior-level undergraduate and graduate ECE students. The course assignments and project, developed and taught between 2013 and 2014, are organized such that students are exposed to the three fundamental components of MEMS design: crystalline planes, bulk micromachining profiles realized after etching, and designing the step-by-step fabrication process of a selected MEMS device.

The assignment modules are given throughout the semester, and count for 10% of the final grade. The first is given within the first two weeks of class, to reinforce the understanding of crystalline planes in a silicon wafer. The second assignment module is assigned in week five of the course to build on assignment 1 on the use of crystalline planes in creating isotropically- and anisotropically-etched structures in a silicon wafer. Designed to familiarize the students with the 3D modeling software, SolidWorks, and the 3D printing process, these assignments prepare the students to successfully complete the course project. Evaluation of the assignments is based on reports and the 3D printed prototypes produced. Individual students give a 10-minute oral presentation on the 3D printed prototype and challenges they faced, in order to ensure that students are given an opportunity to learn how to present their work in a group setting.

The project is assigned at the beginning of the semester. Students are and expected to work on this, in pairs, throughout the semester. The project deliverables were due at the end of the semester, and the overall grade for the project was assigned 20% of the final course grade. Students work in pairs to develop teamwork, communication, and organizational skills. This project module also allows the students to experience the group interactions that occur in a multidisciplinary MEMS industry setting where professionals of varying backgrounds work together in the design and fabrication of a device. For the project, a final report is required, in addition to a poster presentation similar in format to a conference poster presentation. Suggested formats for these are provided in an information packet at the start of the course. The students are graded individually on their assignments, but for the project report and presentation the students in each pair receive the same grade. Thus, assessment takes into consideration both individual and group performance. Emphasis is also placed on design layout, scaling, printing resolution, and device release design processes.

C. Project and Course Learning Outcomes

The students' learning outcomes for the course project module were assessed against a rubric developed based on the criteria reference assessment (CRA) [16], listed in Table I. The project learning outcomes (PLOs) were measured based on each pair's:

- Formal IEEE-style report describing their design approaches, diagrams, observations, and conclusions.
- PowerPoint poster presentations in which each member takes turns to explain the procedure.
- Demonstration of 3D printouts to supervisor and peers.

Course learning outcomes (CLOs) addressed in this assessment were also used to evaluate overall student performance and include:

- CLO1: A good understanding of the crystalline planes in a silicon wafer and the importance of the alignment of a given photomask to these planes (assignment 1 module),
- CLO2: A good understanding of how the anisotropic and isotropic etch processes work with various photomask geometries and various crystalline plane orientation (assignment 2 module),
- CLO3: Ability to design a MEMS device and visualize a step-by-step fabrication process given a device outline and specification (project module).

TABLE I
ASSESSMENT OF STANDARD OUTCOMES FOR THE COURSE PROJECT

Criteria	Intended Learning Outcomes (Mark)
REPORT (10%)	
PLO1. Mask Designs • Were the masks designed correctly? • Was the type of photoresist used considered? • Were anchor masks included?	Ability to create photomasks needed to make MEMS device (Mark: 30%)
PLO2. Process of Scaling/3D Models • Were the dimensions used practical for 3D printing? • Correct use of SolidWorks • Did the students discuss problems faced in design	Ability to scale up and create 3D models using SolidWorks and problem solving (Mark: 40%)
PLO3. Report Writing Skills • Was this report correctly formatted? • Was IEEE referencing done correctly?	Improve formal report writing skills (Mark: 30%)
POSTER PRESENTATION (10%)	
PLO4. Team work • Was there an equal share of responsibilities between team members? • Was the model and report handed in on time?	Improve team work and time management skills (Mark: 50%)
PLO5. Final 3D model • How close to the actual MEMS model is the print out? • Is the scaling done correctly?	Ability to carry out successfully 3D print out (Mark: 20%)
PLO6. Presentation Skills • Were the explanations clear and detailed? • Did they talk about challenges and answer technical questions?	Improve presentation skills (Mark: 15%)
PLO7. Poster Layout • Did the poster include fabrication pics, mask and 3D model schematics of each layer? • Did the poster follow format requirements?	Improve presentation and writing skills (Mark: 15%)

III. COURSE MODULES

A. *Assignment 1: Evaluating Silicon Crystalline Planes*

Bulk micromachining, the removal of the bulk of a substrate, is an essential part of fabricating MEMS. By aligning the photomask to a specific crystalline plane, different 3D geometries can be realized within the bulk of the silicon wafer. Therefore, it is critical for the students to understand the geometric relationships between the different crystalline planes within a silicon wafer lattice to appreciate the different profiles that result from an isotropically or anisotropically chemically etched silicon wafer. The first 3D printing assignment given to the students involves calculating the angles of these crystalline planes for a silicon wafer of [100] orientation with a [100] mask, or a [100] with a [110] mask, similar to the process described in [13] and as illustrated in Fig. 1(a). The students then use their calculations and the illustrations provided to create 3D printed models with the major crystalline planes extruded from the silicon wafer surface. This exercise of drawing and printing the 3D model was created to help the students better visualize and understand the different crystalline planes while also allowing them to physically examine the final product. Fig. 1(b)

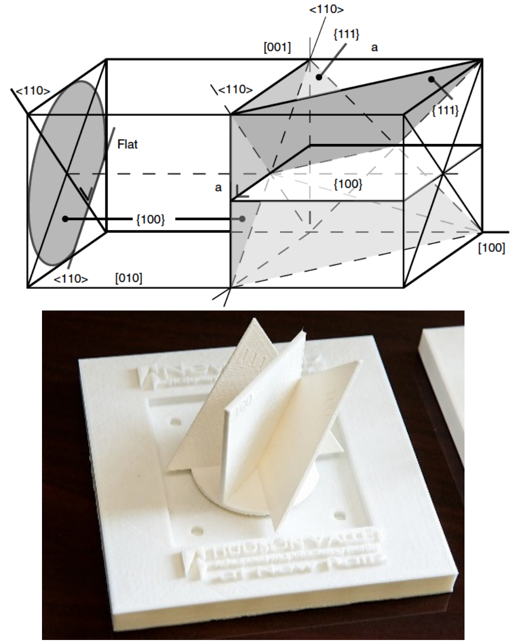

Fig. 1. (a) Illustration given to the students [14] and (b) 3D printed prototype.

illustrates an example of a printed model with extruded crystalline planes for a [100] silicon wafer with a mask aligned to the [100] plane. Students are required to clearly label each of the extruded planes as part of the assignment.

B. *Assignment 2: Isotropic and Anisotropic Etching*

In assignment two, the students are required to generate 3D models of the resulting etch profile in a silicon wafer given a mask of specific geometry. They are provided with various mask geometries (including a rectangle, square and circle) and told which primary orientation the mask is aligned to ([110] or [100]). They are also given specifications including chemical etchant used, and the required etch depth. Using their understanding of the etch process, crystalline planes, and trigonometry, students then calculate the resultant profile, taking into consideration undercut and over-etch. Some of the sample 3D models created by the students are shown in Fig. 2.

Fig. 2. Samples of the etch profiles created given a specific depth and mask geometry as seen clockwise from the top left: rectangular mask, circular mask and two square masks of varying depths.

C. *Course Project: MEMS Device Design*

In this project, the students design and fabricate a MEMS switch [10] or a MEMS inductor [11] using SolidWorks, and 'fabricate' it using the 3D Stratasys Dimension 1200es printer located in the Hudson Valley Advanced Manufacturing Center (HVAMC) at SUNY New Paltz [12].

1) *MEMS Capacitive Switch Design*

The authors in paper [10] presented a novel design for a shunt MEMS capacitive switch. The switch consists of RF signal and ground lines, a switch bridge and a dielectric for isolating the signal line. This switch also has beams, which warp up due to the residual stress. The basic mechanism of this switch is that when a DC voltage is applied to the electrode, the bridge closes, the dielectric layer between the switch and the signal line keeps the switch from shorting with the signal line.

The original MEMS switch layout and dimensions as well as the scaled up MEMS design dimensions are shown in Fig. 3 and Table II. Student groups evaluate the MEMS device assigned to them and devise a scaled-up design and step-by-step process to successfully print out and release the MEMS switch. A scaled-up design is required due to the printing resolution limit of the Dimension printer, which can print layer thicknesses of 254µm [9]. This layout design process is very similar to the design process a MEMS engineer in industry experiences when creating a MEMS device limited by the resolution of the lithography exposure system. The MEMS switch release process is recreated with the Stratasys SCA-1200 support-removal system where the support structure, similar to the sacrificial layer in a MEMS device, is dissolved using a water-based solution bath soak. Fig. 4 illustrates a sample of the solid works models created by a group of students for each of the MEMS switch layers and their respective photomask. A total of four masks were used for this five-step process, and students made the assumption that they were using positive photoresist to create their switch. The photomask in Fig. 4(a) creates the signal and ground lines for the signal transmit path, and the photomask in Fig. 4(b) creates the thin insulating dielectric layer. For the sacrificial support layer, the photomask in Fig. 4(c) creates vias in a surface coat to generate the posts for the final switch bridge. The final mask in Fig. 4(d) then creates the switch structure. The student pair who created the 3D printed prototype illustrated in Fig. 5 scaled-up the device dimensions by a factor of 35, except for the switch thickness, where the thickness was scaled up to measure 1 mm. Details such as conformal coating during deposition and anchor post indents, as illustrated in Fig. 4(g) and Fig. 5, were also included to create a more realistic rendering of a fabricated MEMS device. Students are expected to include all the fabrication and design knowledge they acquired throughout the course, including conformal coating, release etch holes and resolution limitations.

TABLE II
MEMS SWITCH MACRO AND MICRO MODEL DIMENSIONS

Switch Bridge Parameters	MEMS Dimensions (µm)	3D Model Dimensions (µm)
W_b	150	5,250
L_b	450	15,750
L_{wb}	80	2,800
W_{wb}	25	1,000
W	120	4,200
G	180	6,300
S	60	2,100
T_b	1.25	1,000

[a]All dimensions with b subscripts are dimensions of the MEMS bridge whereas all other dimensions are dimensions of the signal and ground lines.

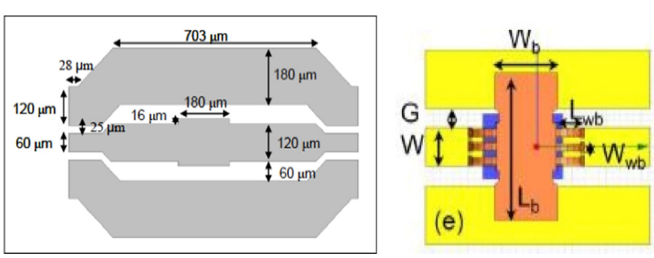

Fig. 3. Original dimension layouts of the MEMS switch bridge, signal and ground lines [10].

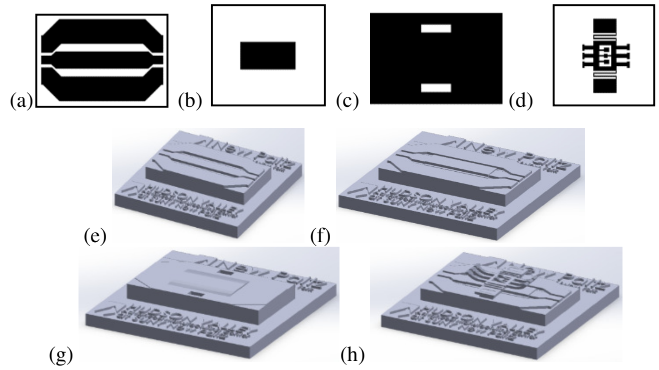

Fig. 4. (a) to (d) Photomask layouts generated in SolidWorks , (e) to (h) 3D models for each layer required for the fabrication of the MEMS switch.

2) *MEMS Inductor Design*

An inductor is a device that converts electrical energy into magnetic energy a device that converts electrical energy. There are several types of MEMS inductors: straight inductor, spiral inductor, solenoid inductor and toroid inductor. Among

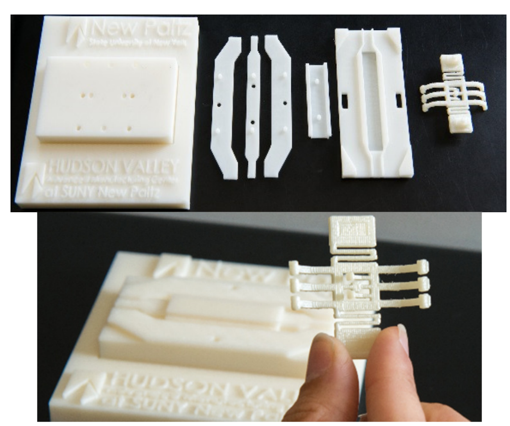

Fig. 5. 3D print of the scaled-up MEMS switch with an overall footprint of 5cm by 5cm.

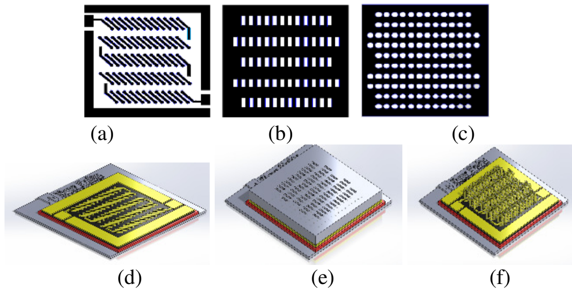

Fig. 6. (a) to (c) Photomask layouts generated in SolidWorks , (d) to (f) 3D models for each layer required for the fabrication of the MEMS inductor.

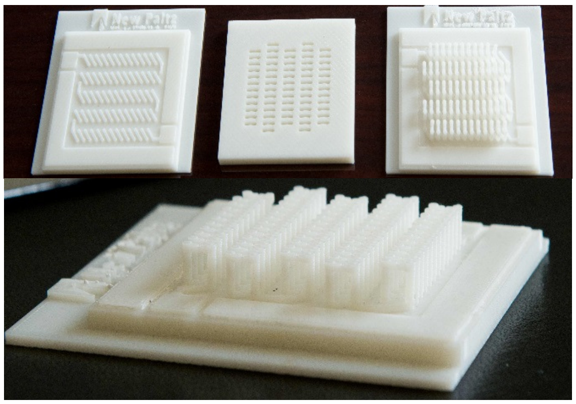

Fig. 7. 3D print of the scaled-up MEMS inductor, layer-by-layer and fully integrated and released.

them the spiral and solenoid inductors are known for their high Q factors [11]. The authors in [11] presented a high Q MEMS inductor using surface micromachining fabrication techniques. Some of the student groups were assigned this device and asked to create a 3D prototype of each layer of this device. In a similar manner to the MEMS switch design process, the MEMS inductor is scaled up and designed in SolidWorks. The photomasks and 3D SolidWorks models created by one of the student groups are shown in Fig. 6. The photomask in Fig 6(a) creates the signal and ground lines. The photomask in Fig. 6(b) is used to create the sacrificial support layer of the inductor in order to create the height of the bridges of the inductor. Finally the photomask in Fig. 6(c) is used to form the bridges of the inductor coils. Fig. 7 illustrates one of the prototypes created by a student group. The overall footprint was approximately 5cm by 5cm.

IV. Assessment and Evaluation

To evaluate the impact on student learning as result of implementing these design modules in the Introduction to MEMS course, among the assessment measures used were: scores on final exam questions that target all the course learning outcomes listed above, project learning outcomes scores, and post-course student questionnaires. Samples of the final printed prototypes presented in the Section III above also demonstrate the successful realization of the project. The project and assignments were introduced in Spring and Fall 2014 semesters, so data from the Fall 2013 semester was used as a reference to see the effect on learning outcomes of

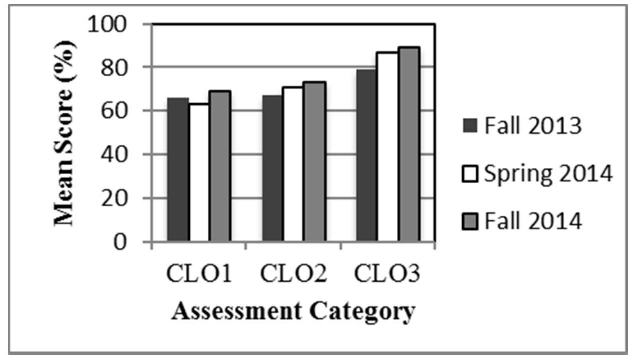

Fig. 8. Overall mean scores in the three assessment categories for Fall 2013, Spring 2014 and Fall 2014.

including these design modules in the course.

A. *Assessment Methodology*

Assessment groups include final exam question 1 geared towards assessing CLO1, final exam question 2 geared towards assessing CLO2, and final exam question 3 geared towards assessing CLO3. Fig. 8 illustrates these scores analyzing student performance for the overall course. Students struggle with silicon crystal plane orientation because of its abstract nature, however a still slight improvement in performance is observed between Fall 2013 and Fall 2014. Overall final exam scores show a significant improvement between Fall 2013 and Fall 2014. This is primarily due to improvement in performance in a fabrication design question Q3 on the final exam worth 40%, indicating that the project design module has significantly improved students' understanding of MEMS fabrication.

To better understand the impact on student learning outcomes as a result of introducing the project module, and to assess the strengths and weakness of the project module, students' project scores for all PLOs are plotted for the Spring 2014 semester, Fig. 9. Students continued to struggle with the use of SolidWorks as can be seen with PLO2, where 40% of the students had difficulty with creating a 3D model of the MEMS device. This can partially attributed to the fact that out of the 12 students, seven are graduate students with no background in 3D modeling software.

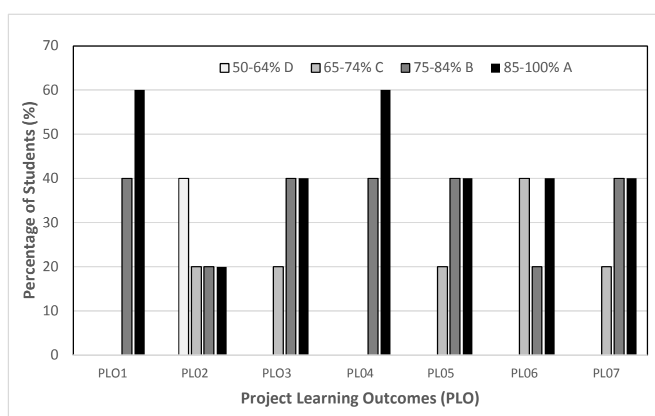

Fig. 9. Percentage of students achieving each project module's learning outcome in Spring 2014.

B. Student Survey

End-of-semester questionnaires were administered to the students in the semesters of Fall 2013, the semester prior to introducing the course modules, and Spring 2014, the semester in which modules were implemented. The questionnaire asks students to rate whether the teaching methods used in the course engaged their interest on a Likert-type scale: strongly agree, agree, neither agree nor disagree, strongly disagree and not applicable. The results in Fig. 10 show that, in general, the implementation of these modules in the course was very positively received by students.

C. Limitations of This Study and Future Improvements

In the future, this course will be offered to mechanical engineering students. By having students of different disciplines work together in groups, they can learn from each other and benefit from their different backgrounds [7]. Also, given the poor performance reflected in assignment 1, the authors would like to redesign the instructions for assignment 1, and make the course 'Introduction to Engineering Science' a pre-requisite to the MEMS class so as to introduce students to the use of the SolidWorks software earlier in their undergraduate program. To address the graduate students' lack of background in 3D modeling, course instructors will offer a two-hour training session on the software and provide online video tutorials. Future plans are to develop additional projects, so that students can select a project according to their diverse backgrounds and interests. To make the project more challenging and interesting, the authors are in the process of evaluating the introduction of actuation and movement in the project design. This will allow the students to evaluate stress and mechanics to create an even more realistic experience of the MEMS device design process.

V. CONCLUSION

This paper presents course modules developed to experimentally reinforce students' understanding of design principles, scaling, and fabrication of MEMS devices. Student feedback and assessment data indicate that the learning objectives were achieved. The information presented in this paper will hopefully provide engineering educators a more affordable, realistic, and effective method for teaching MEMS modeling and fabrication in settings without a cleanroom. The study of MEMS provides a rich environment that presents students with truly interdisciplinary work and with design problems that have real constraints [7]. Throughout the semester, the students are challenged with assignments and a design project, having multiple constraints imposed by dimensions, resolution, fabrication, process flow, and structural release. These constraints are not always simple to address, and many items are interrelated. The result is a rich and challenging design process in which students obtain a hands-on experience of modeling and iterative design of MEMS devices. The results of final exam performance and student surveys across semesters suggest that these 3D printing modules, when incorporated into a MEMS course, enhance the educational experience and improve student performance.

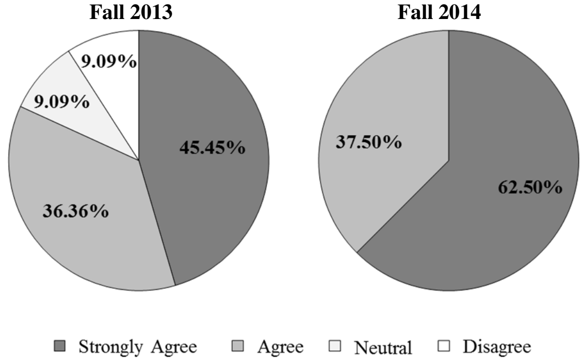

Fig. 10. Overall student rating of whether teaching methods used engaged their interest.

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Reena Dahle (M'14, SM'04) received the B.S. and M.S. degrees in electrical engineering from the University of Manitoba, Winnipeg, and the MB in 2003 and a Ph.D. degree from Waterloo University, Waterloo, ON, Canada in 2008. From 2008 to 2011, she was a Senior Microwave Systems Engineer at MITEQ Inc in Hauppauge, Long Island. She is currently an Assistant Professor with the Division of Engineering Programs at SUNY New Paltz, New Paltz, NY.

Rafiul Rasel (SM'13) received the B.S. and M.S. degrees in electrical engineering from the State University of New York at New Paltz in 2013 and 2015, respectively. He is currently enrolled at Ohio State University to complete his doctoral studies in numerical electromagnetics.