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Advanced Microfabrication Manufacturing Course Comparison of Online and In-person Teaching with Hands-on Lab Component for Interdisciplinary Graduate Education

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Abstract:

Semiconductor/Microsystems education is in growing demand due to the demand to bring semiconducting manufacturing back to the USA. At the University of New Mexico (UNM), we have six courses that teach different aspects of semiconductor/microsystems manufacturing from theory to hands-on experience. The Advanced Microfabrication course is a multidisciplinary graduate course that is taken by students with various background and primarily from two different programs i) Nanoscience and Microsystems Engineering (NSME) Program (an interdisciplinary program across various schools and departments) and ii) students from the Mechanical Engineering Department. The course typically consists of a series of lectures along with hands-on microfabrication labs in a cleanroom which were designed to complement the lectures. The course material is multidisciplinary with topics ranging from chemistry, physics, mechanical engineering, electrical engineering, chemical engineering, statistics, material science and biomedical. This comparison study investigates several factors such as lab components, synchronous online versus in-person lectures, and students discipline to determine impact on the final exam (performance) in the course. Based on n=99 students over seven years it was determined that students from the interdisciplinary programs performed better with an average score of 64.04 ±13.26% compared to ME students 55.02 ±16.81%. It was also determined that both in-person lectures and students participating in labs had a significant impact on their final exam grades. Students who attended in-person lectures scored an average of 64.35 ± 15.11% whereas online students scored 51.81 ±14.77%, that is an increase of 12.54%. Students attending hands-on labs also had a significant impact resulting in a 10.17% increase in scores. The results demonstrate that the multidisciplinary material of advanced semiconductor manufacturing is potentially best learned through a combination of in-person lectures and hands-on lab experience and that students who have a more interdisciplinary background are likely to perform better due to the multidisciplinary course contents.

Introduction:

Engineering education in the fields of semiconductors and microelectromechanical systems (MEMS) have been extensively investigated as a method to teach multidisciplinary subjects and learning across various engineering disciplines [1, 2]. In recent years there has been a significant increase in semiconductor engineering research due largely to the Chips Act which aimed to bring semiconductor/microsystems manufacturing back to the United States [3-5]. The subject matter is highly multidisciplinary due to the complexity of micro/nanofabrication, and therefore the topic can be challenging for students, as most courses that graduate students take are focused on a single subject, and typically students take courses in their specific discipline. For instance, mechanical engineering (ME) students typically only take other ME courses to meet their course requirement, so their knowledge in electronics, solid-state physics, chemistry etc. are limited. There are numerous courses that can be focused on different aspects of semiconductor education, such as solid-state physics courses or transistor technology-based courses. These courses are typically theoretical and often taught using traditional teaching methods as they are focused on a single subject such as solid-state physics or electronic design. Advanced manufacturing of semiconductors or MEMS devices using nanofabrication involves theoretical knowledge, but it also requires a significant amount of experience [6]. The topic requires multidisciplinary knowledge, such as chemistry (photolithography and etching), electrical engineering (doping, design, bandgap etc…), optics (photolithography), mechanical engineering (equipment, vacuum, heat transfer, MEMS), and numerous other disciplines.

Most undergraduate engineering education is taught by traditional engineering departments such as ME, Chemical Engineering, Electrical Engineering, etc. Interdisciplinary programs, which focus on teaching multiple disciplines, do exist at some universities, but they are less common. However, there is a growing demand in graduate education to have more interdisciplinary studies as it can broaden the knowledge of students and make them more diverse, which can lead to increased job readiness [7-9]. Multidisciplinary work combines knowledge of multiple disciplines but maintains those disciplines within specific boundaries, so for instance the individual course on advanced microfabrication would be multidisciplinary, as the disciplines are being applied to a similar subject. Whereas interdisciplinary combines two or more academic disciplines, when the term is used in this paper it is being used to describe the program/department that students are enrolled in, for instance the interdisciplinary program used in this study was the Nanoscience and Microsystems Engineering (NSME) program at UNM, which is a graduate program that spans multiple schools (school of engineering, arts and sciences, health services, and school of management). The NSME program is designed to give graduate students diverse knowledge and experience across various schools.

It is common for MEMS or advanced microfabrication courses to combine theoretical teachings through lectures which are supplemented with hands-on lab experience. The lab components are often believed to be necessary to master the subject of nanofabrication as hands-on experience helps students gain experience and skills [10-12], which is highly desired by industry. However, there is limited research in determining how much impact the lab component can have on the student's education and their ability to retain the information.

After COVID and with the growing demand of online MS degrees, there has been a significant increase in engineering courses being taught online [13-15]. Numerous theoretical only courses have been adapted to be taught online, and there have even been advances in developing virtual lab components [16]. However, these are typically created for single discipline courses, and creating a virtual lab in a cleanroom is quite difficult [17]. Since hands-on experience has been deemed critical for micro/nano fabrication education there is a need to determine the impact of not only the lab component but also the method of which the lectures are given (online or in-person).

The research involved in this paper aims to determine the potential impact on student's final exam grade in a micro/nano fabrication course with the following variables 1) lecture format (synchronous online vs in-person), 2) labs vs no labs, and 3) student program (ME (single discipline) vs NSME (interdisciplinary program). Since microfabrication courses are highly multidisciplinary and it is widely accepted that hands-on experience is necessary to enhance student education in the area, a course on the subject is an ideal test vehicle to investigate these impacts. The results of this study will give some insight into the importance of how the course material should be delivered to optimize student education in the advanced manufacturing field. The layout of the paper consists of first describing the course details, then the academic background of the students, then methodology of the study, and then results and discussion.

Course Description:

The course being used to perform the evaluation was originally developed by the author in Fall 2017. The course is focused on teaching theory and skills associated with micro/nanofabrication which is relevant to students interested in a career in semiconductor manufacturing or MEMS. The course covers the theory and fundamentals of microfabrication including photolithography, thermal oxidation, physical vapor deposition, chemical vapor deposition, etching, implantation, diffusion, process integration, and microelectronics packaging. In addition, it briefly covers MEMS transduction mechanisms such as piezoelectrics, magnetics, electrostatics, and thermal actuators. The course consists of 2.5 hours of lecture per week and is supplemented with 3 hours of lab each week (consisting of n=10 labs). Where students learn the theory during lecture and the labs are meant to complement the theory by teaching students' hands-on experience. For instance, the week prior to the photolithography lab the students learn the theory so that when they do the labs it reinforces their understanding of the subject. The labs and lectures were developed by the instructor to complement each other, and cover fundamental microfabrication techniques such as photolithography, doping, oxidation, soft lithography, etching, and then a series of labs which combines the above topics so the students can fabricate a MEMS device (electrothermal actuator, electrostatic actuator, or pressure sensor) [6, 18-22]. The course is highly multidisciplinary, which is different than most traditional engineering courses that focus on a single subject, and it is taught using problem-based learning (PBL) where students learn the theory through real-world examples and case-studies, so they learn why the material is important and how it can be applied. Then in the lab students get hands-on experience on how to apply the principles and see the effects. The course often involves topics or subjects that are new to the students, for example in photolithography and etching there is a significant amount of chemistry knowledge that is involved, and chemistry is a subject that ME students often have very little exposure to. Whereas Chemical engineers have little exposure to topics focused on mechanics of cantilevers. Overall, there is a not a single topic that is dominated in the opinion of the instructor, so no matter what background discipline the student has they will likely have topics during the semester that the student has little prior knowledge on, which makes the course challenging for every student.

The course is a mandatory course for NSME students, whereas ME students take the course as an elective. However, there were n=44 ME students and n=55 NSME students who were evaluated during this study. The evaluation of the course consisted of both MS and PhD students, which were not separated into two categories. Most graduate students take the course within their first year of enrolling in their graduate program (especially NSME students as it is mandatory for PhD students to take this course within their 1st year of enrolling in the program). However, the author did not consider what year into their graduate studies the students were when performing the evaluation.

Participants Academic Background:

The ME students who participated in the course all had a ME undergraduate background, from various institutions around the world. The NSME program is an interdisciplinary graduate program that has been around for nearly 20 years that spans multiple schools and departments within each school. Therefore, students in the program have diverse backgrounds including but not limited to chemical engineering, bioengineering, ME, electrical engineering, nuclear engineering, civil engineering, materials science, physics, biology, chemistry, agriculture science etc. The author did not have access to each student's undergraduate background discipline, but the majority would have some engineering background, and all have a STEM background. Required NSME courses are interdisciplinary with faculty instructors from various STEM fields, so students in NSME typically have a more diverse background than traditional engineering students. Although the overall group of students in NSME have a diverse background the individual student might not have a large diversity background in STEM courses prior to taking the course, but they understand the importance of having an interdisciplinary education.

Students taking the course can also have a wide range of experience with fabrication and semiconductor knowledge. For instance, some students have had internships with industry or national labs working in a cleanroom, but this applies to both ME and NSME students. The institute, in which the course was taught, has three other courses focused on semiconductors and microsystems design and fabrication which students may have taken prior to this course. Although students with prior work experience might have an advantage in the lab, they often lack knowledge in theory, based on the author's previous experience. Previously the author compared grades of students who had taken multiple fabrication courses prior to this course, to students who have never had a fabrication course and found no statistically significant difference in performance (unpublished). Demographics of students in the NSME program consist of 27.8% female on average and 50.5% of students were Caucasian, and the courses consisted of both international and domestic students. The ME graduate program has slightly different demographics typically around 15-18% female and 40-45% Caucasian. However, the age, sex/gender, and ethnicity of the participants were not individually evaluated in this study.

Methodology:

The course was taught once per year from 2017-2024 which included n=99 graduate students with n=44 from ME and n=55 from NSME. The labs were developed in 2017 and were kept the same in each course along with the book and course material. The lectures were also kept the same except for some occasional minor updates, but the technical aspects remained the same. The courses were taught by the same instructor, the structure of the course was also kept constant. The final exam grades were used in the evaluation for this study to rule out any possible subjective bias in the lab and project grades. The final exam questions and rubric were the same throughout the different courses.

The observation comparison study that was investigated included:

1) Comparing student's final exam grades from two different programs NSME (interdisciplinary program) and ME (single discipline program) to determine if there is any significant difference in performance.

2) Determine impacts of lab and in-person lectures by comparing students who had a) Lab and in person lectures, b) lab and online lectures, c) no lab and in-person lectures, and d) no lab and online lectures.

Students were placed in one of the four various categories which included students who either took the course in person or online as well as with or without lab to create four sub-categories described in study 2 above. Each section was taught in different years. The section consisting of no-labs had n=42 students, while students with labs were n=57. In person lecture had n=66 students and online were n=33 students. For all courses the lecture slides were uploaded online to allow the students to review the slide content at any point during the semester. However, lectures were not recorded for any of the courses. The online lectures were synchronous. All courses had the same assignments and readings except the section with no labs did not have any lab report assignments.

The final exams were open notes and open book, so students were allowed to look back at posted lectures during the exam. Questions related to microfabrication and consisted of some fundamental true/false short answer questions (25% of exam) and the other 75% consisted of quantitative problems and process design questions. The final exam grades were used in the evaluation, as the questions remained the same throughout all the courses. In addition, the final exam grades accounted for 30% of the final grade so it was a good indicator on the student's overall performance in the course and determining how much material they retained during the semester. The instructor's exams were known to be quite challenging with low scores similar to methods used in UK and Ireland, where 60-70% is typically equivalent to an A [23], this style of exam was designed to assess all students equally to determine which topics they mastered.

Results and Discussion:

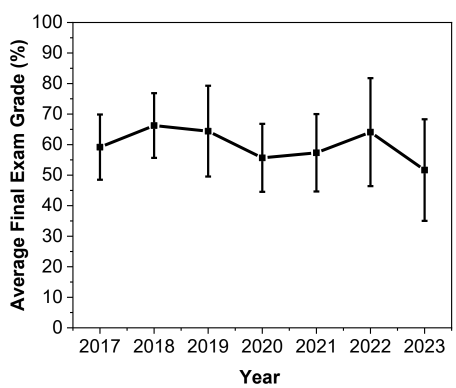

Figure 1- Results showing the average final exam grades as a function of year with error bars representing the standard deviation

The average final exam grades for each course taught arranged by year are shown in Figure 1. The results show there was not a significant difference in final exam grades with $p < 0.05$ between the years, based on student t-test evaluation. The overall average of all students was 59.4 ±14.47%. The highest average was 66.25% in 2018 whereas the lowest average final exam was 2023 with an average of 51.67%. The results illustrate consistency in the test scores and student preparation in the course, demonstrating that the year the course was taught was not a significant factor.

The next evaluation compared NSME (interdisciplinary) students' performance versus ME (single discipline) students. The results comparing students from these two categories are shown in Figure 2. The results show that NSME students had an average final exam score of 64.04 ±13.26% whereas the ME students obtained an average of 55.02 ± 16.81% which illustrates a significant difference ($p < 0.05$). This shows that students in the NSME program typically obtain higher grades on the final exam than ME students. The standard deviation was also lower for NSME students compared to ME students, which illustrates a higher consistency. This could be due to numerous reasons which were not monitored such as the NSME program is known to have more PhD students than MS students and just the opposite is true for ME, or it could be that students in an interdisciplinary program are more likely to function well in a multidisciplinary based course. Other reasons that were not controlled include criteria for accepting students into the programs and age or level of experience of both types of students.

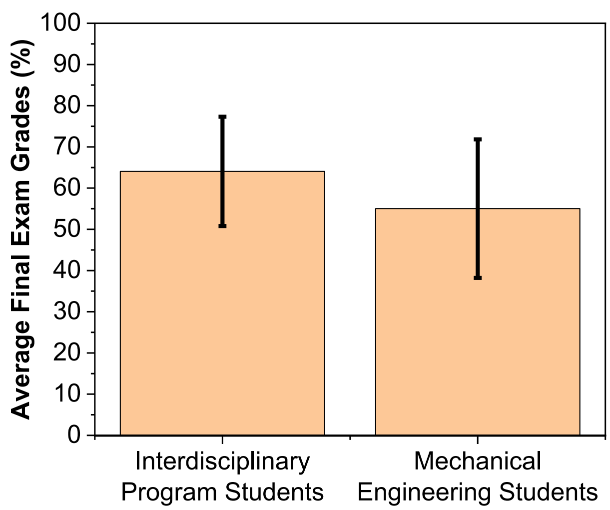

Figure 2- Results showing the average final exam grades for students in the interdisciplinary program versus a single discipline.

The next evaluation method aimed to compare final exam grades for the four various sections with variables consisting of in-person lectures, online lectures, sections with and without labs. The results are shown in Figure 3. Students participating in in-person lectures scored significantly higher on the exam (64.35 ±15.11%) when compared to online lectures (51.81 ±14.78%) as shown in Figure 3a. This could be due to numerous reasons including 1) students being more distracted losing focus on online lectures, 2) lack of engagement, 3) not being able to recognize facial or gesture clues and various other reasons [15]. This also could be due to the teaching style by the instructor, but the instructor underwent training on giving online lectures prior to the courses. The results illustrate that students participating in in-person lectures on average scored 12.54% higher on the final exam compared to online lectured students. Since the final exam grade was 30% of the overall course grade this meant that in-person students would have gotten on average 3.7% higher grade or about half a letter grade higher than online students for the overall grade in the course.

Figure 3b illustrates the final exam grades for students who participated in labs versus students who did not participate in labs. As expected, students that participated in the labs scored significantly higher on the final exam with an average exam of 64.44 ±12.81% versus 54.27 ± 17.93% for students that did not have labs. This demonstrates a 10.17% higher grade on the final for students that had labs. The reason for the higher grade could be due to multiple reasons 1) the labs hands-on experience helped the students learn or b) having the labs gave the student more knowledge of the subject through repetition [24]. The standard deviation between lab and "no lab" sections were different, where the students with lab had a standard deviation of 12.81% whereas students with "no lab" had a standard deviation in test scores of 17.93%, illustrating a larger variation in test scores for students with no-lab. The results could be different based on the content of the labs, but in this course the labs were developed to specifically complement the lectures.

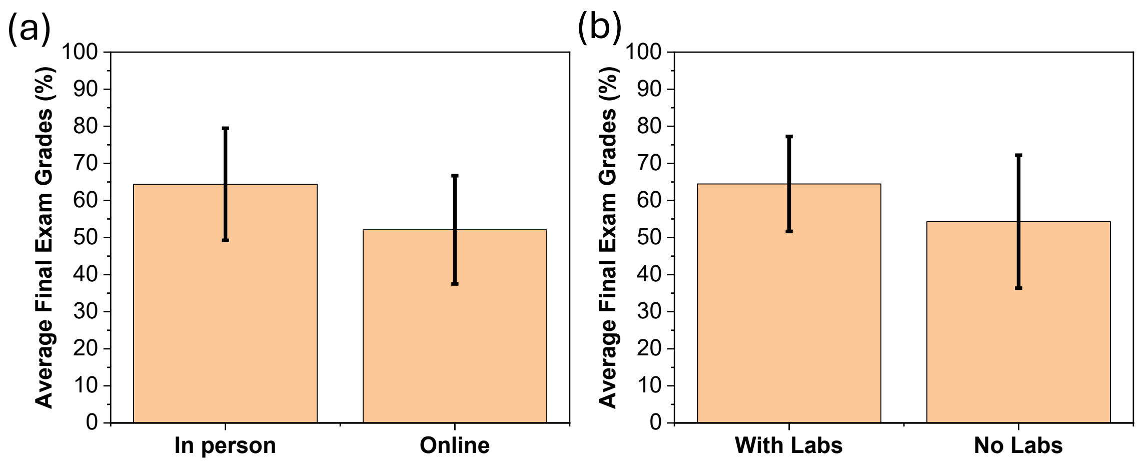

Figure 3- Results showing the average final exam grades for various sections (a) in-person lectures versus online synchronous lectures and (b) sections with and without labs.

The results shown in Figure 4 combine the results of the four sections of courses. The sections consisting of both in-person lectures and labs performed the best on the final exam and students with no labs and online lectures did the worst. Although the averages are quite different the highest scores in each section were similar with a grade of 89 for "no-lab/in-person", 87 for "lab/in-person", 83 for "lab/online", and 82 for "no lab/online". This demonstrates that students can achieve high scores in each of the sections, but on average students score higher if they had labs and in-person lectures. This is also illustrated by viewing the standard deviation where no lab/ in-person had a standard deviation of 18.05, labs/in-person had a standard deviation of 11.85, labs/online had a standard deviation of 11.13, and no labs/online had a standard deviation of 16.7. This shows that the lab component variable had a bigger impact on the standard deviation but less of an impact on the overall average grade than the method of which the lectures were given.

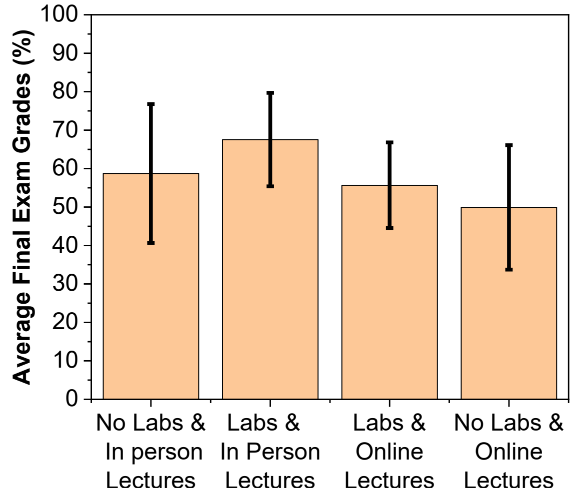

Figure 4- Combined results showing the average final exam grades for various sections.

Conclusion and Summary:

Based on the data it can be concluded that for this course students attending in-person lectures with a lab component to complement the lectures resulted in a higher final exam grade. The in-person lectures had the largest impact where students scored an average of 12.54% higher than online lectured students even though both students had access to the lecture slides throughout the semester and on the final exam. The lab component also had a significant impact on the final exam grade as students scored 10.17% higher on average when they participated in labs. However, the lab component had a bigger impact on the standard deviation, (5.13%) higher deviation with no-labs, whereas the in-person and online had a similar standard deviation with a difference of only 0.33% between the two sections. Therefore, while both in-person and labs made a significant difference the in-person lectures had a larger impact on final grade exam score, but the lab variable had a larger impact on the deviation between students. In addition, the interdisciplinary program students also scored higher on the exam than students from a single discipline, however, there are numerous variables that could be the cause for the difference which need to be further investigated. These included the course being a required core class for NSME while an elective for ME students, however, that should not be a significant factor as ME students took the course due to interest in the course (it was their choice) whereas NSME students were required to take the course regardless of interest.

The evaluations provided in this study were for a specific semiconductor/microsystems course, which is a highly multidisciplinary field of study, which can be quite different than traditional engineering courses that students are familiar with which could also impact the findings. In the future it would be interesting to apply these methods to other semiconductor courses to determine if the results are based on the field of study or just this individual course. In addition, it would be interesting to determine if the results are only based on semiconductor manufacturing topic or if they apply to other engineering areas.

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