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Interdisciplinarity through Microelectronics Reliability Course

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Abstract

As boundaries between engineering disciplines continue to fade, providing platforms for students to interact and communicate across disciplines becomes ever more beneficial and urgent. An engineering course on microelectronics and related reliability concerns was developed at SUNY New Paltz in spring 2020 in an attempt to promote interdisciplinarity between electrical and mechanical engineering majors. In this paper, the strategies adopted to stimulate interdisciplinary learning will be illustrated, including demonstrating relevance, sharing expertise cross-discipline, adequately adjusting scientific rigor in communication, and practical team projects. Learning effectiveness will be demonstrated by surveys and student feedback. Opportunities for the department to further establish its interdisciplinarity will be highlighted and plans for future course improvement will be illustrated.

Introduction

With the insatiable demand for technological advancement, complexities and challenges faced by today's engineers are extending beyond the conventional scopes and responsibilities [1]. Though discipline-specific skill sets remain essential for solving typical engineering problems, it is apparent that their limitations in handling modern applications are increasingly exposed. Also, the boundaries among traditional disciplines are becoming much less defined as the areas of interest expand and overlap. Therefore, interdisciplinary skill, communication, and collaboration become ever more critical in today's industry and society [2], [3], and providing interdisciplinary opportunities for engineering students to extend their skill and experience beyond discipline boundaries should be a priority in higher education [4].

As an engineering department in a liberal arts college, the Division of Engineering Programs at SUNY New Paltz hosts electrical engineering (EE), computer engineering (CE), and mechanical engineering (ME) programs and continues to leverage its technical diversity to promote and prioritize interdisciplinary learning experience. As a recent example, a course in Microelectronics Reliability was offered as a one-semester 500-level professional elective in spring 2020 to EE and ME undergraduates and graduates. This course was designed to demonstrate that this industry is a tremendously successful example of interdisciplinary collaboration with excellent employment opportunities across several engineering disciplines. Note that course design for microelectronics related subjects have been discussed, either for a stand-along course on fabrication [5] or for a series of related courses [6] for interdisciplinary audience. In this paper, we discuss the development of a platform to establish interdisciplinarity and communication between EE and ME disciplines, and the opportunity for students to apply technical skills for solving problems in unfamiliar area.

Primary learning objectives of this course include applying fundamental science and engineering principles to solve practical and multidisciplinary problems to motivate students [7], as well as collaborating and communicating proficiently across different engineering disciplines [8]. To leverage the multi-disciplinary class environment and ensure the interaction across disciplines, the course was designed with the following considerations and resulting structure.

Considerations

The target audience for the course were engineering graduate students and juniors/seniors. The engineering department has a graduate program only for the EE major, and the class of 17 students was made up of three groups of similar sizes coincidently, including five EE graduates (EE-g), six EE undergraduates (EE-u), and six ME undergraduates (ME-u). Pre-requisites for the course include Signals and Systems and Mechanics of Materials for EE-u and ME-u students, respectively. Thus, according to the curriculum plan, enrolled EE and ME majors should have a proper background on basic circuit/device operations and materials science/stress analyses, respectively, to contribute to the course design and learning effectiveness.

The course framework was structured with the following learning objectives in mind.

- Establishing relevance: Based on a preliminary survey results from a total of 31 engineering students in the department before the course was offered, including 20 ME and 11 EE students, the majority of ME students (about 75%) did not consider taking the course. Most of them assumed it involved advanced circuit analysis and electronics architecture that they were not familiar with. About 36% of EE students did not think the course was relevant, with some of them linking reliability to failure of mechanical structures and expressing little interest. Therefore, establishing relevance to both EE and ME students in the very beginning of the course was critical to raise interest and engagement.

- Cross-disciplinary communication: Dialogue across disciplines are particularly challenging due to unfamiliar terminologies on the other side [8], and it has been discussed and debated over decades [9]. For example, having to analyze transistor degradation in an advanced course might be intimidating to ME students who have only taken circuit analysis. Similarly, having to study thin film mechanics without prior experience in mechanical properties of materials could discourage EE students. Developing a platform for interdisciplinary dialogue between EE and ME majors is thus another primary goal for this course, where students from one discipline can have the opportunity to share knowledge and learn from the perspective of the other to align technical background for readiness.

- Interdisciplinarity by examples: With the proximity to local microelectronics industry in the Hudson Valley area in New York State, including GlobalFoundries and IBM, the course was designed to leverage the resources and to demonstrate interdisciplinary opportunities in the field through guest lecturers on selected core topics. Also, invaluable industry experiences can be shared by lecturers with different technical background.

- Solving multi-disciplinary engineering problems: Cross-discipline problem solving skill is particularly difficult to acquire with conventional curriculum structure lacking inter-disciplinary consideration [10]. In such situations, the problems students are trained to solve tend to be confined within the respective discipline. For example, ME students might have difficulty identifying the stress-related issue in an interconnect with an IC chip, even though they have the skill to conduct stress analysis in a composite beam. This course was designed to provide students with unfamiliar cross-disciplinary problems in microelectronics reliability, requiring them to identify prior knowledge within their discipline for technical judgement and analysis.

- Interdisciplinary teamwork: Originally, a final project was designed for multi-disciplinary teams of EE and ME students to work together, involving several skills including circuit and waveform analyses, stress calculation, and heat transfer simulation. The goal was to provide a platform for teams to communicate across disciplines, and to leverage their own technical strength for contribution. However, the project was cancelled due to the COVID-19 pandemic, but the plan will be illustrated for future adoption.

Course Structure

Based on the design considerations, the course structure can be roughly categorized into the following modules through the semester, as illustrated in Figure 1.

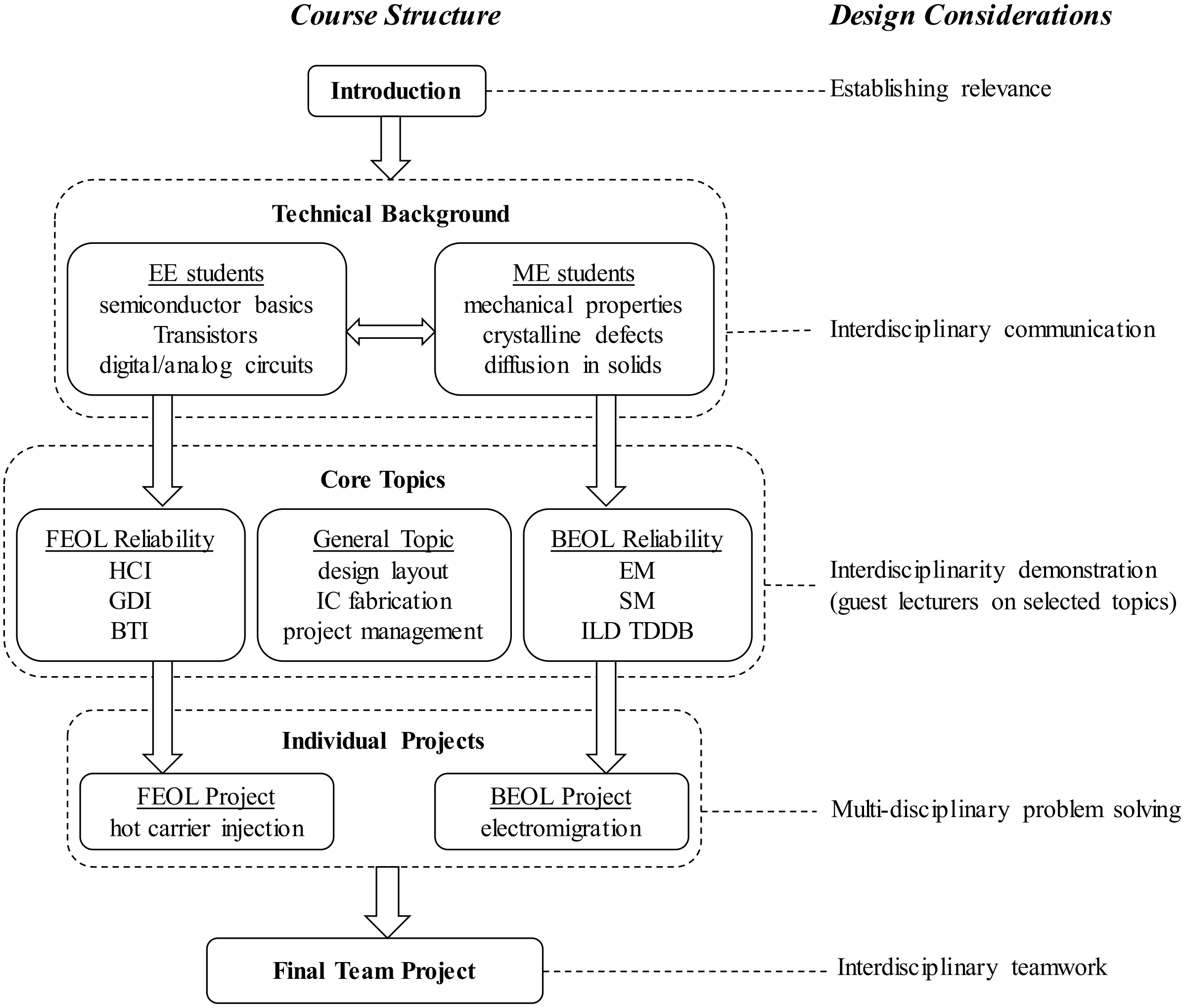

Figure 1. Outline of the course structure along with the corresponding considerations.

- Introduction: To establish technical relevance, particularly for the ME students who had not been exposed to the field of microelectronics, a general overview of the industry was first provided which covered its market trend, prediction, and challenge in keeping up with

Moore's Law. "Scaling" in device miniaturization was introduced, including the implications on performance, integration, profit margin, and reliability, as well as the ever-approaching end of scaling due to physical limit. Additionally, basic reliability concepts were overviewed, where the "bathtub curve" was used to illustrate the three stages of product failure: infant mortality failures, random failures, and wearout failures. Note that all students in the class had taken a course in Applied Probability and Statistics previously, thus the goal here was to relate a previous rigorous mathematical exercise to practical applications, such as the rationale behind burn-in test and warrantee period.

- Technical background: This part of the course offered opportunities for students to communicate across disciplines for aligning their basic knowledge on semiconductors, transistors, and digital/analog circuits, as well as on mechanical properties of materials, crystalline imperfections, and diffusion in solids. Volunteers were asked to present a basic and qualitative description on each topic to a hypothetical audience with little prior exposure. Even though there was no restriction on topic selection, it is interesting to note that all the device and circuit related topics were presented by EE students, while materials science related topics by ME students. It was somewhat expected, as the EE students had more experience on electronics and circuit analysis, while ME students had taken courses on engineering materials and solid mechanics. The challenge and skills to develop in this situation involved delivering technical messages in a manner understandable to different disciplines, as well as trading off between technical rigor and communication effectiveness.

- Core topics: The main body of the course addressed several reliability degradation mechanisms in microelectronics, including the underlying physics, characterization methodologies, and corresponding structures for enabling the test. Lectures were categorized into the following sections that were not limited to specific disciplines.

    - General topics, including integrated circuit (IC) fabrication, design and layout of test structures, and project management in microelectronics manufacturing environment.

    - Front-end-of-line (FEOL) degradation, involving the fundamental principles and implication of several transistor wear-out processes in IC. Covered topics include hot carrier injection (HCI), gate dielectric integrity (GDI), and bias temperature instability (BTI), all of which are primary intrinsic mechanisms causing shifts in transistor characteristics under specific bias conditions.

    - Back-end-of-line (BEOL) degradation mechanisms, including the wear-out processes in metal interconnects and surrounding dielectrics in IC chips. Selected topics include electromigration (EM), stress-induced voiding (SIV), and time-dependent dielectric breakdown (TDDB), which could lead to either electrical opens or shorts.

To further demonstrate interdisciplinarity through these subjects, guest lecturers were invited from local microelectronics companies to teach selected topics, and to share their experiences in this field. Technical background of the guest lectures ranged from physics, computer science, chemical engineering, materials science, mechanical engineering, and electrical engineering. From the student engagement and interaction with lecturers, it was observed that the boundary between EE and ME students was evidently disappearing toward the end of the lecture series.

- Individual projects: Two projects were implemented following the respective lectures, including HCI and EM modeling. In both cases, students designed hypothetical structures and experiments to investigate degradation. Raw data was then provided to analyze, establish an empirical model, extract equation parameters, project product lifetime, and discuss engineering solutions to mitigate reliability exposure. To illustrate the multi-disciplinary nature of these projects, HCI analysis involved electrical biasing and operation of transistors, thermal analysis for self-heating, and the understanding of atomic structure at the interface between Si (channel) and SiO_2 (gate oxide); EM modeling required basic circuit design, Kelvin testing, thermal analysis, mechanical stress, and knowledge on atomic diffusion in crystalline metals. Students in these situations had the opportunities to solve problems in areas unfamiliar within their discipline.

- Team project: Originally, a final team project was planned to promote interdisciplinary teamwork where a simple circuit (comprising a transistor, a resistor, and DC power source) would be assigned to teams of three students (with at least one EE and one ME) for design with reliability. Reliability limitations would be provided for various degradation mechanisms as well as the required operation condition and lifetime expectation. Teams would come up with the physical design and dimensions of each circuit component that could pass qualification. However, this project was not implemented due to the COVID-19 impact on the syllabus for spring 2020. Nevertheless, it could be anticipated that students would have leveraged individual strengths and maintained close communication throughout the exercise, including circuit simulation from EE and finite element analysis (FEA) from ME.

Outcome and Discussion

Surveys were conducted in the beginning and at the end of the semester to assess the effectiveness in establishing interdisciplinarity. Despite the limited sample size of 17 participants, the results provide some useful insight for further development. Two of the survey questions are listed below along with the discussions.

- "*With the technical trainings in your major, what is your confidence in working in the microelectronics industry.*" This survey evaluated the confidence level of working in the microelectronics industry. The purpose of this question was not just to evaluate the general effectiveness of the course delivery. Rather, it was primarily intended to observe the shift in each of the three groups: EE-g, EE-u, and ME-u. As observed in Figure 2, the course improved the overall confidence level as expected under normal circumstances. Though the differences among groups are within uncertainty, it is interesting to note that, on average, EE-u started the semester with a confidence level somewhat higher than EE-g and ME-u. It can be surmised that the EE-g could have better insight into the course scope and their technical limitation, and thus may have been more conservative before starting the semester; the EE-u could have been prematurely optimistic about their technical capability without considering the challenge in interdisciplinary contents, while the ME-u could have underestimated their skill with the perception that the course is more relevant to the EE discipline. Regardless, the difference in confidence levels among the groups was minor and within uncertainty in the beginning.

At the semester end, the improvement in confidence levels was significant for EE-g and ME-u with 38% and 32% increase, respectively. The outcome for EE-g could be again due to more extensive technical background and experience that benefited their learning effectiveness, while for ME-u with relatively lower expectation in the beginning, the course appeared to have encouraged their interest and engagement. The result for EE-u is somewhat surprising, but it can be speculated that the students have realized their limitations in cross-discipline skill throughout the course. However, the lowest confidence level among the groups at the end is puzzling and needs to be investigated with better statistics.

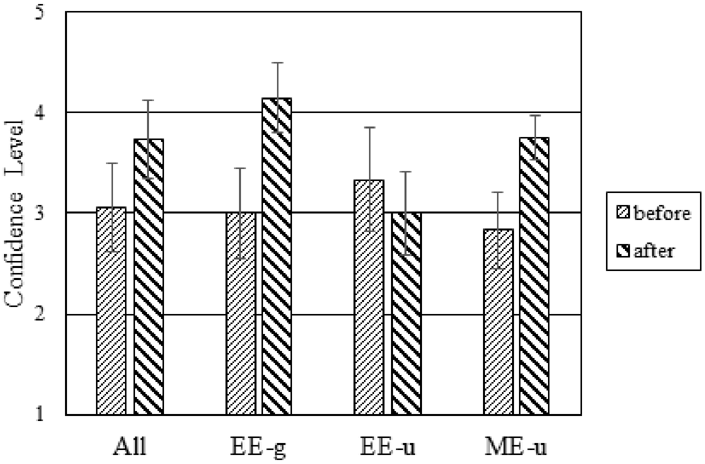

Figure 2. Confidence level for students to work in the microelectronics industry before and after taking the course.

- "<u>*In your opinion, which engineering discipline (EE or ME) is more relevant to the study of microelectronics?*</u>" Perception of the discipline more relevant to the field of microelectronics was surveyed before and after the semester, with the intention to assess the effectiveness in demonstrating interdisciplinarity. Students were asked to choose the relevant discipline(s) as they perceived. The number of votes were separated into the three groups, which were normalized by the group size, and the resulting "relevance perspectives" are shown in percentage. Figure 3 summarizes the results from the beginning of the semester. Overall, majority (~67%) of the class perceived the industry as more relevant to EE, and only ~28% considered it interdisciplinary between EE/ME. Specifically, all EE-g students voted for EE, two-thirds of EE-u students voted for EE and the rest for EE/ME, while only one-third of the ME-u group voted for EE and 50% considered it interdisciplinary. Interestingly, none of the EE students regarded the industry more relevant to ME discipline before the course. This is consistent with the relative higher confidence level for EE students in the beginning (Figure 2). Also, only one ME-u student regarded the industry as more relevant to ME, while almost all of them considered it more relevant to EE or EE/ME. These observations are consistent with the preliminary survey result from randomly chosen engineering students in the department described earlier, again showing the biased perspective on the microelectronics industry. With the excellent employment opportunity from local microelectronics industry in proximity, these findings highlight the opportunity for SUNY New Paltz to provide engineering students (particularly ME majors) with an interdisciplinary view of the field.

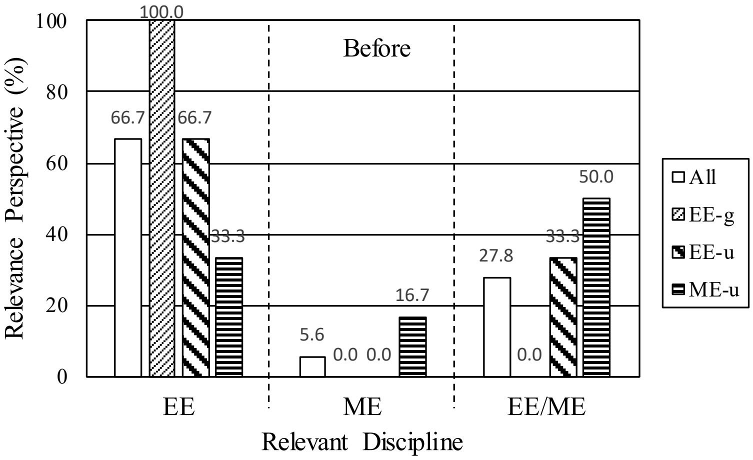

Figure 3. Students' perspective on the discipline(s) that is/are more relevant to the microelectronics field, surveyed in the beginning of the semester.

Figure 4 shows the same survey conducted at the end of semester, where shift in relevance perspective across all the groups can be clearly seen. Overall, 75% of students considered the microelectronics industry as interdisciplinary after the course, in contrast to 28% before the first lecture. In particular, EE-g students showed the most noticeable shift, with 71% regarding microelectronics an interdisciplinary field after the course, in contrast to 100% of them considering it more relevant to EE discipline. Also, after the course none of the ME-u students considered microelectronics as more relevant to EE discipline. Instead, all of them identified the industry as either interdisciplinary (80%) or more relevant to ME discipline (20%). Furthermore, the relevance perspectives are reasonably consistent among all groups after the course, contrary to the significant variation in the beginning. These results demonstrate the effectiveness of the course as a platform to establish interdisciplinarity between EE and ME majors in the engineering department.

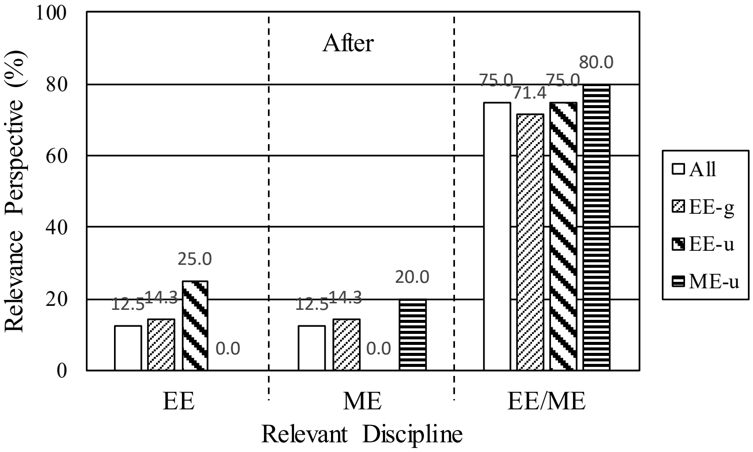

Figure 4. Students' perspective on the discipline(s) that is/are more relevant to the microelectronics field, surveyed at the end of the semester.

Student Evaluation of Instruction (SEI) was conducted near the end of semester to assess the teaching effectiveness and learning experience. With 88% participation from the class, the SEI result can be used as another reference for the course effectiveness. Regarding "*teaching method engaged my interest in the subject matter*," the course received a score of 4.93 on a scale of 1 (strongly disagree) to 5 (strongly agree), with 14 students strongly agreed and one agreed. With respect to "*instruction was effective*," it scored 5.00. When asked to reflect on their experience in the course, all the available 10 responses were positive and encouraging, including the following examples with more specifics for reference.

- "*the class smoothly integrated mechanical, electrical, statistical, and some manufacturing topics to engage students. The use of student/professional presentations made the class more engaging*"
- "*I am sad that we were disrupted by Covid-19 and did not get a chance to work as a true interdisciplinary group. Even without this project this class has open my eyes to an entire field that I did not think was a viable option for my career path.*"
- "*This class allowed me to gain a deeper understanding of engineering in general and the interdisciplinary efforts that going into making a complex product.*"

These comments, though subjective, can be used as another positive indicator to reflect on the course goal: providing a platform to establish interdisciplinarity between electrical and mechanical engineering majors.

Future Work

As described previously, the final team project was cancelled in spring 2020 due to COVID-19 related course adjustments. It was a disappointing decision based on a few comments from SEI, but the project will be implemented in the next offering of the course to provide experiences in interdisciplinary teamwork. Additionally, microelectronics reliability related hands-on labs will be planned for better engagement through active learning [11]. Basic wafer- and chip-level characterizations can be entertained for students to acquire further experience and confidence in the field where IC device such as an interconnect structure or a transistor can be probed with a micromanipulator under various biases and temperatures. Considerations and challenges in integrating these plans into course framework will be shared in the future.

Conclusions

A course was developed as a platform to establish interdisciplinarity in the engineering department at SUNY New Paltz. Leveraging the local resource and expertise, microelectronics and its reliability were chosen as the subject matter to stimulate communication and collaboration between EE and ME students. Result of surveys conducted before and after the course demonstrates the effectiveness of this attempt, with an apparent shift in student perception on the relevant discipline for the microelectronics industry (from EE to EE/ME interdisciplinary). Course feedback also revealed that students overwhelmingly appreciated the opportunity to explore how they could contribute to fields unfamiliar within their major.

Acknowledgement

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