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Interactive Lecturing in a Mixed Undergraduate/Graduate Semiconductor Innovations Course

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Abstract

This paper explores the development of a new course created in collaboration with SCALE, a DoD/DoW-sponsored workforce development program, which embedded active learning activities within lectures.

A national network for microelectronics research identified a curriculum gap in the topic of "leap ahead technology". Thus, it was decided a new course on this topic was to be created in collaboration with the SCALE program, a DoD/DoW-funded workforce development program, and the authors of this paper. The first question to answer in creating this course was: what is "leap ahead" technology? Through collaboration with experts in academia and industry, determining a widely accepted leap ahead technology was the first step. From this, we were able to expand into technologies that have yet to reach commercial success and analyze why they may or may not be future leap ahead technologies, using existing and past technologies as a framework. The first clear leap ahead technology was the transistor, and for a second example the slightly more niche but commercially successful vertical-cavity surface-emitting laser (VCSEL) was selected. These were presented as case studies across four lectures at the beginning of the course. Later class topics explored new and emerging technologies for students to analyze, with these case studies acting as a framework for successful leap ahead technologies.

The core learning objective of this course was to have students gain the ability critically analyze new and emerging technologies in the semiconductor field. Thus, an interactive lecturing approach was selected where both lecturing and active learning activities happen in a single class period. 80-minute lectures were selected over 50-minute lectures due to the incorporation of active learning. Each class was approximately 40-50 minutes of lecture to build the student's foundational background, and 30-40 minutes of active learning to engage with the topics discussed and practice critical analysis. Multiple active learning activities were utilized to best match the content being explored in lecture, adjust to the time availability after the lecture concluded, and give variety for the students to not become complacent with a specific assignment or activity.

Instructor takeaways from the first implementation of this integrated lecture/active learning style includes the following: active learning components were useful for student engagement, attendance, and understanding of material. However, when the lecture precedes the active component, many students would show up part-way through the lecture. Additionally, lectures were variable in length depending on questions and presentation speed, requiring flexibility in the active learning component. Future applications of this approach may find it useful to begin the course with an active learning component, so students are primed to ask questions during the lecture, enforce strong attendance from the beginning of the class period, and move the flexibility requirement to the lecture component which can easier adapt to variable times than the active learning components which may need to completely change to fit in different time frames. Ultimately, the integration of active learning components alongside the lecture was a benefit for both the instructors and students.

Introduction

Industry and research fields are constantly advancing, and curriculum updates do not always match the speed of advancement outside the classroom. A curriculum gap in “Commercial Leap Ahead” technologies for microelectronics was identified by the Silicon Crossroads Microelectronic Commons (SCMC) Hub. To attempt to bridge the current gap, a new course was developed and ran at a large midwestern R1 institution to provide a broad introduction to the current state of research for field.

Titled “Semiconductor Innovations,” this course aimed to prepare students to interface with emerging technologies throughout their career in industry or academia and fill a gap in curriculum around “Commercial Leap Ahead technologies” as identified by the Microelectronics Commons Program. Constructive Alignment [6] is utilized to guide the course design. Starting with the course learning outcomes, the aligned teaching and learning activities (TLAs) and assessment tasks (ATs) are selected and designed.

The course Learning Outcomes (LOs) were:

LO1: Students will be able to identify and assess current and past commercial leap ahead technologies including transistors and vertical-cavity surface-emitting lasers (VCSELs).

LO2: Students will be able to analyze wide-bandgap semiconductor devices with applications in power electronics and photonics.

LO3: Students will be able to conceptualize, critique, and compare photonic technologies including silicon photonics, photonic integrated circuits, and electro-optic systems.

LO4: Students will be able to conceptualize, critique, and compare wafer and chiplet bonding techniques and applications including high temperature direct bonding, plasma-activated bonding, and metal-assisted bonding.

LO5: Students will be able to identify and propose commercial leap ahead solutions to current technical problems.

This combines modern pedagogy of active learning [1] while retaining the opportunity to explore foundational topics with lecturing, a blended approach defining both a block of time to lecturing and a block of time to active learning in each class period was explored. This pedagogical approach aims to address consistent issues of student attention [2] and engagement [3] issues in classrooms. While complete removal of lecturing may seem an intuitive solution, it has largely been found to be ineffective [4], undesirable by students [5], and/or has too large an upfront time investment.

An overview of the course structure is presented, which may be utilized in the implementation of a similar course, or adapt the split lecture style of utilizing a lecture and active learning component in each class to fit different subject matter. This was implemented in a department that has little implementation of active learning in lectures, resulting in reflections from the instructors which may be useful for those who are interested in adding active learning to their own classrooms with similar departmental context.

Course Structure

The course was a senior undergraduate/early graduate-level course offered at a large R1 midwestern university. It consisted of two 80-minute class periods each week for a 14.5-week (29 class) semester. Each class period was separated into a lecturing component and an active learning component. The informal and formal cooperative learning activities [7, 8] are chosen as the TLAs to engage and support students towards attainment of the course LOs [9].

The first class consisted of an introduction to the course. This included a traditional syllabus discussion, but also included an introductory to the terminology, "leap ahead technology" and an introduction to active learning, overview of the in-class activities and the term project. The active learning component of this class was a think-pair-share of existing "leap ahead technologies" based on the definition provided in class. Thise lecture and activity prepared students for the non-traditional learning of the course. This early transparency allowed students to make a deliberate and informed decision about their continued enrollment in the course. For the first 2 weeks after the introductory class, the lecturing component consists of an atypical approach to lecturing, what the instructors referred to as "case studies," discussed in detail below.

Table I. Course Overview: Weekly breakdown of lecture topic and in-class activity.

1) Case Studies: The 2nd – 5th classes of the course explore historical narratives through presenting two case studies of "leap ahead technology" within the semiconductor field: transistors and vertical-cavity surface-emitting lasers (VCSELs). Each of these hold important historical context for the field and provide critical insight into the timelines of invention, the necessary context for industry to adapt new technologies, and allow for the exploration of several relevant technical topics (scaling, fabrication techniques, III-V and emerging materials, device and material theory and phenomena, etc). They are explored using the stories of their inventions and inventors, with technical information interleaved within the narrative.

These specific inventions narratives were chosen due to their relevance to the field and existence of interesting and useful stories within. Transistors are one of the most famous semiconductor inventions. However, the precise history of researchers and their contributions to making transistors the ubiquitous technology of today is less understood. VCSELs are perhaps a less famous but still important semiconductor device, common throughout the communications field and emerging 3D imaging field with its own unique stories and difficulties towards reaching commercial success. Both topics highlight several impactful researchers from across the country and world, utilizing multiple methodologies to achieve significant research with entertaining stories throughout.

2) Lectures: After the case studies are concluded, traditional lectures are presented throughout the course to communicate technical information to the students. Relating the technical topics back to the themes of the case studies is done to help preserve student motivation and interest throughout the remaining classes. Topics included Wide-Bandgap Semiconductors (Transistors, Power, Photonics, Ultra-Wide Bandgap), Tunability (Electro-Optic Effect, Quantum-Confined Stark Effect), Heterogeneous Integration (Direct bonding, Metal-assisted bonding), Fiber Systems, and MEMS.

3) Active Learning: To keep students engaged during the lecture, active learning activities were embedded throughout the class. Typically in the format of a 5-minute think-pair-share, where students are presented with a relevant question (sometimes asking about the just lectured material, or asking to predict something about the upcoming material) and given 30 seconds to consider their answer to the question, 3 minutes to discuss their answer with their peer, then 2 minutes for 1-2 students to share their responses with the class.

Each class period concludes with 20-40 minutes of an active learning activity. Each activity is slightly different, and may consist of extended think-pair-shares [10] with more complex questions; creating an exam question based on the lecture [11], then sharing with a neighbor to solve and comment on, then discussing the types of questions students asked; or having a jigsaw discussion [12] on readings, where students first organize into expert groups who all read the same reading and agree on main takeaways, then organize into home groups who have all read different readings and share what their expert groups concluded, then determine a cohesive takeaway from all the readings within the home groups, concluding with each home group sharing their cohesive takeaway with the class.

Examples of active learning activities include the following:

For jigsaw assignments, the following general introduction is given:

> "Each student in a group will be reading a paper or set of papers (depending on length and complexity) with a shared theme.
>
> Before class, each student will submit a reflection to verify reading.
>
> During class, students who read the same paper ("expert groups") will first meet to discuss their primary takeaways, clarify any questions, and critically reflect upon their readings together.
>
> Each group will then meet, with each student having read different papers, to share the key takeaways from their readings and expert group discussion. The teams will then discuss to form a cohesive takeaway of all readings, and critically reflect upon each paper with the insight provided by the others."

A specific jigsaw example includes exploring modern transistors, where students would first submit a reflection before class, is as follows:

> "In preparation for a Jigsaw discussion, students are assigned reading(s) to complete. Depending on your reading group, read your assigned paper(s) and write a 200-600 word reflection in which your critically reflect on your readings. This should NOT just be a summary of your readings, instead you should discuss and critique what you have read (ex. Do you agree with their conclusions? What barriers do you see towards commercialization/ replacing existing technology? What future do you see for the technology discussed? Did you find anything particularly interesting/concerning/promising?).

Post your reflection as a reply in this discussion post. After you have posted, you will be able to view other students' responses who have read the same paper(s)."

Each group would have a reader who explored a different topic within the larger theme of modern transistors, including the limitations of lithography, sub-10 nm transistors, 2D transistors, and specifics of transistors in industry using recent announcements of large fabrication houses.

During class, they would first join their expert groups, i.e. groups of all the students who read the same journal articles. These expert groups would then submit 3-5 key takeaways from their shared reading and briefly link their reading to what has been discussed in class/ other readings.

After 10 minutes with their expert groups, they would return to their home groups (the same as their term project groups) with the following instructions to complete in 20 minutes:

"As a group, share your summaries and key takeaways from all your readings. Then compare your readings, and decide on some key takeaways from all the readings

Submit your names, 5-10 key takeaways (from all the readings), and briefly link all the readings together and to what has been discussed in class/ other readings.

All these readings explore some shared ideas(s). May want to discuss commonalities between all the readings, and/or differences between the different materials systems/structures discussed. Also linking all this back to the course is a good idea. What are your takeaways as a group."

At the very end of class, each home group would share with the class their overall takeaways as a group.

Another in-class activity example is a think-pair-share, where students would be assigned a short reading from literature, typically a letter or excerpt from a journal article, with associated questions to answer. After they independently read and answer the questions, they form small groups to discuss their answers, then each group shares with the class. The amount of time for this activity is heavily dependent on the length of the assigned reading and the number and depth of questions asked. An example given for the independent portion for the topic of visible photonic integrated circuits:

"Read the following letter:

Christian De Vita, Fabio Toso, Natale Giovanni Pruiti, Charalambos Klitis, Giorgio Ferrari, Marc Sorel, Andrea Melloni, and Francesco Morichetti, "Amorphous-silicon visible-light detector integrated on silicon nitride waveguides," Opt. Lett. 47, 2598-2601 (2022), doi: 10.1364/OL.455458

Answer the following questions:

Based on the Lithography Limits reading from the transistor jigsaw assignment, what lithography technique do you expect they used to pattern the:

a) Si_3N_4 waveguide

b) a-Si:H photoconductor

What do you find most interesting/promising from the letter?

What is your greatest critique of the letter?"

4) Term Project: As a key goal of this course is to have students be capable of proposing solutions to current technical problems, a term project is implemented to assess the development of this skill and to continue to have students actively engage with course topics outside of class time. The course project is framed as the writing of an initial research proposal. Suggested topics were extracted from ME Common's 2024 Call for Projects, where students were organized into teams in part by which topics they found most interesting. For the term project, however, they are only required to propose a solution to at least one of the success criteria. The project is scaffolded across the semester, with students first being asked to individually identify relevant background peer-reviewed articles, then as groups write their introduction/background section, then identify their solutions by completing the Heilmeier Questions [13], and finally write their complete white paper research proposal and give a 20-minute group presentation on their proposal during the final exam period.

For group formation, to support student autonomy [14], students were asked if they would prefer to organize into their own groups or have their groups decided for them based on a poll. For this implementation, 71% of students selected for team assignments. Thus, students were assigned to groups of 4 based primarily on their topic interests, with topics being High Permittivity Dielectrics, III-Nitride Transistors, III-Nitride Radiofrequency (RF) Electronics, Silicon Carbide (SiC) Junction Field Effect Transistors (JFET), Gallium Oxide Power Switches, Silicon Carbide (SiC) Power Switches, III-Nitride Power Switches. For each topic, students were able to select from: I don't know what this is, Not interested, Marginal, Neutral, Interested, and Very Interested. Groups were secondarily assigned based on their availability outside of class, with groups adjusted to make sure each group had a minimum of 3 hours outside of class hours that they were able to meet to work on their term project. Students availability was determined via a question were they were asked to identify when they were busy/ unavailable for group work between 8 am and 9 pm on all days of the week, and to identify their preference in working on the weekends ("I have no time for team activity during the weekend", "I would prefer to avoid working with my team during the weekend", "The weekend is as good as any other time", "Weekends are the best time for me to meet with my team"). These questions were asked to prevent scheduling conflicts and support working and non-traditional students in the course.

After the groups are formed, each group submits a team identity form where they pick a team name, motto, and create their own bylaws. Groups are asked to pick a name and motto to promote identity interdependence [15], and by creating their own bylaws groups define expectations within the group and determine conflict resolution techniques, reinforcing student autonomy [14].

The final paper was due after the group presentations to allow students to implement any feedback from their presentations in their term paper. During the presentation, students were required to engage with other projects. After each 20-minute presentation was completed, the non-presenting groups were given a few minutes to discuss what questions they had for the presenters, then each non-presenting group was required to ask at least one question about the proposal. All students were also required to complete a form where they wrote down the questions they had for each presenter, in addition to a summary of the key takeaways they had for each presentation. After all groups presented, they completed the form by answering, "If you were on a funding agencies board, rank the order in which you'd provide funding to the proposed research projects." This assessment was implemented to encourage students to engage with all the projects, and for the presenters to receive ample feedback, and not just from the instructors.

Instructor Reflections

In-class active learning was a new concept to many students who initially enrolled in the course. On the first day of class, there were 36 students enrolled, and after the drop deadline, only 16 remained in the course with 6 graduate students and 10 senior (4^{th} year) undergraduates. Those who remained were largely enthusiastic about the course topic and willing to engage with the active learning components. As the course was a new elective, it is assumed that many students registered with a vague interest, and in hopes that it would be an easy course. As the course was explained and students engaged in active learning activities, a large number dropped. Of the students who remained, many expressed appreciations for the in-class active learning component and term paper for experience in technical reading and writing.

Incorporating active learning activities during and after lectures was a great boon to the course. The primary lecturer for the course commented that an 80-minute traditional lecture is a "ritual of pain for everyone," professor and student alike. These activities provide respite for everyone from technically dense information and allow time for students to play with the information, weaving it into their knowledge basis and practicing engaging with it in an active way. Additionally, the activities provide a sense of community building amongst the students in addition to ownership of their own learning. Student engagement with the activities has been strong, with initial hesitancy being alleviated through practice and repetition.

Student attendance was also improved in comparison to other courses run by the same faculty member which do not implement active learning activities. However, as the semester progressed, students would start to arrive late to class, likely due to the active learning activity consistently being after the lecture. It may be useful in future implementations to alter the timing of the active learning activity. As the first 15 minutes has the highest attention span, it is recommended that the class begins with some lecturing. However, variations of placement and length of active learning components may be useful. Options to explore for an 80-minute course include 30/20/30 of lecture/active learning/lecture, 20/20/20/20 alternating lecture and active learning, or 60/20 as was done in this implementation. Alternating between these may also help with students not falling into complacency with the structure of each class, and with various active learning activities and lectures taking different lengths of time.

For the term project, issues of mosaic plagiarism were found during the initial introduction submission. To avoid this in future implementations, an in-depth discussion of plagiarism emphasizing what mosaic plagiarism would be useful. When this issue was detected for this implementation, the following actions were taken: first, an announcement to the course was sent explaining that plagiarism issues were detected. Specific groups and issues were not identified, but students were asked to self-report and face limited consequences. When none self-reported, direct emails to affected groups were sent, and students were asked to submit a write-up identifying how each instance of plagiarism occurred and groups with identified issues were given a reduced grade on the introductory assignment, as benefit of the doubt was given to the students' claim of ignorance regarding mosaic plagiarism. All critical issues were fixed for the final paper submissions. This opportunity to rectify issues is one of many benefits towards the scaffolding of the term project.

The course was graded on a 100-point scale, with a letter grade breakdown of: 100-85 A+, 85-80 A, 80-75 A-, 75-70 B+, 70-65 B, 65-60 B-, 60-55 C+, 55-50 C, 50-45 C-, <45 F. For the whole class, the average grade was an 81 (A), with graduate students averaging an A+ (87) and undergraduates averaging an A- (77). For the active learning components, for the in-class activities students averaged an A+ (88) with graduates averaging 97 (A+) and undergraduates 83 (A), and for the term project students averaged an A+ (89), with graduates averaging 93 (A+) and undergraduates averaging 87 (A+). It broadly appears that graduate students did better than undergraduate students, potentially due to them more likely having more experience and expertise in the field. However, utilizing a two-sample t-test, the final grades are not found to be statistically significantly different between undergraduates and graduates ($t=1.71$) for a standard significance level of $\alpha=0.05$. The p-value for this analysis is calculated to be 0.11.

For the following implementation of the course, incorporating more mathematical rigor in the course's activities and/or homework may also be beneficial. This first implementation leaned heavily into high-level analysis, and an improved balance of mathematical rigor and conceptual exploration may be useful.

Conclusion

Embedding active learning components with lecturing allowed a "best of both worlds" approach to instruction. Lectures allowed for the dissemination of foundational information, and the active learning activities allowed students to more deeply explore and engage with the topic. Both students and faculty expressed their appreciation for the mixed approach, although some students had resistance to non-lecturing during class time.

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