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Developing Microelectronics and VLSI Field Education for the Potential Workforce

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Dr. Koo received his Ph.D. degree in Electrical Engineering from the University of Washington, Seattle, in March 2016. He then joined the Analog I/O design team at Intel Corporation in Hillsboro, OR for i5/i7 CPU design. After the first tape-in with CMOS 10nm technology, he moved to the RF technology team in Advanced Design group. He worked as a RF/Analog Circuit Design Engineer and participated in 140GHz Transceiver/Receiver system design for server chips communication. He also had additional responsibilities as a lab manager controlling all measurements for Intel 22nm FinFet technology development. He joined Cooper Union as Assistant Professor at 2020 Fall, and teaches Microelectronics/VLSI related courses. His current research interests are in the area of RF IC design for wireless applications.

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Abstract

Rapid evolution of semiconductor technology has resulted in an unprecedented reliance on microelectronics and Very Large Scale Integration ("VLSI") systems across various industries. As technology of this field continue to advance and profoundly affect various aspects of the modern world, educational institutions are recognizing the crucial need of a specialized curriculum tailored to these domains. By establishing a curriculum that emphasizes these specialized areas, educational institutions can equip students with skills and knowledge required to address the challenges and opportunities present in the microelectronics and VLSI landscape. Such curriculum shall extend from theoretical foundations to practical hands-on experience, exposure to industry-standard tools, and collaborative projects to foster innovation and problem-solving abilities. Such integration of microelectronics and VLSI-focused courses will help bridge the gap between academia and industry standards, and will be able to foster potential workforce that meets industry demands. This paper introduces such curriculum for each class year and explores in detail its contents and its outcome shown via students' course survey results. Course survey results from the last 4 years show how the students were affected by the proposed curricula, ultimately leading to their success in academic research and industry career in the microelectronic field.

Introduction

Microelectronics lies at the heart of countless technological advancements and often acts as a catalyst for innovation across various industries. Recognizing its critical importance, the United States Congress passed the CHIPS and Science Act of 2022, which aims to bolster the nation's position in microelectronics research, development, and manufacturing. This paper describes how author's Electrical Engineering department re-designed its curriculum in response to this transformative legislation, an innovative model incorporating industry practices for microelectronics related education. This development aims to entice students into microelectronics and VLSI field and to create a cutting-edge, industry-relevant curriculum by utilizing design kits provided by a semiconductor manufacturing company. Up-to-date industry standard design software tools are provided to students as well. This paper illustrates the importance of having such "practical" environment in school's microelectronics education. Each class year's curriculum is shared in detail and how they correlate to each other. Microelectronics and VLSI curricula consist of Circuit analysis and Microelectronics I for sophomores, Microelectronics 2 and Analog VLSI for juniors, and Digital VLSI for seniors. One distinct uniqueness of this curricula is that all students are required to participate in practical courses, every semester throughout all academic years. Each semester, a two-credit electrical engineering projects class is included as a requisite. This course offers students hands-on experiments that reinforce the microelectronics theories presented to them in the lecture-only classes. Junior project class is dedicated to implementing circuits and systems on bread boards such as crystal oscillators and active mixers with off-chip components. Through experiments, students encounter issues and challenges which are caused by unpredicted parasitic components from bread board and wire connections in test environment. These hands-on experiments motivate students to conduct in-depth research beyond their textbooks and to realize the inevitable necessity of on-chip implementation. Then, students go through the whole IC design tape-out process in their senior project class, which equips them with invaluable lessons learned via their trials and errors for them to use when designing their own chips in the near future. The last session of this paper shows the results of the course surveys which reveal the positive outcome of these classes; how much each course helped the students understand the topic and how these courses influenced them to taking another course in the same field or to conduct research in this field. Notably, it has shown that junior project course sparks enthusiasm regarding this field in most students for them to voluntarily advance to conduct advanced research in following semesters or plan their career path in this field. This verifies the importance of and the effectiveness of hands-on experiments for nurturing potential workforce for VLSI fields. The recent development of technology shows enlarged scale of circuits and systems. In turn, both industry and academia are relying on design tools for design and for predicting behaviors of the systems. Whether for academia or industry, however, hands-on practical experiments will play a crucial role in students' understanding of theories they learned through books and lectures, spark interests in and lead to their continuance in VLSI fields after graduation.

Sophomore – Microelectronics I

Microelectronics I

Microelectronics I course includes fundamentals to start understanding recent CMOS technology for chip design. The course focus on studying theories of how CMOS devices work and how to utilize such in designing a system within a chip [1][2][3]. Previously, these were taught through textbook or materials only. This leads to build a bridge between what students learn in school and the actual design skills used in practice in recent technology developments. The new curriculum collaborates with semiconductor manufacturing companies, Taiwan Semiconductor Manufacturing Company ("TSMC") and Muse Semiconductor LLC ("Muse") to effectively link academia with manufacturing companies. NDA (non-disclosure agreement) need to be executed between the school and the manufacturing companies to ensure that the company's technology will be used only for education purposes and not to be disclosed outside of the school. The educational institution, in turn, receives design kits containing recent CMOS technology. These design kits, called PDK (Process Design Kit), are essential for designing circuits for fabrication in the industry and therefore essential for students to be educated and experienced on them. Through the sophomore project, students learn this process

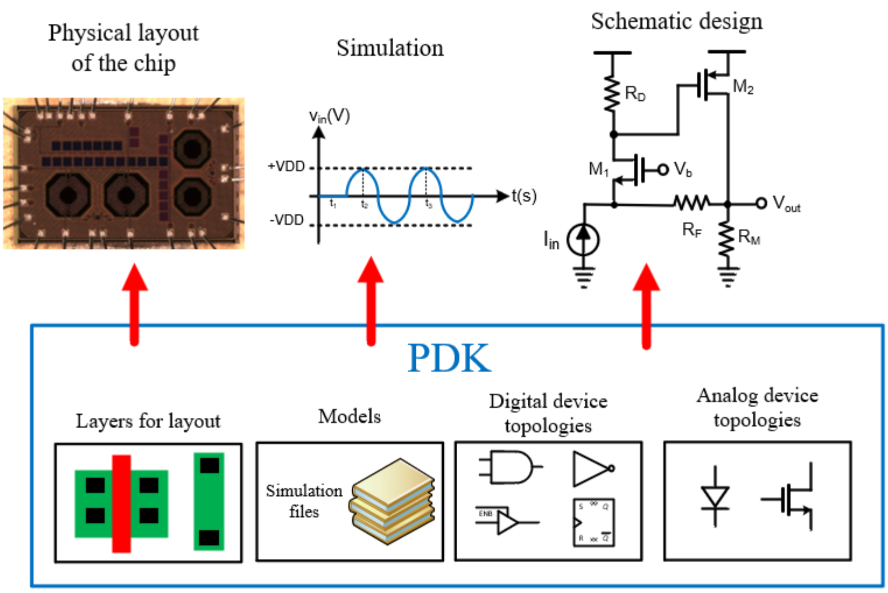

Fig.1 Block diagram of PDK elements utilizing for circuit design.

of actual design and are able to see the simulation results predicting how the actual chips and systems will behave.

Fig.1 shows the block diagram of how PDK is used in design and simulation. Industry standard tools and PDK help students understand and clarify how theories from class work in real design by simulation results. As semiconductor technology is developing at a fast pace, there are inevitable side effect phenomenon found in recent technology. Students discover that they need to consider those effects in the actual design and simulation. That is why it is critical for students to learn based on PDK of recent technology in addition to theories. This is important from the industry perspective as well. Often, industry spends much effort in training newly graduated employees on new technology trends because students are not exposed to such trends while in school. Having PDK experience is an invaluable tool for students to start few steps ahead in their professional careers and an efficient time and money saving method that will be welcomed by the industry.

First half of the Microelectronics I curriculum focus on fundamental theories and the latter half works on design procedure projects with industry standard tools. At the sophomore level, students are given a simple circuit design, such as single stage operational amplifier, as their final project. This is to help students understand how to apply their textbook knowledge in the actual design phase.

Junior: Microelectronis II, Analog VLSI and Junior Project

Microelectronics II

While Microelectronics I focuses on fundamental behavior of the device itself, Microelectronics II moves on to circuits and systems that utilize such devices and introduces more necessary skills for analog circuit designs. Fundamental circuits being used throughout systems such as current mirror, bandgap reference and differential amplifiers are covered and introduced as projects. In addition to design and simulation, layout, the last step before the fabrication of the real chip, is another requirement for the course. Industry trend shows increased complexity of layouts as the number of metal layers used in recent CMOS technology and process steps are increasing. This is why it is critical for students to learn how to efficiently do a layout, how to decrease difference between simulation and real behavior of the chip. Fig.2 shows one of steps in the layout called Layout Versus Schematic (LVS). This is to compare schematics in design with the layout and to check whether they are identical. Although the projects are not complicated circuits, it is important to expose students to the industry's standard flow of the chip design. This course acts as a steppingstone for the following advanced curriculum such as Analog VLSI.

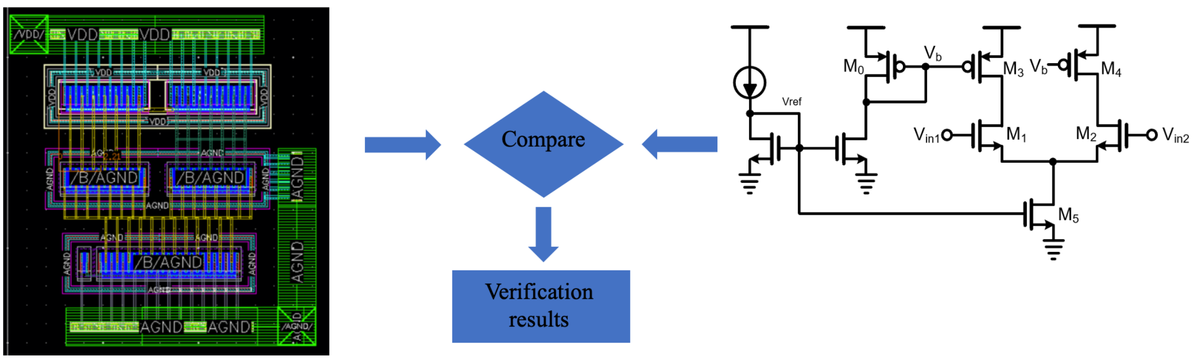

Fig.2 Layout versus Schematic (LVS) steps in layout

Junior Electrical Engineering Project

The proposed curriculum includes project-based class for each academic year – Digital logic design (DLD) for freshmen and Sophomore/Junior/Senior Electrical engineering projects. Senior students choose their topics freely and work on their projects for the entire year and show the demo at the end of year. All the projects prior to the senior project have covered specific topics chosen by relevant faculties based on what students have learned at that stage.
In their projects, students use off-chip components with solderless breadboards which have many parasitic components that cannot be measured and predicted. That is why projects cannot aim high frequency application such as Bluetooth (2.4GHz) or WiFi (5GHz). The target frequency range, therefore, lies in the smaller range of MHz. As the recent technology works at the GHz range, admittedly, these projects using off-chip components may not fit the industry standard. However, integrating hands-on experiments building circuits and integrating them for implementing a system into the curriculum is essential as this step allows students to remember what they learned through textbooks and to discover any challenges that may arise from test environment which are not predicted through theory-based courses.
Fig.3 shows the RF front-end module implemented on bread board. The project consists of building crystal local oscillator (LO), active mixer using CMOS or BJT and passive low pass filter (LPF). The target operating frequency spectrum is low frequency (< 10MHz), but it is important that students get to work on part of a wireless system that is frequently used in real life. Fig.4 shows the measurement results of output of mixer from one student group. The active mixer successfully generates intermediate frequency (IF) at the output but with all the harmonics at high frequency. The undesirable output harmonics are mainly due to reciprocal mixing from parasitic components which are unavoidable in real design and system [4][5][6].

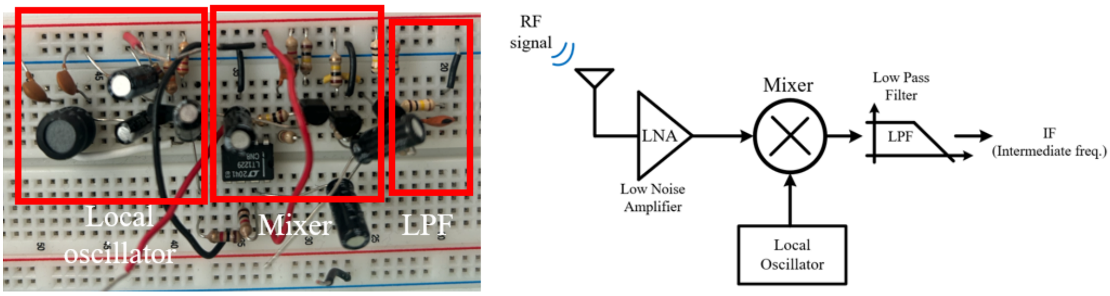

Fig.3 Block diagram of RF Receiver font-end and its equivalent implementation on the breadboard

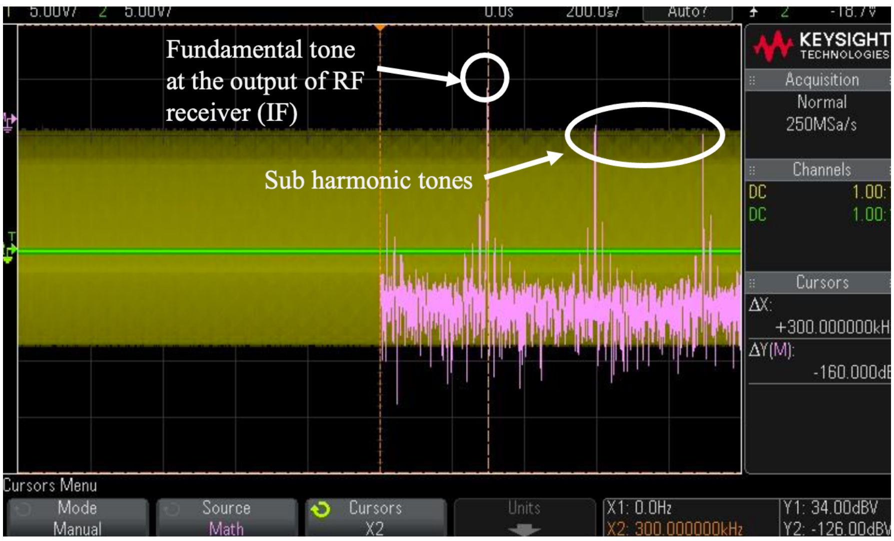

Fig.4 Experiment results of RF Front-end receiver

This is an important challenge for students to tackle in this course. Those unpredictable outcomes cannot be found in previous courses such as Circuit Analysis that only focus on theories. The junior project requires students to run simulation ahead of hands-on experiment so they can directly compare the difference between simulation and real experiment. This triggers students' interest and enthusiasm regarding what to consider in design phase and how to diminish those parasitic components. Junior project is the key course in this proposed curriculum as this project entices students to study advanced topics and lead them to microelectronics and VLSI fields. The course survey clearly shows that more students choose to take Analog VLSI course at following semester. It also helps students understand one important industry trend – why advanced technology tries to integrate more systems into a single chip. This is because on-chip integration helps to reduce those parasitic components and gain more controllability on avoiding unpredictable effects such as harmonics as shown in Fig.4.

Analog VLSI

Now, students understand the necessity of integrating circuits and systems. More importantly, students recognize the side effects of device and circuit operations [7][8]. Analog VLSI covers advanced techniques including skills used to avoid those side effects and introduce more system level circuits. Students continue using what they designed through Microelectronics I and II for more complex blocks such as multi-stage operational amplifier and DLL/PLL. Students already have experience doing layout through Microelectronics II, so this course moves one step further such that students need to extract parasitic components from their layout and include them in the simulation. This is called post-layout simulation. The simulation results consider more realistic situations, so it is closer to real circuit behavior. Fig.5 shows the overall procedure of entire steps of design.

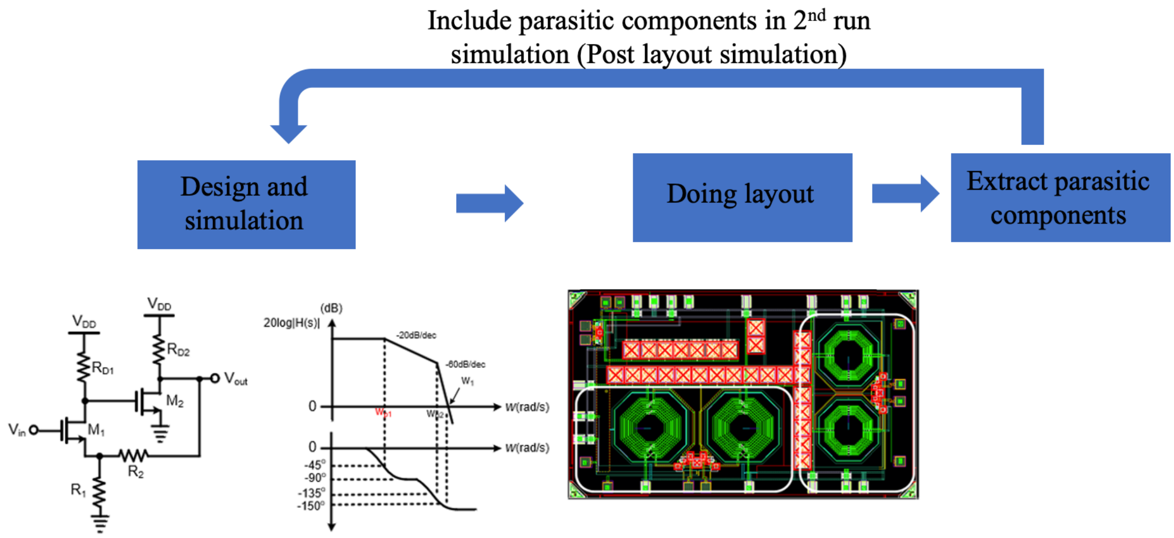

Fig.5 Design steps including layout and post-layout simulation

Layout is critical process to convert design into real physical layers for the chip fabrication. Even if the simulation results verify circuits' functionality and performance meeting the target, poor layout results in degraded performance in real measurements from the chip. That is why the simulation running after layout including all the 2nd effects from real layers is critical. The proposed VLSI course will emphasize the importance of the layout and introduce useful skills to minimize the difference between before and after layout simulation. Just a few years back, 4G LTE was operating at low frequency spectrum (<5GHz). Now, we are talking about next generation communication such as 6G targeting more than 100GHz [9][10][11]. Even though 5G service has started recently, most of base stations still work at 5GHz. However, the matured service is heading fast toward 60GHz. This is why the curriculum needs to emphasize and focus on efficient layout. When the chips works at low frequency, the 2nd effects called parasitic components from the layout have little impact on the post-layout simulation and real performance. But as the industry standard is moving toward such high frequency (> 60GHz), any inefficient layout can severely degrade the performance. This Analog VLSI course will aim to prepare students for the impending high frequency era.

Senior – Senior Electrical Engineering Project

Senior project course is another key course in the proposed curriculum. Senior students are challenged to utilize all knowledge and skills from the previous courses. Students, in teams, select a topic of their choice and work on the topic through 2 consecutive semesters. There is an end-of-year show where each team demonstrates a demo of their outcome of their senior project. This demo is a showcase of students' 4-year efforts, involving every technique and knowledge they acquired throughout all their class years. Most teams have selected software related projects or macro systems for hardware related topics. The proposal supports 1 or 2 teams to work on microelectronics topics from chip design to PCB board design. The tape-out process, however, will need support from fabrication company. For example, fabricating 1mm by 1mm chip costs roughly $5,670 for CMOS 65nm technology. Electrical Engineering department of the author's institution has supported 1 or 2 teams for the cost. When there are more than two teams working for tape-out, the author helps students to utilize free and open-source tape-out [12]. This tape-out process is using 130nm CMOS technology provided by another fabrication company, SkyWater Technology, and use open-source design tool provided by efabless.com. Although it uses relatively older technology, the entire process is free of cost and open-source. Fig.6 shows the entire design flow for the tape-out and getting the chip.

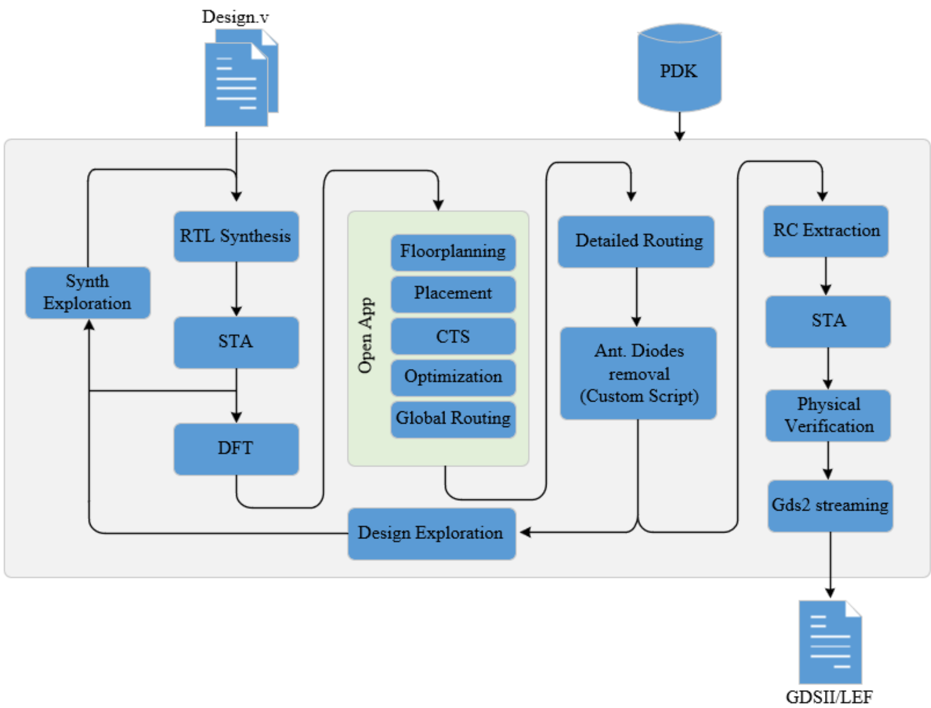

Fig.6 Overall design flow using free and open-source tool.

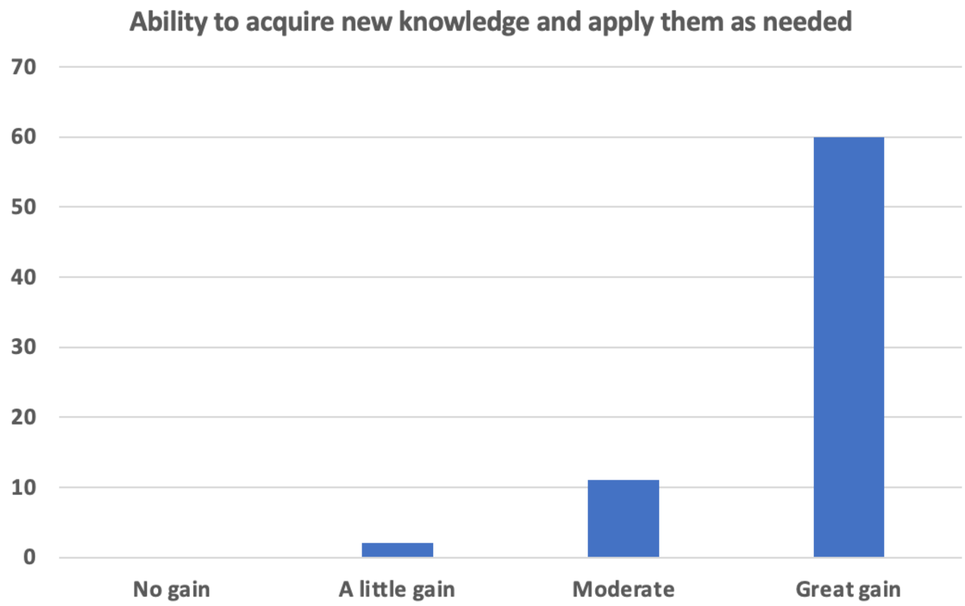

Fig.7 Course survey results about Microelectronics I and II

• *It was valuable how to use industry standard tool and flow.*
• *I learned how to understand circuits using a large signal and small signal model.*
• *I really liked learning how to solve diode circuits because it really tested how well you understood the fundamentals.*
• *The layout was really hard for me. Thankfully Professor was able to guide me and give the proper feedback so that I can do an even better job in VLSI next year. For example, my layout worked but was very sloppy. I have new ideas to work on it and make it even better after disscussng with Professor.*
• *The power of a transistor and how they interact with the rest of the circuit. Learned how to analyze the entire circuit step by step.*

Table1. Comments or feedback about project or about the class in general

For now, the tape-out process using the new advanced technology have been conducted only at the graduate degree program due to high costs. However, recent technology has advanced enough for older (but still relevant to current industry standards) technology to be accessible in terms of costs by educational institutions. There even are companies such as SkyWater and efabless that provide free tape-out to undergraduate students. As we find ways to mitigate the barriers to students' fabrication of their own chips continues, the proposed curriculum covers the entire tape-out.

Course Survey Results

Author have conducted course survey after every semester ever since first microelectronics and VLSI courses were offered to students 4 academic years ago. Fig.7 above shows students' confidence in acquiring new knowledge and in applying such knowledge to any subjects as needed after they take Microelectronics I and II. As previously mentioned, these courses focus on learning fundamental theories, so it is important for the students to fully understand the topics.

Table1 shows some comments from students regarding the projects and the class in general. The author would like to highlight the feedback of how students appreciated learning industry

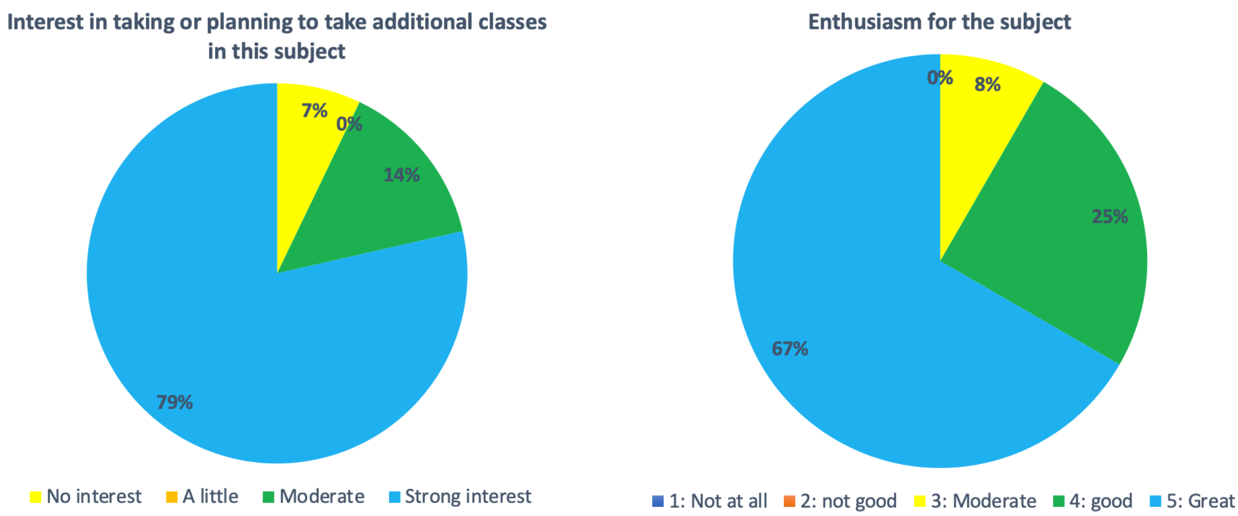

Fig.8 Course survey result showing students' interest and enthusiasm on VLSI field.

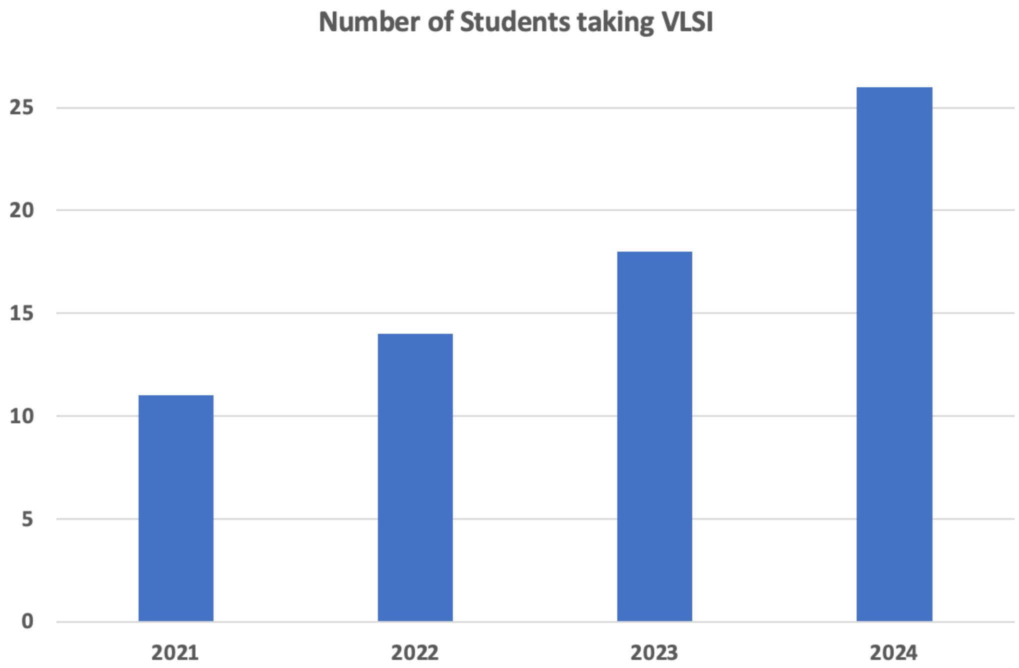

Fig.9 The number of students enrolled VLSI course at each academic year

standard tool flow. Another valuable feedback is about layout. Many students left comments expressing how hard the layout was and how difficult it was to do floor planning in the beginning. Most of them showed willingness to learn more about circuits at VLSI course in the following semester.

Junior project is an important required course. Students are challenged to integrate all the knowledge they learned from previous courses and conduct both simulation and hands-on experiments. Analog VLSI is an optional course offered at the following semester. Fig.8 survey results from junior project course show how much students showed interest on this field and their desire to continue to take advanced classes such as Analog VLSI. This survey results are notable in that it shows how much the junior project course influenced students' enthusiasm regarding the subject and attracted them to study more about this field. Fig.9 shows statistically the number of students taking Analog VLSI. The proposed junior project course has tailored and innovated contents from 2022 Fall semester. Prior to the new 2022 junior project, the number of students taking following Analog VLSI course had been between 10 and 15. Since 2023 Spring semester, the number has increased over 15 students and reached 26 students in recent academic year (Spring 2024). Considering that the total number of Electrical Engineering class size is between 30 to 33, enrollment of 26 students clearly represents the effectiveness of the proposed junior project and Microelectronics courses. It also indicates that the curriculum was able to attract more students to the VLSI field. Fig.9 outcome is also valuable for industries and communities trying to recruit and sustain related work force.

Conclusion

The creation of a curriculum tailored to Microelectronics and Very Large-Scale Integration (VLSI) is a notable endeavor necessary in contemporary education. The ever-expanding influence of these fields across industries calls for a dedicated educational approach that equips students with in-depth knowledge as well as practical skills. The significance of integrating specialized courses in microelectronics and VLSI lies not only in preparing students for the technological demands of today but also in fostering a future-ready workforce capable of innovating and addressing the challenges of tomorrow.

The proposed curriculum, which includes spanning theoretical foundations, practical applications, industry tools collaborations and hands-on experiences, is shown to be effective in helping students grow their interests of the field. The software design tools provided to students have helped decrease the gap between measurement results and simulation. This in turn helped students focus on simulation by using design tools with less time and energy spent on hardware related experiments. Students often easily get lost in theory-based designs and lose insight about real behavior of the circuits and systems. Hands-on experiments via junior and senior projects, therefore, are essential in the proposed curriculum. As course survey reveals, students encounter side effects from real world and realize the importance of and spend considerable time and efforts on circuit debugging. This process helps them realize textbook knowledge, allows them to learn industry knowledge and, en route, entice more students to microelectronics field. Author believes that this proposed curriculum is necessary for all future workforce and will help in nurturing and producing skilled professionals into the rapidly evolving technological landscape.

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