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Preparing Future Semiconductor Talent in the Global Context: A Comparative Study of the Semiconductor Engineering Curriculum in the US and Taiwan

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1. Introduction

Due to the exponential surge in global chip demand and strategic initiatives such as the *CHIPS and Science Act* to bring semiconductor manufacturing back to the United States, the industry is facing a severe talent shortage. Consulting companies such as Deloitte have also estimated that by 2030, more than one million additional skilled workers will be needed to meet the global demand in this field [1]. Similarly, the joint report released by The Semiconductor Industry Association (SIA) and Oxford Economics, has projected that after the enactment of *CHIPS and Science Act*, about 58% of new jobs in semiconductor industry will be unfilled by 2030, as shown below in Fig. 1 [2]. Higher education will play a key role in meeting this need, including preparing future engineers with semiconductor expertise. Federal funding agencies, such as the National Science Foundation (NSF), and leading research universities, have started to create educational and training programs designed to accelerate the development of a skilled workforce for the future of semiconductor engineering.

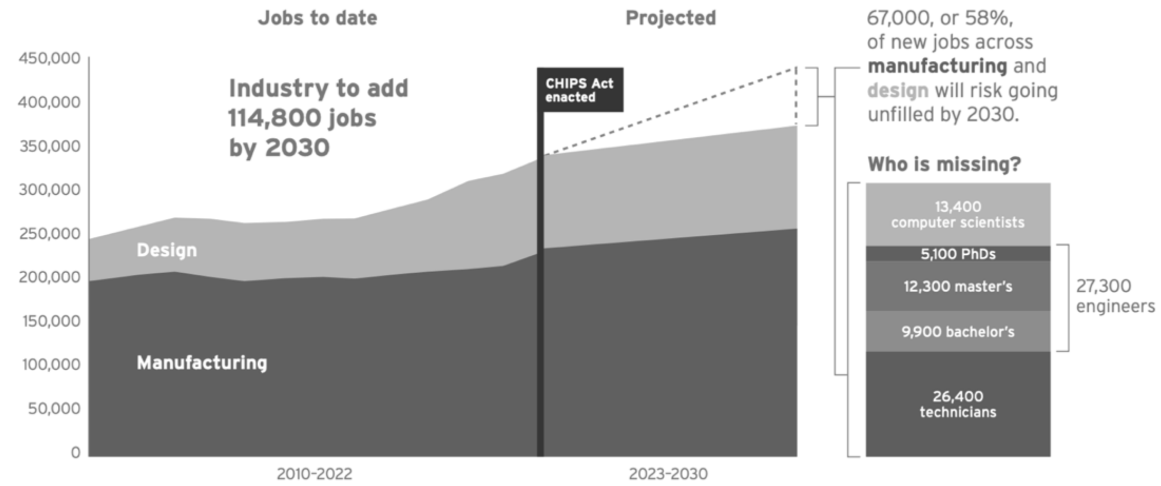

Figure 1. Historical semiconductor workforce and projected 2023-2030 gap. [2]

The United States and Taiwan are two key sites for addressing this global talent shortage. The former has recently begun its domestic chip manufacturing endeavors (note that the terms chip and semiconductor are used interchangeably in this paper), whereas the latter has long held a critical position in global chip production [3]. A collaboration between the two has recently started following the United States' intention to maintain leadership in critical emerging technology domains (see, e.g., [4], FuSe2 Grant, or ETSTE Grant). Both countries have undergone a recent revamp of curricula among some universities, introducing a range of specialized degree programs in semiconductor engineering education at various levels and across various higher education institutions (HEIs); including undergraduate, graduate, certificate, and undergraduate research opportunities at research-intensive universities, as well in community colleges.

At this point, it is essential to conduct research on the curriculum structure of these programs to understand whether the curricula effectively impart the competencies demanded by the global industry. Specialized curricula should facilitate the cultivation of "chip competency" amongst all graduates, as well as the professionalization of students entering the semiconductor industry. Furthermore, these curricula will form a key part of the institutionalizing and boundary-making process that establishes semiconductor expertise as a distinct disciplinary domain. In this exploratory study, we selected programs from four research-intensive universities in the U.S. and Taiwan, and two research questions were explored:
(1) What are the distinct program design features and educational objectives in the four programs?
(2) How do the four programs structure their courses and develop roadmaps to prepare future semiconductor talent effectively?

The paper is organized as follows: we begin with an overview of current semiconductor education efforts in the U.S. and Taiwan. We then introduce our guiding analytical framework for this comparative curriculum analysis, as well as the types of curricular data collected. The next section introduces the four selected programs from both the U.S. and Taiwan. In the Findings section which follows, we identify three distinct approaches to semiconductor engineering education, and present our analysis. We conclude the paper with a critical review of the semiconductor engineering education at research-intensive universities in these two countries.

2. An overview of semiconductor education in higher education

In this section, we hope to give the readers a general mapping of the current endeavors made by HEIs to address semiconductor talent shortage in the U.S. and Taiwan. To begin with, we note that chip manufacturing is a vertically specialized, labor and technology intensive, and high-value-added industry. The upstream industries include the design stage and the front-end process associated with wafer fabrication, including product design (IC design), wafer manufacture, and photo mask production. Downstream industries are comparatively more extensive, including the back-end processes of semiconductor manufacturing such as IC packaging, testing, assembly, as well as the manufacturing of lead frames, connectors, and circuit boards [2]. This breakdown, outlined in Table 1, gives a big picture of the different steps involved in manufacturing semiconductors.

Design	1. **Semiconductor design** refers to the complex process of building a computer model of a new chip, ensuring it is free from errors and meets the design rules necessary for manufacturing. 2. **Electronic Design Automation (EDA)** refers to the programming of and support for specialized software tools used in semiconductor design.
Manufacturing	3. **Semiconductor fabrication** refers to the front-end process of manufacturing silicon chips in a semiconductor fab. Back-end

	semiconductor manufacturing for assembly, test, and packaging with the same job codes are included in the scope of this report. 4. **Semiconductor machinery manufacturing** refers to the manufacture of the specialty equipment used in semiconductor fabrication.

Table 1. The breakdown of the semiconductor manufacturing process [2]

As Table 1 clearly demonstrates, such a vertically integrated semiconductor industry will therefore require various talents with different expertise. It is projected that the U.S. will face a significant shortage of skilled and highly educated workers in semiconductor industry in three primary occupational groups: technicians, engineers, and computer scientists:

1. **Semiconductor technicians** operate, maintain, and troubleshoot equipment used in the manufacturing of semiconductor components.
2. **Semiconductor engineers** research, develop, and improve semiconductor devices and fabrication processes, playing a crucial role in innovation in both fabrication and chip design.
3. **Semiconductor computer scientists** apply computational principles and algorithms to design and develop software and hardware solutions for semiconductor-based systems and technologies, primarily in the chip design sector.

Each category demands specific knowledge and expertise, underscoring the specialized skill sets required in the semiconductor industry. For instance, the silicon wafers are precisely manufactured to have a smooth and defect-free surface, as any imperfection at this stage could propagate throughout the entire manufacturing process. Therefore, on the manufacturing front, individuals in semiconductor fabrication should have expertise in the front-end processes of manufacturing silicon chips within a semiconductor fab. Engineers who are responsible for crystal growth process (e.g. Czochralski or Float-Zone) require expertise in crystallography to understand the crystal structure of silicon and other materials used, which is vital for growing high-quality crystals and controlling their orientation.

There have been some industry endeavors to create training courses on these topics. For example, Intel, a leading semiconductor chip manufacturer, has partnered with community colleges in Ohio to create a one-year semiconductor technician certificate program [5]. A similar program is the Semiconductor Technician Quick Start program initiated by the Maricopa County Community College District (MCCCD) in Phoenix, Arizona.

We also note that the semiconductor design company Arm has founded a global initiative titled the Semiconductor Education Alliance, to develop educational materials, including resources for VLSI design and distance learning [6]. Similarly, the Taiwan Semiconductor Manufacturing Company (TSMC), a leading semiconductor manufacturer in Taiwan, has started off the TSMC Semiconductor Programs at local research universities in Taiwan, offering various tracks such as Device/Integration, Process/Module, and Equipment Engineering [7].

Noting the key role for industry involvement, our focus shifts to research-intensive universities, to focus on their roles in preparing students for exploring career paths in the semiconductor industry? What expertise and knowledge do students need to acquire to become semiconductor engineers? How can we best ready our students for a smooth transition into the chips industry?

To our best understanding, there has been no study conducted to analyze various curricular approaches in semiconductor engineering education at research-intensive universities. Accordingly, this study hopes to provide a broad mapping of different semiconductor educational approaches to provide insights and guidance to both educators and policymakers, contributing to the ongoing discourse about preparing the future of the semiconductor workforce.

3. Analytical framework and Data collection

This study is a comparative study on curriculum, with our analytical framework informed by Bereday's four-stage model [8], and our interpretative approach proposed by Tang and colleagues [9]. Bereday's four-stage comparison model involves description, interpretation, juxtaposition, and comparison, as shown in Figure 2. — The first two stages involving mapping out social, political, economic, and historical factors. These stages situate the educational setting in its contextual backdrop, noting that this needs to acknowledge the risks of methodological nationalism [10] [11]. The subsequent stages involve the identification of similarities and differences and generating hypotheses for further comparison.

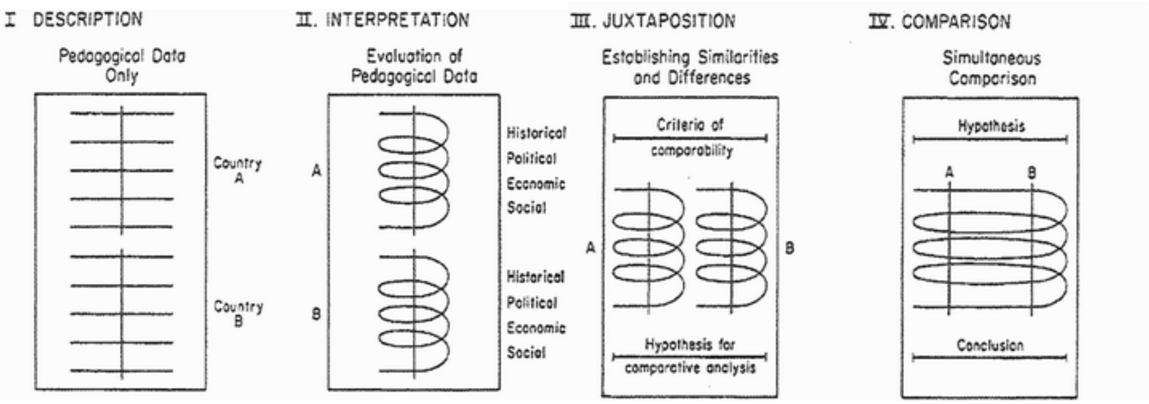

Figure 2. Bereday's four-stage comparison model

Building in the interpretive approach proposed by Tang et al. [9] we aim to "*understand the cultural and social contexts behind educational phenomena*" (p.35). They highlight its strength in being grounded and contextualized, providing researchers with a deeper understanding of the selected cases. However, they also warn that it may pose challenges for researchers, given that we might be able to address "why" certain educational initiatives are launched, yet to explore "how" and deriving improvements from the studied cases requires further endeavor.

In sum, this study seeks to go beyond a simple comparison between curriculum in Taiwan and the US. That is, we hope to overcome the plight of methodological nationalism as mentioned above. Here, we instead aim to contextualize the four selected programs within a more detailed context (be it geopolitical or curricular), as well as a more practical emphasis on their course structures and requirements. Data for this study draws on a wide variety of primary and secondary source material, including curriculum, course structures, requirements, pathways, program objectives and alignments, as well as press releases or reports in the selected programs. We will introduce the programs chosen in the next section.

4. The study sites and Contexts

Four programs, two from the US and two from Taiwan, were chosen for our study. As for the US side, we chose (1) the Chips-Scale Integration major in Department of Electrical and Computing Engineering at Virginia Tech and (2a) Microelectronics and Semiconductors Concentration for Electrical Engineering and (2b) Semiconductors and Microelectronics Certificate at Purdue University. In Taiwan, we chose (3) the Department of Microelectronics from National Yang Ming Chiao Tung University (NYCU) and (4) the TSMC-NTU Semiconductor Program from National Taiwan University (NTU). The rationales behind the choice of the four programs are twofold. Firstly, all four universities are research-intensive institutions in the US or Taiwan. Secondly, the programs are all recent efforts to mitigate the semiconductor talent shortage, as explicitly stated in each program objectives or press releases. Below we introduce each of the four universities and its context.

Virginia Polytechnic Institute and State University, or Virginia Tech (VT), is a public research-intensive university founded under the Morrill Land Grant Act of 1862. Its College of Engineering was founded in 1903. VT is also part of the Northeast University Semiconductor Network launched jointly by Micron Technology and NSF in 2023 [12]. Purdue University, also a public land-grant research-intensive university, was founded in 1869. The College of Engineering was renamed in 2004 from the School of Engineering. Purdue is part of the Midwest Semiconductor Network formed in 2022 [13]. Also, SkyWater Technology has just announced a $1.8 billion chip fabrication facility in West Lafayette in 2022, where Purdue University is located [14].

National Yang Ming Chiao Tung University (NYCU) is a research-intensive university in Taiwan. It was created under the merger of National Yang-Ming University (NYMU) and National Chiao Tung University (NCTU) in 2021. These two original universities have different histories and missions. The latter, NCTU, was reestablished in Hsinchu, Taiwan, in 1958. And as NCTU expanded, their College of Engineering was founded in 1970. National Taiwan University (NTU), on the other hand, is the most prestigious research-intensive university in Taiwan, founded in 1928 under Japanese Colonial Period in Taiwan as an Imperial University, and was renamed in 1945 after the Kuomintang Party retreat. Its College of Electrical Engineering and Computer Science was founded in 1997.

5. Findings: Three curricular approaches to semiconductor engineering education

In this section, we present three distinct curriculum structures that we identified from our analysis of programs at these research-intensive universities in Taiwan and the U.S. (full program details are given in Appendix). Table 2 summarizes the three approaches and which programs are illustrative of each of them.

Approach		**Example**		**Credits**
Independent	**As an independent department**	**NYCU**	Department of Microelectronics	130 credits

Integrated	**As a specific major in the ECE Department**	**VT**	Chips-Scale Integration major, Department of Electrical and Computing Engineering	131 credits
Add-on	**As an undergrad concentration or certificate not necessarily limited to the ECE students**	**Purdue**	Microelectronics and Semiconductors Concentration for Electrical Engineering (for EE students only)	9 credits
			Semiconductors and Microelectronics Certificate (university-wide)	16 credits
		NTU	TSMC-NTU Semiconductor Program (university-wide)	15 credits

Table 2. Three curricular approaches to semiconductor engineering education in the four selected programs

Firstly, the **independent approach** sees semiconductor knowledge as a standalone field of study, typically housed within an independent department. An example is the Department of Microelectronics at NYCU.

Secondly, the **integrated approach** incorporates semiconductor knowledge as a subfield under the broader umbrella of electronic engineering, as in the case of the Chips-Scale Integration major in the Department of Electrical and Computing Engineering (ECE) at VT, which integrates semiconductor studies within the curricular structure of electronic engineering. Students within the ECE program can choose semiconductor studies as their primary focus by choosing this major.

Thirdly, the **add-on approach** involves universities with an electronic engineering department where students may not necessarily take a dedicated semiconductor program. These institutions instead focus on providing a comprehensive understanding of semiconductor engineering within the broader context of electronic engineering. They, in addition, offer “add-on” concentrations and certificates for students, whether they are majoring in ECE or within the entire university, allowing them to enroll in semiconductor engineering courses for a specialized education.

5.1 Independent Approach: NYCU

An independent approach means the department is focused exclusively on semiconductor engineering education, as is the case of the Department of Microelectronics at NYCU. It was only in 2023 that this department received governmental approval from the Ministry of Education in Taiwan to be renamed as the "Department of Microelectronics" [15]. During the department's inaugural ceremony, President Dr. Lin said, "*Taiwan holds a crucial strategic position in the semiconductor industry supply chain*". Interestingly, prior to this renaming, the department was referred to as the "Undergraduate Honors Program of Nano Science and Engineering in the Nanotechnology Graduate Institute" since 2001. In retrospect, this specific focus on nanotechnology talent was established to meet the nanotech talent needs outlined by then Taiwanese government, as stated on their department website: "*In view of the government's active involvement in nanotechnology research, the College of Engineering at National Chiao Tung University submitted applications to the Ministry of Education to establish a nanotechnology research institute as early as 2001.*" Note that NYCU also has a separate and earlier established Department of Electrical Engineering, which will be discussed in the next section.

Currently, the Department, after the renaming, will still maintain the nanotech track; however, the number of students enrolled in this track (25 students) is significantly lower compared to the new semiconductor track, which sees an intake of 40 first-year students each year. As for the faculty, all the professors in this department hold affiliate positions, except for the department head. Such a composition of the faculty members, according to their website, holds the potential for "*combining the strong faculty resources of the College of Engineering, College of Science, College of Electrical Engineering, and College of Life Sciences*" due mostly to the interdisciplinary nature of semiconductor manufacturing.

In terms of the curriculum, students are required to complete 130 credits for graduation. This total comprises 71 credits for required professional courses (see Appendix), 18 credits for elective professional courses (each of the course is worth 3 credits; see Table 3), 15 credits for elective courses (which may be within the program or outside the major), 2 credits for free electives, and 24 credits for common courses, including liberal arts. The degree conferred for this program is a Bachelor of Science.

1st Year	Logic Design Introduction to Materials Science and Engineering
2nd Year	Signals and Systems Complex and Variables Digital Circuits and Systems Semiconductor Physics
3rd Year	Introduction to VLSI Design Integrated Circuit Design Laboratory Introduction to Analog Integrated Circuits Analog Integrated Circuits Lab Semiconductor Engineering Introduction to Crystallography and Diffraction Introduction to Compound Semiconductor Device and Process

	Thermodynamics
4th Year	Solid State Physics Electronic Materials Integrated Circuity Technology Device and Circuity Characterization Laboratory Integrated Circuity Technology

Table 3. *Elective* professional courses at Department of Microelectronics, NYCU

5.2 Integrated Approach: VT

In contrast to the independent approach, an integrated approach involves incorporating semiconductor knowledge into the curriculum of the ECE/EE department. The Chips-Scale Integration major in Department of Electrical and Computing Engineering at Virginia Tech is an example of this approach. In this model, students need to choose this specific major, among the 14 ECE undergraduate majors, to acquire the relevant knowledge. The 14-major curriculum structure is an educational and departmental reform developed with the Revolutionizing Engineering Departments (RED) grant from the NSF. In this way, the program structure has been introduced in a way that incorporates a shared first- and second-year curriculum for both EE and CE degrees. Students then need to declare their choice of major before entering the third year, . At this point students can immerse themselves in these more specialized areas and gain technical depth. Here, the Chips-Scale Integration major, according to their website, "*harnesses the advances in integrated digital and analog electronics to add even greater functionality, improve performance, minimize power consumption, and expand applications*."

In terms of the curriculum, students majoring in chip-scale integration require 131 credits for graduation, distributed across five categories: (1) Pathways to general education (7 pathways), 57 credits, (2) Core courses, 23 credits, (3) Major-associated courses, 24 credits, (4) Advanced math, 12 credits, and (5) Free elective, 5 credits. Additionally, as this major falls under the ECE department, students are also required to select a "Secondary Focus Area" (e.g. "Control, robotics and autonomy" or "Machine learning") worth 9 credits. The degree conferred for this program is a Bachelor of Science with Chips-Scale Integration major.

5.3 Add-on Approach: Purdue and NTU

An add-on approach indicates that the university maintains an independent electronic engineering department, offering add-on concentrations, minors, or certificate programs for students to enroll in, whether they major in EE or in other fields. Examples can be seen at Purdue, where two options are provided: (1) the Microelectronics and Semiconductors Concentration for Electrical Engineering (for EE students) and (2) the Semiconductors and Microelectronics Certificate (open to all students). In a same vein, NTU features the TSMC-NTU Semiconductor Program, which is accessible to all students.

At Purdue, the semiconductor talent shortage is emphasized in press releases and serves as a backdrop to the program: *"In the next five years, a minimum of 50,000 trained semiconductor engineers will be needed in the United States to meet the overwhelming and rapidly growing demand. ... Purdue's comprehensive new Semiconductor Degrees Program (SDP) is a suite of innovative credentials and degrees that will educate both graduate and undergraduate students, enabling a quick ramp-up of skilled talent and creating the next-generation of semiconductor* *workforce to reassert American preeminence in this critical industry.*” More specifically, aside from the “Interdisciplinary, 6-in-1 MS degree” and Graduate Concentration (for MS and PhD), SDP provides two undergraduate programs tailored to different student needs. On the one hand, the Microelectronics and Semiconductors Concentration for Electrical Engineering is designed for EE students, requiring a minimum of 9 credits in elective courses from the 13 courses listed in Table 4. In contrast, the Certificate in Semiconductors and Microelectronics is a 16-credit program open to all undergraduates at Purdue. The certificate comprises courses grouped into (1) a required course (1 credit), (2) Semiconductor Experience for Undergraduates (6 credits), and (3) technical courses chosen from five technical areas (9 credits).

At NTU, the TSMC-NTU Semiconductor program is an industry-university program, consisting of 15 credits. Interestingly, this program, launched in 2020, is part of the TSMC Semiconductor Academy, in which TSMC collaborates with several universities in Taiwan on semiconductor program projects [16]. Having the certificate might increase the likelihood of getting internships, gaining job interview opportunities, and even enhance one’s bargaining power for a higher salary at TSMC, as indicated on the TSMC website. NTU is the sole university offering the “semiconductor” program, while others are categorized as “components/integration”, “process/module”, “equipment engineering”, “advanced circuit design”, “smart manufacturing”, and “advanced packaging”, which signifies different stages of the semiconductor manufacturing process. Students enrolled in this program are required to choose 5 required courses out of the 16 courses, as well as the additional 5 elective courses out of 29 courses (Appendix).

Overall, with an add-on approach, students typically have their own major, whether in EE or another department. And the courses taken within the add-on program may also be double counted as electives or even fulfill electives requirements within their primary major.

6. Analysis

In this section, based the examples chosen, we first discuss the curriculum designs in more detail. We then compare each approach, as well as their strengths and limitations. We wrap up this section with a discussion on the research limitations.

6.1 Curriculum design

Our comparison of curricula will be discussed in three parts: (1) foundational courses, (2) core EE and semiconductor-specific courses, and (3) labs and research courses.

6.1.1 Foundational courses: Comparing the majors at NYCU vs VT

Generally speaking, all engineering programs require students to take foundational courses, such as physics, chemistry, and calculus. According to the ABET Criteria for Accrediting Engineering Programs, Criterion 5 specifies that students must complete a minimum of 30 semester credit hours (or equivalent) in a combination of college-level mathematics and basic sciences, including experimental experiences relevant to the program. Note that the Department of Microelectronics at NYCU is not accredited under the Washington Accord, yet ECE at VT is an ABET-accredited program. Here, NYCU requires 8 credits for physics, 17 credits for math-related fundamental courses, and 8 for chemistry, while VT requires 8 credits for physics, 19 credits for math-related fundamental courses, and 4 for chemistry (Table 4).

Furthermore, regarding experimental experiences, NYCU requires a lab course in physics, whereas VT requires a lab course in chemistry. See Table 6 for comparison. As for more advanced courses, echoing [17], they contend that, from an industry perspective, while the foundational principles of science and mathematics remain crucial, they also suggest that students may benefit from additional coursework, such as modern physics. Notably, modern physics is a mandatory course at NYCU but not at VT.

Apart from physics, math, and chemistry, NYCU also requires students to take a Career Planning course (0 credit) in the first year, and 2 service-learning courses (0 credit) in their second year. Comparatively, VT requires students to take First-Year Writing (3 credits), Foundations of Engineering I, II (4 credits), and Introduction to ECE Concepts (3 credits) during their first year.

	NYCU (33)		**VT (31)**	
	credit	**Course**	**credit**	**Course**
Physics	**8**	Physics I, II (6), Physics Lab I, II (2)	**8**	Foundations of Physics I (8)
Math	**17**	Calculus I, II (8), Linear Algebra (3), Differential Equations (3), Probability and Statistics (3)	**19**	Calculus of a Single Variable (4), Introduction to Multivariable Calculus (3), Introduction to Linear Algebra (3), Introduction to Differential Equations (3), Probability and Statistics for Electrical Engineers (3), Introduction to Discrete Math (3)
Chemistry	**8**	Chemistry I, II (6)	**4**	General Chemistry (3), General Chemistry Lab (1)

Table 4. Comparison table listing the foundational courses required by NYCU and VT

6.1.2 Core EE and Semiconductor-related courses: four programs

The absence of a standardized checklist for required semiconductor-related courses in undergraduate programs leads us to perform a thematic analysis on the selected programs (Table 5). This is perhaps also due partly to the fact that the expertise needed by different stages of the semiconductor manufacturing process vary, as discussed in the previous section. Hence, we compare the relevant required courses in each program to identify emerging themes.

Types	**Courses**	**NYCU**	**VT**	**P-Con**	**P-Cer**	**NTU**
Core EE courses	**Electronics**	R	R			(R)
	Electromagnetics	R	(E)*			(R)
	Circuit Theory	R	R			(R)
	Signals and Systems	(E)	R			
Semiconductor-related	**Semiconductor Device Physics**	R		(R)		(R)
	Modern Physics	R				(R)
	Material Science	(E)			(R)	(E)

	Solid State Physics	R				(R)
	Quantum Mechanics/Physics	R			(R)	(R)
	VLSI Circuit Design	(E)	R	(R)		
	Integrated Circuit Design	(E)		(R)	(R)	(E)
	Embedded Systems		R	(R)	(R)	
	Thermodynamics				(R)	(E)
	Crystallography	(E)				
	Manufacturing-related		(E)*		(R)	(E)

Note: R: Required course; (R): Required courses to be chosen from among other courses;
(E): Elective courses to be chosen from among other courses;
(E)* Elective courses from the Secondary Focus Area requirement at Virginia Tech

Table 5. Comparison table listing the core EE and Semiconductor-related courses required for each program

As Table 7 shows, we label Electronics, Electromagnetics, Circuit Theory, and Signals and Systems as core EE courses. NYCU curriculum covers the first three EE courses, with Systems listed as elective. VT, on the other hand, requires all but Electromagnetics (listed in Secondary Area Focus). As for the add-on approach, Purdue's two programs do not include these EE core courses in their requirements. Given that the Concentration track is only for the EE students, they are already required to take the core EE courses back in their home department. However, it is important to note that the university-wide Certificate track also does not require completion of EE core courses for earning the certificate. As for TSMC-NTU program, it lists the first three as required among other 12 courses, from which students choose 5 out of 16. Yet upon a closer look, the course requirements in this program appear to be loosely regulated, considering the broad spectrum of eligible 16 courses. Consequently, students enrolled in this program may not necessarily need to take the core EE courses to meet the requirement.

Semiconductor-related courses, on the other hand, are designed to equip students with insights into the design, fabrication, and optimization of semiconductor manufacturing process. These courses might include the intricate workings of transistors, integrated circuits, and semiconductor materials, as listed in Table 7. For starters, each program has its unique set of requirements and approaches towards semiconductor-related courses. Courses like Material Science, Thermodynamics and Quantum physics, highlighting an interdisciplinary approach, are listed as required courses at NYCU. VT, on the other hand, mostly relies on their unique curricular structure of a secondary focus area for students to choose courses from other disciplinary area. An add-on approach, as the table reveals, shows that most semiconductor-related courses are listed either as required or elective courses in the requirement. This flexibility of the curricular structure gives students the freedom to select courses from a diverse pool, enabling them to customize their academic path to align with their specific interests and goals.

6.1.3 Labs and research courses

The laboratory component in STEM education, as literature shows, is still strongly advocated by educators and researchers [18]-[20]. Semiconductor engineering education is no exception. In providing students with practical, hands-on experience, the NYCU curriculum lists three laboratory courses among its 20 required electives. Students, who are required to choose at least 18 credit hours, can choose from the Integrated Circuit Design Laboratory, Analog Integrated

Circuits Laboratory, and/or Device and Circuit Characterization Laboratory. VT, on the other hand, requires only a lab course on AC Circuit Analysis. As for the add-on approach, Purdue's Concentration track offers ASIC Design Laboratory and Integrated Circuit Fabrication Laboratory as electives among a set of 7 courses. The Certificate track also features several laboratory courses. In contrast, TSMC-NTU program's course pool does not list any laboratory courses.

In addition to laboratory coursework, some programs also expect students to engage in independent research. At NYCU, this involves a 2-credit hour Research requirement in the third year, with an option for an additional Independent Study in the four-year program. VT requires students to complete a senior design project (6 credits) during their fourth year. The Concentration track at Purdue does not require any independent study, while the Certificate track asks the students to gain "Semiconductor Experience", which can be fulfilled through independent studies, Vertically Integrated Projects (VIP) courses, or internships in the semiconductor industry. In contrast, the TSMC-NTU program does not mandate research experiences as part of its course requirements.

6.2 Potential strengths and limitations of each approach

6.2.1 Independent approach

The independent approach can sometimes be a double-edged sword. NYCU offers an interesting context for comparison, housing both a specialized department (independent approach) and a major housed in the EE department (integrated approach). The following tables, Table 8 and 9, provide a comparative analysis of the curriculum between a conventional EE department at the same university (NYCU) and the specialized semiconductor-focused approach. In the EE department, students are required to take 33 elective credits, and at least 24 to be chosen within the department. Table 9 outlines the curriculum for the "Semiconductor Device and Engineering Program" track. Yet it is also important to note that students are not obliged to take all the courses listed, and the completion of these courses will not be explicitly stated on their graduation certificates. Instead, these courses serve as recommended options for students interested in pursuing this track.

Furthermore, referring to Appendix, 5, 6, and 7, it becomes evident that (1) the foundational courses are also included in the EE curriculum (excluding Chemistry), and (2) EE students opting to fulfill the course requirements for the Semiconductor Device and Engineering Program track may potentially cover most of the subjects outlined in the Department of Microelectronics curriculum.

	1st Year	2nd Year	3rd Year
NYCU McrE	Physics I, II (6) Physics Lab I, II (2) Calculus I, II (8) Introduction to Computers and Programming (3) Chemistry I, II (6) Linear Algebra (3)	Electronics I, II (6) Electronics Labs I, II (4) Electromagnetics I, II (6) Differential Equations (3) Circuit Theory (3) Modern Physics (3) Probability and Statistics (3) Research I, II (2)	Semiconductor Device Physics (3) Introduction to Quantum Mechanics (3) Semiconductor Laboratory (2)

			Solid State Physics I (3)
NYCU EE	Calculus I, II (8) Physics I, II (8) Linear Algebra (3) Intro to Computers and Programming (3) Logic Design (3)	Differential Equations (3) Probability (3) Electronics I, II (6) Electronics Labs I, II (4) Circuit Theory (3) Electromagnetics (3) Signals and Systems (3)	

Table 6. Comparison between Dept. of Microelectronics (as McrE in the table) and EE at NYCU

Core courses	Introduction to Material Science Introduction to Modern Physics Semiconductor Device Physics Introduction to Quantum Mechanics
Related Undergrad Electives	Basic Semiconductor Physics Numerical Analysis Solid State Physics Semiconductor Engineering

Table 7. Semiconductor Device and Engineering Program in EE department at NYCU

Overall, on the one hand, such an independent approach offers students a focused expertise, producing graduates with a specialized knowledge of the semiconductor field. However, it may also have its drawbacks, such as a too narrow scope, where students might miss out on broader electrical engineering perspectives and applications. Besides, institutionally, this approach demands significant effort (e.g. renaming, organization restructuring, or creating a new department), and although it might cater to the current global semiconductor talent needs, adapting to new technological trends also requires overcoming institutional inertia (such as the lengthy renaming process at NYCU).

6.2.2 Integrated approach

In the case of Virginia Tech's integrated approach, being under the umbrella of electronic engineering can foster interdisciplinary learning for students by integrating semiconductor studies within electronic engineering. This leads to graduates possessing a versatile skill set spanning various engineering disciplines, as the inclusion of a "secondary focus area" exemplifies this. However, institutionally speaking, being under the ECE department may result in a dilution of focus and resources, where the integrated nature might reduce the depth of semiconductor knowledge compared to a specialized program and leading to competition for resources with other majors.

6.2.3 Add-on approach

The add-on approach, finally, provides flexibility for students in various engineering majors to explore semiconductor engineering. It allows students to customize their education by choosing an "add-on" concentration based on their interests. However, it may suffer from a surface-level understanding, in which students acquire a more superficial grasp compared to a dedicated semiconductor engineering program. It might also lack practical, hands-on, or laboratory courses since students are not obliged to include them in the certificate requirements.

6.3 Research Limitations

Two research limitations of this paper are discussed below. The first lies in the narrow scope of the cases selected for study. It falls short of providing a more comprehensive examination beyond the context of research-intensive universities, such as the cases of community colleges mentioned earlier. Additionally, given its focus on undergrad programs, the paper is unable to offer insights into postgraduate programs, pre-employment initiatives, or on-the-job training. For example, in Taiwan, there exists a collaboration between NYCU and the Ministry of Labor, offering month-long pre-employment semiconductor courses for individuals from non STEM-related fields who seek to transition into the semiconductor industry with academic and practical learning opportunities.

Another limitation is the depth of the analysis. Given the exploratory nature of this study, our focus primarily revolves around the collected text data, lacking interviews with key stakeholders such as the department head, faculty, or students in the selected programs, and the student learning outcomes from each approach are still not well established. For instance, if interviews with the department head or provost at NYCU were included, a deeper understanding of the institutional effort behind the adoption of the “independent approach” might have been gained, rather than remaining at a surface-level analysis.

7. Discussion and future work

This exploratory study serves as an example of how higher education institutes are responding to the emerging technologies talent needs in engineering curriculum, using a case of semiconductor technology. We identified three approaches to semiconductor engineering education at research-intensive universities in the U.S. and Taiwan. In the conclusion section, we start by placing the identified approaches in a broader context. We then hope to highlight the importance of the cultural aspect when discussing the diverse approaches to cultivating semiconductor talents in today’s landscape. We conclude this paper with a call for a more nuanced understanding of “talent shortage” in semiconductor industry.

Firstly, we posit that the choice of a curriculum structure fundamentally reveals how a higher education institution perceives and prioritizes semiconductor knowledge, and their belief in the most effective way for students to gain related expertise. In other words, opting for an add-on approach might signify that the institute still values the significance of basic electrical engineering knowledge, and an add-on certificate programs allows students the flexibility to acquire specific knowledge as needed, and will suffice for the current semiconductor talent need. An integrated approach acknowledges semiconductor knowledge as a subfield of study, allowing students the autonomy to choose this major while retaining the freedom to explore various subfields in electronic engineering. Finally, an independent approach requires the most institutional effort to address the talent needs of a specific era. It demands substantial institutional commitment and entails the risk that students holding this diploma may demonstrate a comparably narrowed understanding of electrical engineering in a broader context. Note that for how HEIs can respond to the talent need for emerging technologies, approaches are not limited to the following three (independent, integrated and add-on), other options, albeit in a way falling under the add-on approach, ranging from module, standalone course, or summer institute, as in the case of quantum engineering education [21].

Furthermore, the analysis of curricular structures presented here does not fully cover the cultural dimension of semiconductor talent training, particularly evident in Taiwan's semiconductor work culture (see, e.g., [22]). When placed within a broader cultural context, one may understand that, aiming for a higher yield rate and considering the nature of semiconductor manufacturing, it requires a disciplined workforce, a diligent work culture, and a collective ethos. These cultural aspects might not be explicitly emphasized in any of the approaches discussed above, yet it has been argued they remain essential for fostering a successful semiconductor manufacturing environment [23]. How the approaches are embedded in the respective cultures, be it learning culture or a general one, for example, is an important element to examine whether the semiconductor workforce preparation could succeed or not.

Finally, this study should prompt a more in-depth reflection on the definition of the "talent shortage" in the semiconductor industry, and how HEIs policy follows and responds. Do the programs discussed above solely seek to train high-level engineers, or does it encompass a broader spectrum, such as engineering technicians? If the latter is the case, how can we establish a more well-rounded talent cultivation ecosystem that not only focuses on training high-level talents but also addresses the needs of fundamental workforce? Delving into these questions, as we argue, can provide insights into developing comprehensive strategies for talent development in the semiconductor field.

Finally, future work in this study involves (1) expanding data collection within each approach, as well as the use of interviews with different stakeholders; (2) exploring different types of programs across various HEIs to learn more about current educational initiatives addressing the semiconductor talent shortage.

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Appendix

<table>
<tr><th colspan="2"></th><th>1st Year</th><th>2nd Year</th><th>3rd Year</th><th>4th Year</th></tr>
<tr><td colspan="2">NYCU (130)</td><td>Physics I, II (6)
Physics Lab I, II (2)
Calculus I, II (8)
Introduction to Computers and Programming (3)
Chemistry I, II (6)
Linear Algebra (3)</td><td>Electronics I, II (6)
Electromagnetics I, II (6)
Electronics Labs I, II (4)
Differential Equations (3)
Circuit Theory (3)
Modern Physics (3)
Probability and Statistics (3)
Research I, II (2)</td><td>Semiconductor Device Physics (3)
Introduction to Quantum Mechanics (3)
Semiconductor Laboratory (2)
Solid State Physics I (3)</td><td></td></tr>
<tr><td colspan="2">VT (131)</td><td>General Chemistry (3)
General Chemistry lab (1)
First-Year Writing (3)
Calculus of a Single Variable (4)
Foundations of Engineering I, II (4)
Foundations of Physics I (4)
Introduction to ECE Concepts (3)
Introduction to Linear Algebra (3)</td><td>Introduction to Differential Equations (3)
Foundations of Physics I (4)
Circuits and Devices (3)
Computational Engineering (3)
Fundamentals of Digital Systems (3)
Introduction to Multivariable Calculus (3)
Physical Electronics (3)
Embedded Systems (3)
Signals and Systems (3)
Integrated Design Project (2)</td><td>Principles Computer Architecture (3)
Data Structures and Algorithms (3)
Digital Design I (4)
Probability and Statistics for Electrical Engineers (3)
AC Circuit Analysis (3)
AC Circuit Analysis Lab (1)
Applied Software Design (3)</td><td>Senior Design Project (6)
VLSI Circuit Design (3)
Introduction to Discrete Math (3)
Digital Design (4)</td></tr>
<tr><td>Purdue</td><td><i>Concentration</i> (9)</td><td colspan="4">Semiconductor Devices, ASIC Design Laboratory, Microprocessor Systems and Interfacing, Computer Design and Prototyping, Integrated Circuit Engineering, Digital Integrated Circuit Analysis and Design, Electrical and Computer Engineering Projects, Junior Participation In Vertically Integrated Projects (VIP), Senior Participation In Vertically Integrated Projects (VIP), Integrated Circuit Fabrication Laboratory, MOS VLSI Design, Embedded Systems</td></tr>
</table>

	***Certificate* (16)**	**Required Course**	Introduction To Engineering in Practice (1)
		Semiconductor Experience for Undergraduates (6)	Research courses including relevant independent studies and Vertically Integrated Projects (VIP) courses, or Full-time internship relevant to technical areas of semiconductors and microelectronics. Summer or semester-long of full-time internship/co-op/SURF or similar experience is considered equivalent to 6 credit hours.
		Technical Courses (9 credit of courses in at least two out of five technical areas)	1. Semiconductor and Microelectronic Devices 2. Semiconductor Materials, Characterization, and Processing Integrated Circuit and System Design, Electronic Design Automation 3. Electronics Packaging, Heterogeneous Integration, and Thermal Management 4. Semiconductor Manufacturing and Global Supply Chain Management
NTU (10)		**Required (5)**	Electromagnetics (I, II), Electronics I, Semiconductor Device Physics, Advanced Semiconductor Devices, Solid State Physics (and Advanced), Semiconductor Processing, Advanced Integrated Circuit Engineering, General Physics IA, Engineering Mathematics I (Differential Equations, Linear Algebra, Probability and Statistics), Quantum Physics and Applications, Modern Physics, Circuit Theory
		Elective (5)	Electronics II, Component Measurement, Semiconductor Band Structure Simulation Memory, Magnetic Materials, Introduction to Nanoelectronics, Silicon Photonics, Quantum Computing and Information, Spintronics, Piezoelectric Materials, Microelectromechanical Systems (MEMS), Integrated Circuit Design, Diffraction Principles, Electron Microscopy Theory and Practice, Surface Electron Spectroscopy, Material Analysis and Detection, Introduction to Materials Science (and Advanced), Electronic Materials, Material Growth, Polymer Materials, Metal Materials, Computational Materials Mechanics, Thermodynamics, Heat Conduction, Transport Phenomena, Fluid Mechanics, Chemical Reactions and Electrochemistry, Introduction to Semiconductor Smart Manufacturing

Comparison table listing the *core* courses required for each program (note: electives are *not* included)