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A Semiconductor Knowledge and Literacy Test for High School and Community College Teachers

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Introduction

In recent years, the shortage of semiconductors has grown to be a worldwide issue. The first sign of shortage appeared during the COVID-19 pandemic when the extended lockdown disrupted chip production. Meanwhile, the demand for computer chips increased as more people shifted to remote working. The chip shortage also revealed our country's dependency on foreign manufacturing, which soon became a geopolitical issue that involved supply chain resiliency and national security concerns [1]. As a result, the US government introduced the 2022 Chips and Science Act to boost domestic semiconductor production. The Chips Act also emphasized the importance of science, technology, engineering, and mathematics (STEM) education and workforce development programs for all backgrounds, regions, and communities, especially people from marginalized, under-served, and under-resourced communities, to develop advanced chips at home [2]. Teachers play a vital role in STEM education and workforce development programs. To improve their knowledge of semiconductors, they need to have access to professional development opportunities in this dynamic field.

To meet this critical need, we developed a Research Experience for Teacher (RET) program at Oklahoma State University to increase teachers' semiconductor knowledge and address contemporary issues associated with the Chips Act [3]. The RET program included a 6-week paid internship in multiple integrated circuit (IC) design labs at Oklahoma State University for high school and community college teachers to learn about semiconductors and chip design fundamentals. After the RET program, teachers were also required to translate their research experience into new curriculum modules. The RET program is also mutually beneficial to the US semiconductor industry and teachers. It benefits the industry by encouraging teachers and students to become familiar with new technologies. Teachers gain from enhanced self-efficacy at the same time [4].

However, it is challenging to measure the progress of teachers in acquiring semiconductor knowledge. In contrast to other aspects of evaluating teachers' performance, like their alignment with Design, Engineering, and Technology (DET) [5], there is no survey or questionnaire available to assess the semiconductor content knowledge of an average adult. In [6], Ene and Ackerson proposed the Physics of Semiconductor Concept Inventory (PCSI). However, it focuses primarily on undergraduate physics students and lacks the scope to address broader chip design and policy dimensions. Several RET programs have been reported [7, 8, 9, 10], however, none of these programs have needed to develop their assessment instruments.

This paper describes the development, verification, and analysis of a specialized evaluation instrument—the Semiconductor Knowledge and Literacy Test (SKLT)—intended to evaluate high school and community college instructors' literacy and understanding of semiconductors. It also provides the initial validity evidence informing the design of the test and the results for the first test administration. The SKLT test is the first evaluation instrument for semiconductor knowledge. The assessment data was collected before and after teachers' participation in the RET.

This instrument is significant because it allows us to quantitatively evaluate teachers' progress in gaining semiconductor knowledge. With the help of this instrument, we can better evaluate the effectiveness of our RET program (one of its goals was to increase teachers' semiconductor knowledge). Even though we initially developed the instrument to assess RET, the instrument is independent of the RET training agenda. Hence, we hope other semiconductor education and training programs can also adopt or contribute to the further refinement of the SKLT test.

Development of Semiconductor Knowledge and Literacy Test (SKLT) and Methodology

The SKLT test includes a comprehensive 15-question test focused on analog and digital IC content knowledge. These items include twelve multiple choice responses, two short answer responses, and one question that asked participants to organize information in a serial order. The test was meticulously designed to be administered with high school teachers covering both technical and semiconductor literacy aspects.

Design, front-end fabrication, testing, and assembly are the main parts of semiconductor manufacturing [11]. So, the SKLT comprises four key areas:

1. Semiconductor Materials: Understanding silicon properties.
2. Design: Basic concepts of diode and transistor operation and logic gates.
3. Manufacturing: Familiarity with fabrication processes, photolithography, and device scaling.
4. Semiconductor Literacy: Include semiconductor literacy quizzes on major US semiconductor companies, economics, and federal policy.

Test Questions

The survey questions were designed to cover a spectrum of perspectives and experiences related to IC design. Table 1 describes the alignment between the test items and the Key areas referenced above. The following sections explored the questions outlined here.

1 Semiconductor Material

Three items on the SKLT related to semiconductor materials as shown in Figure 1. Question 1 evaluates comprehension regarding materials commonly employed in semiconductor manufacturing. The expected response is Silicon (Si). This question aims to gauge the participant's fundamental knowledge of the materials utilized in electronic components and

Table 1: The alignment between the test item and the Key area

Question	Related Area
Q1	Semiconductor Material
Q2	Semiconductor Material
Q3	Design
Q4	Semiconductor Literacy
Q5	Semiconductor Literacy
Q6	Semiconductor Literacy
Q7	Semiconductor Material
Q8	Design
Q9	Design
Q10	Design
Q11	Design
Q12	Semiconductor Literacy
Q13	Semiconductor Literacy
Q14	Manufacturing
Q15	Manufacturing

technology. Question 2 aims to gauge the familiarity of the respondent with semiconductor technologies and their relative importance in the electronics industry, the correct answer is“B” which shows the popularity of Complementary-Metal-Oxide Semiconductor (CMOS) devices. The purpose of the Q7 is to assess the understanding of the advantages of Metal-Oxide Semiconductor (MOS) devices in electronics. So, the question aims to evaluate whether the respondent recognizes the various advantages of MOS devices in electronic circuitry, the correct response is “D.”

2 Design

Five items on the SKLT related to the design area as shown in Figure 2. Question 3 asked to choose the smallest unit of measurement with the expected response “A.” Question 8 is intended to evaluate teacher’s knowledge of PN junctions. The four plots in the image show the current-voltage (I-V) characteristics of a PN junction under various scenarios, all four graphs are correct. Thus, the goal of the question is to find out if the respondents recognize the figure that accurately depicts the I-V properties of a PN junction. Given the wide variety of electrical devices that use PN junctions, this is a crucial concept in electronics. Question 9 is designed to assess participants’ expertise in the area of digital electronics. The purpose of the question is to gauge the respondent’s knowledge of fundamental concepts in digital electronics. Typically, binary digits or bits—which can individually represent a high voltage (1) or a low value (0)—are used in digital systems to encode data, so the correct answer is “A.”

The goal of Question 11 is to gauge teachers’ comprehension of an important idea in electronics, specifically as it relates to field-effect transistors (FETs). The right response is “C” which emphasizes how a transistor’s threshold voltage is affected by several variables, including temperature, manufacturing process, and the transistor’s physical dimensions (length and width).

<table>
<tr>
<td>1. Semiconductors, or integrated circuits, are most commonly made from:
a. Carbon (C)
b. Silicon (Si)
c. Germanium (Ge)
d. Galium (Ga)</td>
<td>2. Among the semiconductor processes, which is the most widely used?
a. Bipolar process
b. Complementary Metal-Oxide-Semiconductor (CMOS) process
c. Bipolar-CMOS-DMOS (BCD) process
d. Silicon-on-Insulator (SOI) process</td>
</tr>
<tr>
<td colspan="2">7. Why are Metal-Oxide Semiconductor devices used often?
a. They are easy to create circuits from.
b. They can be universal in terms of switching based on the Voltage
c. Fabrication is easy
d. All of the above</td>
</tr>
</table>

Figure 1: Three items related to semiconductor materials

One kind of digital logic gate, the NAND gate, is the subject of Question 10. There are two inputs (A and B) and one output (Q) on a NAND gate. A NAND gate behaves as follows: it only produces a 0 (LOW) output when both of its inputs are 1 (HIGH). Because the output of a NAND gate is only 0 when both inputs are 1, “A” is correct.

3 Manufacturing

Two questions on the survey, as seen in Figure 3, focus on the manufacturing process. The primary goal of Question 14 is to evaluate the respondents’ comprehension of key ideas in semiconductor production, particularly yield. This covers the ways in which die size, price, and other variables that have the ability to affect and enhance yield are impacted. The right response is “B.”

The purpose of including a question like Question 15 is to determine the respondent’s understanding of the semiconductor product development cycle as well as their ability to accurately sequence the stages. The correct sequence is F/I/J/B/E/D/H/C/G/A. Understanding the sequential steps required in creating a semiconductor product, from its original design to its ultimate retirement, is necessary in order to properly respond to this issue.

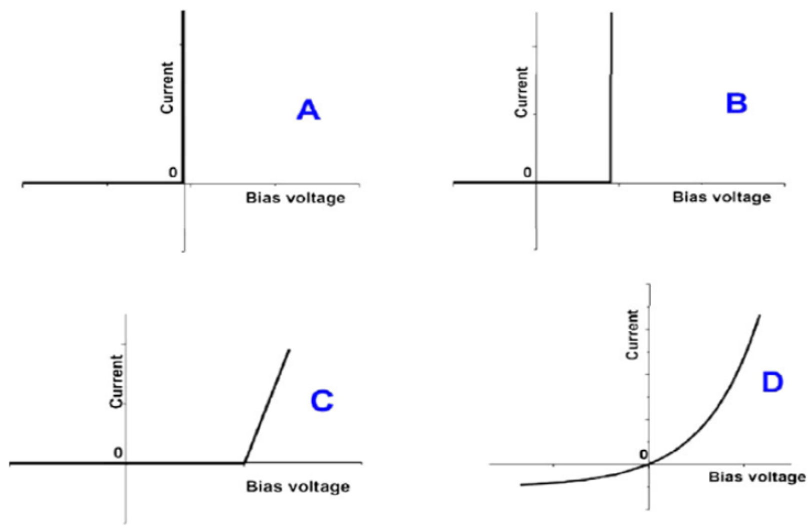
4 Semiconductor Literacy

Five questions related to semiconductor literacy are carefully incorporated into the survey as shown in Figure 4. These questions mostly focus on semiconductor literacy tests covering well-known semiconductor companies, economic, and federal policy to evaluate the understanding and awareness of participants in this field.

Question 4 seeks to determine the respondent’s level of understanding and familiarity with Moore’s Law. It explores their understanding of the observed trend, initially discussed by Gordon Moore, which involves the transistor count doubling on a single integrated circuit every two years. Focusing on Moore’s Law specifically, the questionnaire aims to evaluate the respondent’s understanding of this important idea in semiconductor technology.

3. Which of the following represents the smallest unit of measure?
    a. Angstrom
    b. Micron
    c. Millimeter
    d. Nanometer

8. Which of the following plot best represents a PN junction?
    a. Plot A
    b. Plot B
    c. Plot C
    d. Plot D



9. Most digital integrated circuits represent 1 bit of information in the form of
    a. High voltage OR low voltage
    b. High current OR low current
    c. High capacitance OR low capacitance
    d. High inductance OR low inductance

11. What is the threshold voltage?
    a. It is the level of voltage that defines logic high.
    b. The definition of voltage for $V_{gs} = 0$ where I_{ds} becomes 0
    c. Depends on length, width, temperature, and processing but is typically used to define when a transistor is on or off.

10. Which operation of a NAND is correct?
    a. 1 NAND 1 = 0
    b. 1 NAND 0 = 0
    c. 0 NAND 1 = 0
    d. 0 NAND 0 = 0

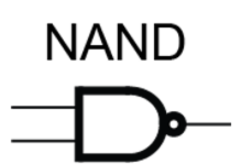


Figure 2: Items associated with design

14. Yield is the percentage of "good" dice among all the dice produced on one wafer. It can also be considered as the opposite of the defect rate. Which of the following statements is false about yield: a. For the same-sized wafer, yield is a function of the die size b. It is easier to achieve a higher yield when the die size is bigger c. Higher yield translates to lower cost per chip d. Yield can be improved with better fabrication process control
15. Arrange the semiconductor product development cycle in the right order: a. Product Retirement b. Packaging and Assembly c. Product Introduction to Customers d. Design revision (Pass-2/Pass-3/Pass-4/..), if necessary e. Characterization Test, Functionality/Performance Validation f. Production Definition: Initial Objectives and Specification (IOS) g. Yield Improvement, Customer Returns, and Failure Analysis h. Production Test, Reliability Test, and Datasheet Development i. Design and Verification: Schematics, RTL, Chip layout, and high-level abstraction j. Fabrication: Mask Generation, Wafer Fabrication (front-end-of-line, back-end-of-line), and dicing

Figure 3: Items related to the manufacturing and production

The second question in this section (Question 5) explores the primary goal of the Congress-passed Chips and Science Act of 2022. It attempts to determine how well the respondent understands the main points and objectives of this law. It seeks to determine precisely which part of semiconductor production the Chips and Science Act intends to re-establish in the United States. The correct response is "B."

Question 6 is about US-based semiconductor companies. The objective of this question is to ensure that the general public is well-informed about both domestic and international companies so that when working on sensitive and security-related projects, they can prioritize companies. Intel Corporation, Analog Device, and NVIDIA are located in the US, but NXP Semiconductor is headquartered in Eindhoven, Netherlands.

Asking participants to name four examples of chips that are mostly analog or digital in this test (Questions 12 and 13) might help evaluate their understanding and skill with semiconductor technology. We can gather essential information about participant knowledge, experience, and preferences regarding analog and digital chips by incorporating these kinds of questions. Radio transceivers, image sensors, amplifiers, and temperature sensors are examples of analog chips. Microcontroller Units, Random Access Memory (RAM), Graphic Processing Units (GPU), and Central Processing Units (CPU) are examples of digital chips.

Expert Panel

As an additional content validity evidence, a team of semiconductors experts from Qualcomm, pSemi, and UNISOC were invited to provide feedback on the SKLT. The four experts have combined experiences in IC design, testing, production, business management, and electronic design automation (EDA). Their years of experience span from 15 to 33 years. Some of these experts have previous connections with the authors through prior work experience, and they

4. Moore's Law, famously described by Gordon Moore, the founder of Intel, observed an industry trend that: a. The transistor count on an integrated circuit doubles about every two years b. The fabrication cost of a chip reduces by half about every two years c. The minimum features size of a transistor reduces by half about every two years d. The power consumption of a transistor reduces by half about every two years
5. The Chips and Science Act passed by Congress in 2022 primarily focuses on bringing which part of semiconductor manufacturing back to America? a. Semiconductor Design b. Semiconductor Fabrication c. Semiconductor Assembly, Test, and Packaging (ATP) d. Semiconductor Equipment Manufacturing
6. Which of the following is not a US-based semiconductor company? a. Intel Corporation b. Analog Devices, Inc. c. NVIDIA d. NXP Semiconductor
12. Name four examples of predominantly analog chips.
13. Name four examples of predominantly digital chips.

Figure 4: Items related to semiconductor literacy

represent a balanced view from the semiconductor industry to the best of authors' knowledge. The expert panel was tasked with assessing the technical accuracy and relevance of the questions. Below are some key insights from their feedback that guided revisions to the items.

Originally, question 1 was framed as "Semiconductors, or integrated circuits, are made mostly from." However, it was recommended that "made mostly" be replaced with "most commonly made" to account for the fact that semiconductors can also be produced from compounds like Gallium Arsenide (GaAs). Regarding Question 4, feedback noted that the geometric reductions in the transistor area have driven the growth of integrated circuits, overcoming seemingly insurmountable challenges across multiple cycles.

Question 10 did not initially include a symbol for a logic gate, however, feedback indicated that drawing a logic gate with the word NAND on it might provide clarity. Initially, the first response to Question 11 was, "It is the level of voltage that defines conduction." Panel feedback noted that it was a good question, but that the first answer was nearly correct. It was recommended to modify the language from "conduction" to terms like "current" or "logic high" to introduce demonstrably incorrect values or meanings. They further explain that V_{th} determines when conduction in the transistor occurs, making answer one not "wrong enough."

Concerning the alignment of Q1 to Q7 with general/analog semiconductor knowledge, a focus on the key differences in purpose, functionality, and challenges between analog and digital chips was proposed.

Analyzing the alignment of Q12 to Q15 with more advanced semiconductor knowledge, feedback noted that the questions lean toward manufacturing aspects. It was suggested to focus on exploring the bottlenecks faced in reducing channel length and how challenges were addressed in advanced nodes, such as the introduction of SOI FET, FinFET, and the latest GAAFET in 3nm and below.

Finally, when asked about the proposed interpretation and use, a recommendation was made to provide RET participants with a guide on how to direct high school students if they are interested in pursuing a career in semiconductor engineering. This validation is based on AERA standard [12].

Participants and Data Collection

Participants include 10 high school, middle school, and community college STEM teachers who participated in a RET program. Data was collected at the beginning of a six-week summer research experience via Qualtrics and again at the end of the summer program.

Analysis and Results

In order to assess differences in content knowledge based on their participation in the RET program, a percentage change in the number of correct responses was found for the SKTL overall, for the four key areas assessed, and for individual items.

Figure 5 provides an overview of the average percentage of correct responses for the pre- and post-survey administrations. Following completion of the RET summer program, the percentage of correct responses increased from 40% of responses to 67% of responses, indicating that participants demonstrated increased knowledge of semiconductors during the program.

Figure 6 provides an overview of the average percentage of correct responses for each of the four areas of focus in which the test was designed to assess. The largest area of growth was for Semiconductor Materials at 33%. The average percent difference for Design and Semiconductor Literacy were the same at 29%. Notably, there was not a change in the average percentage of correct responses for Manufacturing.

A final comparison was made to better understand which questions indicate the largest and smallest gains throughout the program (see Figure 7). Results indicate an increase in the percent correct for questions 1, 2, 3, 4, 5, 6, 9, and 10, with large increases from pre to post for questions 2, 5, 9 and 10. Several questions did not have any changes pre to post – number 8, 11, 13, and 15. One question saw a drop in the percent correct – number 7.

Discussions

We purposefully developed the SKLT test to be independent of the RET training materials. In other words, our goal was not to train teachers to score well on the SKLT test. Neither did we limit our RET training to the SKLT test contents. For example, our 2023 RET activities included lectures on semiconductor basics, curriculum design workshops, two parallel projects in analog and digital circuit design, and Zoom seminars with pSemi engineers to discuss semiconductor career paths. Nevertheless, the 2023 results showed an increased semiconductor knowledge and literacy pre- and post-survey, probably due to their project experience and exposure. By keeping

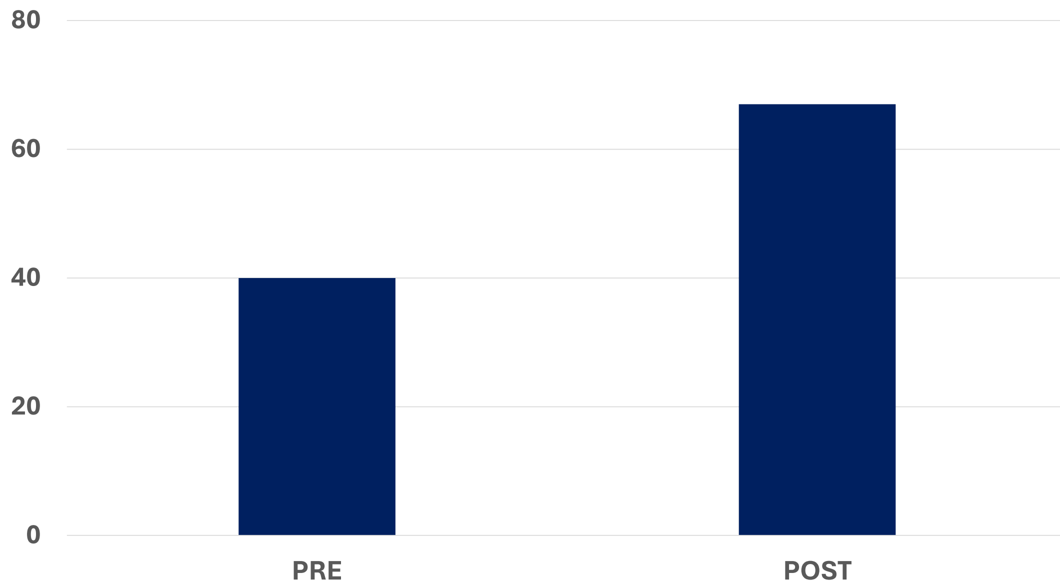


Figure 5: Mean percent change from pre to post assessment

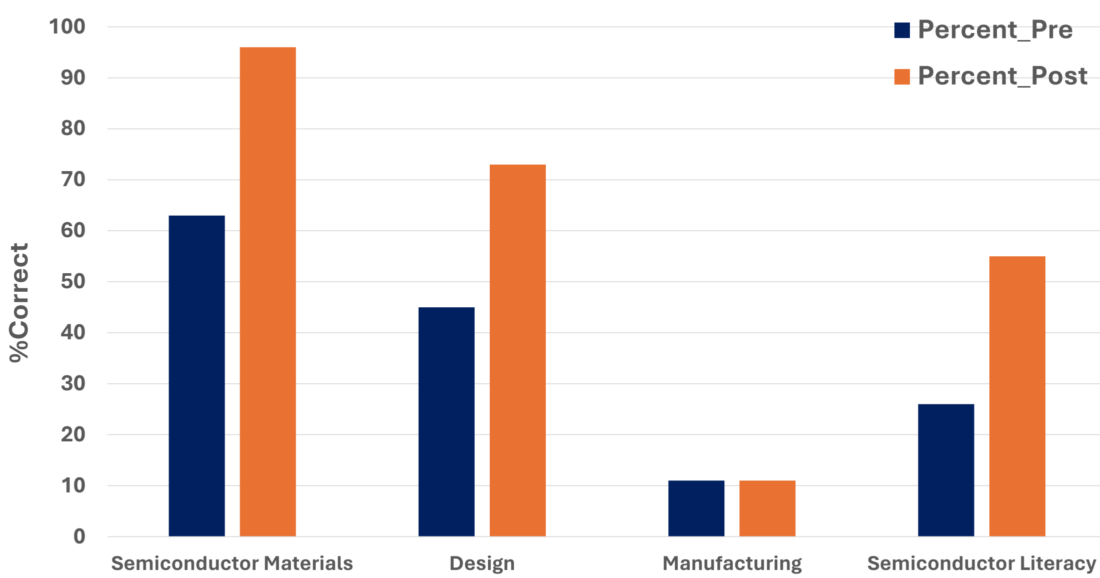


Figure 6: Mean percent change from pre to post assessment

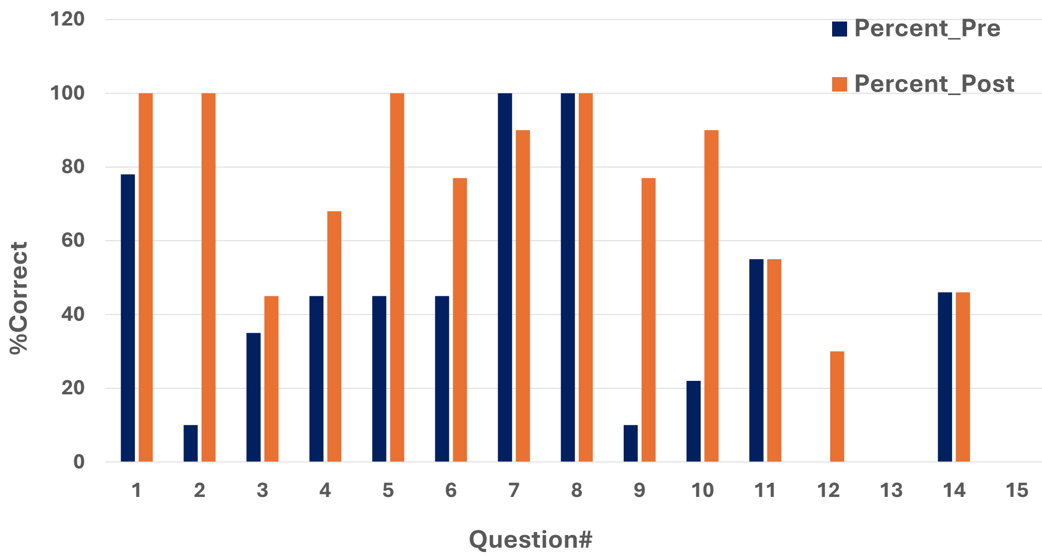


Figure 7: Comparison of percent correct by question pre to post assessment

the RET training agenda and the SKLT test content separate, our RET program can be more flexible in meeting teachers' needs. The SKLT test can also be adopted by other institutions in different educational settings.

Conclusion

In this paper, we provide an overview of the development of the SKLT, content validity evidence for test items, and results for the initial implementation of the test. With initiatives focused on increasing knowledge and career interest in advanced technology such as semiconductors [2], it is important to have aligned assessments to evaluate the effectiveness of programming. Results from the initial implementation of the assessment find evidence that programming, such as an RET, could aid teachers in increasing their content knowledge for aligned topics. The percentage of right answers rose from 40% to 67% after the RET summer program ended, demonstrating that participants' semiconductor expertise had grown throughout the program.

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