WIP: Introducing Semiconductors in a High School Calculus Class: A Pilot Implementation

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***Abstract*—This work-in-progress research-to-practice paper presents the development and pilot implementation of curriculum that introduces semiconductor contents in a high school calculus class. The demand for chips soared through the COVID-19 pandemic, exposing our country's semiconductor manufacturing and supply chain risks. The need to reassert US semiconductor leadership will require training a well-educated workforce, starting at the K-12 level. Meanwhile, K-12 STEM teachers often juggle the conflicting requirements of standardized tests and the need to cultivate 21st-century skills, deeper learning, and transferable knowledge, among others. This paper presents a pilot implementation that could address both problems. Selected teachers attended an NSF-funded Research Experience for Teachers (RET) summer program to learn about chip design basics. They also received curriculum development support to design new modules on semiconductor topics that would attract their students' interests.**

***Index Terms*—IC design, Semiconductor, Calculus, High school, Education, RET**

I. Introduction

The semiconductor industry has played a vital role in economic growth. Semiconductors are an essential component of electronic devices which are used in computers, cellphones, communication systems, healthcare, transportation, and numerous other applications. In 2021, global semiconductor sales totaled 556 billion dollars. Increasing employment opportunities in semiconductor related fields are generating a high demand for a new generation of workers skilled in semiconductors [1], [2]. Based on [2] the US semiconductor design industry is poised to encounter a shortage of 23,000 highly skilled professionals by 2030. The lack of semiconductor-focused curriculum in K-12 education is a significant challenge in addressing the workforce shortage in the semiconductor industry [3]. Many students are not made aware of the vast career opportunities in this field at an early age.

In contemporary K-12 classrooms, educators face multifaceted challenges that necessitate innovative approaches to instruction. Firstly, there is a critical need to transition away from traditional rote skill instruction towards fostering 21st-century skills such as critical thinking, collaboration, and creativity. This shift acknowledges the evolving demands of a modern workforce and society [4]. Secondly, educators struggle with the conflicting requirements imposed by standardized tests, which often prioritize memorization over deeper understanding and critical inquiry. This conflict can hinder teachers' ability to offer rich and meaningful learning experiences [5]. Finally, urban charter schools encounter unique challenges stemming from resource disparities, community dynamics, and diverse student needs. These schools often deal with the challenge of providing quality education in complicated socioeconomic situations, showing the need for personalized support and fair resources [6]. Addressing these challenges demands holistic approaches that prioritize student-centered learning, professional development for teachers, and systemic reform efforts.

Semiconductors offer a unique platform to engage students in interdisciplinary learning [7], [8], but achieving this requires educators to move beyond memorization-based teaching methodologies. Balancing the curriculum to cover both the foundational principles of calculus and the practical applications of semiconductor physics while meeting standardized testing requirements can be challenging. This challenge necessitates thoughtful curriculum design that aligns with both educational standards and the broader learning objectives [9], [10].

Over the last two decades mathematics educators, international policymakers, and various initiatives have developed a Calculus course that incorporates significant engineering-related material to show how Calculus concepts can be used in engineering [11], [12]. Between 2004 and 2008, the National Science Foundation (NSF) Research Experience for Teachers (RET) site at the Illinois Institute of Technology collaborated with K-12 teachers, community college faculty, and university researchers to develop educational modules to engage more K-12 students in the exciting practice of hands-on engineering. The modules were tested with middle and high school students during summer workshops and then implemented during the following school year. According to pre-project and post-project assessments from 2006-2008, the students' mathematics, science, and engineering knowledge improved significantly, from 26 correct to 63 correct across all the modules [13]. In [14], which is a part of RET project conducted by Arizona State University, a series of modules developed to create a connection between high school mathematics and physics of high-tech products such as smartphones and iPods is presented. Although these efforts were successful, none of them focused on integrating semiconductor concepts into Calculus.

This work in progress Research-to-Practice paper presents the development and pilot implementation of a course unit that introduces the semiconductor curriculum in Calculus classes. The objective of this study is to explore ways to incorporate semiconductor basics into high school Calculus classes and to provide students with a better knowledge of Calculus applications in new technology. This can increase the practicality and attractiveness of complex mathematical concepts. Additionally, introducing semiconductor topics to high school students prepares them for future careers in engineering and technology. This Design-based Research (DBR) is a collaboration between teachers and RET mentors. The data collection process involved classroom observations conducted by RET researchers, interviews with the teachers, and teacher self-reflections at different stages of the new curriculum development. Qualitative methods were employed to provide context for the findings [15]. The study is being carried out in compliance with IRB-23-242-STW. Our study group was made up of 25 students in a public charter high school in Oklahoma.

II. Teacher Preparation

To address the need for a more relevant and engaging high school curriculum, an interdisciplinary collaboration emerged from a NSF funded RET program. During the teacher preparation phase, a collaboration between university faculties, graduate students, and STEM educators from high schools and community colleges was undertaken for a six-week summer program [16]. The program focused on immersing these educators in the world of semiconductors and chip design fundamentals through hands-on experiences in the Oklahoma State University IC design laboratory. This research experience then served as a springboard for curriculum development. The teacher Preparation phase includes the curriculum development support on interdisciplinary, alignment with Next Generation Science Standards cross-cutting concepts, and backwards unit design. The participating teachers were then able to translate their knowledge into engaging curriculum modules for their classrooms.

III. Lesson Plan Development

As part of a post-RET collaboration, teachers and university mentors worked together to develop a new lesson plan aimed at enhancing the appeal and promoting a deeper understanding of calculus. This new lesson plan integrates real IC design problems into the existing calculus syllabus. While the lecture component of the course remains unchanged, students are introduced to IC design principles.

This section presents the calculus syllabus taught in Oklahoma high schools. Following that, we will discuss the new lesson plan, which incorporates IC design principles and practical examples. This approach emphasizes how these real-world applications provide an engaging context for teaching integrals and derivatives, which are fundamental concepts in calculus.

A. High School Calculus Curriculum

The mathematics education in Oklahoma should follow state-specific standards derived from the National Council of Teachers of Mathematics (NCTM). In Calculus classes, a comprehensive curriculum covering a wide range of topics is represented. The coursework starts out with a detailed investigation of limits and continuity. As the course progresses, students learn about differentiation. Furthermore, students explore Integration and accumulation of change. After that differential equations are introduced. The course ends with a focus on applications of integration.

Elements Symbol	Resistor	Capacitor	Inductor
Denoted by	R	C	L
Equation	$R = \frac{V}{I}$	$C = \frac{Q}{V}$	$L = \frac{V_L}{(\frac{di}{dt})}$
Series	$R_T = R_1 + R_2$	$\frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2}$	$L_T = L_1 + L_2$
Parallel	$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2}$	$C_T = C_1 + C_2$	$\frac{1}{L_T} = \frac{1}{L_1} + \frac{1}{L_2}$

Fig. 1. Symbol of a resistor, capacitor, inductor

B. New Lesson Plan

Among the numerous terms related to semiconductors and IC design, we believe the following concepts are not only understandable but also directly applicable to the context of high school Calculus instruction. These concepts have been chosen specifically for students at this level due to their ability to provide a solid foundational understanding of semiconductor technology and IC design.

a) Resistor: A resistor, denoted by R, is an electrical component with two terminals that limits or regulates the flow of electric current in a circuit. The unit of the resistor is ohm. In Fig.1 the resistor symbol is depicted. The equation that describes the relationship between the current (I) passing through the resistor and the voltage (V) across the resistor is known as Ohm's Law represented as:

$$V = R \cdot I \tag{1}$$

b) Capacitor: A capacitor, denoted by C, is an electronic component with two terminals that stores and releases electrical energy. They are used in circuits to store and control electrical charges. The unit of the capacitor is farad (F). The relationship between the current flowing into and voltage across the capacitor is described by:

$$I = C\frac{dV}{dt} \tag{2}$$

In the above equation, dV/dt is the rate of change of voltage with respect to time.

c) Inductor: An inductor, denoted by L, is an electronic component with two terminals that stores energy in a magnetic field when electric current flows through it. The unit of inductance is the henry (H). In an inductor, the relationship between current and voltage is described by:

$$V = L\frac{dI}{dt} \tag{3}$$

Circuits containing resistors, inductors, and capacitors can be connected in series or parallel.

d) Series Connection: In a series connection, elements are connected in a single loop and the same current flows through all resistors, inductors, and capacitors. The total voltage across the circuit equals the sum of the voltage across each element. A group of resistors connected in series has a total resistance equal to the sum of its resistors (see Fig. 1). The same law is also followed in inductors. When capacitors are connected in series, their combined capacitance equals the reciprocal of the sum of the reciprocals of each capacitor's capacitances.

e) Parallel Connection: Elements that have independent branches connecting to the same two nodes are said to have parallel connections. Every component of the circuit that is linked in parallel receives the same voltage. The total current is the result of adding the currents flowing through each component separately. When a set of resistors is connected in parallel, the total resistance of the group can be calculated by adding the reciprocals of each resistance and taking the reciprocal of the total. The same law is followed by inductors. When capacitors are connected in parallel, their combined capacitance is equal to the sum of their individual capacitances.

As demonstrated above, the relationship between voltage and current in an RLC circuit is fundamentally based on derivatives and integrals. This illustrates the application of calculus principles in real-world scenarios. In educational settings, teachers can initiate this discussion by emphasizing the significance of electricity and electronics in our daily lives, particularly highlighting the vital role of integrated circuits. Following this introduction, the concept of RLC circuits can be introduced, highlighting (2) and (3) as foundational relationships in microelectronics that rely heavily on derivatives and integrals. Real-world examples, such as circuits containing inductors or capacitors, can then be presented to illustrate the practical applications of these mathematical concepts.

IV. Implementation

In the second quarter of 2024, a teacher who participated in the RET program transferred their knowledge of microelectronics into a newly implemented module for their calculus class in a high school in Oklahoma. To gain a comprehensive understanding of the new curriculum's organization, RET research team initiated an examination of the curriculum organization. Data collection included classroom observations by RET researchers, interviews with the teacher, and teacher self-reflections during various stages of the new curriculum development. Qualitative methods is used to contextualize the findings [15]. The research is being conducted in accordance with IRB-23-242-STW.

The curriculum structure appeared to be heavily teacher-directed, aiming to provide students with a comprehensive learning experience. The 1.5-hour lesson began with the teacher outlining the agenda and objective: "understanding the role of calculus in chip design". This objective was achieved through a review of previously learned calculus concepts. The teacher's lesson curriculum was divided into four main sections: 1) introductory lectures on basic semiconductor theory, 2) exploration of RLC circuit specifications, 3) hands-on circuit simulation using LTspice software, and 4) dedicated time for student questions. This approach suggests a focus on foundational knowledge delivery followed by practical application through simulation.

A. Introductory Lectures on Basic Semiconductor Theory

The introductory lesson began with semiconductors and their properties. The teacher highlighted common materials used in the semiconductor industry like silicon (Si), gallium nitride (GaN), and gallium arsenide (GaAs), emphasizing silicon's dominance due to its cost effectiveness. Following this, a video illustrated the semiconductor fabrication process. The lesson then shifted to the analog chip design area and its applications. Here, RET mentors explained the concept of analog signals. A final video on semiconductor terminology solidified the foundation. The session also wisely included a discussion of units and prefixes – an often under-practiced but crucial concept for students.

B. RLC Circuit Specifications

The RLC components as outlined in section III-B were introduced by the instructor to start this part of the course. They also offered demonstrations with actual examples of capacitors, resistors, and inductors. Following that, the instructor introduced the inductor as a real-life example of the derivatives and integrals. They began by reviewing the Calculus concepts: definite integral, indefinite integral and derivative.

$$\int f(x)\,dx = F(x) + C \tag{4}$$

$$\int_a^b f(x)\,dx = F(b) - F(a) \tag{5}$$

$$f(x) = \frac{dF(x)}{dx} \tag{6}$$

Then without getting into too much physics, (3) was presented in the classroom which describes the fundamental relationship between an inductor's voltage and its current. (3) states that V_L is proportional to the rate of change of the current, represented mathematically by the derivative dI(t)/dt. This concept highlights the crucial role of calculus in analyzing inductor behavior. By knowing the instantaneous current through the inductor at any given time (t), we can leverage calculus to determine the inductor's voltage. After introducing inductors, the following example was demonstrated.

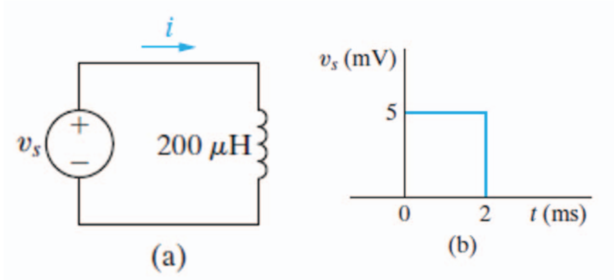

Fig. 2. Circuit using in example

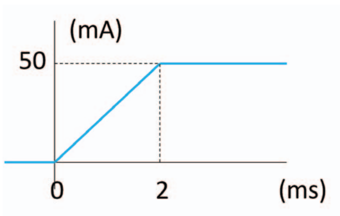

Fig. 3. Results of example

a) Example: Solving for an RL Circuit

Question: The voltage at the terminals of the $200\,\mu H$ inductor is shown in Fig. 2a. The inductor current is known to be zero for t $\leq$ 0.

Derive the expression for i for t $\geq$ 0. Sketch i versus t for 0 $\leq$ t $\leq$ ∞. Note: μ : 10^{-6}, m : 10^{-3}

Solution: Using (3) and (5)

$$i(t) = i(0) + \frac{1}{L}\int_0^t v(t)dt \tag{7}$$

We also know $i(t) = 0$ for $t \leq 0$, which means $i(0) = 0$.
For $0 \leq t \leq 2ms$:

$$i(t) = \frac{1}{200\mu H}\int_0^t 5mV\,dt = \frac{5mV}{200\mu H}\int_0^t dt = 25t \tag{8}$$

For example, when $t = 2ms$, $i = 50mA$.
For $t > 2ms$:

$$\begin{aligned} i(t) &= \frac{1}{L}\int_0^2 v_s(t)dt + \frac{1}{L}\int_2^t v_s(t)dt \\ &= 50mA + \frac{1}{L}\int_2^t 0 \cdot dt = 50mA + 0 = 50mA \end{aligned} \tag{9}$$

By employing (8) and (9), Fig. 3 can be extracted.

C. RLC Circuit Simulation Using LTspice

To enhance comprehension of RLC circuits in practice, the instructor shifted from theory to hands-on learning using circuit simulation software. Highlighting the importance of such tools in the field of semiconductor engineering, the teacher introduced various options for simulating simple and complex circuits. Following this, the previously discussed RLC circuit example (Fig.2) was then simulated using LTspice software. The results of this simulation are shown in Fig. 4.

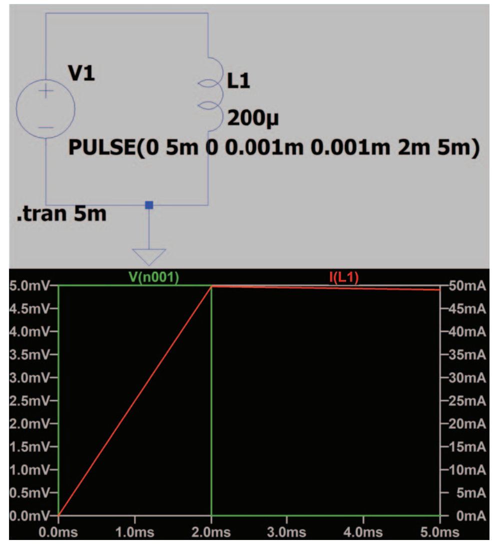

Fig. 4. LTspice simulation results

V. Classroom Observation Results

A. Student Engagement

During the introductory slides, the majority of students appeared attentive. Some were actively engaged in taking notes and following along with the presented examples. This attentiveness was punctuated by a question from a student: "What do you mean by noise as a challenge in analog chip design?" This inquiry demonstrated a grasp of the introductory material and a desire for deeper understanding. During this phase of the course, the instructor utilized support from RET mentors to answer student questions.

As the lecture progressed, a consistent level of engagement was observed, with approximately 5 out of 25 students asking questions throughout. Notably, the questions posed were well-considered and often focused on practical applications. For instance, students inquired about the use of the letter "L" to denote inductors in equations and the specific behavior of inductors within circuits. One student even delved deeper, questioning the relevance of the inductor examples to the work of practicing electrical engineers.

Finally, some students directed their questions towards the RET mentors, inquiring about their motivations for choosing microelectronics as a major at university. This shift in focus suggests a broader interest in the field and the career paths it offers.

B. Discussion

Based on observations conducted by the RET research group, it was found that the teacher effectively translated their semiconductor knowledge in the classroom. They demonstrated exceptional proficiency in elucidating various topics and successfully covered all planned content within the designated class period. The curriculum's introductory module on basic semiconductors, while informative, presented a potential challenge for some students. The level of detail may have exceeded the foundational knowledge typically expected at this stage in the program. The instructor's reliance on RET mentors to address student inquiries highlights the need for a more scalable program design that minimizes dependence on external support. Student engagement during these sessions indicates its potential to make semiconductor education appealing, potentially fostering interest and encouraging more high school students to pursue this field. This, in turn, could contribute to the development of a highly skilled workforce in the semiconductor industry.

VI. Conclusion

This paper presents an innovative approach to bring microelectronics concepts like RLC circuits into high school Calculus classes, offering students a sensible connection between mathematics and real-world technology. This approach not only makes Calculus more engaging but also prepares students for future careers in engineering and technology.

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