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Revolutionizing Semiconductor Education: An Immersive Virtual Cleanroom for Enhanced Nanofabrication Training

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(Work in Progress Paper)

Abstract

The semiconductor industry is advancing rapidly, and initiatives like the CHIPS and Science Act are making it clear that there's a pressing need to develop a skilled workforce. With nearly $53 billion allocated to boost U.S. semiconductor supply chains, create jobs, and strengthen national security, the CHIPS Act is setting the stage for a significant workforce shift, potentially generating over 115,000 new manufacturing and construction jobs. This work-in-progress paper introduces a new approach to semiconductor education, using virtual reality (VR) to create a cleanroom simulation aimed at improving experiential learning in semiconductor nanofabrication. This VR system provides an interactive and safe space in which students can practice cleanroom and nanofabrication techniques. These experiences include a feedback system that tracks student actions in real-time, and helps them adjust, correct mistakes and improve their nanofabrication skills. Early feedback has been promising, and ongoing research will examine how this technology affects student understanding, retention, and engagement. This work aims to explore how immersive technologies will be a key tool in addressing the workforce gap highlighted by the CHIPS Act, while also making semiconductor education more accessible.

Introduction

The semiconductor industry plays a major role in technologies that we rely on every day. As new advancements push the boundaries of what is possible, the U.S. faces the challenge of developing a workforce capable of supporting this rapid growth. The CHIPS and Science Act: a piece of legislation signed into law in 2022, set aside nearly $53 billion to bolster semiconductor manufacturing, create jobs, and strengthen national security. The Act aims to generate over 115,000 manufacturing jobs alone, but to fill these positions, there is an urgent need to train a skilled workforce.

This is where the challenge lies. Semiconductor manufacturing requires highly specialized training, especially when it comes to cleanroom environments where semiconductor devices are fabricated. These cleanrooms require precise protocols, and the processes are delicate and complex. However, traditional methods of training in semiconductor manufacturing are often costly and limited in scope. Not every educational institution has access to cleanroom facilities, and the expense of such equipment can be prohibitive.

In this work-in-progress paper, we explore how VR technologies could address these barriers. Our goal is to create a cost-effective, scalable, and engaging way to teach students the key skills needed for semiconductor manufacturing. With a fully immersive VR, we can simulate cleanroom environments, allowing students to practice without the constraints of physical space or the risk of damaging expensive equipment. This approach not only offers more accessible solutions but also aims to boost student engagement through interactive, hands- on learning.

Theoretical Foundation of the Immersive VR Design

To maximize the effectiveness of our immersive VR platform, it is crucial that the design is guided by relevant theories and design principles. A key consideration in designing immersive virtual reality systems is the concept of "immersion," defined as the ability to "shut out physical reality" while being enveloped in a virtual environment. This immersion reflects the technological quality of the VR environment, measured by how vividly it presents itself. While achieving a high level of immersion is often a design goal, recent research reveals that such immersion can create a learning experience markedly different from conventional multimedia environments, potentially draining cognitive resources. In particular, the perceptual realism of an immersive VR setting can introduce interesting yet irrelevant information that detracts from learning. Therefore, employing a theory-based design approach is essential to provide clear learning direction and mitigate any negative impacts associated with high immersion levels.

Cognitive load refers to the amount of information that our working memory can effectively process, highlighting the cognitive limits of information processing. When cognitive demands exceed these limits, it can lead to cognitive overload, which negatively impacts both learning outcomes and overall satisfaction. Therefore, when designing virtual training programs that incorporate various multimedia elements and interactive features, it is essential to manage cognitive load carefully. Maintaining an optimal cognitive load will facilitate effective learning, ensuring that participants can engage fully without becoming overwhelmed by excessive information [1-3]. This approach is particularly crucial in the context of our immersive VR platform, where the integration of technology must support, rather than hinder, the learning process.

Research in embodied cognition [6] suggests that learning is deeply tied to physical interactions with the environment. This raises concerns about whether a VR experience that lacks physical feedback can fully prepare students for real-world cleanroom work. Studies such as Wang et al. (2024) have explored cleanroom microfabrication training in VR, finding that while students benefit from immersive, guided learning experiences, the lack of tactile feedback presents a challenge. They suggest that haptic feedback integration—such as force-feedback controllers or gloves—could enhance VR training by simulating the fine motor control required in cleanrooms.

Additionally, Andersen et al. [7] examined distributed VR simulation training for medical dissection and found that while cognitive load was reduced, physical skill transfer was not fully achieved without hands-on practice. This suggests that while VR provides an effective cognitive training tool, it should ideally be paired with physical reinforcement exercises, such as hybrid programs where students transition from VR to real-world cleanroom tasks.

Cognitive load can be assessed as an outcome through various methods that measure mental effort, and processing demands placed on learners during instructional activities. Some approaches include Self-Report Scales: Students can complete surveys or questionnaires that ask them to rate their perceived cognitive load during specific learning tasks; Time on Task: Measuring the time students spend on specific tasks or content can offer insights into cognitive load. Longer times may suggest that learners are experiencing higher cognitive demands; Performance Metrics: Analyzing student performance on assessments can help infer cognitive load. If students struggle significantly, it may indicate high cognitive load, particularly if they are familiar with the material.

Two relevant theories that address unintended cognitive processing in immersive VR environments are Cognitive Load Theory (CLT) and the Cognitive Theory of Multimedia Learning (CTML). Both theories assert that instructional design must avoid overloading learners with limited cognitive capacities. CLT distinguishes three types of cognitive load: intrinsic cognitive load, which is inherent to the difficulty of the material; germane cognitive load, which is beneficial to the learning process; and extraneous cognitive load, which detracts from it. Effective learning occurs when extraneous load is minimized while promoting germane load within the limits of

working memory. CTML, grounded in CLT principles, focuses specifically on learning within interactive, technology-enhanced environments. It outlines three types of cognitive processing in multimedia learning that correspond to the cognitive load categories: extraneous processing (extraneous cognitive load), essential processing (intrinsic cognitive load), and generative processing (germane cognitive load). CTML provides several design principles aimed at fostering deeper learning in these environments. By applying CTML principles, our immersive VR platform is designed to minimize cognitive overload and reduce extraneous processing for learners engaged in an immersive educational environment. However, empirical research utilizing these principles in STEM-focused immersive VR designs is still limited, especially regarding younger learners and informal learning contexts. Furthermore, most studies examining CTML, and immersive VR have not assessed cognitive load as an outcome, which is essential for validating the design’s effectiveness in enhancing cognitive processing during the immersive VR experience [4]. This project aims to address this gap by integrating CTML principles into our fully immersive VR design, thereby creating a robust educational tool that promotes meaningful learning experiences for a diverse array of students.

Moreover, a 2023 study by Huang et al. [9] on immersive VR in science learning suggests that generative processing - the cognitive load necessary for deep learning - is enhanced in VR but may not always translate into muscle memory or procedural expertise. Thus, an optimal semiconductor training approach would involve initial VR instruction, followed by physical laboratory work to ensure students can perform delicate tasks such as wafer handling and photolithography.

Semiconductor Fabrication in a Physical Cleanroom Environment

Photolithography is a critical technique in semiconductor fabrication, enabling the precise patterning of microstructures on silicon wafers. This process is essential for producing integrated circuits and various electronic components. Understanding photolithography is vital for students as it encompasses key principles of optics, materials science, and cleanroom protocols. Proficiency in this process equips students with the practical skills necessary for careers in the semiconductor manufacturing industry, where precision and attention to detail are paramount. Training in photolithography fosters a comprehensive understanding of the complexities involved in microfabrication and prepares students for real-world challenges in the field.

Steps of the Photolithography Process in a Cleanroom Environment

1. **Wafer Cleaning and preparation**: The silicon wafer is thoroughly cleaned to remove any contaminants to ensure optimal adhesion of the photoresist.
2. **Photoresist Application**: A thin layer of photoresist material is uniformly applied to the wafer using a spin-coating technique, which creates a smooth and even film.
3. **Soft Bake**: The wafer undergoes a soft bake process to evaporate solvents from the photoresist, enhancing its adherence to the wafer surface.
4. **Mask Alignment and Exposure**: A photomask, which contains the desired pattern, is precisely aligned over the wafer using a mask aligner. The wafer is exposed to ultraviolet (UV) light, which transfers the pattern from the photomask to the photoresist, causing a chemical change in the exposed areas.
5. **Post-Exposure Bake**: A post-exposure bake is performed to further stabilize the photoresist and enhance the resolution of the pattern.
6. **Development**: The wafer is immersed in a developer solution, which removes either the exposed or unexposed areas of the photoresist, revealing the underlying silicon.
7. **Hard Bake**: A hard bake is applied to the wafer to strengthen the remaining photoresist, preparing it for subsequent etching processes.
8. **Etching**: The exposed silicon is etched away using either wet or dry etching techniques, transferring the pattern into the wafer material.
9. **Photoresist Removal**: The remaining photoresist is stripped away, leaving behind the patterned silicon structure.

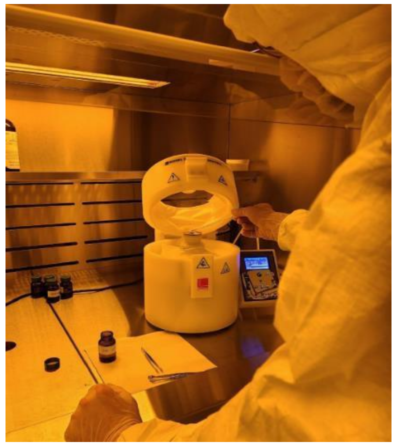
Nanofabrication and nano-characterization techniques are two of the major enablers for the development and realization of miniaturized devices for a wide range of scientific and technological applications, from optical devices, photonics, quantum structures, nano-electronics, photovoltaics to bio-medical devices. These techniques are critical to support research and innovations in semiconductor and quantum device fabrication areas. It is imperative that we educate and train the current and next generation of scientists and engineers in these key areas. Research, education and hands-on activities go together for learning to be more effective. The need for workforce development in this area is driven by the CHIPS and Science Act, known for its intent to revive the US semiconductor industry and perhaps the most significant new workforce initiative in the last 15 to 20 years. However, education and training in this area may be falling short. To help address this critical gap, recent lab sections were supported for undergraduate courses, such as the Semiconductor Devices course. This was the first offering of cleanroom labs designed for an introduction of the basic semiconductor fabrication processes. Figure 1 below shows undergraduate students engaging in hands-on experience with equipment in the cleanroom to master the essential steps in semiconductor fabrication.

As technology continues to evolve, so do the ways we approach education. One area that has seen significant promise is the use of VR in learning. These technologies can create highly immersive, interactive environments, allowing students to engage with complex concepts in ways that traditional methods simply can't match. In the case of semiconductor education, VR offers an exciting opportunity to simulate the cleanroom experience—giving students a chance to practice the critical steps of semiconductor fabrication, such as photolithography, etching, and deposition, all within a virtual space.

The VR cleanroom platform proposed in this paper is designed to help the students "learn by doing". The platform provides an interactive space where students can perform semiconductor fabrication tasks and adhere to cleanroom protocols. Real-time feedback is provided as students interact with the virtual environment, helping them correct mistakes and refine their techniques. For example, if a student makes a mistake—such as not properly handling a piece of equipment—the system can flag the issue, offer corrective guidance, and track their progress.

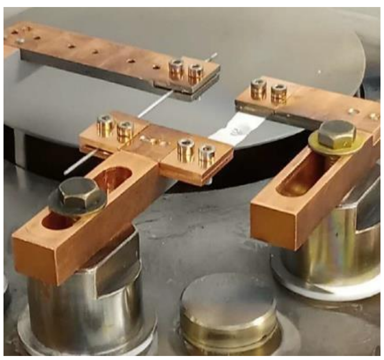
Though we have made significant strides, the system is still in its early stages. We are working on enhancing the user experience by fine-tuning the virtual environment to make it more intuitive and engaging. We are also expanding the range of processes that students can interact with to ensure that the simulation offers both foundational tasks and more advanced challenges as students' progress.

Undergraduate student using a tweezer to pick up a silicon wafer



Spin coater, silicon wafer, photoresist bottle, pipette, tweezer

Undergraduate student performing the mask alignment & exposure photolithography step



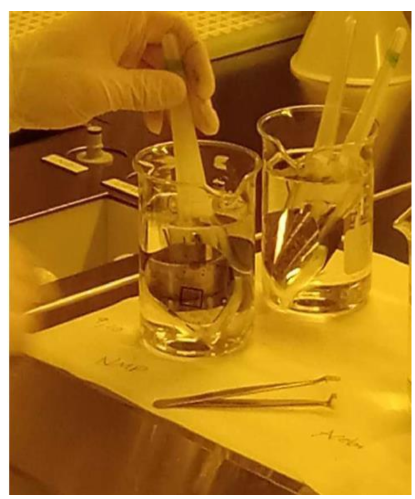


Figure 1. Undergraduate students engaging in hands-on experience with equipment in the cleanroom to master the essential steps in semiconductor fabrication

Addressing Educational and Workforce Gaps

The CHIPS Act places a strong emphasis on workforce development, but addressing the skills gap in the semiconductor industry isn't just about creating more jobs—it's about ensuring that educational institutions can provide the training needed to fill these roles. Traditional methods of teaching semiconductor manufacturing often rely on expensive and specialized equipment that many schools simply can't afford. This means that access to hands-on training is often limited to a select few.

One of the most promising aspects of the immersive VR platform in semiconductor education is its ability to scale. With an immersive reality platform, institutions don't need to invest in costly cleanroom facilities or worry about the safety risks involved in hands-on training. Instead, students can access the virtual cleanroom anytime from anywhere, making this technology a potential game-changer for institutions with limited resources.

Another key benefit of this approach is that it gives students the chance to practice their skills without the pressure of real-world consequences. They can make mistakes in the virtual environment, learn from them, and refine their techniques. This allows for more repetitions and better retention of skills over time, which is particularly important for fields that require a high degree of precision, like semiconductor manufacturing.

Our research is ongoing as we continue to explore how immersive technology platforms can be used to provide scalable, effective training. We are assessing the feasibility of this technology in a variety of educational settings and gathering data on how it impacts student outcomes. We are particularly focused on ensuring that this technology is accessible to all students, regardless of their background or the resources available to their institution.

Preliminary Feedback and Ongoing Assessment

The early feedback from students who have used immersive reality cleanroom platform has been encouraging. In pilot tests, students have reported that the experience helps them feel more confident and comfortable with semiconductor manufacturing processes. Students appreciated the hands-on nature of the training and the ability to make mistakes without real-world consequences. Many students have also commented on how much easier it is to understand complex processes when they can interact with them in a virtual environment.

As part of our ongoing assessment, we have been tracking students' progress and comparing their performance on tasks before and after using the immersive reality. The preliminary data suggests that students who engage with the simulation show improved understanding of key concepts and better performance on assessments. However, this is just the beginning, and more comprehensive studies are underway to evaluate how well these gains translate into long-term retention and career readiness.

We are also collecting qualitative data on student motivation. Early results indicate that immersive simulations like this one can significantly increase students' interest in the subject, which could lead to higher enrollment in semiconductor programs. However, more research is needed to confirm whether these motivational boosts translate into long-term career engagement.

Next Steps and Future Directions

Looking ahead, we're focused on expanding the capabilities of the immersive platform to include a wider variety of semiconductor manufacturing tasks. This will involve both adding more advanced processes and improving the platform's real-time feedback mechanisms to give students even more detailed guidance as they work. We are also working to ensure that the simulation is scalable and can be easily integrated into existing educational programs. Our goal is to make it accessible to as many students as possible, including those in underserved communities who might not have access to traditional semiconductor training facilities. Finally, we'll continue to assess the broader impact of this VR approach on student outcomes, career readiness, and workforce development. In particular, we'll be tracking whether students who use the simulation are more likely to pursue careers in semiconductor manufacturing or related fields.

Conclusion

Immersive technologies like VR hold a great promise for revolutionizing semiconductor education, offering a cost-effective and scalable way to train students for the growing workforce demands highlighted by the CHIPS Act. Our early results suggest that VR simulations can improve student understanding, engagement, and performance, while also making semiconductor education more accessible to a wider audience. However, much work remains to refine the technology and assess its long-term impact. We look forward to continuing this research and expanding the potential of VR in semiconductor workforce development.

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