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NSF IUSE - From Simulation to Skills: VR-Powered Cleanroom Fabrication Training

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Introduction

Hands-on cleanroom training is a foundational component of semiconductor education, requiring students to adhere to strict safety protocols, execute complex fabrication procedures, and operate specialized precision equipment with accuracy and control. However, authentic cleanroom training is constrained by limited facility access, strict protocols, and the high cost and sensitivity of fabrication equipment. Even minor errors can result in wafer loss or equipment damage, restricting opportunities for repeated, low-risk practice for class and students. Due to these limitations, instruction often relies on demonstrations and tutorials, which convey conceptual knowledge but provide limited active rehearsal of procedural skills. Immersive virtual reality (VR) offers a promising alternative by enabling structured, repeatable practice in realistic cleanroom environments without associated risks. Prior research suggests that VR-based training can enhance self-efficacy, task efficiency, and skill transfer while improving scalability [1] [2] [3] [4].

Despite these advances, recent work on virtual reality (VR) cleanroom and nanofabrication training has largely emphasized engagement, accessibility, and perceived learning gains rather than validated procedural skill transfer. Several reported improvements in student confidence, interest, and perceived understanding of semiconductor fabrication processes [5] [6] [7] [8]. A recent scoping review of extended reality (XR) environments for semiconductor fabrication education identified only five relevant studies and concluded that research in this domain remains limited, with most systems focusing on feature implementation rather than demonstrable operational competence [9]. None of the reviewed studies provided empirical evidence of near transfer from VR-based rehearsal to accurate physical cleanroom execution. Collectively, the literature suggests that while VR effectively supports cognitive familiarization and workflow visualization, measurable evidence of operational skill transfer to real-world cleanroom settings remains lacking.

This study draws on the training theory, which examines the extent to which knowledge and skills acquired in one context are applied effectively in another [10]. Prior research indicates that effective transfer depends not solely on visual realism, but on functional alignment between training and real-world tasks, including procedural similarity, workflow structure, and task fidelity. Moreover, transfer is not automatic; it is strengthened by instructional scaffolding, structured reflection, and careful alignment between virtual and physical environments [11] [12] [13].

Building on this theoretical foundation, the present study investigates immersive VR as a bridge between simulated instruction and real-world cleanroom fabrication. The proposed VR-based photolithography training system is intentionally designed to mirror physical cleanroom workflows and provide structured, repeatable rehearsal of critical procedures. This study specifically examines near transfer [14] as VR-rehearsed procedures are subsequently performed in a highly similar physical cleanroom setting. By focusing on operational skill transfer rather than simulation fidelity alone, this work contributes empirical evidence on how immersive technologies can effectively prepare engineering students for real-world laboratory and semiconductor manufacturing tasks.

VR-Based Cleanroom Training System

Unlike tethered, resource-intensive VR setups, our system was developed and optimized for standalone headsets (Meta Quest Pro and Quest 3), enabling scalable deployment while maintaining sufficient graphical fidelity and instructional clarity. The system was developed using Unity3D, Blender, and the UltimateXR toolkit. Design decisions emphasized functional and visual alignment with authentic cleanroom workflows, with optimized modeling and lighting to maintain stable performance within the constraints of a standalone headset. Instructional features include just-in-time visual cues to support sequential task execution, custom hand poses to simulate realistic, intuitive equipment manipulation, and an interactive learning hub that facilitates structured, guided VR practice (**Fig. 1**). This VR-based cleanroom training system is designed to include multiple cleanroom processes. The focus of this study is on photolithography.

(a) (b) (c)

Fig. 1 Instructional features in VR (a) just-in-time visual cues (b) custom hand poses (c) the interactive learning hub

Research Study

We conducted a small-scale study examining cleanroom photolithography training with undergraduate students majoring in Electrical Engineering. Ten undergraduate students enrolled in a 4000-level Electrical Engineering course (MEMS Labs), which includes required hands-on cleanroom fabrication as part of the curriculum, participated in the study. The VR training module was implemented as a preparatory intervention prior to students entering the physical cleanroom to operate actual fabrication equipment.

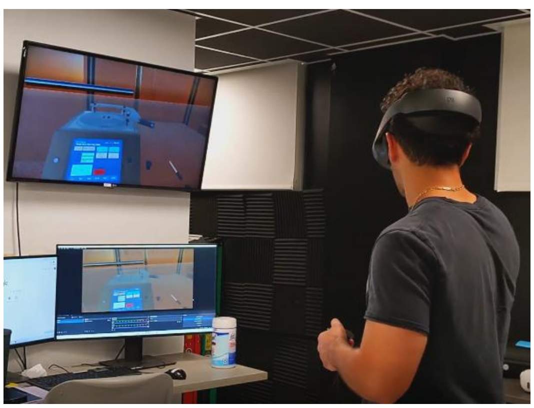
This paper focuses specifically on the transfer of knowledge and procedural skills from the VR environment to real-world cleanroom operations. The research questions guiding this study are:

- **RQ1:** How did students perform in the physical cleanroom following VR-based practice?
- **RQ2:** How did students perceive their learning, practice, and operational experiences in both the VR environment and the physical laboratory?

Each student participant had a 90-minute VR practice session and a 30-minute physical cleanroom session within a one-week period (**Fig. 2**). During the VR session, students completed the full photolithography workflow once with embedded highlights and instructional guidance (illustrated in Fig. 1a, 1c), followed by a second full execution without built-in instructions. This structured progression from guided to unguided practice was designed to support procedural familiarization and rehearsal prior to physical laboratory execution.

To assess changes in perceived readiness, a pre/post self-efficacy survey [15] was administered immediately before and after the VR session. Results indicated an increase in mean confidence ratings from pretest ($M = 4.04$, $SD = 0.70$) to posttest ($M = 4.58$, $SD = 0.62$), $p = .020$, suggesting improved perceived preparedness prior to entering the physical cleanroom.

During the physical laboratory session, each student was paired with a laboratory teaching assistant (TA), who evaluated performance using an established step-by-step scoring rubric. The physical assessment comprised two primary operational phases: photoresist application and mask alignment. The photoresist application phase involved operation of a spin coater and included wafer loading and positioning, photoresist dispensing, selection and execution of the appropriate spin recipe, post-application soft baking on a hot plate, and wafer unloading. The mask alignment phase involved use of a mask aligner and included wafer loading, parameter configuration, mask installation, wafer setup, and precise mask-wafer alignment. Student performance was evaluated using a standardized rubric in which each subtask was scored on a 4-point ordinal scale (1 = unsuccessful/major errors, 2 = partially correct with substantial assistance, 3 = mostly correct with minor assistance, 4 = fully correct and independent) as shown in **Table 1**. The cumulative score across all subtasks yielded a maximum possible score of 40 points for the complete laboratory operation.



(a)

(b)

Fig. 2 Students conducting a photoresist application step using a spin coater in (a) VR and (b) physical cleanroom

Following the laboratory session, a researcher conducted a semi-structured interview with each student to examine their learning experiences and perceptions of the training. Sample interview questions included:

- In general, how would you compare the VR Cleanroom practice and the actual cleanroom operations?
- Do you think the VR Cleanroom practice affected your performance in the actual cleanroom operations? Why or why not?
- Do you feel more confident in operating the devices in the actual cleanroom after the VR Cleanroom practice? Why or why not?

Study Results

Operation Score Results

Table 1: TA's scores for the lab operations.

Photoresist steps (20)					Mask Alignment (20)					
Set the wafer (4)	Apply photoresist (4)	Select & run the recipe (4)	Bake wafer on HotPlate (4)	Pick up wafer (4)	Set the wafer (4)	Set parameter (4)	Set up Mask (4)	Set up Wafer (4)	Align Mask (4)	**Total score** (40)
3.9	3.65	3.8	3.95	4	4	3.7	3.1	3.45	3.75	37.3

As shown in Table 1, the average score across the complete laboratory operation was 37.3 out of 40, indicating that students successfully completed more than 93% of the required steps. Based on the instructional experience of the teaching assistant and course instructor, this performance meets or exceeds the expected competency level for cleanroom photolithography operations in the course curriculum.

Interview Results

The interview data collected revealed students' perceptions of the VR training and its influence on their performance in the physical cleanroom. All participants reported that the VR practice substantially increased their confidence and reduced anxiety related to operating cleanroom equipment. Several themes emerged from the students' responses, as summarized below.

Psychological Safety

One of the most prominent student comments was that the VR practice allowed them to make mistakes safely, without risking damage to equipment or other negative consequences. "VR allowed me... to virtually use all the machines without fear of damaging or breaking something. I wasn't so concerned about messing up." Hence, when in the physical lab dealing with the real equipment, "I think I would have definitely been a lot more lost than if I hadn't done it... I felt like I could do it with maybe less supervision".

Procedural Fluency

The students perceived the VR training as particularly effective in supporting procedural learning, helping them understand and execute the correct order of laboratory operations. One student put, "I mean ... like just kind of understanding what step needs to be taken after the other." Another one mentioned, "I learned the entire process in the VR, and that was helpful for the hot plate, the spin coater... I have an idea of what to expect from each of the machines."

Environmental Awareness

Students also reported that the virtual lab helped them develop a mental map of the cleanroom, increasing their familiarity with the physical layout and equipment prior to entering the actual cleanroom. One student commented, "I felt comfortable enough to get started and use the machines because I already knew what they looked like and what they did." Another one stated, "Having the layout in the VR helped me know exactly where to go once I got into the actual lab."

Pedagogical scaffolding
Students also acknowledged the effectiveness of pedagogical scaffolding, such as visual cues, sound effects, and micro-animations, throughout the virtual lab practice. They regarded these scaffolding elements as particularly effective for initial learning and as helpful for providing real-time validation of their actions. One student put, “The glowing red on the button you need to press next is very nice... it helps you learn the process quickly.” Another student noticed that “In the VR like it would give you a ding every time you did a step right, so like you knew when you're done with it.”

Besides all these compliments and positive feedback, the students also raised several concerns, which can be broadly categorized into design concerns and technical limitations. For example, while acknowledging the benefits of the visual cues, such as the highlighted buttons in VR, some students expressed that their memory might be weaker without those clues in the physical lab, as one student put it, “In the VR lab, the buttons light up. This real lab, they don't... it's a lot to remember each of the buttons [in the lab] cause they don't [light up].” Regarding technical limitations, students reported that the VR environment could not fully reproduce the physical feel of real-world tools. For example, “You don't really have the same sense of the weight... and how much pressure you're putting on things.”

Conclusion
Based on the results of this initial study, VR training effectively supported students’ performance during subsequent physical cleanroom laboratory operations. Students achieved high scores across photolithography tasks, suggesting successful transfer of rehearsed procedural skills from the virtual environment to real-world equipment use. Qualitative findings further indicated that VR practice enhanced students’ confidence and reduced anxiety prior to entering the cleanroom, consistent with the role of self-efficacy in supporting independent task execution. Together, these findings suggest that structured immersive rehearsal can strengthen both procedural fluency and psychological readiness in high-stakes laboratory settings.

At the same time, student feedback highlighted several design- and technology-related limitations that warrant further refinement. Their concerns about reliance on visual prompts indicate a need to better support memory consolidation and transfer. Future iterations will consider incorporating strategies such as gradual cue fading and increased recall-based practice to encourage deeper internalization of procedural sequences. Additionally, limitations related to the absence of tactile feedback and perceived tool weight highlight areas where virtual environments cannot fully replicate physical interaction. To mitigate this gap, future designs may incorporate supplementary visual or auditory annotations that convey physical properties and operational constraints. While these enhancements cannot replace embodied experience, they may provide complementary scaffolding to better prepare students for real-world cleanroom operations.

Overall, this study provides preliminary evidence that immersive VR can function as an effective preparatory bridge between simulated instruction and physical laboratory performance. By aligning virtual workflows closely with authentic procedures and supporting learners’ confidence, VR training shows promise as a scalable approach to cleanroom training and education.

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