IMMERSIVE VIRTUAL REALITY-BASED TRAINING ENVIRONMENT TO PERFORM THE PHOTOLITHOGRAPHY PROCESS

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ABSTRACT

The CHIPS and Science Act, enacted in 2022, aims to bring semiconductor manufacturing back to the US by calling for significant expansion and improvement in semiconductor research, workforce preparation, and training. As the industry increasingly relies on advanced technologies, integrating Virtual Reality (VR) into training programs provides early exposure and hands-on experience with these platforms, enhancing the workforce's skills and readiness. Immersive VR technology provides a more engaging and interactive learning experience, fostering greater motivation and understanding among trainees. VR training is inexpensive, injury-free, easily adjustable, scalable, and can be conducted remotely. VR environments are easy to supplement, strip, or modify, allowing one system to train for multiple processes, thereby saving costs.

This research focuses on developing an immersive VR-based Training Environment (VRTE) for photolithography, addressing the challenges of traditional practical training, such as high costs and injury risks. The immersive VRTE prototype for photolithography is designed and prototyped using the Unity development platform. The developed version is a high-fidelity VRTE and already features full-scale navigation within the 3D space, as well as controller integration for effective interactions. The research focuses on evaluating the effects of (a) realism and authenticity, (b) presence and immersion, (c) degree of user Interaction, (d) e-learning and scaffolding features, and (e) accessibility across multiple platforms and devices. The research contributes to professional training and workforce development in the semiconductor industry.

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INTRODUCTION

Semiconductor manufacturing forms the backbone of modern electronics, enabling the production of integrated circuits (ICs), which power most of the devices we use today (Mitchell et al., 1995). One of the primary steps in the semiconductor manufacturing process is photolithography, which is used to create intricate circuit patterns on silicon wafers. This process is performed in cleanroom environments and involves several steps, including cleaning the wafers, applying light-sensitive photoresists, and precisely patterning the circuits onto the wafer using UV light. This cleanroom environment presents unique challenges to the trainees, as it requires strict contamination controls with hazardous chemicals and specialized equipment that demand expert handling. The concern of causing costly damage or contamination incidents often leads to restricted trainee participation, where most students are limited to mostly observing rather than actively practicing the photolithography steps (Kamali et al., 2018). This approach, hence, results in trainees who may understand photolithography theoretically but lack the extensive practical confidence needed for cleanroom work in the real world.

Virtual Reality (VR) is being adopted as an effective training tool in fields where real-world practices carry significant risks or costs. With the use of VR technologies, surgeons are able to practice complex medical procedures multiple times without endangering patients (Pedram et al., 2024; Todsen et al., 2018). At the same time, aviation trainees are allowed to experience emergency scenarios safely using flight simulators (Pirker, 2022; Rostami et al., 2023). The significance of virtual reality technologies lies in their ability to create immersive and repeatable learning environments that bridge the gap between theoretical knowledge and practical skills.

To date, while several VR-based training modules have been developed for training in photolithography (Wang et al., 2020; Xu & Wang, 2022), most existing systems focus on demonstrating the system's feasibility rather than analyzing the effectiveness of the VR training with respect to how specific parameters affect the performance of the trainees and the overall learning experience. This limitation represents a missed opportunity to maximize the learning and training potential of virtual reality, where even subtle differences in the design of the VR system can significantly impact learning outcomes.

PROJECT OBJECTIVE

Project Overview and Objectives

The primary objective of this research is to develop a Photolithography Virtual Training Environment (PL-VTE) and investigate how various parameters of the VR-based training module impact the performance of its users. This is achieved by tailoring the parameters of a basic prototype of PL-VTE and conducting a validation assessment with a control group to evaluate the impact of these changes on the effectiveness of PL-VTE training. The research aims to eventually provide results that will serve as design guidelines for the development of VR-based training platforms.

METHODOLOGY AND DESIGN

Topic: Photolithography Process

The photolithography process serves as the core of the PL-VTE. A breakdown of the process steps, including the equipment used at every stage, is provided in Appendix A. The outlined procedures are based on industry-standard protocols currently practiced in the Micro and Nanofabrication Laboratory at Norfolk State University. A summary of the steps is shown in Figure 1. The steps form the basis for the VR module design and are used to determine the actions that could be realistically and effectively implemented within the virtual environment.

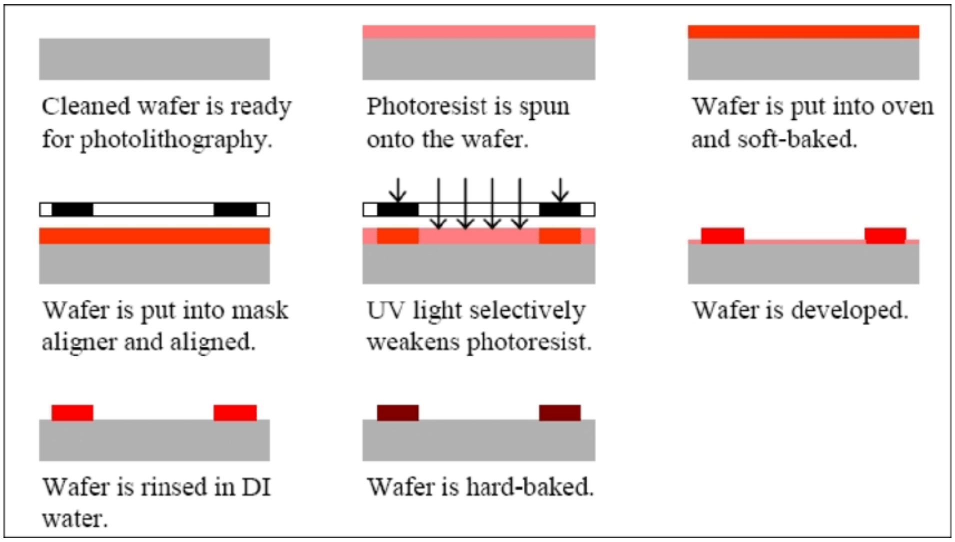

Figure 1. Photolithography Steps

PL-VTE Design

The PL-VTE module is developed using the Unity 3D platform, where the environment is populated with 3D Models created in Blender, and the main photolithography steps are programmed using C#. The development follows a structured and iterative approach to upgrade, optimize, and evaluate the module. For testing purposes, PL-VTE is deployed on Quest 2 and Quest 3 Head Mounted Displays using the Meta Quest Developer Hub for easy accessibility. Based on established design guidelines, the main VR parameters are varied systematically in different module versions to assess their impact on trainee performance. Based on the insights gained from the analysis, evidence-based design guidelines for developing effective VTEs are established. The overall methodology for this research is outlined in the flowchart shown in Figure 2.

Instruments and Materials

The specific instruments, platforms, and materials that will be used throughout the design, development, deployment, and evaluation phases of the PL-VTE module are outlined in this section. These include both the hardware and software components to be used.

<u>VTE Development Platform</u>: Unity
Unity 3D serves as a foundational platform for the development of the PL-VTE and will be used as the development platform for modifying the virtual training environment.

<u>3D Modeling Software</u>: Blender
Blender is an open-source 3D modeling tool used for sculpting, modeling, texturing, and preparing assets for real-time virtual and simulation environments. In this research, the tool will be used for creating and editing the 3D models required in the PL-VTE. The developed models will represent the cleanroom equipment and tools and will be exported in the form of .fbx or .obj formats and imported into the Unity 3D assets folder for interaction scripting once they are finalized. Several developed 3D models are shown in Figure 3 below.

<u>VR Headsets</u>: Meta Quest 2 and Meta Quest 3
The Meta Quest 2 and Meta Quest 3 head-mounted displays will serve as the primary hardware for delivering and testing the PL-VTE. These HMDs are selected for their ability to deliver a high-fidelity, immersive experience without

the need for PC tethering or external sensors (inside-out tracking). In this research, headsets will be used to deploy multiple versions of the PL-VTE, allowing for an assessment of the impact of the selected VR parameters on user performance.

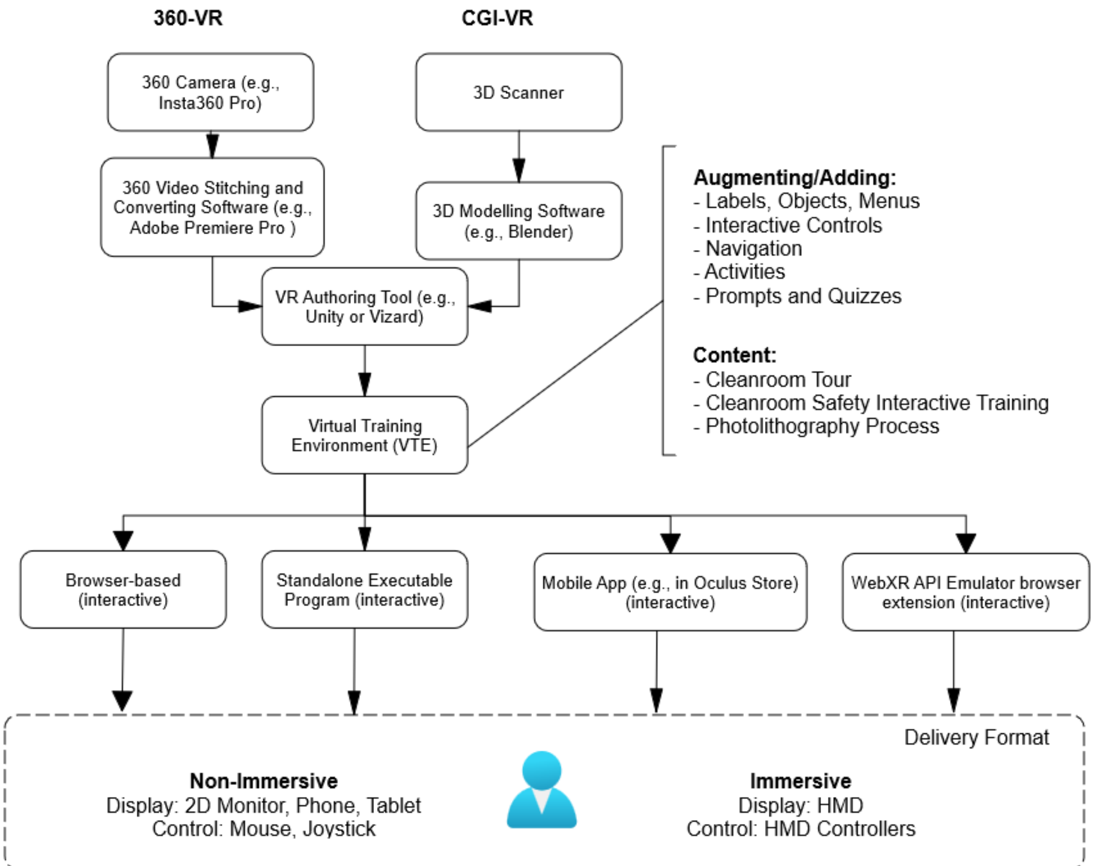

Figure 2. The PL-VTE development flowchart.

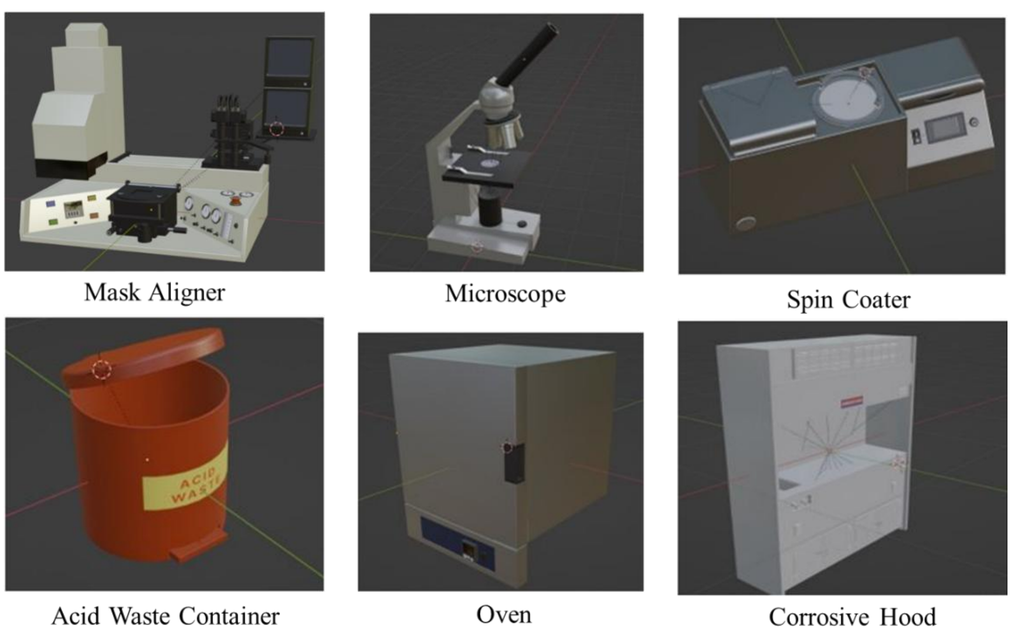

Figure 3. Several developed 3D models in Blender.

<u>Mobile Platform</u>: Meta Quest Developer Hub (MQDH)
The Meta Quest Developer Hub is the official development management platform provided by Meta for deploying, organizing, and testing applications on Quest headsets. In this research, MQDH serves as the link between the Unity 3D environment and the HMDs for immersive training evaluation. It is used to upload, distribute, and monitor multiple versions of the PL-VTE. Each version of the PL-VTE, containing specific VR parameter configurations, is managed under the Alpha and Beta release channels, which enable the organized distribution of builds for different testing phases. The visual interface of the MQDH supports streamlined app management, which is useful in conducting iterative testing cycles involving modified training environments.

RESULTS

The PL-VTE prototype was successfully developed and iteratively modified.

NSU Photolithography Lab — Developed Photolithography VTE

Figure 4. An actual NSU Photolithography lab (left) and the developed PL-VTE (right).

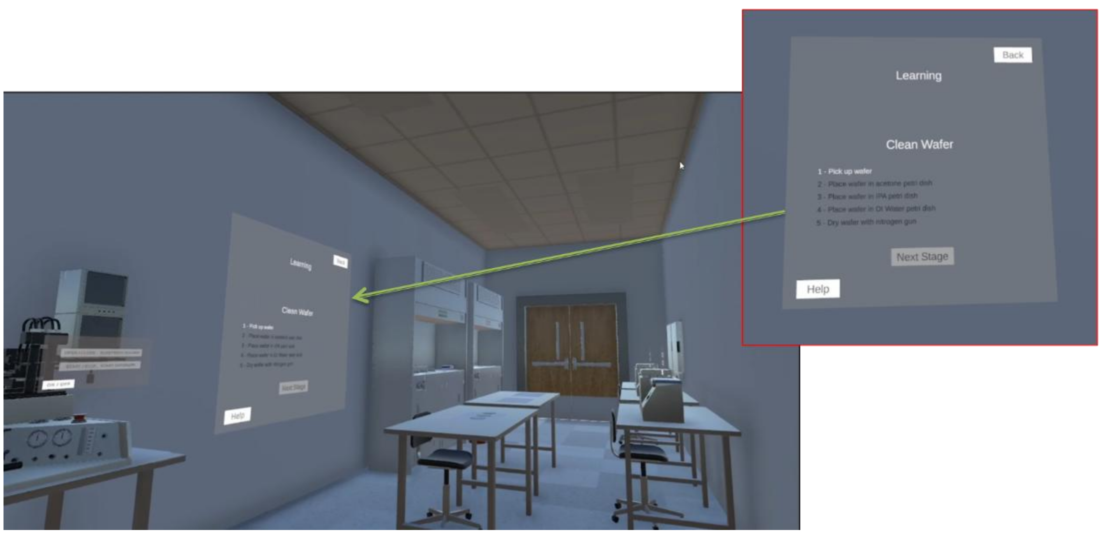

Figure 5. Progress Menu on Photolithography Steps

Main PL-VTE Parameters and Features

- Proper content development and augmentation, including help menus (see Figure 5)
- Interaction level
- E-Learning tools (built-in Assessment)
- Delivery Format for immersive training (VR Headset)
- Spatial Navigation

A detailed comparison was conducted between the real-world photolithography process and the virtual process implemented in the PL-VTE prototype. These are summarized in Table 1.

Table 1: Summary of Process Simplifications in PL-VTE

Stage	Actual Process	PL-VTE Process	Simplifications in PL-VTE
Substrate Preparation	Pick up the wafer Clean with Acetone solution Clean with IPA solution Rinse with DI water Dry the wafer with a nitrogen gun	Pick up the wafer Clean in Acetone solution Clean in IPA solution Rinse in DI water Dry the wafer with a nitrogen gun	Tweezers not used Wash bottles are not included The wafer is not tilted for drying
Photoresist Application	Edit the spin process on the spin coater Put the wafer onto the chuck of the spinner Deposit the photoresist fluid onto the wafer using a pipette Start the spinner	Pre-bake the wafer Apply photoresist to the wafer Spread resist on the wafer with the spin coater Post-bake the wafer	Spin coating parameters are not set/edited A pipette is not used to apply photoresist
Baking	Put the wafer in the oven Set oven temperature Set the timer and start baking Get the wafer from the oven onto a napkin Set the wafer on a napkin to cool	Place the wafer on a napkin Press the panel to activate the oven Press OPEN to open the oven Place the wafer in the oven Press START to bake the wafer Press STOP to stop and take the wafer out	The oven temperature is not set before baking A timer is not used
Alignment	Load the mask onto the mask holder Attach the mask holder to the system Turn on the illumination controller Turn on the camera controller Load the wafer X-axis, y-axis, z-axis control	Press ON on the panel to activate the mask aligner Press OPEN to open the cover Place the wafer on the substrate holder.	Photomask not used The mask holder is already attached in the setup
Exposure	Tap substrate vacuum Tap level Tap move to contact position Tap contact vacuum Tap the cycle to begin UV exposing	Press START to expose the wafer to UV light Press STOP to finish exposure Press OPEN to open the cover CLOSE the cover of the mask aligner and turn it OFF	Alignment steps are completely skipped.
Development	Dip the wafer in the developer solution Gently move the wafer in the developer for 60 seconds Rinse the wafer with DI water for 30 seconds Dry the wafer with a nitrogen gun	Dip the wafer in the developer solution Rinse the wafer in DI water Dry the wafer with a nitrogen gun	The wafer is not moved in the developer No timer is used

Module Refinement and Adjustments

Following the analysis of the earlier developed basic PL-VTE prototype, several refinements have been made to improve interaction, sequence control, and the overall user experience. These updates were made using Unity 3D and C# scripting.

Special attention was paid to enabling full-scale spatial navigation in the module, as shown in Figure 6. The updated module now supports two distinct movement methods: joystick-based movement, implemented using the XR Interaction Toolkit, and natural walking within a mapped physical space.

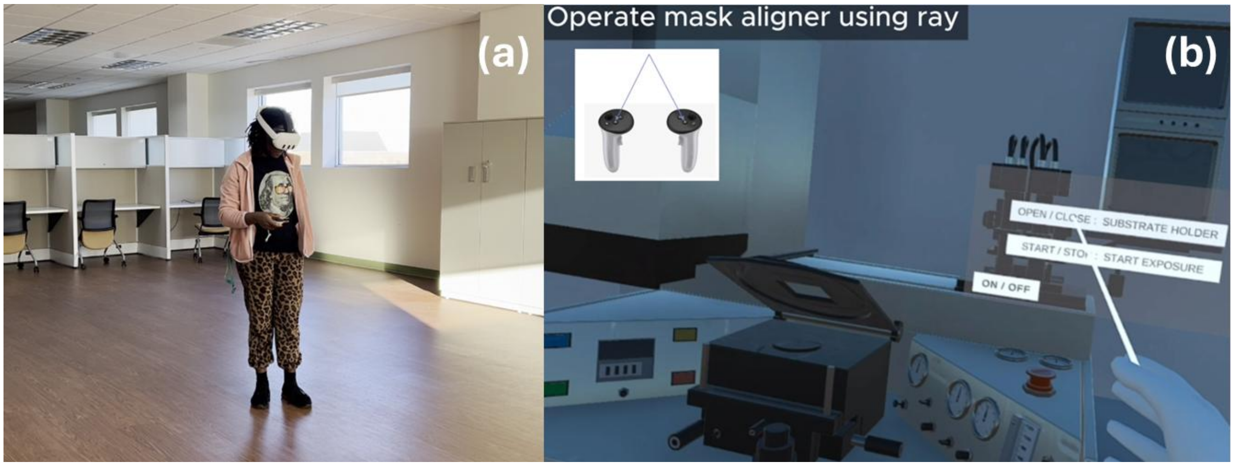

Figure 6. A 10m x 10m empty training space allows for full-scale navigation during a photolithography procedure.

To improve realism and facilitate more natural user interaction, the ray-based object selection mechanism, which allows users to point from afar to grab items, has been disabled. Users must now move closer to virtual objects to interact with them. This better aligns with how tools are accessed in a real cleanroom setting.

VR Parameters Relevant to the Proposed PL-VTE Module

Table 2 summarizes the major VR parameters relevant to the PL-VTE module, organized under six thematic groups. These groupings reflect the multi-dimensional considerations required for designing effective VR-based training tools. Parameters such as Display Quality, Presence and Immersion, Functional Fidelity, and Interactivity directly affect how realistic and engaging the module feels to the user. Others, such as Gamification, Assessment, Feedback, and Tailoring to Experience Level, enhance instructional alignment and learner engagement. Meanwhile, factors like User Safety, Accessibility, and Distribution Channels ensure practical usability and inclusivity.

Table 2. VR Parameters Relevant to the proposed PL-VTE Module

Group	Parameter(s)
Realism and Visual Fidelity	Visual Fidelity (FOV, Stereoscopic effect) Audio Fidelity Display Quality
Psychological and Social Factors	Presence and Immersion Distribution Channels
Content and Context	Authenticity Functional Fidelity
Engagement	Tracking and input devices Interactivity User Experience Design (tailoring the activities to the user's knowledge level, job role, and experience) Navigation
E-learning and Pedagogical Aspects	Instructional Design (scaffolding elements) Gamification Built-in Assessment and Feedback Visualize hidden/not accessible

Ethical and Practical Considerations	User Safety Accessibility

Development of User Instructions

To ensure that participants can engage confidently and effectively with the PL-VTE module, a tutorial is being developed as part of the instructional support for users. The tutorial is intended to guide users through the controls and interactions within the virtual training environment. The tutorial provides visual instructions on how to:

1. Enable and disable the beam interactor for object selection and interaction
2. Navigate using either physical room-scale movement or the joystick on the VR controller
3. Pick up and return movable items such as the wafer, nitrogen gun, and photoresist bottle
4. Interact with devices and the main control panel
5. Operate instruments and devices used in the photolithography process, such as the spin coater and mask aligner.

Figure 7 shows a screenshot from the tutorial, where the user is instructed to operate the spin coater using the ray.

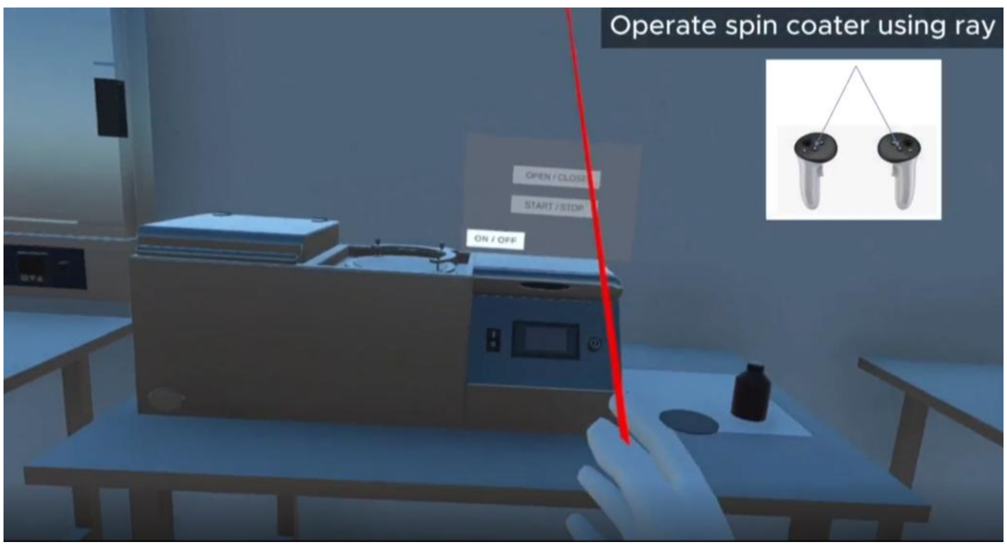

Figure 7. Instruction of Module Usage

Assessment Materials Development

A custom pre- and post-training test has been developed to assess the participants' understanding of the photolithography process before and after the PL-VTE training. The current version of the test consists of a combination of multiple-choice questions, short-answer questions, equipment identification questions, and procedural sequencing questions (a total of 16 questions). The content for the test was compiled from the NSU cleanroom instructional materials and published journal articles. To ensure instructional accuracy and credibility, the questions will be subject to internal validation by NSU cleanroom experts before use.

CONCLUSIONS

This research outlines an approach for how the proposed PL-VTE module should be designed to be an effective, validated training tool, and how various VR parameters impact trainee performance in the developed VTE. Specifically, through the systematic enhancement of the basic PL-VTE module, the study aims to investigate how design factors influence procedural understanding, user engagement, and training effectiveness. A detailed literature review guided the identification of major VR parameters, which were grouped under categories such as realism, interactivity, pedagogical alignment, accessibility, and technological advancement.

The proposed validation methodology involves comparing traditional and VR-based training outcomes using assessment materials and experimental controls. By iteratively refining the module to reflect user feedback and performance data, this research aims to establish practical and scalable guidelines for designing effective VR training systems. The findings are expected to inform the development of immersive VR-based educational tools not only in photolithography but across other complex learning domains.

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