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Virtual Reality to Improve Nanotechnology Education

Development methods and example applications.

REZA KAMALI-SARVESTANI, PAUL WEBER, MARTY CLAYTON, MATHEW MEYERS, AND SKYE SLADE

NANOTECHNOLOGY HAS HAD A tremendous effect on industries, from material designs to manufacturing processes, and in various applications, from drug delivery for medicines to reducing airplane noise through the use of nanofibers. This impact has been described as the next industrial revolution, and there is a large investment from countries all across the world to improve teaching and training in nanotechnologies [1]. The biggest challenge in nanotechnology education is providing hands-on laboratory instruction, which requires expensive tools, a cleanroom environment, and safe interaction with hazardous chemicals. In this article, a successful new method for teaching nanotechnology using virtual reality (VR) is presented. VR training is a promising method that has the benefit of personalized instruction and an engaging media format [2].

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VR has already become an important tool for technical education and training applications across a wide range of fields as diverse as agricultural technology, vacuum systems, aviation technology, nuclear training, optical technology, and so on [3]. There are compelling reasons why VR has spread throughout the technology education community. First, equipment in these areas tends to be very expensive, meaning that very few sets of necessary instruments are available—often, there is only one. This creates challenges for scheduling time for instruction. Second, the training to use such instrumentation requires practice time, and it must also allow students to make errors, from which they learn a great deal. However, mistakes made on real machines can lead to a significant loss of time, expensive repair bills, and much worse. Finally, we have found that a well-written tablet guide included within simulations provides significant economy in training when learning a new device, such that students are often able to guide themselves, or "figure it out." This helps students develop a sense of resourcefulness, as they learn from situational awareness.

In addition to these reasons, there is a fun factor involved, and students typically have no fear when they encounter VR programs. In the simulations that we have developed for nanotechnology education, we can go a step further and introduce a game aspect where students compete against a clock or receive a score from the software after they have completed the training, the outcome of which can be used to judge when a student is ready to move on to working with a real machine.

The challenge of how to make expensive equipment available to students, especially in rural areas, is also being addressed by other means. Good network connectivity has led to the development of the Remote Access Instruments in Nanotechnology network [4], where students and educators of all academic levels can schedule an online session from their home institution with, e.g., an electron microscope at a university elsewhere in the country. An expert at the host university acts as an overseer during the process, and the images and controls from the machine are shared with the remote users, who then actually operate the instrument from afar through guided exploratory activities or even study specimens of their own that were sent beforehand. These sessions can provide valuable follow-up for students who have completed the VR exercises, again, as intermediate steps leading to their encounters with real instruments.

In this article, we share development methods for creating VR simulations for an electron microscope; a radio-frequency (RF) sputter-deposition unit; a photolithography process laboratory, including a spin coater and a mask aligner; and an atomic force microscope (AFM). We also show images for the process steps that accomplish the training on these instruments. These simulations were developed for specific instruments available at Utah Valley University. However, we offer the same development capabilities to corporate nanotechnology industries, where the instruments are far more elaborate, large-scale, and expensive. In these industrial environments, there is an even greater premium on technicians learning to operate machines in a safe, exploratory virtual environment before ever being called upon to operate them in a factory.

VR AS A SUCCESSFUL METHOD OF PERSONALIZED TRAINING

The broad field of digital reality has applications in many different modes, as illustrated in Figure 1. As one of the main applications of digital reality, VR

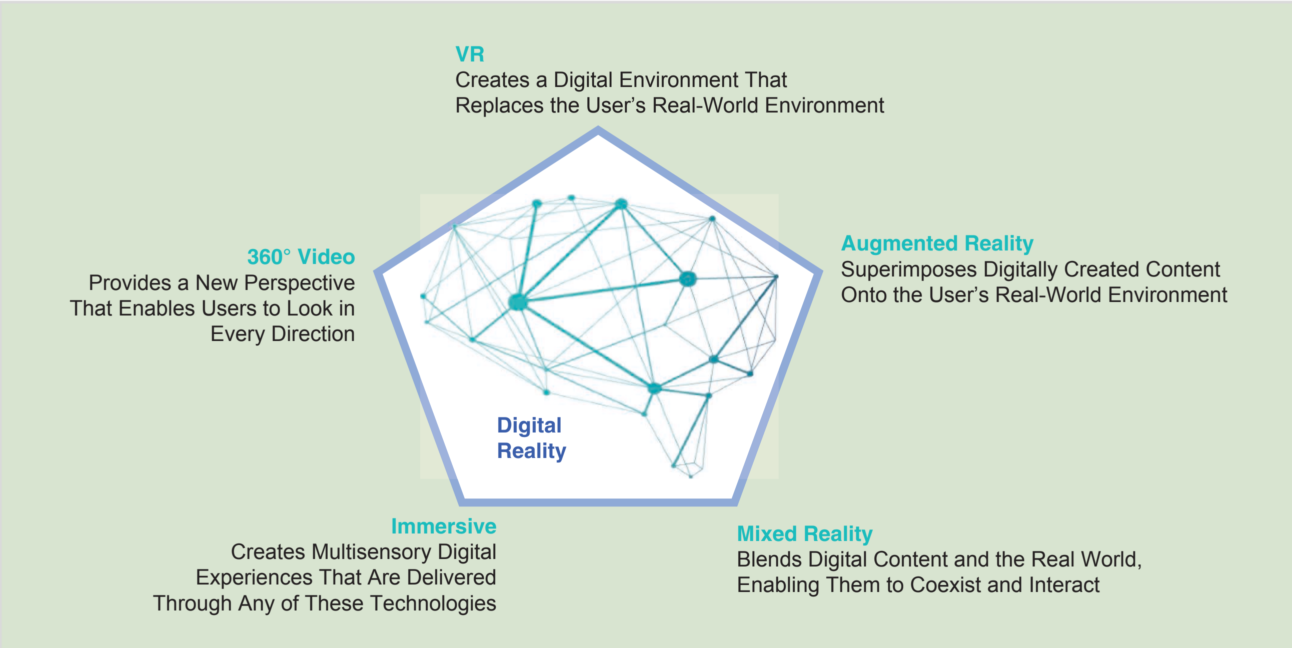

FIGURE 1 The different applications of digital reality.

can provide quality educational content in ways that a traditional learning environment is unable to offer. As this chart shows, VR can replace the real-world environment with a digital version, where students can experience new settings and events that they may never be able to encounter in daily life. VR has a unique capability to "allow students to visualize abstract concepts, to observe events at atomic or planetary scales, and to visit environments and interact with events that distance, time, or safety factors make unavailable" [5]. One example is an app created by Google called *Google Expeditions*. It enables students to take trips to the bottom of the ocean or to Mars from their classrooms and homes, and all they need to accomplish this is a mobile phone. VR creates a world where students can have hands-on experiences that are too costly or dangerous to create within a traditional learning environment. This training can provide students with a chance to learn skills in areas pertinent to their career choice.

VR can even provide life-saving skills that would otherwise go untaught. An example of this comes from a Walmart in El Paso, Texas, where the staff experienced the ability of VR to provide them with life-saving skills. On 3 August 2019, the El Paso Walmart had 22 people fall victim to a mass shooting, but Doug McMillon, Walmart chief executive officer, says that because of VR training for an active-shooter plan that the management team had taken, managers "acted so fast and engaged other associates and executed the plan" [6]. McMillon added that because employees were able to respond so effectively under a stressful situation, the company is "very confident that lives were saved and seconds were gained." In traditional lecture education, this training most likely would have been conducted through some simple exercises and videos, but with VR, the store's employees were able to experience and learn what needed to be done during an active-shooter incident to take control of the situation.

To make different nanotechnology experiments in VR, we have created an environment where students can perform trials simulating the process of fabrication and characterization for a silicon wafer device. These simulations increase the quality and level of education by providing students with virtual versions of machines that would normally cost thousands of dollars, and they enable learners to go through the process of creating samples on their own without any risk of breaking a wafer or the equipment. A single mistake during this process could cost a school or person hundreds to thousands of dollars or create a significant safety hazard, and experience in a VR simulation reduces the risk of this happening.

Another environment that this project simulates is a fully automated clean room, similar to industry-grade clean rooms, which are 100 times cleaner than a hospital room, with fewer than 100 particles per cubic foot. This simulation enables students to explore a clean room and follow a wafer through its process of fabrication without having to visit such a facility for themselves. This VR creates a private environment, generally not open to the public, that students can explore and learn in.

Within this fully automated fabrication room, students can follow a series of prompts that lead them through the process for converting a wafer into an electronic chip. Each step of the process includes a written explanation of what is happening as well as a simple animation showing what the wafer is undergoing within each machine. By the end of the simulation, a student will have run through all the steps to create a wafer, a process that usually takes more than one month to complete, within less than half an hour. Along with following the fabrication process, students also have the chance to simply explore a clean room, taking in all the sights and sounds, experiencing what it is like to work there.

VR MAKES HANDS-ON SIMULATIONS AVAILABLE FOR EDUCATION

VR, as explained, provides opportunities for students to have hands-on experiences that would otherwise be impossible. This can be used in many disciplines, as illustrated by the chart in Figure 2, which shows papers published about trainings that were made possible by using VR. VR is even being used by primary schools to teach children how to code at a young age in a fun, immersive manner by "putting the power of the developer directly in students' hands," enabling them to create their own virtual environments as they learn.

Universities everywhere continue to implement VR to enhance their technical education programs. The University of Utah is developing the world's first full-service simulation to train new dentists, and it has taken the tool to India to teach more than 100 students procedures that they would never have been able to practice without VR. Oxford University uses VR simulations for its medical students to help cement conventional lectures

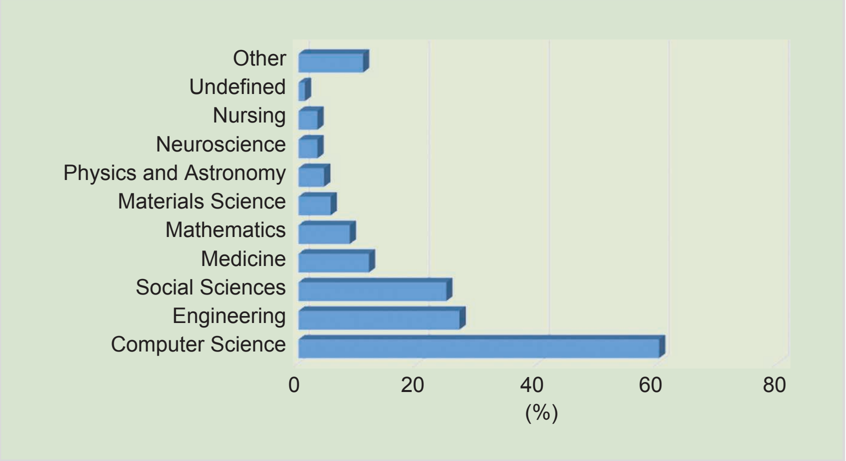

FIGURE 2 The percentage of published papers that concern training using VR, presented by subject.

Traditional methods of teaching can, and most likely will, lead to disengaged, disinterested students.

with hands-on virtual experiences. Utah Valley University employs VR to improve teaching and training in programs such as nursing, automotive technology, aviation, and nanotechnology.

VR IS ENGAGING

During an age when 92% of teens are online daily—playing games, livestreaming memorable experiences, sharing ephemeral moments on Snapchat, and posting pictures of exciting daily occurrences on Instagram—it is often difficult for teachers and professors to keep the interest of their students through traditional lecture-based instruction. Traditional methods of teaching can, and most likely will, lead to disengaged, disinterested students, but the hands-on, immersive, and interactive environments and experiences of VR can provide an opportunity to boost student participation and draw pupils' attention to subjects that they might otherwise have found disinteresting or boring. VR increases engagement by improving the sense of presence and immersion compared to traditional learning environments. Where conventional classroom settings would simply provide a lecture, movie, or, where possible, a lab here or there, VR offers multidimensional computer environments with advanced forms of interaction that can add motivation to the learning process by placing students in situations where they can interact with objects how they want [7].

Another way VR increases student engagement is by placing pupils in the driver's seat. Students can test their knowledge through meaningful experiences. VR enables them to learn at their own pace and in their own style. VR is a platform for education that can provide room for students' imagination and create experiences that would not be possible in a traditional classroom setting.

NANOTECHNOLOGY EXPERIMENTS DEVELOPED USING VR

Utah Valley University has been working on implementing multiple modules in VR for use in its nanotechnology curriculum. There are currently five distinct modules, each focusing on specific aspects of nanofabrication (Figure 3). Each one takes place in separate, self-contained rooms that hold all the materials students need to successfully complete a simulation. While the modules are self-contained, they have commonalities that enable students to smoothly transition from one simulation to the next.

First, the controls do not change. The way students interact with machinery, pick up objects, and move about the

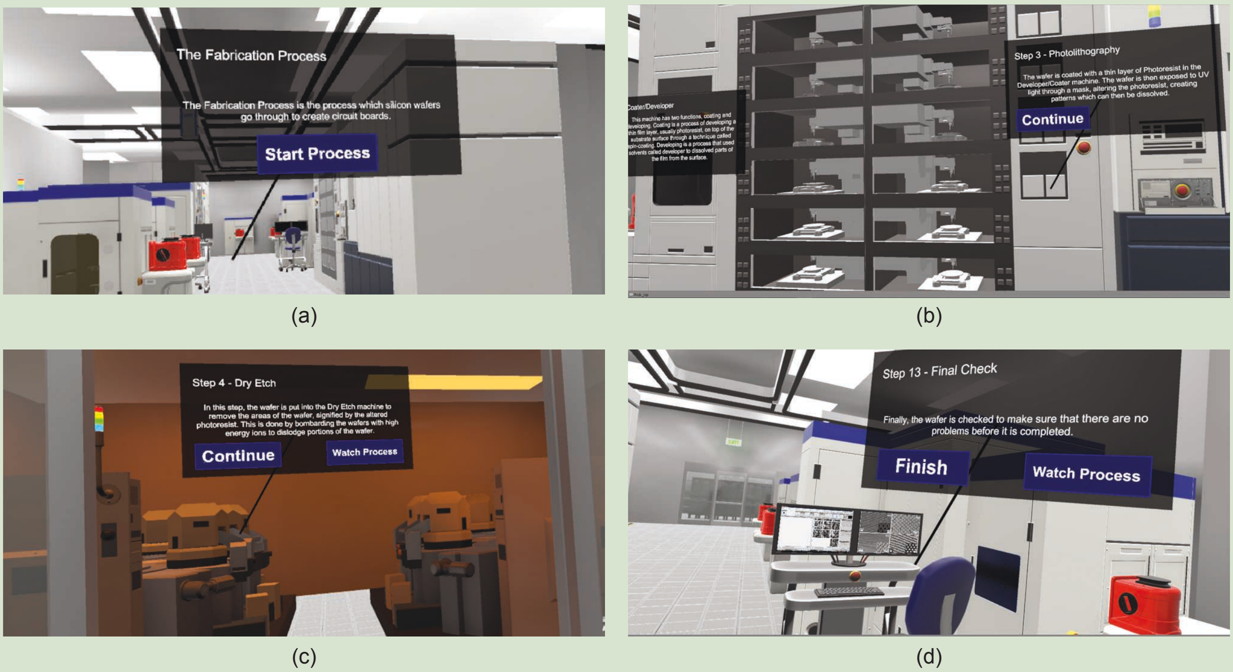

FIGURE 3 An industry-grade silicon wafer line of fabrication in VR, including (a) coating and exposing, (b) developing, (c) etching, and (d) characterizing.

room is the same across all modules. Second, each module has three different difficulties, which enables students to better test their abilities within the simulation. Third, each module has a clearly marked tablet that holds the instructions for the exercise. This tablet, as illustrated in Figure 4, can be carried with the student, and it updates itself as learners progress through the simulation. Finally, students receive feedback on their efforts via a blackboard, which displays the steps of the simulation, what the pupils did correctly and incorrectly, and a letter grade.

MODULE ONE: PHOTOLITHOGRAPHY

The first module simulates the process of photolithography. Students familiarize themselves with a spin coater, photoresist (PR), mask aligner, hot plate, developer, and light exposure. Figure 5 presents the photolithography room configuration. The first step is to prepare the room by turning off the main light so the PR doesn't get exposed. Then students prepare a silicon wafer with a PR for placement on the spin coater. Once they have closed the lid to the machine, the module instructs them on how to correctly program the spin coater through a series of two-step commands, each consisting of how long and

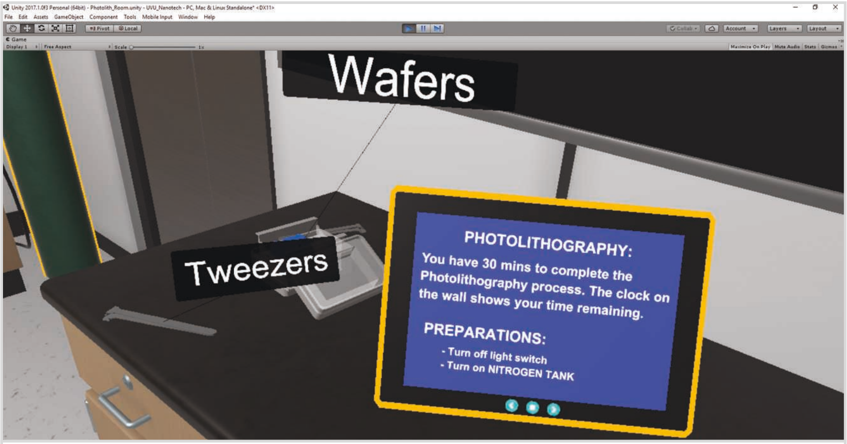

FIGURE 4 A tablet with instructions as seen within the VR simulation.

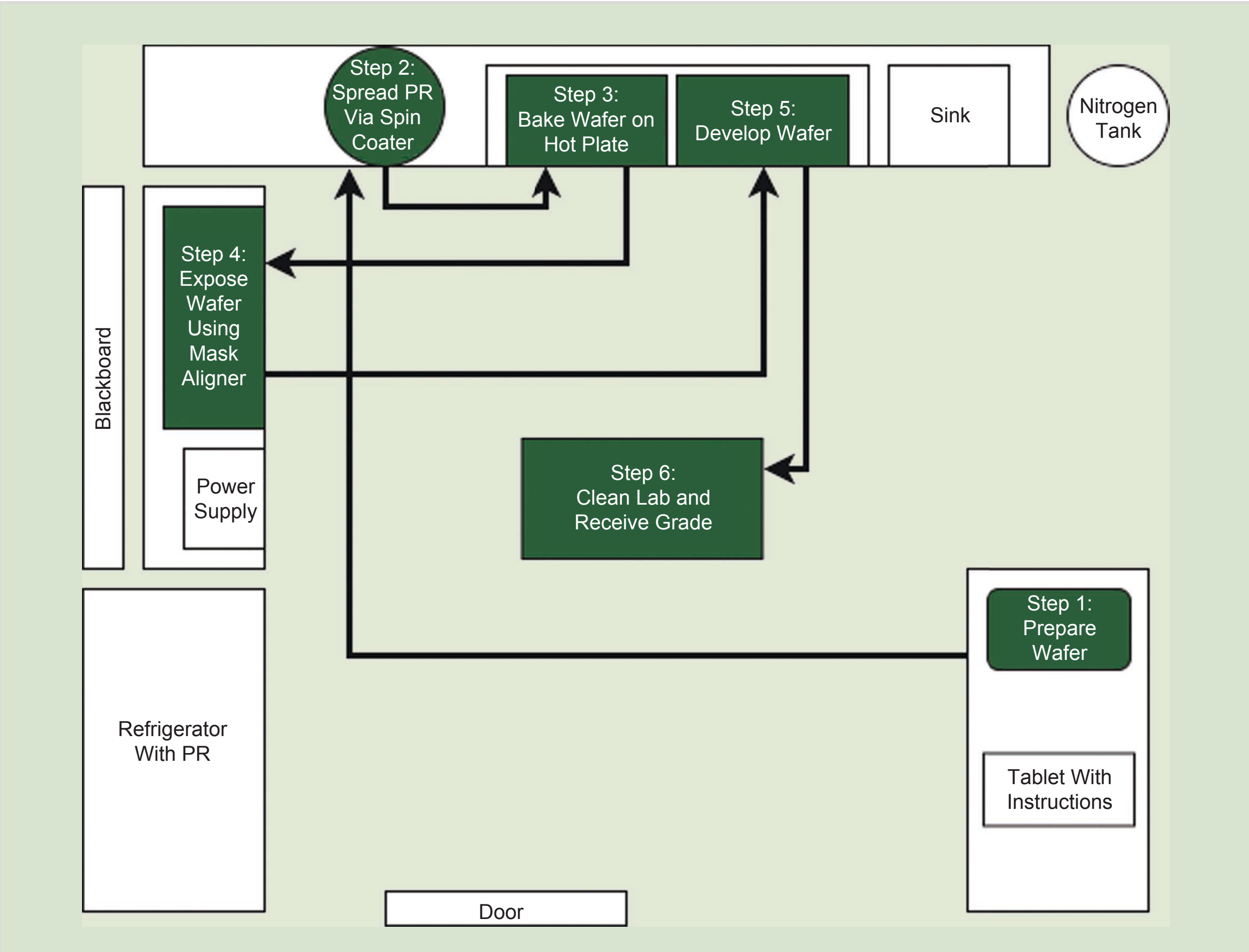

FIGURE 5 The layout of the photolithography simulation as well as the steps students take to complete the training session. PR: photoresist.

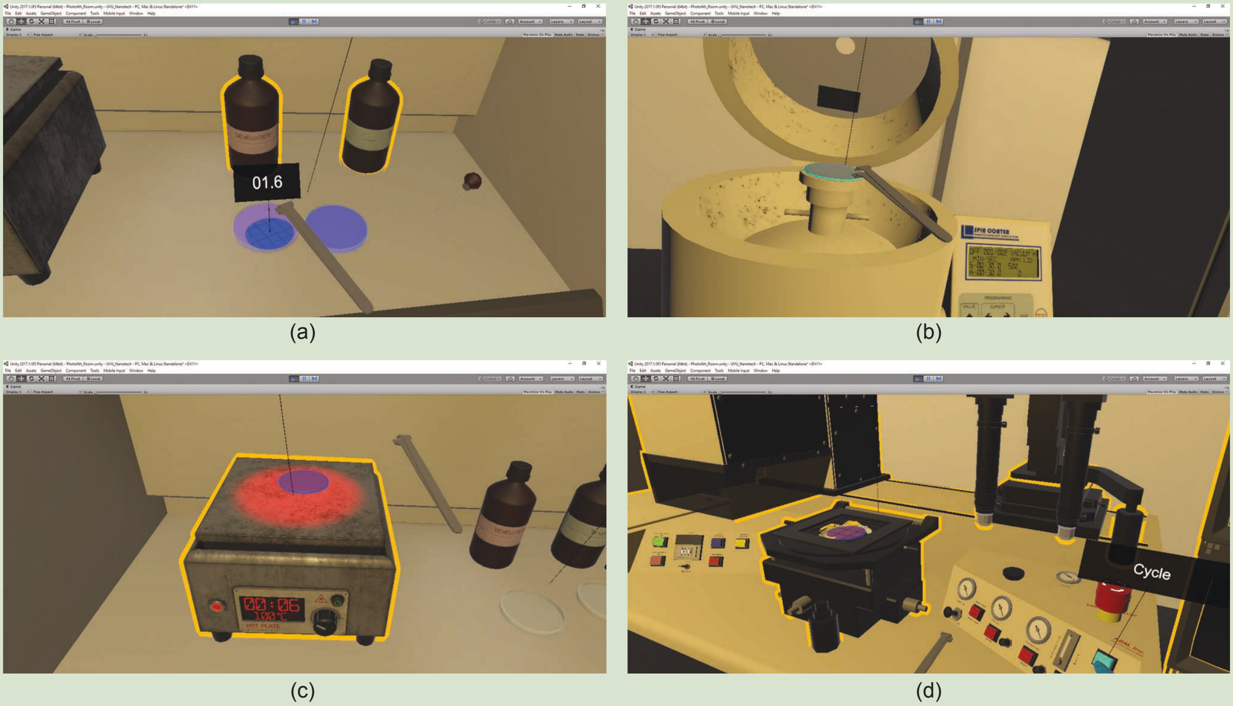

FIGURE 6 A student's VR view when (a) dispensing PR, (b) using the spin coater, (c) cooking a wafer on a hot plate, and (d) using the mask aligner to develop a wafer.

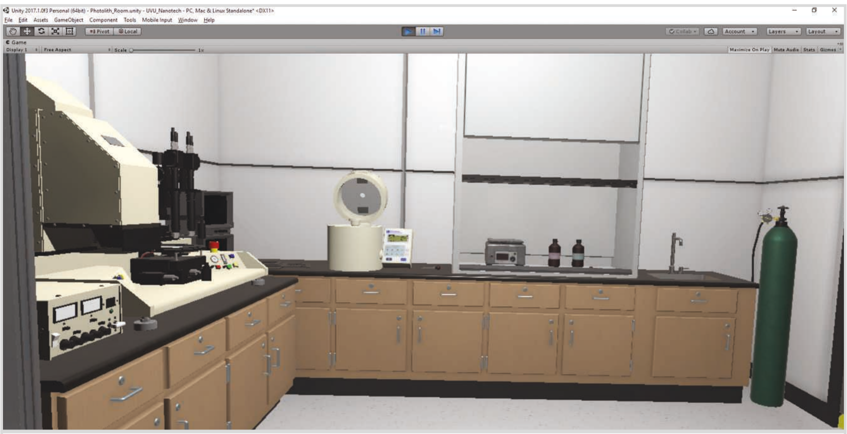

FIGURE 7 A VR view of the photolithography room showing, from left to right, the mask aligner, spin coater, fume hood with a bottle of PR, and nitrogen tank to power the mask aligner's pneumatics.

how fast to spin the wafer. These steps are illustrated in Figure 6.

After the PR has been spun across the wafer, students place the wafer onto a hot plate and cook it for a few seconds. Next, students must prepare the mask aligner. This involves turning on a tank of nitrogen, correctly powering on the machine, setting the length of time to expose the wafer, selecting which mask pattern to use, and setting the mask aligner to the correct mode. Upon exposing the wafer, students are asked to develop the pattern using a two-step process: placing the wafer in a developer chemical, then rinsing it in deionized water. Finally, students clean up the lab, shut off the equipment, and receive feedback via the blackboard.

On average, students take 10–15 min to complete the module. Most errors occur in one of two areas: not completely reading the instructions and learning the controls. For example, the most common error involves students dropping a wafer on the floor, causing the silicon to break. In every case where this has occurred, it has been due to a student incorrectly pressing the button that controls the VR hand when, in fact, he or she was trying to move or use the opposite hand. In cases where students haven't read the instructions correctly, there is more room for error. They can overexpose the PR and program the spin coater for incorrect speeds or inappropriate lengths of time. Students might use a hexagon mask to expose the wafer instead of the requested grid. Finally, they could leave the wafer in the developer for too long, spill the PR or developer, or forget to dispose of the chemicals after use. A general view of the photolithography laboratory is provided in Figure 7. The rooms are reasonably sized to match the limitation of walking in VR.

MODULE TWO: SPUTTER DEPOSITION

In the sputter-deposition module, students are taught the use of a manual

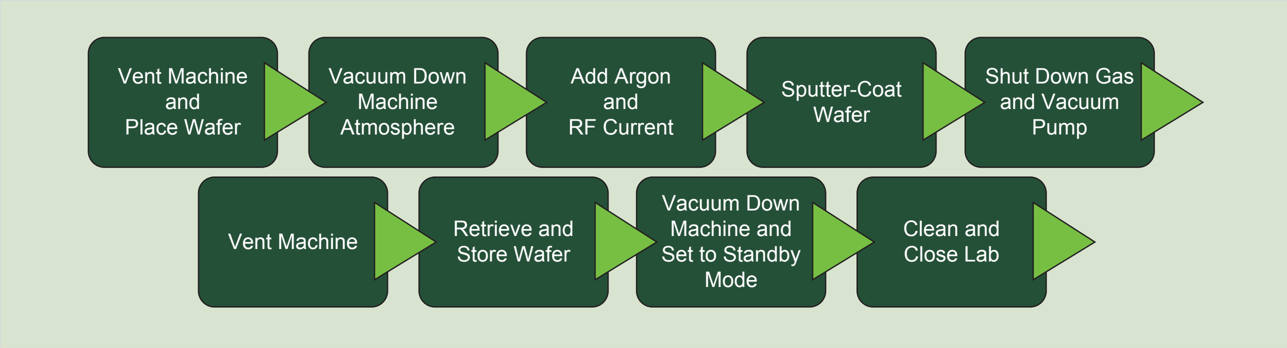

FIGURE 8 The steps in the sputter simulation.

FIGURE 9 Dr. Paul Weber (left) and a student performing the sputter simulation.

FIGURE 10 A VR view of the sputtering room. From left to right: the argon tank, a PerkinElmer 2400 RF sputtering unit, the roughing pump, and the air compressor.

sputter-coating machine. This includes the correct regulation of pressure, heat, and time to produce a good sputter coat on a silicon wafer. The sequence of steps is shown in Figure 8. The simulation begins with students venting the sputter chamber and lifting the lid. They then put the sample inside the machine and set the device to the correct sputter material, which is called a *target*. Once they close the machine, they must reduce it to a low pressure [<1 millitorr (mTorr)] using a two-pump system. Next, they must add a low-pressure flow of argon gas to the chamber while holding the pressure between 6 and 14 mTorr. Upon successfully regulating these two systems, students introduce RF waves into the chamber, causing a plasma to form and begin to sputter coat the wafer. After a set time has passed, students are tasked with safely shutting off the RF current, removing the gas, and reintroducing the chamber to normal atmospheric pressure. The final task is to remove the wafer and set the machine to the standby mode. As with the photolithography simulation, students receive feedback from the blackboard regarding what they did correctly/incorrectly.

Figure 9 shows a student engaged in performing the sputter simulation process. This simulation has an average completion time of 10–15 min. Students can still break wafers during this simulation; however, the other potential areas of error are vastly different. Since the sputter simulation relies heavily on maintaining the correct vacuum, most mistakes relate to that procedure. Errors include trying to open the machine before it has vented, letting the pumps overheat, contaminating the sputter chamber, putting too many wafers into the machine, trying to pump down the atmosphere while the chamber is venting, incorrectly opening valves and causing the machine to "burp" oil into the chamber, and turning on pumps without opening the corresponding valves. Figure 10 depicts the sputter machine room in VR.

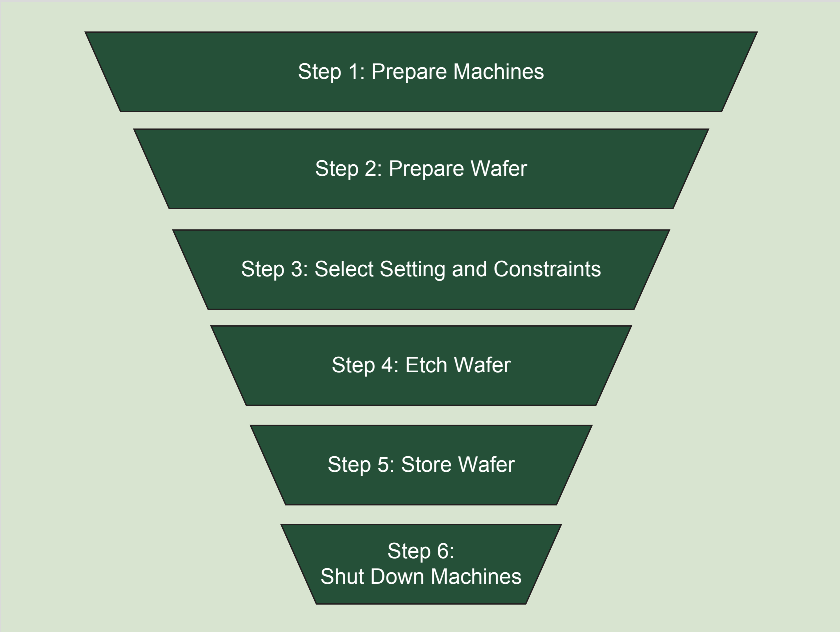

FIGURE 11 The steps in the etching simulation.

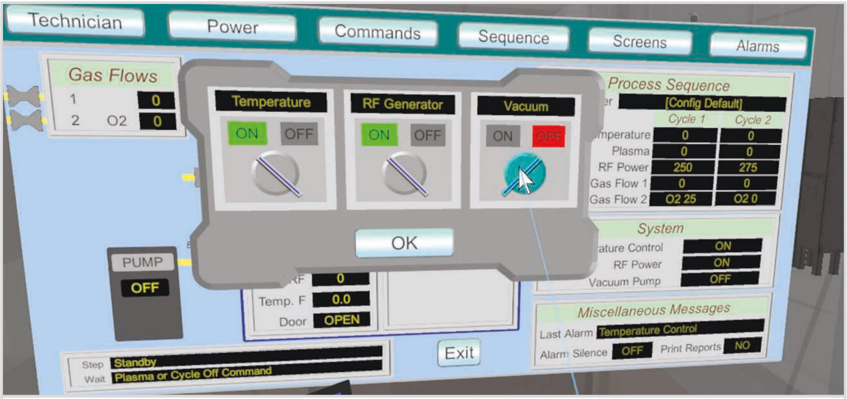

FIGURE 12 A student's VR view when activating the power systems via the computer.

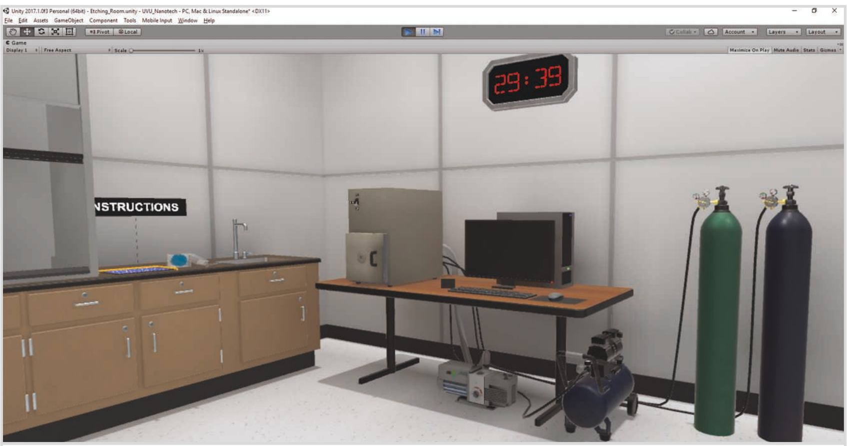

FIGURE 13 A VR view of the etching room. From left to right, the plasma etcher, computer control, and tanks of nitrogen and oxygen.

MODULE THREE: ETCHING

The third module teaches students dry etching using a plasma etcher. In this module, they must prepare the machine to receive a silicon wafer by turning on the supporting systems and power supplies. These systems include an air compressor, vacuum pump, tank of nitrogen, and computer. This sequence of steps is diagrammed in Figure 11. Once the wafer has been placed in the etching machine, students are asked to choose how long to etch the wafer via the computer (Figure 12). The next step is to give the computer the start command and wait for the machine to complete the etching cycle. As with the previous modules, students must then safely store the wafer and shut down the machine and its support systems. Finally, they receive feedback and a grade from the blackboard.

The VR simulation of the etching room appears in Figure 13. Etching has the shortest completion time, with an average of 5–7 min. It also has the lowest number of average mistakes, due to the simplicity of the simulation. However, there are still potential areas for error: students could drop and break wafers; forget to close the door to the etcher, preventing the machine from forming a vacuum; neglect to turn on the gas, resulting in the plasma not forming; and run the etcher for too long.

MODULE FOUR: CHARACTERIZATION

Two modules are developed for characterization: a scanning electron microscope (SEM) and an AFM. In the SEM module (the steps shown in Figure 14), students must prepare a sample for examination through the microscope by using a small sputter machine to coat a desiccated ant specimen with a thin layer of gold for conduction. Once the ant is ready for use, students must turn on a computer, access the program that controls the SEM, and vent the machine so it can be opened. After placing the ant inside the microscope, they need to prepare the instrument for use by regulating the pressure and setting the electron current strength. Next, they are instructed to take three images, each of a separate part of the ant. Students do

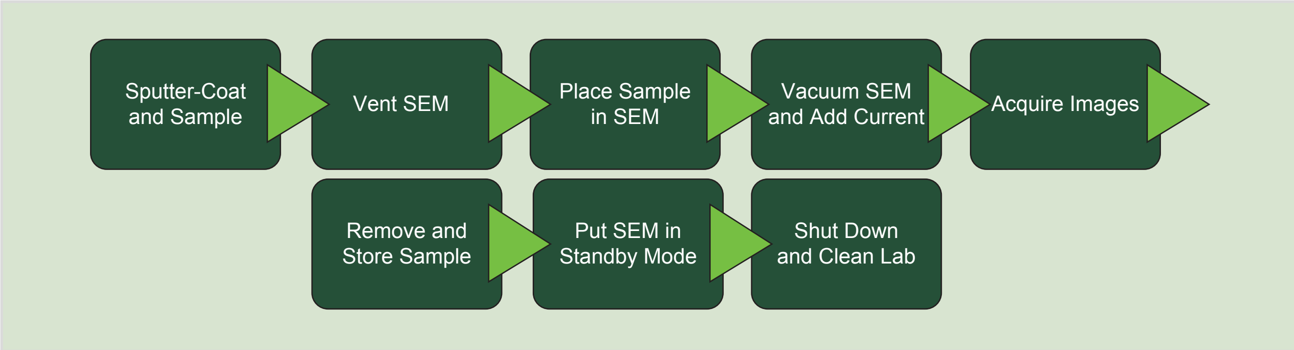

FIGURE 14 The steps for the SEM simulation.

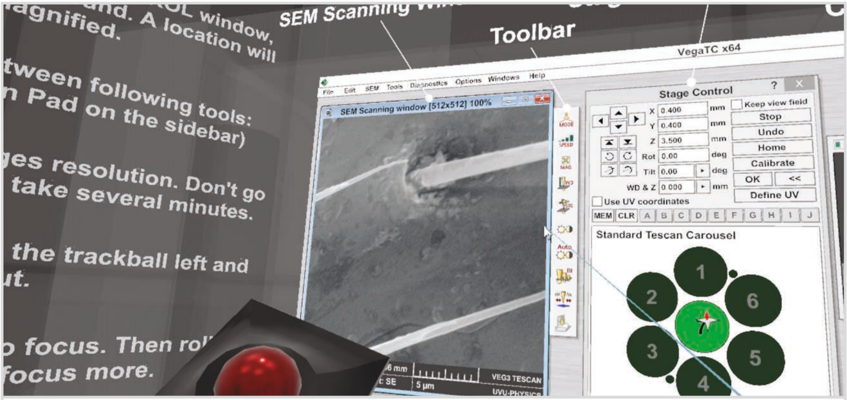

FIGURE 15 A student's VR view of adjusting an image before saving it.

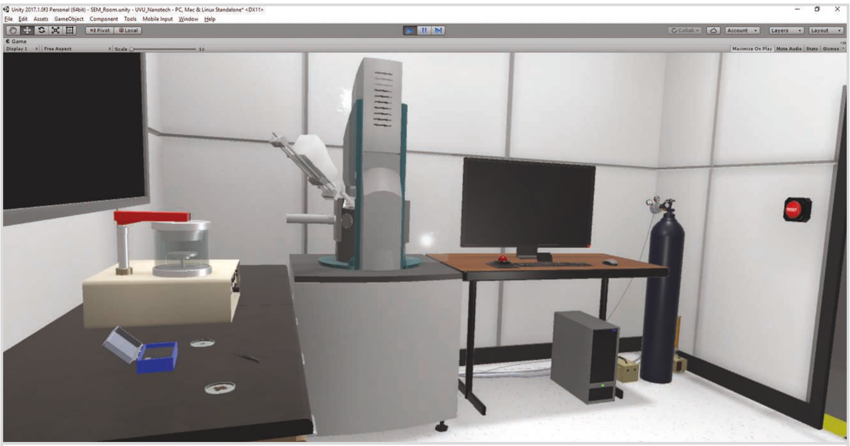

FIGURE 16 A VR view of the SEM room. From left to right, the sample box, small sputter-coating unit, electron microscope gun tower, computer control, and nitrogen tank for powering the pneumatic controls.

this by zooming in to the correct area, setting the focus, adjusting the brightness/contrast, and choosing the scan speed. Figure 15 shows hairs on an ant leg. Upon saving these images, students must remove and store the sample and shut down the machine, which enables them to receive their feedback and grade.

The SEM simulation has the longest average completion time, at 15–20 min. Most mistakes in this module come during the process of acquiring the images, as many students are unfamiliar with how to tell if an image has good contrast, is in focus, and so forth. Other potential mistakes include not sputtering the sample, using incorrect settings to get the electron beam to start, and forgetting to put the sample into the microscope before starting the instrument. Figure 16 gives the VR reproduction of the electron microscope room.

In the AFM simulation, students are required to prepare the machine for use by first making sure the probe is raised sufficiently to avoid breaking it when a sample is placed. They then must insert the sample into the vibration-free carriage system. After placing the sample, they have to align a laser light for use in lowering the probe. Next, they lower the probe until it is close to, but not touching, the sample. Once the probe is close to the surface of the sample, students instruct the computer to take over and finish lowering the instrument. Students then direct the computer to scan the sample using settings that they provide, including the scan speed, angle, and other factors. After receiving the scan, students can change settings to improve the image or save the result and move on. Finally, they raise the probe, remove the sample, shut down the machine, and get their feedback and grade. The AFM simulation is still in the process of being built and has not yet been tested with students.

ASSESSMENT OF STUDENTS IN A VR ENVIRONMENT

Since the purpose of these simulations is to assist student learning, a blackboard is developed to not only provide feedback but give students a grade. This grading process watches what students do, assigns them points for success, and withholds points for mistakes. There are certain cases where students will incur penalties if they drop a wafer, spill fluids, damage machines, or

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perform an action that would otherwise endanger themselves or the equipment. Students can also receive bonus points for properly caring for the equipment by keeping lids closed and quickly storing items, rather than doing only what is explicitly requested in the instructions.

The blackboard score system is illustrated in Figure 17. Two levels of feedback are given: first, there is text that details the expectations during each module. This text is colored green for correct actions and red for incorrect ones. Second, points and an overall letter grade are displayed. Each module is split into multiple steps, and each correctly finished step adds to a student's point total, which is displayed in the corner of the blackboard. Penalties also appear in this area. The point total is then translated into a letter grade and displayed prominently on the board.

Several modules of this project were offered during two nanotechnology summer camps at Utah Valley University. Students participated in four activities at those camps, including a theory lecture on nanotechnology, hands-on practice with nanofabrication, measurement practice by scanning-electron microscopy, and the VR trainings developed as part of this project. While all activities were engaging and well received, the VR practices were the most interesting, according to surveys conducted at the end of each camp. Some students were interested in repeating the VR practices.

CONCLUSION

There are almost unlimited opportunities for creating useful simulations to teach technical machine operation in VR and augmented reality. Many companies, schools, and industries are finding practical applications for these pedagogical tools. While such possibilities are not limited to training simulations, this article reported VR applications in nanotechnology education. Four laboratory rooms with instructions and assessment techniques where developed and tested to be nearly identical to real-world practices. These simulations, along with the engaging nature of VR, show that nanotechnology education can become more accessible at universities and that it can even be taught at lower-division programs, such as high school. VR has great applications in nanotechnology education, where expensive and intricate equipment is involved and where it is especially critical to practice operations in a safe environment before running real machines.

FIGURE 17 The blackboard displaying a student's results.

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ABOUT THE AUTHORS

Reza Kamali-Sarvestani (rkamali@csusm.edu) is with California State University San Marcos.

Paul Weber (paul.weber@uvu.edu) is with Utah Valley University.

Marty Clayton (marty.clayton@uvu.edu) is with Digital Media, Utah Valley University.

Mathew Meyers (mmeyers@uvu.edu) is with Utah Valley University.

Skye Slade (skye.slade@uvu.edu) is with Utah Valley University.

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