Fabricating the Invisible: A Case Study of Observing Nano with the NanoFrazor

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Born and raised in Cleveland/Dayton, Ohio, United States, Nick studied chemistry with a focus on polymers during his undergraduate studies at Wright State University. For his graduate studies, Nick went to the University of Massachusetts Amherst to continue studying polymers and materials and graduated with his doctorate in polymer science and engineering.

During his studies, he had the chance to work in numerous internship positions for companies such as General Motors, British Petroleum, Wright Patterson Air Force Base, Intel, and Victoria University of Wellington, New Zealand. After graduation, he worked in various science and engineering positions from photolithography process development at Micron Technology in Boise, Idaho, United States to more academic related work at ETH Zürich in the group of Prof. Rachel Grange and the Swiss Center for Electronics and Microtechnology (CSEM). Nick is the Innovation Manager at Heidelberg Instruments Nano where he explores future product solutions for the NanoFrazor, thermal scanning probe lithography, and nanofabrication in general.

In his free time, Nick enjoys running, watching Cleveland sports, and traveling.

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Tanisha Gupta is currently pursuing a Bachelor of Science degree in Biomedical Engineering at Worcester Polytechnic Institute (WPI). She has worked on several projects, including her Interactive Qualifying Project in collaboration with Heidelberg Instruments Nano AG, which focused on demystifying nanofabrication and developing educational materials for beginners in nanoscience. On campus, Tanisha serves as Vice President of WPI's chapter of the Society of Women Engineers, is a Global Ambassador for the Global Experience Office and works as a Peer Learning Assistant for Introduction to Biomechanics.

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Dr. Emine Cagin is the CTO of Heidelberg Instruments Nano AG, where the NanoFrazor is developed and supported. She has many years of experience in nanofabrication, through her research and product development work throughout her career. She is enthusiastic about making nanofabrication accessible to students and researchers of many backgrounds.

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Brett Mann is currently pursuing a Bachelor of Science degree in Electrical and Computer Engineering at Worcester Polytechnic Institute (WPI), with concentrations in Computer Engineering and RF Engineering. As part of his studies, Brett has worked on several projects, including a research collaboration with Heidelberg Instruments Nano AG, aimed at demystifying nanofabrication and lowering barriers to entry in the field of nanoscience. He has also completed multiple internships, working as a Program Manager intern at SRGE Inc., and completing two engineering internships with BAE Systems Inc., where he supported the Integrated Test Engineering team and the Hardware Engineering team. On campus, Brett is an active member of the Green Team sustainability club, works as a campus tour guide for the Office of Admissions, and is a member of the Phi Theta Kappa Honor Society.

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Sophia Reynolds is currently pursuing a Bachelor of Science in Biomedical Engineering at Worcester Polytechnic Institute (WPI). Sophia is an undergraduate research assistant in the Musculoskeletal Biomechanics Lab run by Professor Karen Troy at WPI. In addition, on campus she is a member of the varsity cross country and track and field teams, Society of Women Engineers, and Alpha Eta Mu Beta Biomedical Engineering Honors Society.

Prof. Nancy Burnham, Worcester Polytechnic Institute

Professor Burnham investigates nanomaterials, principally with atomic-force microscopy (AFM). She also teaches AFM to undergraduates and graduate students. AFM technology overlaps with the technology behind the NanoFrazor tool discussed in this presentation.

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John DePalma is an upcoming senior at Worcester Polytechnic Institute (WPI). He is a mechanical engineering major and enjoys specifically working with computer aided design (CAD). He has worked with Heidelberg Instruments Nano to make their nanofabrication tools more accessible and useable for education. John has worked as a manufacturing engineer intern at Jonal Laboratories in Connecticut, where he improved assembly processes and designed fixtures for polymer and elastomer sealing products. He works at WPI as a lifeguard at the Sports and Recreation Center and is serving as President of the Underwater Hockey Club.

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Abstract

The reach of nanotechnology impacts many industries and the general world population as people interact with nanotechnology daily, knowingly or not. For example, every time someone opens their smartphone, they are using a result of nanotechnology. Nanofabrication, one of the key processes used for creating nanotechnologies, involves manipulating materials at the nanoscale. One tool that is used in nanofabrication is the NanoFrazor which uses thermal scanning probe lithography (t-SPL) to create and observe nanopatterns in real time.

Despite its importance, educational opportunities in nanofabrication are limited and could be improved upon. To make nanotechnology more accessible, educational modules using the NanoFrazor tool have been developed. These training materials are aimed at students with no prior experience in nanotechnology, focusing on effective teaching methods and evaluating the impact of such educational modules.

Introduction

Have you ever wondered just how small “nano” really is? Imagine something so small that it is invisible to the naked eye, yet it holds the power to revolutionize industries such as electronics, energy, and medicine. When you look at the motherboard of a computer or open the back of your smartphone, you will find chips that are crucial for their operation. What you cannot see, however, are the nanometer sized transistors within these chips. A nanometer is one billionth of a meter. The ability to create transistors at the nanoscale means that more can be integrated into a single chip, significantly improving the processing power of modern electronics.

Have you ever considered how these intricate structures are manufactured? The answer lies in the field of nanotechnology. Nanotechnology is a branch of science and engineering focused on manipulating matter on an atomic and molecular scale, typically below 100 nanometers. At the nanoscale, materials exhibit unique properties that open doors to innovations that were once inconceivable or thought impossible.

Despite its wide utility and immense potential, nanotechnology remains surrounded in mystery to laypeople, especially when it comes to the process of creating nanostructures. This process of creating structures at the nanoscale is known as nanofabrication. For beginners, the inability to “see” what happens on the nanoscale makes the concept abstract and difficult to grasp. Given the lack of visibility with the naked eye, learning and adopting nanotechnology becomes a significant challenge. This is especially relevant as nanotechnology plays an increasingly important role in the world’s shift towards advanced technologies. Addressing this issue is important, not just for educational purposes but also for developing a skilled workforce capable of driving future innovations in nanotechnology.

Nanotechnology is interdisciplinary, requiring teaching methods and a curriculum that integrates basic sciences, engineering, and information technology. As such, interdisciplinary learning should be the hallmark of nanotechnology education [1,2]. Traditional teaching methods such as lectures and textbooks often fail to convey the real-time dynamics of nanofabrication, making it challenging for learners to connect theory with practice. While there are tools and technologies available for nanoscale manipulation, there are limited educational resources that help beginners learn to use them effectively.

By identifying the need for innovative teaching methods and tools to make nanofabrication more accessible and engaging, instruments that enable nanofabrication were reviewed. Common nanofabrication techniques such as electron-beam lithography (EBL), focused-ion beam (FIB) lithography, and maskless laser lithography are often found at universities but lack the capabilities to see structures in real-time or have limitations in design freedom, both of which hinder the educational capabilities of these tools. One such tool that addresses both shortcomings is the NanoFrazor, a nanolithography tool developed by Heidelberg Instruments Nano. The NanoFrazor allows users to "see" nanostructures created in real-time, which is particularly useful for hands-on learning and exploration. While the NanoFrazor has been used primarily as a research tool, it is believed that it could be used as an effective educational tool as the equipment and software are beginner-friendly and customizable while providing the opportunity to create and observe nanostructures in real-time.

The goal of this project is to create educational materials that teaches nanofabrication by using the NanoFrazor, with a target audience of general undergraduate engineering students located in North America. To achieve this goal, classroom lectures with accompanying lecture materials and hands-on laboratory exercises where the NanoFrazor is used to introduce students to nanofabrication in an intuitive and engaged way were developed. In combination with effective teaching methods, we believe that the educational materials, including videos and laboratory guides that support project-based learning in nanotechnology, help to demystify nanofabrication by making the topic more accessible and engaging to those new to the field.

The NanoFrazor Technology

The semiconductor industry relies on structures that are often at a scale less than 25 nanometer (nm) in critical dimensions. In educational and research and development settings, conventional nanofabrication techniques often employee lithography processes such as EBL or FIB lithography to generate such structures. The NanoFrazor technology offers an alternative and complementary direct-write nanolithography process that utilizes thermal scanning probe lithography (t-SPL) to generate nanopatterns [3-6]. Table 1 compares the various nanolithography techniques and highlights the advantages (+) and disadvantages (-) for each technique. From Table 1, it shows that there is not a "perfect" nanolithography technique for educational purposes, but that t-SPL is the leader in being able to see nanopatterning in real time and in a cost-conscience manner but at the expense of not being industrially relevant.

Parameter	Electron Beam Lithography	Focused-Ion Beam Lithography	Maskless Layer Lithography	Thermal Scanning Probe Lithography
Resolution	++	+	-	++
Complex Patterning	+	+	+	++
Cost	--	--	+	+
Speed	-	-	++	-
Industry Relevance	+	+	++	--
Infrastructure Requirements	--	--	+	++
Training Period	--	-	+	++
Seeing Nanopattern In Real Time	--	+	--	++

Table 1. Comparison of various nanolithography techniques.

Enabled by the NanoFrazor nanofabrication tool, t-SPL generates nanopatterns by scanning an advanced cantilever with an ultrasharp thermal probe (< 5 nm in radius) over a sample surface to induce local changes with a thermal stimulus. By using thermal energy as the stimulus, various modifications to the sample are possible via removal, conversion, or addition of or to the sample surface. Along with an ultrasharp probe, the t-SPL cantilever contains several other important functions such as electrostatic actuation, height sensing with an integrated thermal height sensor, and heating via an integrated heating element, all of which are advantageous for nanopatterning. Figure 1 shows microscope images of the advanced t-SPL cantilever with the various elements of the cantilever highlighted.

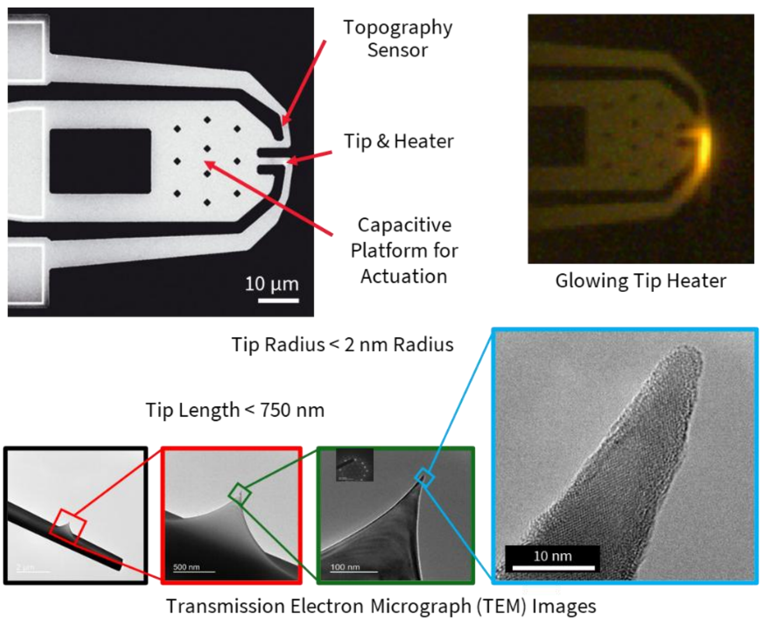

Figure 1. Microscope images showing the various elements of the advanced t-SPL cantilever.

With such advanced thermal cantilevers, the NanoFrazor can feature a closed-loop lithography (CLL) approach, where the written structures are measured and adapted during the same patterning session. Figure 2 shows a cartoon rendition of the CLL approach that is utilized by the NanoFrazor.

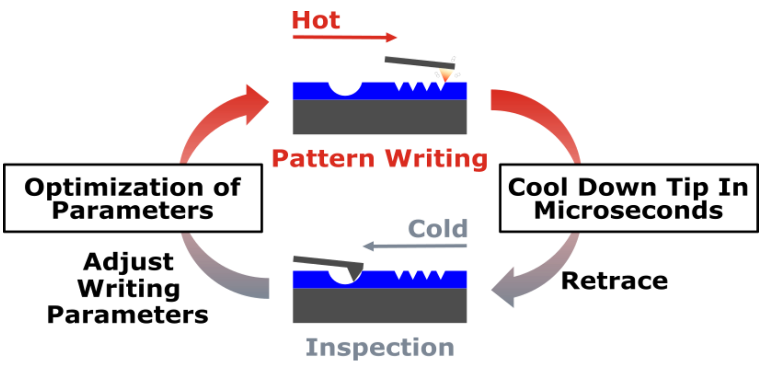

Figure 2. Cartoon rendition of the steps involved in the NanoFrazor CLL approach.

In the initial step of CLL, the cantilever will move from left to right with the cantilever in a heated state, which will locally modify the substrate surface with thermal energy. In this cartoon, removal of material from the thin film is shown. The resistive heating element of the cantilever will then be turned off and the cantilever cooled down in microseconds. In the cooled state, the cantilever will be kept in contact with the surface and moved right to left to trace over the patterned line that was just created. This retrace of surface topography is what allows for the measurement of the surface topography by the integrated topography sensor of the cantilever. The as-measured surface topography of the pattern will then be compared to the desired pattern and the patterning parameters (electrostatic forces, temperature) will be adjusted and optimized to meet the desired pattern dimensions with minimal amounts of patterning error. This cycle of line-by-line patterning and topography measurement is repeated over the entire pattern area until the desired pattern area is completed.

The height detection capability from the integrated thermal height sensor in the thermal cantilever also makes it possible for users to see the nanostructures in real time. Figure 3 is an example topography image of a grayscale pattern generated and imaged by the NanoFrazor.

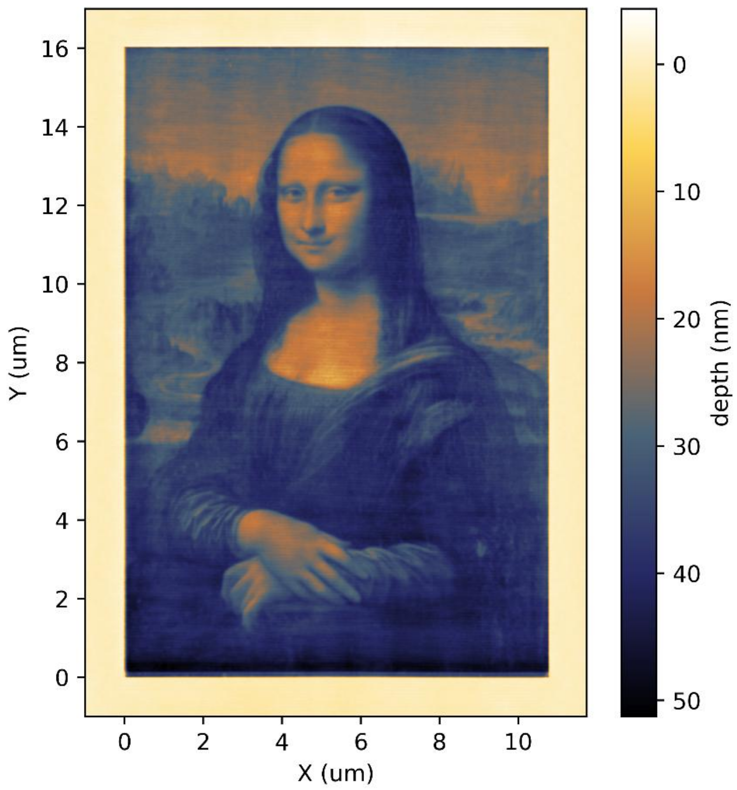

Figure 3. An example image of a grayscale topography pattern generated by the NanoFrazor.

Using this method, users, without any experience, can start writing their first nanopatterns within an hour of training, making the NanoFrazor an attractive tool for introducing new populations to nanofabrication.

The Work

The main objective of this work was to create educational materials for lecturers that target general undergraduate engineering students in North America with no prior nanofabrication experience. To identify and develop effective materials, three targets were created: (1) determine effective teaching methods for nanofabrication, (2) develop educational materials for nanofabrication, that uses the NanoFrazor nanofabrication tool, for general undergraduate engineering students in North America with no prior nanofabrication experience, and (3) evaluate the effectiveness of the educational materials in teaching students basic nanofabrication knowledge.

For the first target, the determination of effective teaching methods was accomplished using a literature review and semi-structured interviews. The literature review examined papers on nanotechnology and nanofabrication basics, perceptions of nanotechnology in society, educational pedagogy, and multiple case studies of nanoscience being taught in classrooms. The semi-structured interviews were conducted with a mix of experts in pedagogy as well as experts in the field of nanotechnology.

From the literature review, it was determined that using a scaffolding approach would be best as its an effective teaching strategy for complex scientific topics. With this educational approach, students are provided with more support early in the learning process and this support will be gradually reduced as students gain confidence and knowledge. During the semi-structured interviews, the interviewees provided invaluable insights into teaching methods and important nanofabrication topics. The experts in nanofabrication all stated the importance of conveying just how small the nanoscale is. This can be done using analogies and real-world comparisons. A recommendation received from an expert in pedagogy was to keep students' attention spans in mind. They recommended making the materials interactive to keep students engaged. Both the experts in nanofabrication, as well as pedagogy, emphasized the importance of providing students with the opportunity to gain hands-on experience, allowing them to apply theoretical knowledge to the real world. Based upon feedback gained during expert interviews and knowledge gained during the literature review, it was concluded that a lecture and laboratory format would be most suitable.

For the second target, current training materials available for the NanoFrazor tool, such as the NanoFrazor User Guide and NanoFrazor Recipe Book, are well aligned for an audience with a technical background or previous experience in nanofabrication as the materials have a great amount of technical depth. However, this material was likely to overwhelm students new to nanofabrication. To make educational materials appropriate for undergraduate students, the current NanoFrazor training materials were used as references to make a balance of lectures for theoretical knowledge and laboratory exercises for practical knowledge, which was the recommendation from the nanofabrication professors. The nanofabrication experts also stressed the importance of providing students with some self-direction within the laboratory exercise such that the students could explore and learn.

From the material review and semi-structured interviews, it was concluded that beginner-friendly language should be emphasized in the lecture materials. Two lectures, with a progression in complexity, were created with the titles of "What is Nano?" and "Nanofabrication". These two lectures are meant to be delivered in two, 50-minute classroom sessions, that introduce the student to nanoscience, nanotechnology, and nanofabrication. The lectures can be delivered as a standalone module or within a broader course on nanoscience or nanotechnology. The "What is Nano?" lecture begins with describing the background on nanotechnology, the nanoscale, and applications as if the student has no previous knowledge of nanoscience or nanotechnology. The learning objective from the initial lecture is to provide the student with the appropriate knowledge to understand nanofabrication. The "Nanofabrication" lecture focuses on nanofabrication before going into depth about t-SPL, the nanofabrication technique used in the NanoFrazor. The learning objectives from the second lecture are to further establish the student's knowledge in nanoscience and nanotechnology and introduce the nanofabrication topic and the operating principles of t-SPL.

Laboratory exercises were developed such that these exercises would be conducted after both lectures were completed. The laboratory exercises were designed to be performed in groups of two to four students within a two-hour laboratory session. Beginner-friendly level writing was used throughout the step-by-step instructions to allow for maximum understanding. Each laboratory exercise contains background, pre-lab, main lab, and conclusion sections. The background section provides learning objectives for the laboratory exercise and what the student is expected to complete during the laboratory session. The pre-lab section provides the student with one to two videos to watch and a corresponding questionnaire for the student to answer, all of which will prepare the student for the main lab. The main lab section is where the student will be operating the NanoFrazor with step-by-step instructions to achieve the end goal of the laboratory exercise. In the conclusion section, the student will complete a questionnaire that addresses the work completed in the main lab section with the goal to reinforce the laboratory exercise learning outcomes.

Four laboratory exercises were created with the titles of "Creating Your First Nanostructure", "Transistors Through Time", "Marklerless Overlay", and "Stitching". For example, the "Creating Your First Nanostructure" laboratory exercise is simple in scope and serves as an introduction to nanofabrication with the NanoFrazor tool and t-SPL. Here the students will be able to select a photo of their interest, see Figure 4 as an example, and use this image for initial nanopatterning as well as to see how adjusting various t-SPL parameters influences the pattern quality of the selected photo. It is critical to mention here that the nanostructure the student prepares is observable in real time such that the student can quickly see how the nanopatterning results are influenced by adjusting various process parameters. As a learning objective for the initial laboratory exercise, the student is expected to be able to understand how the NanoFrazor works and the underlying principles of t-SPL. Such laboratory exercises provide students with a well-defined result that the students can work towards while applying the knowledge from the two lectures.

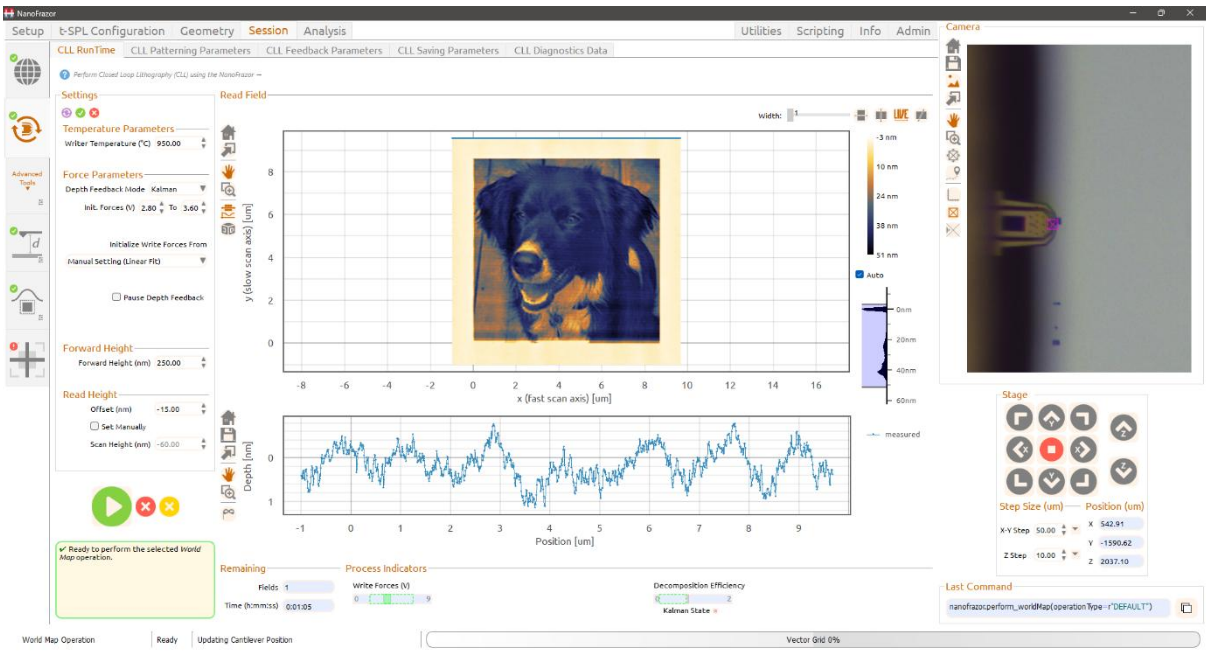

Figure 4. Example of student defined nanopatterning with the NanoFrazor.

The overall objective of this work is to generate interest in nanofabrication that will ultimately lead to interest in the semiconductor industry. To obtain a glimpse into the effectiveness of the lectures and laboratory exercises, a focus group of four students with various general engineering backgrounds at the undergraduate level was formed. The focus group's feedback on the lectures was that the two lectures were able to simplify a complex topic of nanoscience and nanotechnology into understandable parts while being easy to follow. When the lectures and the first laboratory exercise were provided to the focus group, all within a single four-hour session, the participants felt this was an effective method for newcomers to be introduced to the topic of nanofabrication.

For the final target of evaluating educational material effectiveness, pre- and post-surveys were conducted on the focus group. When surveyed before the lectures and the first laboratory exercise, 3 of 4 focus group participants stated no understanding of the nanofabrication process and 1 of 4 stated little understanding. From the post-survey, all focus group participants reported an increase in their understanding of nanofabrication processes. The post-survey also yielded data on the usefulness and clarity of the educational materials. When asked about the connection between concepts, lectures, and the laboratory exercise, all participants found the connection to be clear, well made, and helpful. Furthermore, the laboratory exercise was found to be very useful in teaching nanofabrication to beginners as 3 of 4 participants stated that the laboratory exercise was a great help in their learning. While the initial laboratory exercise was deemed successful and the NanoFrazor tool was viewed as beginner-friendly, there is always room for improvement. Feedback from the focus group suggested to have additional diagrams, in the form of photos and software screenshots, that would further clarify the steps necessary to complete the initial laboratory exercise. It is also acknowledged here that the learning materials need to be evaluated with a larger focus group.

Overall, the educational materials were deemed to not only be effective in teaching students about nanofabrication but the students' enthusiasm and interest in the subject of nanofabrication were increased as well. The results of this work may best be summed up by one participant stating "I knew nothing before and now I understand the basic technical functions and applications of nanofabrication and how to use the nano Frazor device. I definitely would have loved to learn more about the applications especially outside of the academic field.".

The Presentation

In this presentation, we will briefly introduce the NanoFrazor technology and then discuss the course and laboratory modules that have been developed that show how t-SPL can be used as a technique for connecting nanotechnology theory with practice. The lectures and laboratory exercises will be discussed along with the effectiveness of the educational materials from a small focus group of four participants.

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