Seeing is Believing - How the NanoFrazor Generates and Sees Nano in Real Time

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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.

Dr. Emine Cagin, Heidelberg Instruments Nano AG

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.

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.

Tanisha Gupta, Worcester Polytechnic Institute

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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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.

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Abstract

The global semiconductor industry is facing a critical worker shortage that threatens to derail the revenue trajectory of this internationally important industry, one that is projected to generate over a trillion USD by 2030 [1]. To address this, companies are investigating and investing in workforce development. Heidelberg Instruments Nano aims to contribute to this effort by utilizing the NanoFrazor tool in nanofabrication related education modules. By leveraging nanofabrication and imaging capabilities associated with thermal scanning probe lithography (t-SPL), students can create and see nanostructures in real-time and within an hour of training.

In collaboration with Worcester Polytechnic Institute (WPI), Heidelberg Instruments Nano has developed teaching materials for both classroom and laboratory settings. Such materials include guided laboratory exercises, self-learning videos with accompanying quizzes, and lecture slides to integrate nanofabrication into conventional semiconductor courses. The goal here is to spark interest in nanofabrication and, ultimately, the semiconductor industry by seeing the generation of nanostructures in real-time!

Introduction

The semiconductor industry is driving advancements in several modern technologies that are globally critical such as electronics, communications, energy, sensing, and various other fields. The demand for semiconductors will continue to increase for the foreseeable future as innovations such as artificial intelligence, 5G technology, and Internet of Things (IoT) continue to evolve rapidly. However, the growth of the semiconductor industry could be hindered if one critical challenge is not addressed quickly, with that challenge being a lack of skilled workers.

The shortage of semiconductor workers is a crisis that is grabbing the global semiconductors companies' attention today as the worldwide semiconductor industry is expected to generate more than a trillion USD by 2030 [1]. This is an important global industry where a lack of qualified semiconductor workers could hinder this target. To address this issue, significant investments by industry, educational institutes, and governments are being made in workforce development via training, education, and recruitment programs to sustain this critical semiconductor ecosystem. We at Heidelberg Instruments Nano believe we can make a small but significant contribution to this workforce development effort by making the nano visible in real-time, which we think will trigger interest in the available workforce to further investigate a career that involves nanofabrication and, ultimately, the semiconductor industry.

The NanoFrazor Technology

Nanofabrication is at the heart of the semiconductor industry by creating structures that are nowadays often at a scale of less than 25 nanometer (nm). To create such structures in educational settings, conventional nanofabrication techniques often employee lithography processes such as maskless laser lithography, electron beam lithography (EBL), or focused-ion beam (FIB) lithography. Each one of these nanolithography techniques has its own set of advantages and disadvantages when it comes to use in an educational environment. The NanoFrazor technology offers an alternative and complementary nanolithography process that utilizes thermal scanning probe lithography (t-SPL) to generate nanopatterns [2-5]. To compare the various nanolithography techniques, Table 1 highlights the advantages (+) and disadvantages (-) for each technique.

Parameter	Maskless Layer Lithography	Electron Beam Lithography	Focused-Ion Beam 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.

t-SPL, enabled by the NanoFrazor nanofabrication tool, generates nanopatterns by scanning 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, it is possible to perform various modifications to the sample via removal, conversion, or addition of/to the sample surface. Along with an ultrasharp probe, the t-SPL cantilever contains several other important functions such as an integrated topography sensor, capacitive platform for electrostatic actuation, and an integrated heating element, all of which are advantageous for nanopatterning in all three dimensions of X, Y, and Z. Figure 1 shows the various components of the t-SPL cantilever.

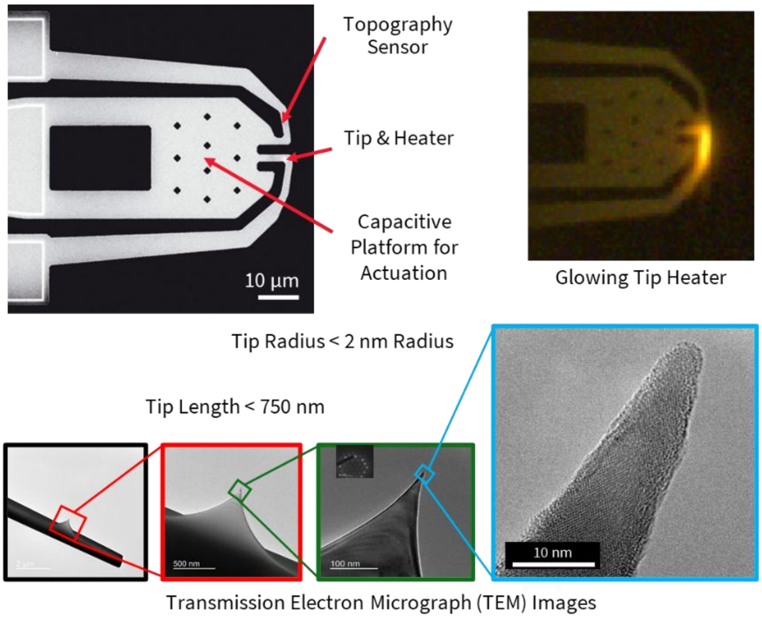

Figure 1. Various components of the t-SPL cantilever.

With such advanced thermal cantilevers, the NanoFrazor features a closed-loop lithography approach, where the written structures are measured and adapted during the patterning session. Figure 2 shows a cartoon of how the closed-loop lithography approach, utilized by the NanoFrazor, works. In the first step, the cantilever will move from left to right with a heated cantilever, which will locally modify the substrate surface, in this example, remove material from the surface. The cantilever will then be cooled down, within several microseconds, kept in contact with the surface, and moved from right to left to trace over the pattern that was just created. This retrace of the surface topography allows for the measurement of the topography with the integrated topography sensor. The measured surface topography of the pattern will then be compared to the desired pattern and the patterning parameters, e.g. electrostatic force, will be adjusted and optimized to meet the desired pattern dimensions. This line-by-line approach is repeated over the entire pattern area until the final pattern is completed.

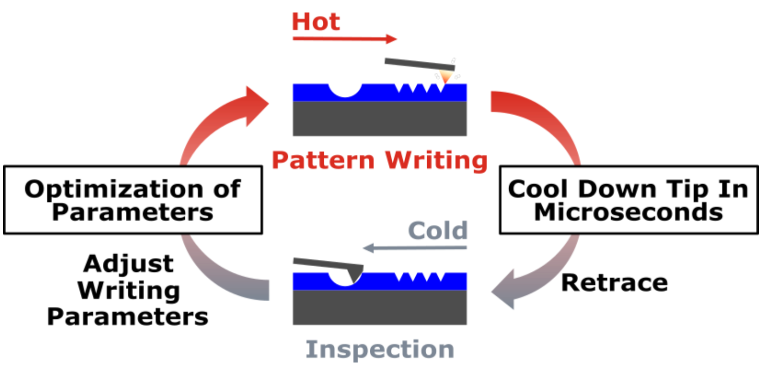

Figure 2. Cartoon showing the various steps involved in the closed-loop lithography approach.

The detection capability from the integrated thermal height sensor in the thermal cantilever is also what makes it possible for students to see the nanostructures in real time. An example of a pattern generated from the NanoFrazor is shown in Figure 3.

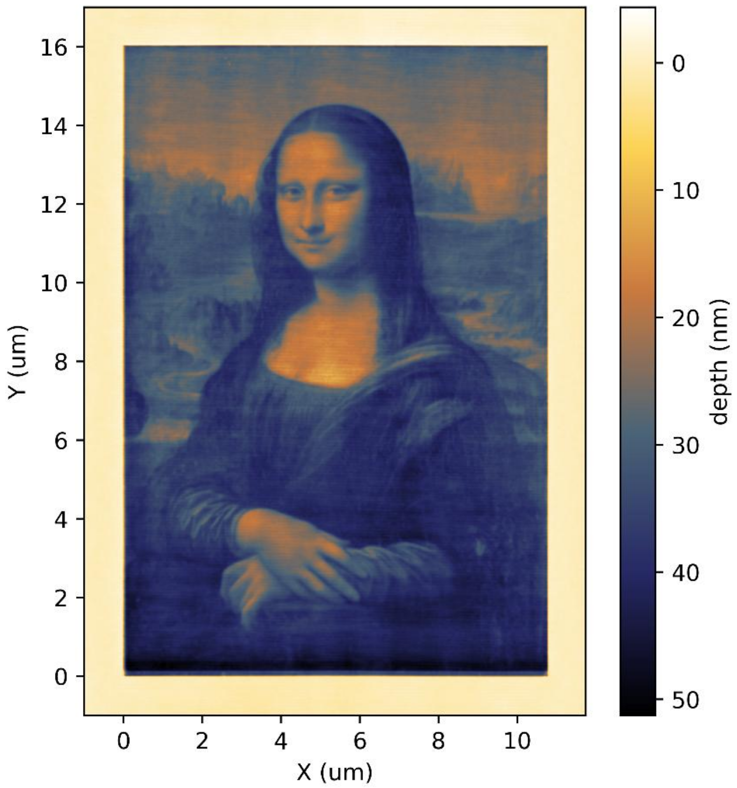

Figure 3. An example pattern generated from the NanoFrazor.

Using this method, novice users can start writing their first nanopatterns within an hour of training, making the NanoFrazor a high potential tool for introducing new populations to nanofabrication.

The Work

In a collaboration building on the 10+ years of nanofabrication experience at Heidelberg Instruments Nano and project-based learning expertise at Worcester Polytechnic Institute, we took additional steps to evaluate how the NanoFrazor could be used in both classroom and laboratory settings. A series of teaching materials for active learning opportunities were developed, ranging from lectures and guided laboratory exercises to self-learning videos with embedded quizzes. The teaching materials include two lectures, meant to be delivered via two, 50-minute classroom sessions, that introduce the student to nanoscience, nanotechnology, nanofabrication, and thermal scanning probe lithography. The first lecture, titled "What Is Nano?" introduces the student to nanoscience and nanotechnology with the assumption that 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 background knowledge to understand nanofabrication. The second lecture, titled

“Nanofabrication”, introduces nanofabrication to the student. The learning objectives from the second lecture are to build upon the student’s knowledge of nanoscience and nanotechnology by introducing the topic of nanofabrication and the operating principles of thermal scanning probe lithography.

The laboratory exercises consist of various complexities with the most basic laboratory exercises consisting of creating the student’s first nanostructure with the NanoFrazor to the patterning of transistors through time that highlights how transistors have shifted in size from microns to nanometers. The laboratory exercises are built upon the two lectures, which provide an opportunity for the student to apply the knowledge gained in the lectures in a laboratory environment. The laboratory exercises were designed to be for groups between two to four students and to be completed within a two-hour laboratory session. The writing used for the laboratory exercises was completed at a beginner-friendly level with step-by-step instructions to allow for maximum understanding. Each laboratory exercise contains sections for background, pre-laboratory, main laboratory, and conclusion. The background section provides the learning objectives for the laboratory exercise and what the student should complete during the laboratory session. The pre-laboratory section provides one to two videos for the student to watch followed by a questionnaire for the student to answer, which will prepare the student for the main laboratory. The main laboratory section is when the student will be operating the NanoFrazor via step-by-step instructions to achieve the end goal of the laboratory exercise. There is a questionnaire at the completion of the main laboratory section to reinforce the laboratory exercise learning outcomes.

In Lab 1, “Creating Your First Nanostructure”, the student will be guided through the setup of the NanoFrazor tool where a basic understanding of thermal scanning probe lithography will be provided. The student will be able to select an image for nanopatterning that is specific to the student, for example, in Figure 4, the student here selected an image of their pet. This image will then be used throughout the laboratory exercise for that student to understand how the various patterning parameters influence the final nanostructure pattern. It is important to emphasis here, again, that the nanostructure is being prepared and observed in real time such that the student can quickly see the results from the nanopatterning process and adjustments that the student makes. At the end of this laboratory exercise, the student will be able to understand how the patterning function of the NanoFrazor works.

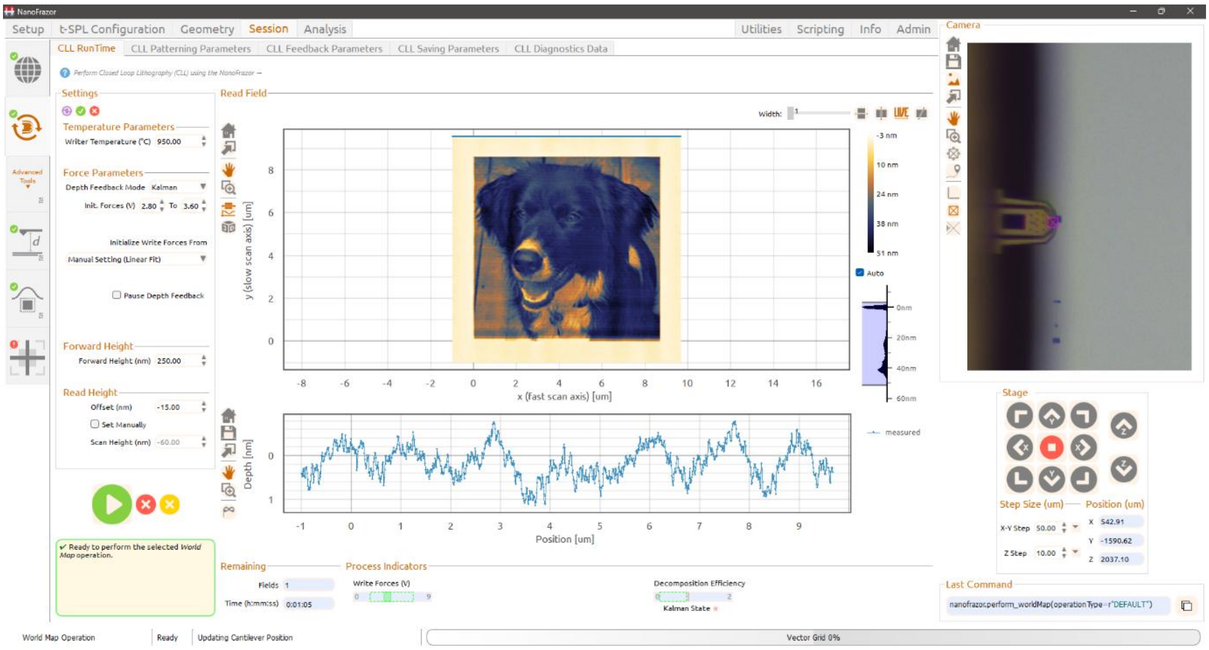

Figure 4. Example of student defined nanopatterning with the NanoFrazor.

In Lab 2 “Transistors Through Time”, the student will be provided with additional hands-on experience with the NanoFrazor while making the connection between nanopatterning and the semiconductor industry through transistors. In this laboratory exercise, the student will pattern various critical dimensions of transistors through time. The critical dimension for the various integrated circuit process nodes consists of either the contacted gate pitch, interconnect pitch, gate length, or minimum metal pitch, whichever dimension is the smallest. At the end of this laboratory exercise, the student will be able to understand how nanopatterning influences integrated circuity and how the critical dimensions of transistors have scaled with time.

The ultimate goal of this work is to trigger interest, either initial or further, in nanofabrication and, eventually, interest in the semiconductor industry. For this purpose, a focus group was assembled to provide feedback on the lectures and the first laboratory exercise. Participants from the focus group found the lecture slides easy to follow and commented that the lectures effectively reduced a complex topic of nanoscience, nanotechnology, and nanofabrication into manageable segments. When the lectures were coupled with the first laboratory exercise, the focus group participants felt this was an effective learning method for beginners with no prior experience with nanofabrication to gain knowledge on the topic. As a result, all participants in the focus group improved their knowledge of nanofabrication as well as increased their enthusiasm to learn more about this topic. This initial result shows that the educational materials being created here are an effective medium for introducing the nanofabrication topic and is an opportunity to excite the next generation of nanofabrication students.

Conclusions

The need for workers with knowledge in nanofabrication is a must for the semiconductor industry to keep growing at the predicted pace. Industry leaders, educational institutions, and governments are aware of this need and are investing aggressively in workforce development. To make nanofabrication more accessible and engaging, and potentially to inspire a new generation of semiconductor professionals, Heidelberg Instruments Nano offers the NanoFrazor technology, based on thermal scanning probe lithography, for nanolithography. With advanced thermal cantilevers, the NanoFrazor features a closed-loop lithography approach, where the written structures are measured and adapted during the patterning session. This method allows novice users to start writing and seeing their first nanopatterns within an hour of training, making the NanoFrazor a high potential tool for introducing new populations to nanofabrication. In combination with comprehensive lecture and laboratory materials, the NanoFrazor tool is positioned to offer an effective entry to nanolithography and, ultimately, to nanofabrication for the masses.

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 thermal scanning probe lithography can be used as a technique for bridging nanotechnology theory into practice by showing the generation of nanostructures in real time right before an audience.

References

[1] Deloitte. “The Global Semiconductor Talent Shortage Report”.

[2] S.T. Howell, A Grushina, F. Holzner, and J. Brugger, "Thermal scanning probe lithography – a review," Microsystems & Nanoengineering, 6, 21 (2020).

[3] O. J. Barker, A. Mohammadi-Motlagh, A. J. Wright, R. Batty, H. Finch, A. Vezzoli, P. S. Keatley, and L. O’Brien, “Thermal nanoconversion of ferromagnetic nanoislands,” Applied Physics Letters, 124, 112411 (2024).

[4] B. Erbas, A. Conde-Rubio, X. Liu, J. Pernollet, Z. Wang, A. Bertsch, M. Penedo, G. Fantner, M. Banerjee, A. Kis, G. Boero, and J. Brugger, “Combining thermal scanning probe lithography and dry etching for grayscale nanopattern amplification,” Microsystems & Nanoengineering, 10, 28 (2024).

[5] L. Shani, J. Chaaban, A. Nilson, E. Clerc, G. Menning, C. Riggert, P. Lueb, M. Rossi, G. Badawy, E. P. A. M. Bakkers, and V. S. Pribiag, “Thermal scanning probe and laser lithography for patterning nanowire based quantum devices,” Nanotechnology, 35, 255302 (2024).