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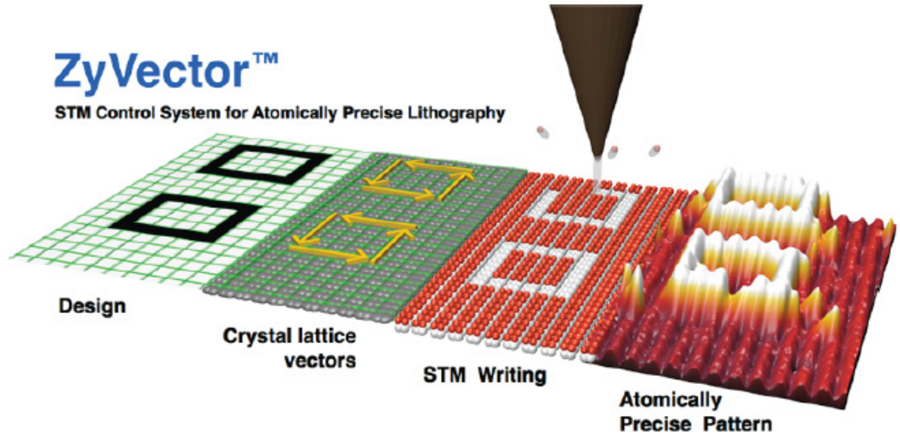

This project will develop a microelectromechanical system (MEMS) platform technology for scanning probe microscope-based, high-speed atomic scale fabrication. Initially, it will be used to speed up, by more than 1000 times, today's single tip hydrogen depassivation lithography (HDL), enabling commercial fabrication of 2D atomically precise nanoscale devices. Ultimately, it could be used to fabricate 3D atomically precise materials, features, and devices.

Graphic image courtesy of University of Texas at Dallas and Zyvex Labs

Innovations in Scanning Tunneling Microscope Control Systems for High-throughput Atomically Precise Manufacturing

Atomically precise manufacturing (APM) is an emerging disruptive technology that could dramatically reduce energy use and increase performance of materials, structures, devices, and finished goods. Using APM, every atom is at its specified location relative to the other atoms—there are no defects, missing atoms, extra atoms, or incorrect (impurity) atoms. Like other disruptive technologies, APM will first be commercialized in early premium markets, such as nanoelectronics for quantum computing.

One potential approach to fabricating atomically precise (AP) nanoscale devices is based on turning a scanning tunneling microscope (STM) used to image atoms into a tool for manufacturing at the atomic scale. Today's STMs work at speeds useful for imaging and writing but are too slow to be commercially viable in manufacturing applications. The objective of this research project is to speed up and improve STM control so large arrays of STMs can quickly and precisely fabricate commercial quantities of AP materials, features, and devices.

Multiple STM tips operating precisely in parallel require streamlined geometry and increased control to achieve the high throughput necessary for commercial viability. STM nanopositioners with precision movement in three dimensions are also needed for the required accuracy and coordination between the multiple STM tips. By dramatically improving the geometry and control of STMs, they can become a platform technology for APM and deliver atomic-level control. First, an array of micro-machined STMs that can work in parallel for high-speed and high-throughput imaging and positional assembly will be designed and built. The system will utilize feedback-controlled microelectromechanical system (MEMS) functioning as independent STMs that can operate 100 to 1000 times faster than state-of-the-art systems and with sub-nanometer accuracy, improving the precision of writing atomic features on a surface while protecting the STM tip in both imaging and writing modes. The speed and throughput will be increased to a rate that could enable industrial-scale fabrication of devices with nanoscale features.

This project's initial approach to STM-based APM is based on the only existing technology used to fabricate AP two dimensional (2D) devices—hydrogen depassivation lithography (HDL). Today's HDL uses a single tip to image and lithographically 'write' with atomic resolution.

Ultimately, high-throughput MEMS-based systems may also be used in conjunction with other scanning probe microscopes, such as an atomic force microscope (AFM), to enable mechanosynthesis (i.e., moving single atoms mechanically to control chemical reactions) of three dimensional (3D) devices and for subsequent positional assembly of nanoscale building blocks.

Benefits for Our Industry and Our Nation

This APM platform technology will accelerate the development of tools and processes for manufacturing materials and products that offer new functional qualities and ultra-high performance. Advancements may lead to a wide range of high value energy-saving products, including applications such as: diffraction arrays with unprecedented optical performance, molecule-specific membrane filters, catalytic surfaces, and improved boiling interfaces for heat transfer.

Applications in Our Nation's Industry

This technology is expected to have broad applicability and enable high-throughput APM of devices. Initial industrial use could involve making nanoimprint lithography and roll-to-roll AP templates that can fabricate devices with previously unattainable electronic properties. The templates are an attractive high value market. Integrated circuit metrology, photomask inspection, and metrology systems integrated into roll-to-roll manufacturing processes are all viable applications for such a system.

Project Description

The project objective is to build a platform technology for high-throughput APM based on innovations that dramatically increase the speed and accuracy of STMs. The first innovation is to use new MEMS actuators instead of the piezoelectric actuators currently used in STMs. Piezoelectric actuators are highly resonant systems that require low-bandwidth (slow) controllers and suffer from hysteresis and creep, which limits their positioning precision. The second innovation is to streamline the connection geometry to enable precise and fast operation of arrays of multiple STM tips to increase throughput.

Initially, the technology will be used to make 2D devices with HDL on hydrogen-terminated silicon. In this method, the tip of an STM injects electrons into the chemical bond holding the hydrogen atom to the silicon surface, causing it to break. Each removed hydrogen is then replaced with a dopant atom. This technique has been used to make single-electron transistors, quantum dots with only a few atoms, and 2D quantum metamaterials for research purposes. HDL coupled with the MEMS STM could lead to additive manufacturing with atomic precision. The envisioned system will enable AP lithography at speeds and throughputs 2-3 orders of magnitude beyond what is feasible with current technology. It will enable the programmable atomic-scale positional control needed to fabricate the smallest building blocks and the positional assembly of these building blocks into atomically precise systems and sub-systems to create more complex atomic-scale electronic devices and systems. This multidisciplinary project will combine innovations in mechatronic system design, feedback control, high-precision engineering, and microfabrication technologies to achieve the increased speed, throughput, and accuracy necessary for commercially viable APM.

Barriers

- Achieving needed imaging speed, parallel operation of probes, and atomic-precision positioning
- Extreme multidisciplinary nature of the project.

Pathways

The project will first design and fabricate all the necessary prototype components required to perform high-speed and high-throughput HDL imaging and writing. These include a high-speed macroscale nanopositioner to enable implementation of high-speed scan patterns; micro-machined MEMS STMs; and atomic force microscopy (AFM) micro-cantilevers with self-sensing and self-actuation functionalities. Feedback control algorithms will be developed to operate the system with high accuracy and with control loops to guarantee stability, robustness, and repeatability of operation.

Subsequently, components will be assembled resulting in a single tip system that can be tested in imaging and lithography modes. At the conclusion of this project, the high-speed imaging capability developed will be used to determine an appropriate location for lithography, and the system will perform HDL with atomic precision, with one or several MEMS STMs operating simultaneously. Follow-up research will demonstrate multiple tips that are needed for parallel operation. These systems could be scaled up into one- or two-dimensional STM arrays consisting of hundreds of nanopositioners operating in parallel to enable high-speed and high-throughput imaging and lithography.

Milestones

This three-year project began in 2018:

- Develop new non-raster modes of imaging for scanning probe microscopes and build a high-speed long-range nanopositioner (2019)
- Improve STM control system to enable new modes of HD lithography and spectroscopy (2020)
- Demonstrate MEMS STMs and an array of high-frequency MEMS AFM cantilevers (2020)
- Demonstrate a closed-loop control system that can achieve a lateral bandwidth of 20 kHz, with the controller achieving a positioning accuracy of ± 0.1 nanometer (2021)

Technology Transition

Successful execution of this project will complete the first step needed to make AP 2D nanoscale devices commercially viable. In the long term, the technologies being pursued offer a path to developing controllable nano-mechanical systems. In the short term, there will be the opportunity to market individual technologies developed throughout this project, such as the MEMS STM and AFM. For example, a possible path for advancing the technology toward the marketplace would be UT-Dallas licensing the MEMS STM scanner technology to Zyvex Labs. Zyvex has successfully commercialized a number of complex nanotechnology systems in the past.

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