A Platform Technology for High-throughput Atomically Precise Manufacturing: Mechatronics at the Atomic Scale

Award Number EE0008322

UT Dallas, Zyvex Labs and NIST

6/15/2018 – 6/14/2021

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One of five coordinated 1465 FOA projects in Atomically Precise Manufacturing

Overview

Project Title: A Platform Technology for High-throughput Atomically Precise Manufacturing: Mechatronics at the Atomic Scale

AMO MYPP Connection:

- **Target 5.4:** Develop new process technologies that can provide production quantities of commercial-scale atomically precise products.
- **Target 16.5:** Develop and demonstrate a one square micron (1 μm^2) atomically precise circuit.

Barriers and Challenges:

- High-throughput Atomic Precision Lithography
  - High-speed imaging for lithography
  - Parallel operation of probes
  - Atomic precision positioning
- Extreme multidisciplinary nature of the project.

Milestones:

- BP1: six quarters, currently in Q4
- All milestones have been met
- On track to meet BP1 Go/NoGo goals

Timeline:

Project Start Date: 06/15/2018

Budget Period End Date: 12/31/2019

Project End Date: 06/14/2021

Project Budget and Costs:

Budget	DOE Share	Cost Share	Total	Cost Share %
Overall Budget	$2,417,938	$605,990	$3,023,928	20%
Approved Budget (BP-1)	$1,230,396	$358,736	$1,589,132	22%
Costs as of 3/31/19	$359,329	$57,428	$412,757	14%

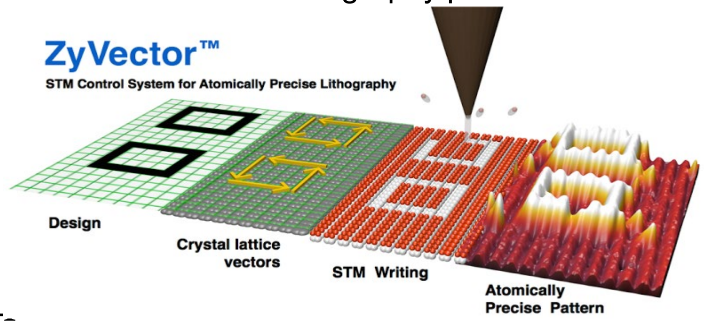
Project Team and Roles:

- UT Dallas Laboratory for Dynamics and Control of Nanosystems collaborates with Zyvex Labs and NIST.
- UT Dallas leads the project and is involved in all aspects of the research.
- NIST will participate in design and fabrication of MEMS STMs.
- Zyvex Labs will integrate the developed systems into existing STMs and perform validation experiments.

Project Objectives

- *The problem:*
  - Develop a high-throughput Atomically Precise Manufacturing (APM) system based on Hydrogen Depassivation Lithography.
  - Requires repeatable positioning control of a large array of probes with sub-nm precision, a challenging task.

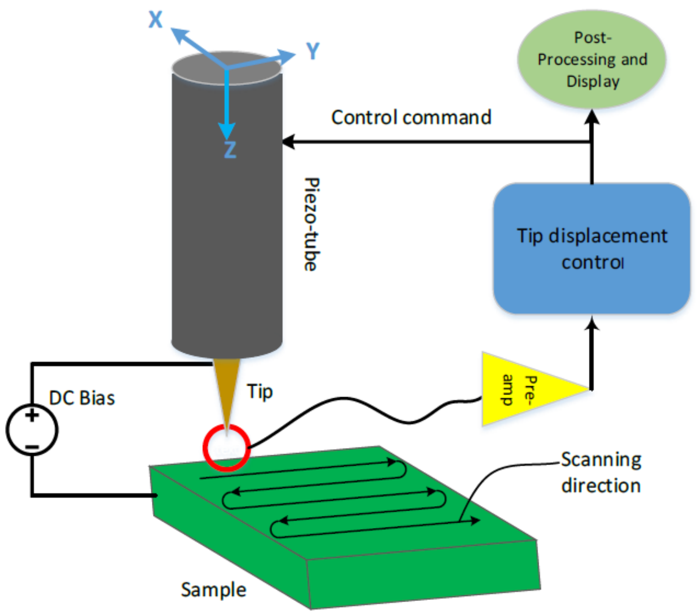
The HD-Lithography process



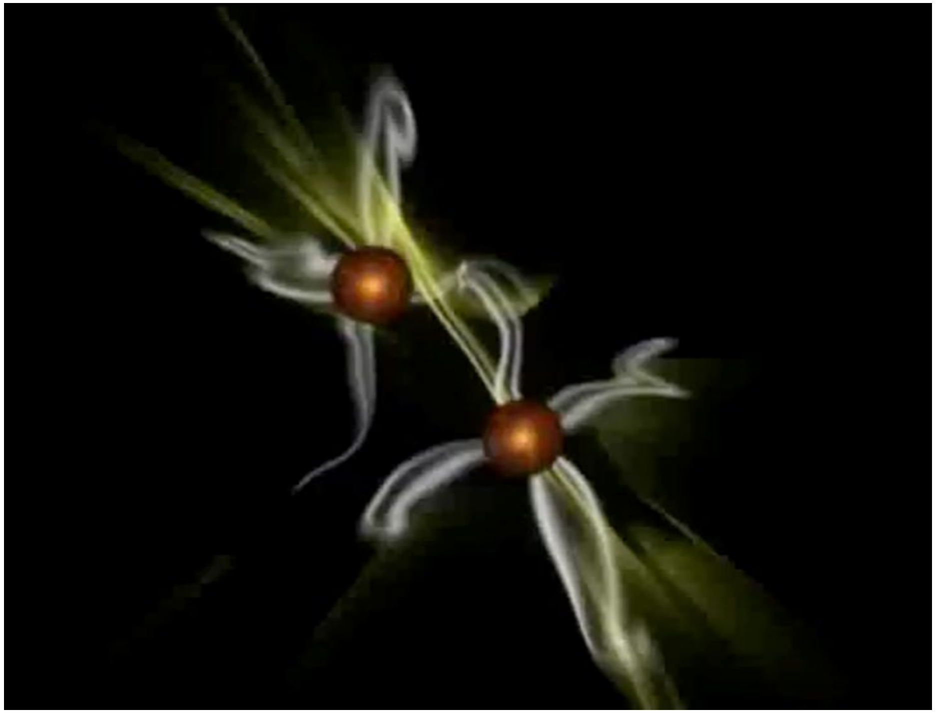
- *Potential benefits and alignment with AMO mission and*
  - This work will enable atomically precise lithography at speeds and throughputs 2-3 orders of magnitude beyond what is feasible today, paving the way for commercial-scale fabrication of APM products. This will address Target 5.4 of AMO's MYPP.
  - This technology will be highly suitable for commercial-scale fabrication of Silicon quantum electronic devices. This will address Target 16.5 of AMO's MYPP.
  - Once the technology is proven in early premium markets, such as quantum computing, the cost should drop rapidly as it is scaled up to manufacturing scale. Relatively fast market penetration is feasible because the technology builds on decades of experience with commercial STM and MEMS technologies.
- *Relevance to energy & energy efficiency:*
  - APM offers the ultimate in miniaturization for a variety of products and thus significant reductions in their embodied energy (e.g. factors of 2-3 in energy savings in their manufacturing processes.)
  - Scaling down computing units from the microscopic to the atomic scale will reduce energy consumption of computing devices —thus enabling the continuation of Moore's Law.

Technical Innovation

- HD lithography is done today using a Scanning Tunneling Microscope (STM). The STM was invented over 35 years ago and has changed little ever since. Its primary use is imaging material surfaces with atomic resolution.
- STMs use a piezoelectric actuator to move an atomically sharp tip over a surface, while a feedback control system maintains a tunnelling current at a constant value.



Principle of operation of the STM



STM-based HD lithography for fabrication of 3D APM products and devices

Technical Innovation

- Use of STM for HD-Lithography is complicated by a number of issues:
  - Piezoelectric actuators are highly resonant systems which require a low-bandwidth controller to function properly – *this sets a hard limit on their speed*.
  - STMs perform lithography with a single tip – *this limits their throughput*.
  - Piezoelectric actuators suffer from hysteresis and creep – *these limit their positioning precision*.
- *Speed, throughput and precision* are the issues that we will attempt to resolve in order to make this technology commercially viable.

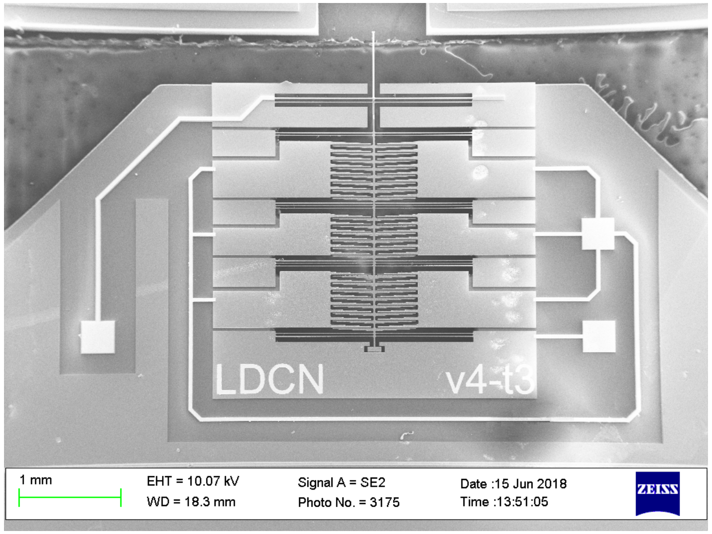
Multi-probe STM array

- This is a multidisciplinary project that will combine innovations in mechatronic system design, feedback control, high-precision engineering and microfabrication technologies to enable atomically precise manufacturing (speed, throughput and precision). Specifically, we will
  - build a high-bandwidth 3 Degree of Freedom (3DOF) nanopositioner with interferometric displacement sensors and feedback control loops to achieve closed-loop atomic precision.
  - build a parallel array of actuators to increase throughput of the system by enabling a large number of tips to perform lithography simultaneously.

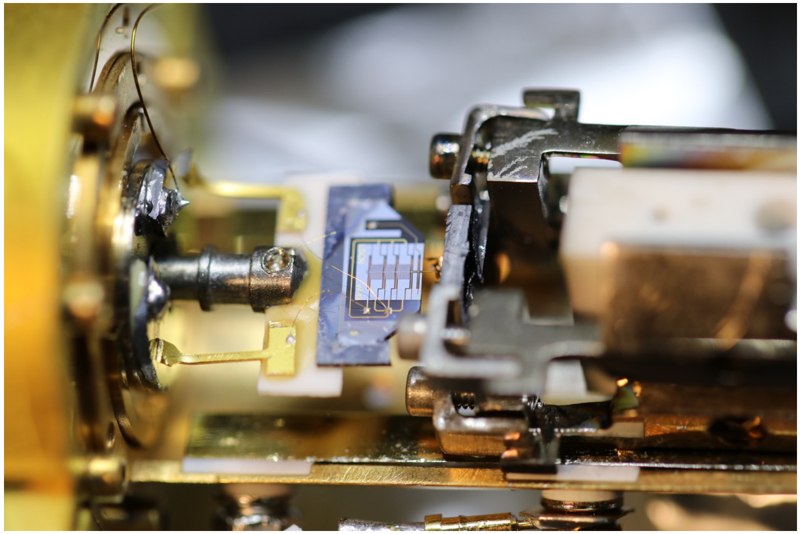
Technical Approach

During this program we intend to progressively move away from using piezoelectric actuators in STM, ultimately replacing them with MEMS nanopositioners.

- The MEMS STM nanopositioners that we design are at least 10 times faster than piezos, thus enabling a faster operation compared with today STMs.
- Using MEMS enables us to build a compact array of STM tips that operate in parallel, thus increasing the throughput of the system for both lithography and imaging.
- The electrostatic actuation used in MEMS is far more suitable for atomically precise positioning than piezoelectric actuation.

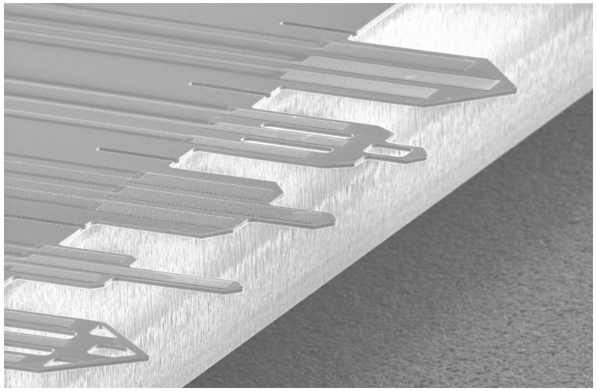


1 DOF microfabricated MEMS STM



Integration in Ultra High Vacuum (UHV)

Technical Approach



Multi-probe microfabricated active AFM cantilevers

- Imaging is an important capability in atomically precise lithography. To enable both higher speed and throughput non-contact atomic force microscopy (ncAFM) and STM, we are:
  - developing novel non-raster scanning methods for high-speed ncAFM and STM.
  - designing and building arrays of active micro-cantilevers for high-throughput ncAFM.

The Team:

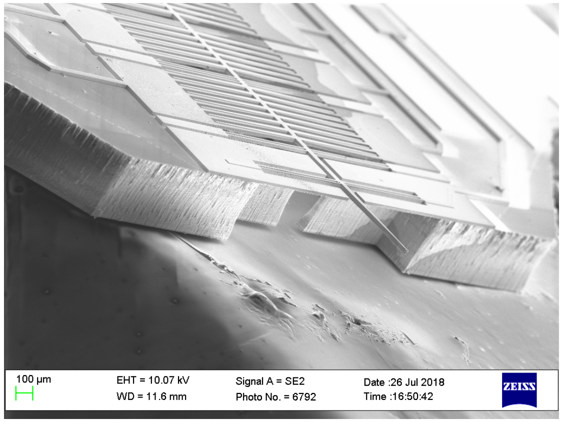
- The project is led by Reza Moheimani (UT Dallas), and involves close collaborations with Jason Gorman (NIST) and the team led by John Randall (Zyvex Labs). We are a multidisciplinary team with a history of close collaboration on complex projects.

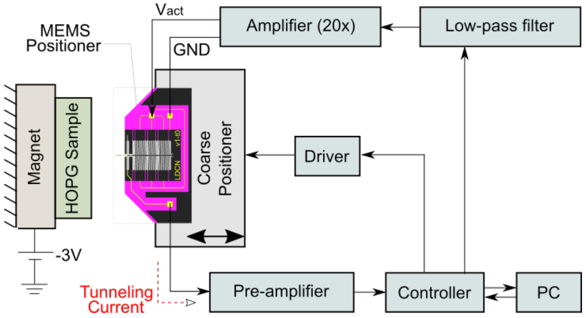
Participant roles:

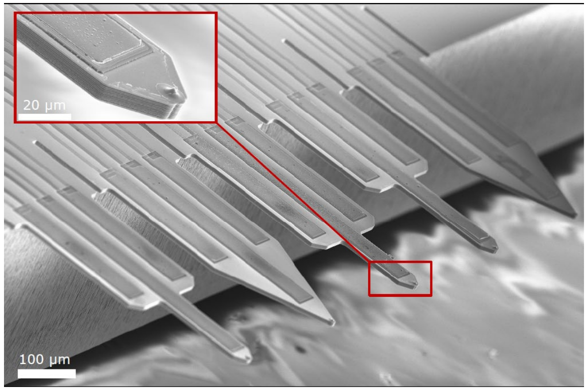
- UT Dallas will design and fabricate 1DOF MEMS STMs, a 3DOF flexure-guided nanopositioner, feedback control algorithms for MEMS STMs and an active cantilever array for both STM and ncAFM.
- NIST will design and fabricate a 3DOF MEMS STM, collaborating closely with UT Dallas.
- Zyvex Labs will participate in the overall design process and will specifically integrate the developed STM systems (1DOF and 3DOF) in a UHV STM system to experimentally demonstrate their functionalities.

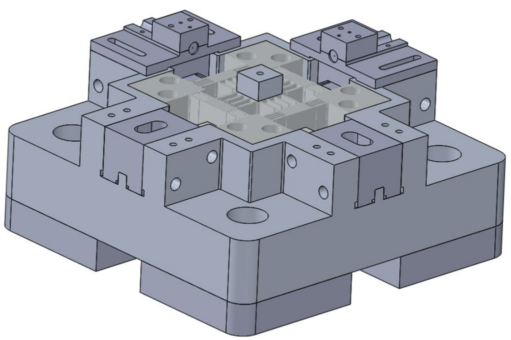
Results and Accomplishments

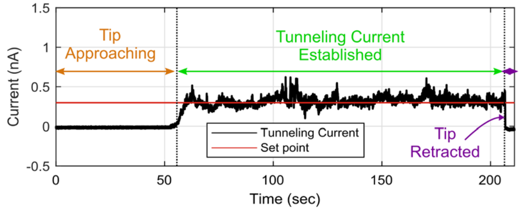
- Results and Progress:
  - All BP1's Q1-Q4 milestones have been met, or exceeded.
  - We developed a process for microfabrication of 1DOF MEMS STMs.
  - We designed a high-bandwidth 3DOF nanopositioner that is being assembled and soon will be characterized.
  - We developed a process for microfabrication of ncAFM cantilevers with integrated piezoelectric sensors and actuators.
  - We developed a non-raster scanning method for high-speed STM and ncAFM.
  - Outcomes have been reported consistently in conference or journal papers.











Transition (beyond DOE assistance)

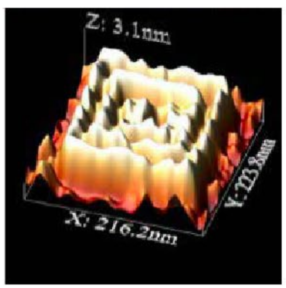
<u>Strategy for further development and commercialization:</u>

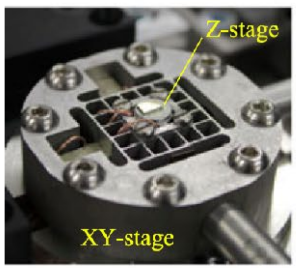
- **Long term strategy:** Outcomes of this project will enable commercial scale fabrication of APM materials and devices. We will work closely with our partners, Zyvex Labs and NIST to further develop the technologies and set a path for successful commercialization.
- **Short term strategy:** We will attempt to commercialize individual technologies as they are developed. In particular:
  - We believe there is a market for MEMS STM devices that we are currently developing. We are a partner in a DOE-STTR project with Zyvex Labs - Phase I completed, Phase II awarded - that specifically aims to commercialize our MEMS STMs.
  - We believe there is a market for the AFM cantilevers that we have designed, and will investigate avenues to commercialize those using SBIR programs – Technology disclosure filed with UT Dallas Office of Technology Commercialization.

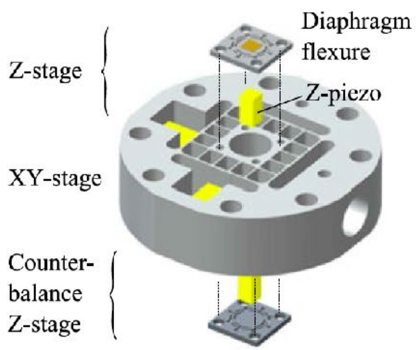
<u>Commercialization Partners:</u>

- We have been working closely with Zyvex Labs and NIST to develop this technology to the point that it can be commercialized.
- Our efforts are also guided through collaborations with ScientaOmicron (the largest manufacturer of STMs in the world).

Questions?


Z: 3.1nm
X: 216.2nm
Y: 223.8nm


Z-stage
XY-stage


Diaphragm
flexure
Z-stage
Z-piezo
XY-stage
Counter-
balance
Z-stage