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Nano-Lithography in Ultra-High Vacuum (UHV) for Real World Applications

J. Gilsinn, H. Zhou, B. Damazo, J. Fu, R. Silver

National Institute of Standards & Technology (NIST)
Manufacturing Engineering Laboratory (MEL)

ABSTRACT

As nano-lithography technology improves, more companies and research groups have the capability to create nano-scale structures. Scanning tunneling microscopes (STMs) are commonly used to create these structures and evaluate them afterward. One difficulty is that these nano-structures are difficult to find on a centimeter-sized sample without very specialized hardware and post-processing. The National Institute of Standards and Technology (NIST) is conducting research into developing an integrated system consisting of a high-precision STM, course motion system, interferometer, and vision system that would allow these structures to be accurately created, recognized, and evaluated in ultra-high vacuum (UHV). The fast scan direction in this high-precision STM uses a piezo-driven flexure stage with an interferometer system that allows the motion to be tracked very accurately. A course motion system allows the sample to be moved in larger steps than the STM could move on its own. A vision system capable of locating micro-scaled structures on the sample is used to map larger features on the sample and aid the STM in writing and locating nano-scale features. By combining all these components into one integrated system, NIST hopes to develop the capability to combine nano-scale features with large-scale structures.

Keywords: nano-lithography, STM, interferometer, microscopy, etching

1 INTRODUCTION

With electronics manufacturing driving commercial devices smaller and smaller, the demand for building nano-scale devices (50 nm to 1000 nm in size) is seen as a future industry with great potential. Nano-lithography is one promising technology for building these structures. Although there are multiple techniques for nano-lithography and the theory behind these techniques has been around for years, nano-lithography has not moved far from research and development facilities. Some barriers preventing broader application of these technologies are the high startup costs and the ability to perform relevant analysis on these nano-structures once created.

One technique for creating and inspecting nano-structures uses a scanning tunneling microscope (STM), but a problem is that these nano-structures are difficult to locate on a centimeter-sized sample without very specialized hardware and post-processing. The National Institute of Standards and Technology (NIST) is conducting research into developing a system that would allow these nano-structures to be more easily manufactured, located, and identified.

2 SYSTEM OVERVIEW

The heart of the new system is a modified commercial STM. Commercial STMs normally uses a lead zirconate titanate (PZT) piezo-electric tube to drive the STM tip in two directions. The tip scans fast in the X direction (left to right) and scans slow in the Y direction (top and bottom). While STMs produce very precise results after post-processing, their scanning motion is not easily controllable. The NIST system replaces the fast scan direction of the STM with a PZT-driven flexure stage with an interferometer system that allows the motion of the STM to be monitored very accurately.

The new system will also incorporate a millimeter-scale motion system for course positioning, allowing larger scale samples to be used and larger features to be written and imaged. Two PZT-driven linear stages mounted perpendicular to one another are used to move the sample in both the X and Y direction relative to the STM tip allowing the entire sample to be utilized [1].

While nano-scale devices have been written for many years, there have been few or no commercial applications of them yet. One of the difficulties has been to place them onto a specific portion of a sample and locate them again once they have been created. Typical STMs cannot image more than a few hundred nanometers in high-precision mode, which is not large enough to locate nano-scale devices on a centimeter-sized sample. A vision system is being developed for the new nano-manufacturing system that will allow the location of the STM tip to be known relative to other sample features. While the features on the current samples are calibrated lines and grids, the technology should allow for circuit lines and other structures to be viewed just as easily.

The technologies discussed above are a key part of writing nano-scale structures on a sample, but proper sample preparation and pattern generation techniques are also necessary. The samples used in the NIST system have been prepared using a silicon etching technique and written using selective modification of a hydrogen-terminated surface.

3 STM SYSTEM

The heart of the NIST nano-lithography system is the STM system. It combines a commercial STM tube, flexure stage, and an interferometer into one complete system allowing the movement of the STM tip to be very accurately known.

3.1 Flexure Stage

The fast scan direction of the commercial STM used in the NIST system can be replaced by the motion of a flexure stage driven by a PZT actuator. The motion of the stage along the X-axis is approximately 1 µm and constrained along the axis by the design of the flexure joints. A sample holder station is mounted to the face of the stage carrying a sample holder and plane mirror for the interferometer. The sample and plane mirror are moved along the fast scan direction with respect to the STM scanning tip. A schematic drawing of the flexure stage and STM system design can be seen in Figure 1.

3.2 Interferometer

A new implementation of a Michelson interferometer capable of approximately 20 pm resolution has been developed [2]. This new method uses a tunable diode laser as a light source with the diode laser wavelength continuously tuned to fix the number of fringes in the measured optical path. High-speed, accurate measurements of the beat frequency created by beating the diode laser against a reference laser enable the diode laser wavelength to be measured.

The basic principle of this measurement system is that the output frequency of a tunable diode laser is adjusted so that as the measurement arm of a Michelson interferometer is scanned, the signal remains locked on a fringe [3]. Figure 2 shows a schematic of the optical apparatus with the measurement and control strategy and a CAD drawing of the in-vacuum equipment. The fringe signal arises in this apparatus from a differential measurement of the reference arm signal against the measurement arm signal, where the measurement arm is the distance from the birefringent crystal to the plane mirror on the flexure stage. To track the laser diode frequency, a portion of the beam is split off and beat against a reference, a stabilized Helium-Neon (HeNe) laser [4]. This allows the diode laser wavelength to have direct, unbroken traceability.

This is a homodyne interferometer system meaning only a single frequency is used in the interferometer portion of the system. The two-frequency portion of the measurement system is independent of the interferometer and measurement mirrors. In addition, no fringe interpolation is required since the measurement is based on holding constant the number of fringes in the optical-path difference between the reference arm and the measurement.

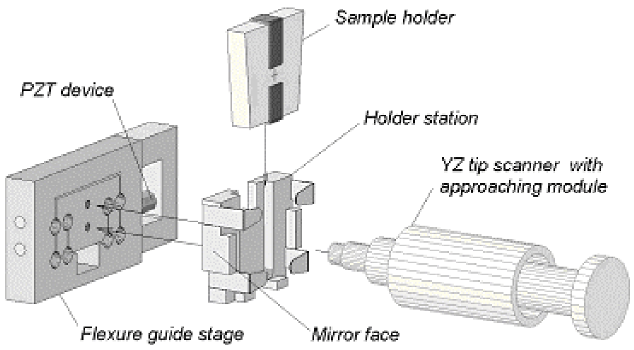

Figure 1 - Schematic Diagram of the Flexure Stage and STM System Design.

The diode laser frequency is continuously controlled by a PZT actuator to lock to a null point in the fringe signal measured at the bicell detector. As the plane mirror is scanned, the diode laser frequency is changed to maintain a constant zero in the difference signal between the two polarization states exiting the 45º rotated birefringent crystal. The diode laser is operated with a control bandwidth of a few hundred hertz since the PZT actuator has a maximum operation speed of 2 kHz.

A stabilized HeNe laser is used as the reference signal to measure the diode laser frequency. The tunable diode laser beam is split with a polarizing beam splitter. Half the signal goes to the reference measurement system and the other half goes to the interferometer. The HeNe reference beam and the diode laser beam are mixed in the reference measurement path so that they cause a beat frequency signal. This nominally 2 GHz signal gives a direct measure of the diode laser frequency relative to the stabilized HeNe reference signal, which has been appropriately calibrated. A computer logs the frequency measurement synchronized with the STM Z height data, providing traceability for the STM data.

4 MILLIMETER-SCALE MOTION

While the STM used in the NIST system is capable of atomic resolution scans and nano-scale writing, it is not capable of doing either of these over an entire sample. The samples used for the NIST experiments are approximately 1 cm square, while the largest motion of a high-precision STM is typically on the order of a few hundred nanometers. In order to increase the motion capabilities of the system, a millimeter-scale motion system is required.

The millimeter-scale motion system consists of two PZT-driven linear stages mounted perpendicular to one another and oriented along the X and Y axes of the STM system. The stages are PZT-driven linear stepper stages that move with 4 nm steps over a distance of 5 mm. While the current stages cannot image an entire 1 cm square sample, they are capable of proving the concept of large-scale nano-structure design and fabrication.

Since the interferometer is not capable of measuring the distances required to scan or write on an entire 1cm square sample, a method to increase the measurement capability of the interferometer is needed. A possible solution that utilizes the existing interferometer system is called fringe hopping. During operation, the interferometer is locked into the null-point on one fringe of a beat signal. Fringe hopping causes the interferometer to lock into the null point from the next fringe, which increases the interferometer's measurable distance.

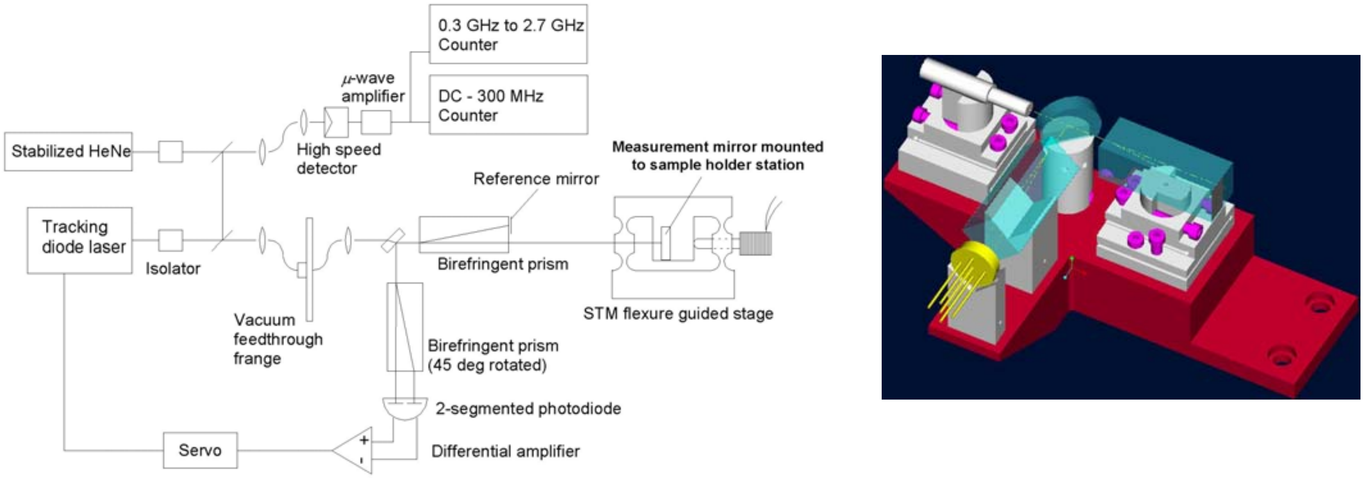

Figure 2 - Schematic & CAD Drawing of the Interferometer Beam Path & System Design

5 VISION SYSTEM

The vision system being designed should be capable of viewing the silicon surface with a resolution of 1 µm using optical technology. While this will not be capable of viewing the nano-scale objects themselves, it will be able to identify a region of the sample surface to be written on and to search for the object in future scans. This is important when trying to connect things like circuit lines or pads with the nano-scale objects.

The main design goals for this vision system are UHV compatibility and long working distance. None of the components of the vision system are vacuum compatible, so a retractable tube with a quartz window is being designed to extend into the UHV chamber. An optical microscope designed with a working distance of approximately 3 cm will be inserted into this tube. The vision system will incorporate both through the lens illumination as well as offset lighting in order to get the best contrast for viewing the micro-scale objects on the sample. The vision system also incorporates interchangeable 10x and 20x lenses that give the appropriate magnification needed for a particular experiment. During bake-out of the UHV chamber, the vision system will be removed from the tube to avoid damaging any of the sensitive components.

6 NANO-LITHOGRAPHY TECHNIQUE

6.1 Sample Preparation

To prepare nanometer scale features in a vacuum environment, nearly atomically flat and ordered surfaces are required. Silicon is a highly desirable substrate for this work because of its widespread usage in semiconductor manufacturing. One difficult challenge several research groups have encountered in attempting to use Si in nanotechnology applications has been in finding a robust method for the repeatable preparation of large, ordered, flat surfaces.

Wet chemical etch processing can produce high quality, atomically flat Si(111) surfaces without requiring high temperature [5]. The etching process results in hydrogen-terminated Si (1x1) surfaces that are quite stable in an ambient environment [6]. The hydrogen termination can be locally removed through electron stimulated desorption [7][8], making it possible to fabricate nano-scale structures using a STM.

Currently, most research groups working on this subject are using a common RCA [9] type pre-cleaning followed by 40% NH4F etching, developed by Werner Kern while at the Radio Corporation of America (RCA). However, details in the methods used vary widely. In order to better understand the mechanisms of the wet etching process and to develop more repeatable procedures, NIST has systematically studied various etching conditions on several different control wafers. We have found that the etching time and wafer miscut play a key role in the determination of the final morphology of the Si(111) surfaces.

Figures 3 and 4 show example results for wafers with a 0.12° miscut in the $\left[1,1,\bar{2}\right]$ direction. This miscut angle results in an average terrace width of 150 nm. The images show a 2μm square area of the wafer surface with the $\left[1,1,\bar{2}\right]$ direction pointing to the right and $\left[\bar{1},1,0\right]$ direction pointing up. After 2 minutes etching, shown in Figure 3, the terraces become the dominant features on the surface. There are still many triangular pits, but they only have an average size of 50 nm on the terraces. After 6 minutes etching, shown in Figure 4, no triangular pits are observed and the step edges are much straighter. Samples prepared in this way are the substrates for the writing technique discussed below.

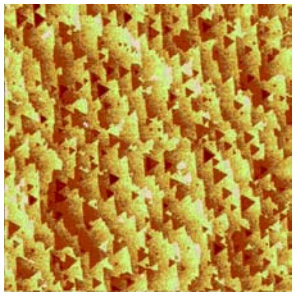
Figure 4 - AFM Image, 2 Minutes Etch

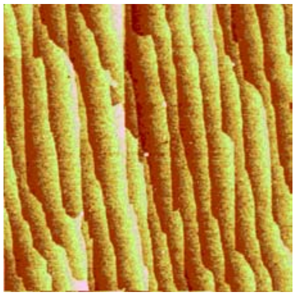
Figure 3 - AFM Image, 6 Minutes Etch

6.2 Pattern Generation

One of the major barriers preventing the widespread application of UHV patterning is the lack of a robust pattern transfer technique or the ability to locate and subsequently image the patterns in an external tool. NIST has developed a robust method to transfer patterns into the substrates, with known feature positions, so that they can be accessed by a variety of external metrology tools.

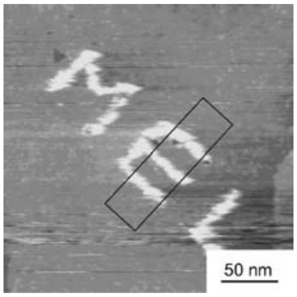

Figure 5 - STM Image of Written Sample

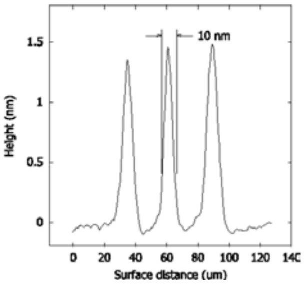

Figure 6 – Cross Section of Sample Image

Figures 5 and 6 show some UHV STM pattern generation results. The pattern generation technique uses selective modification of the hydrogen termination on a surface using a STM. These results were obtained with the writing parameters of 800 pA constant current and +6 V bias voltage. A cross section of the image, showing averaged data from the area delineated, is shown in Figure 6. These patterns have an average line width of nominally 10 nm and, as measured by the STM, have a height of approximately 1 nm.

7 SUMMARY

NIST is integrating commercial and newly developed components and techniques to develop a nano-lithography system capable of creating large-scale nano structures. While none of the components or techniques described in this paper are ground breaking, their combined application in a complete system should demonstrate a capability that has been difficult for many to achieve. Once the motion of the STM tip can be measured and moved accurately, it can be controlled. Also, a vision system capable of viewing micro-scale features allows for writing nano-scale structures in a known location on a sample. These results would allow nano-structures to be integrated with larger features created by standard semiconductor techniques.

8 REFERENCES

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