A Macro-Micro Motion System for a Scanning Tunneling Microscope

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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 one centimeter-size die cut from a silicon wafer without very specialized hardware and post-processing and analysis. The National Institute of Standards and Technology (NIST) is conducting research into developing a macro-micro motion system that would allow these nano-structures to be more effectively located and identified on the die. An XY stage system using linear piezo actuators will perform the macro motion by moving the sample to where the STM tip can scan a particular region of the die to make an analysis. The STM tip would then perform the micro motion by scanning the region for the nano-structure. A vibration isolation system has been designed for this macro-micro motion system using springs and eddy current dampers. This vibration isolation system will isolate the entire system from the outside world and the individual components from each other. Along with the motion systems described above, a high-precision interferometer system will be installed to independently monitor a flexure driven stage for the STM tip. A graphical programming system has been developed for controlling the motion of the STM tip. All of these systems - the macro-micro motion system, the vibration isolation system, the interferometer system, and the graphical programming system - combine to form the initial steps toward coordinated closed-loop control of the STM.

KEYWORDS: nano-lithography, nano-manufacturing, macro-micro motion, STM, interferometer, vibration isolation, graphical programming

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 cost and the ability to perform relevant analysis on these nano-structures.

One technique for creating and inspecting nano-structures uses a scanning tunneling microscope (STM). One problem is that these nano-structures are difficult to locate on a centimeter-size die cut from a silicon wafer without very specialized hardware and post-processing and analysis. The National Institute of Standards and Technology (NIST) is conducting research into developing a macro-micro motion system that would allow these nano-structures to be more easily manufactured, located, and identified on a millimeter-scale surface, such as a die.

OVERVIEW OF NIST SYSTEM

While the Manufacturing Engineering Laboratory (MEL) at NIST has used nano-lithography and a STM to create nano-scale structures in the past, the process has reached the limits of the current system. The current STM in use for nano-lithography does not have the capability to develop large, nano-scale structures or to find those structures once they have been created. By designing a new system, it is hoped that these two goals can be met.

The current system uses a standard Burleigh STM system (max motion, approx. 500 nm square at atomic resolution) and a Digital Instruments controller*. While this system works well for imaging of surfaces, issues remain when trying to create larger structures that were not taken into account when the original system was purchased. Our proposed system will replace the frame and structure surrounding the STM, improve the method for scanning the surface, and develop a new method for programming the motion used by the STM.

To stabilize the floating platform, a replacement frame and eddy current damping system has been designed. To increase the range and accuracy of the STM's motion, a set of macro-micro motion actuators will be used. In order to independently measure the motion of the STM tip, an interferometer system has been developed to measure the motion of the sample. Lastly, to improve the placement and analysis of the sample, a graphical programming system has been developed that allows the user to better design and understand the nano-scale structures.

MACRO-MICRO MOTION

In order to image and/or modify a centimeter-size die cut from a silicon wafer, it is necessary to either move the STM, move the sample, or some combination of both. Since the distances required are much larger than the capabilities of the STM alone, it is necessary to have both a large-, or macro-, scale motion system (1 mm to 10 mm motion with sub-µm resolution) and a small-, or micro-, scale motion system (10 nm to 500 nm with sub-nm resolution) to properly scan the entire area. The system in MEL at NIST uses this macro-micro motion system to move both the sample and the STM.

* Commercial equipment and software referred to in this document are identified for informational purposes only, and does not imply recommendation of or endorsement by the National Institute of Standards and Technology, nor does it imply that the products so identified are the best for the purpose.

A model of the STM used and its mount are shown in Figure 1. The sample holder is mounted to a flexure stage, which will be discussed later. The macro motion system consists of two linear, piezo-driven actuators that will move the flexure stage for large-scale motion. A model of the actuators and their associated coordinate system is shown in Figure 2. The actuators provide gross motions of approximately 5 mm over the X and Y axes. While this is not large enough to image the entire surface of a centimeter die, it provides the capability to image a large section of the die without having to reposition the sample. It also allows for larger structures to be constructed using nano-lithography over multiple micro motion regions.

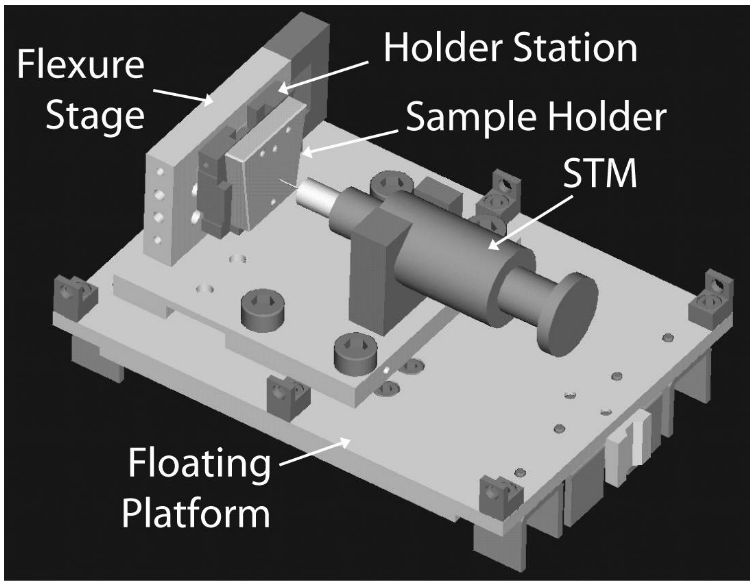

Figure 1. 3D Model of STM and Floating Platform

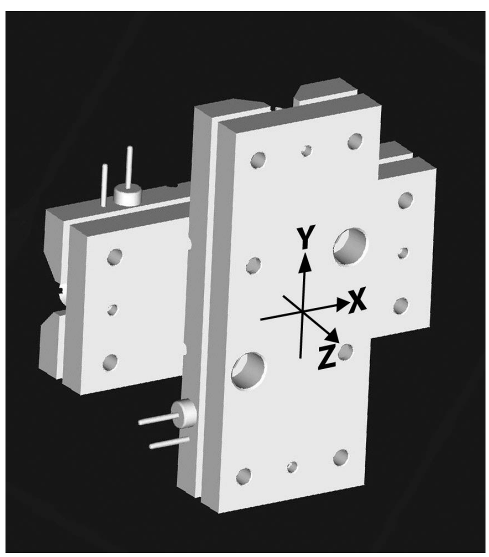

Figure 2. 3D Model of XY Stage System with Coordinate System

Micro motion is accomplished through the coordinated motion of the STM tip with a piezo-driven flexure stage [1]. The slow scan direction of the STM tip is used along the Y-axis of the sample. The fast scan direction, the X-axis, of the STM tip has been replaced with a piezo-driven flexure stage that holds the sample. The flexure stage provides both motion for the sample and a mounting location for a mirror used by the interferometer system. A more detailed description of this system is described below.

VIBRATION ISOLATION SYSTEM

The vibration isolation system consists of three main parts: the outer frame structure, the springs, and the eddy current dampers. The outer frame provides a firm mounting structure that connects all the other components. The springs suspend the central floating platform and provide the major vibration isolation for it. Lastly, the eddy current dampers provide damping, reducing oscillations over time.

The current STM system used by the MEL consists of two separate frame members cantilevered from a flange mounted to the vacuum chamber. The top frame is used to support the weight of the STM and the floating platform via four springs in the corners. The bottom frame holds the eddy current dampers and is only mechanically connected to the top frame via the vacuum chamber flange. Since these two frames are cantilevered off the flange, they move and flex with different frequencies and are subject to different loads. By creating the new frame out of a single piece of stainless steel and creating cross members in the structure, it is hoped to increase the rigidity of the outer frame and eliminate the coupling problems experienced with the two separate frames. Figure 3 shows a model of the frame structure with the STM platform suspended from it. The frame structure is shown mounted to a flange with the eddy current dampers mounted underneath [2,3].

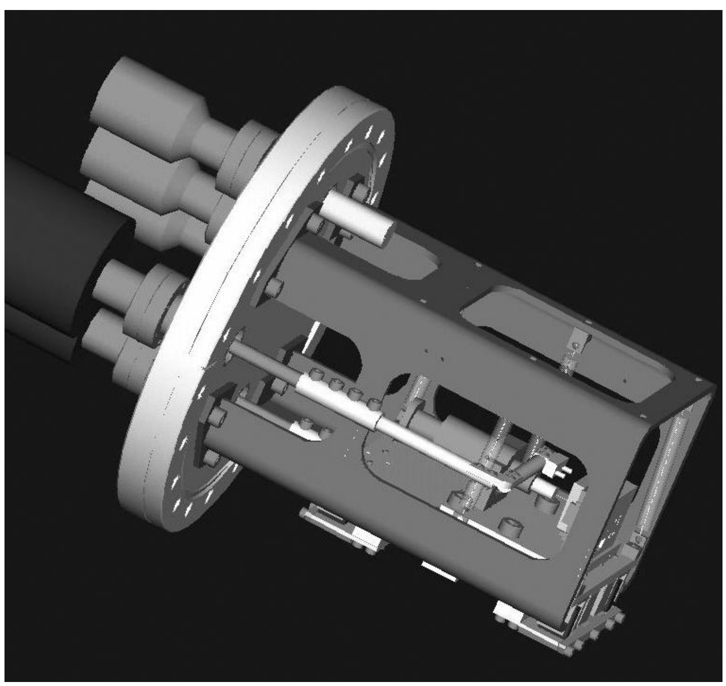

Figure 3. 3D Model of Frame Structure with Floating Stage and Eddy Current Dampers

The springs used in the current STM will not be strong enough to handle the extra components added into the new NIST system. The current platform almost doubles in weight when the STM mounting plate, flexure stage, and piezo actuators are added, which will affect the natural frequency of the system. By increasing the number or strength of the springs used to suspend the platform, the natural frequency of the system should remain approximately constant.

Eddy current dampers are a simple way to damp the vibrations for the STM platform without having an electro-mechanical device attached to the platform. Taking advantage of a basic magnetic principle the design incorporates a mechanism to create a force that counteracts motion in the platform. A magnet is either mounted on the platform or the frame while a conductive surface is attached to the other; in our case the magnet is attached to the frame and a U-shaped copper plate is mounted to the platform. As the platform moves with respect to the frame, the magnet induces a current in the copper plate; the current induced in the copper plate induces a magnetic field that opposes the permanent magnet; and, the magnet is repelled from the copper plate. Figure 4 shows a close-up of the planned eddy current dampers. The magnets are rectangular in shape (shown in black) with the copper plates are wrapped around them in a U-shape. There is a matched set of these on the far side of the platform as well. By using two orientations of magnets and copper plates, it is expected that motion will be damped along the X, Y, and Z axis of the platform [4,5,6].

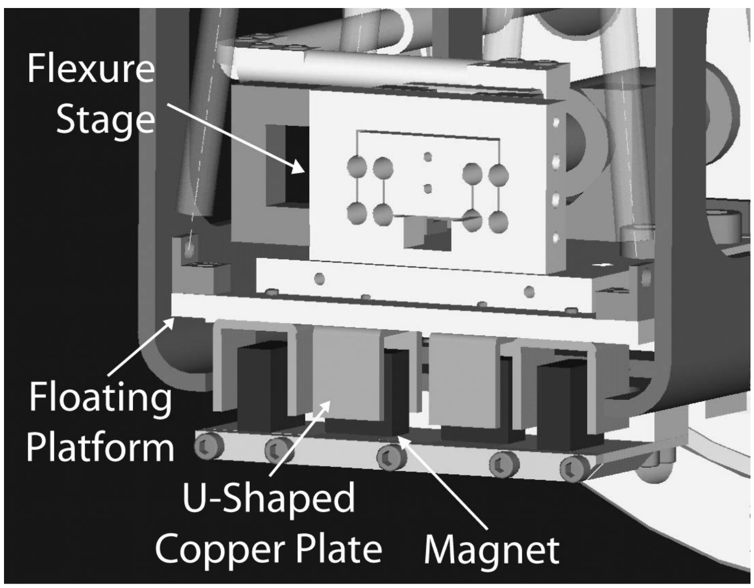

Figure 4. 3D Model of Eddy Current Dampers

INTERFEROMETER AND STM SYSTEM

The goal of using the interferometer system is to make 20 pm resolution measurements of the sample without degrading the atomic resolution imaging performance of the STM. The STM used in this work is a modified commercial instrument, which is routinely capable of atomically resolved imaging. The vertical and lateral noise floor is typically 0.1 Å and 0.3 Å respectively. The STM itself is mounted on a floating Invar stage suspended by springs with an eddy current damping mechanism as shown in Figure 3. The STM system resides in an Ultra-High Vacuum (UHV) facility, which typically operates in the 1.33×10^{-8} Pa (1×10^{-10} Torr) range. The mechanical elements of the STM system are designed to be symmetrical and are manufactured from Invar for its thermal stability as shown in Figure 5. The detachable sample holder and tip carrier enable us to exchange samples/tips quite easily in UHV without breaking vacuum. A 2 μm range of travel piezo device is integrated into the sample stage. The sample stage is flexure guided and the piezo device in the scanning flexure is directly connected to the high-voltage outputs of the STM controller. The measurement mirror is directly coupled to the sample holder station. This design eliminates abbe errors and coupled motions from the piezo tube scanner axes seen in the original design that had the mirror been mounted on the tube [1,7].

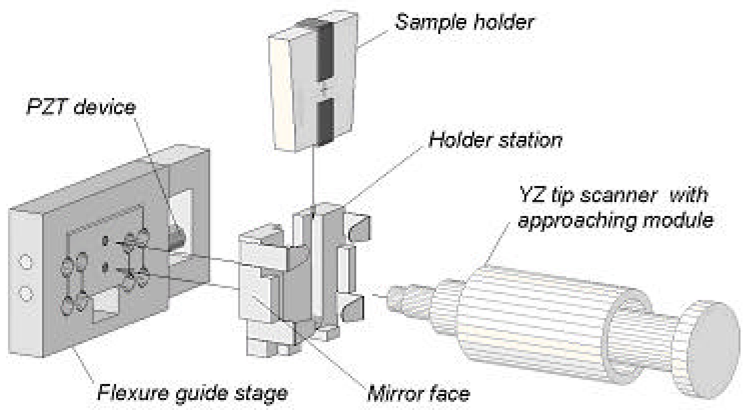

Figure 5. 3D Schematic of the measurement stage, sample holder, measurement mirror and STM piezo scanning tube with tip.

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; there is no movement of the fringe signal [8]. The measured signal arises in this apparatus from a differential measurement of the reference arm signal against the measurement arm signal. The diode laser signal is split between the interferometer signal and a calibration signal, which is beat against a reference stabilized HeNe laser. This allows the diode laser wavelength to have a direct, unbroken tractability path. This beat frequency is logged with a trigger simultaneous to the acquisition of the STM images. This is a homodyne interferometer and is unique in that only a single frequency is used in the interferometer portion of the system. The heterodyne portion of the measurement system is completely independent of the interferometer and measurement mirrors. In addition, this is not a Doppler based system and no counter integration is required as in some commercial measurement systems. This measurement is based on the number of fringes being held constant in the optical path difference between the reference arm and the measurement arm in a “static” sequence. Shown in Figure 6 is a schematic of the optical apparatus and measurement and control strategy.

The calibration of the system comes from counting the number of fringes in the optical path difference between the reference and the measurement arms. The number of fringes is determined by the wavelength of the diode laser and the path difference. This distance is analogous to the free spectral range in a Fabry Perot cavity and determines the scan range for the interferometer, when no mode hopping is allowed, based on the tunable diode laser range [9,10]. Although mode hopping can be allowed, it is simplest to explain the principle with a fixed fringe measurement. By scanning the diode laser and monitoring its wavelength based on the HeNe reference, the optical path difference can be obtained. This is accomplished by “mapping” a beat frequency fringe between the diode laser and HeNe laser, while scanning the diode laser wavelength and acquiring the intensity signal of the bicell detector at the interferometer output. The bicell intensity signal of one full or half fringe is then plotted against the beat frequency signal. The map of the diode laser wavelength against the bicell detector intensity pattern results in a unique number of wavelength making up the optical path difference.

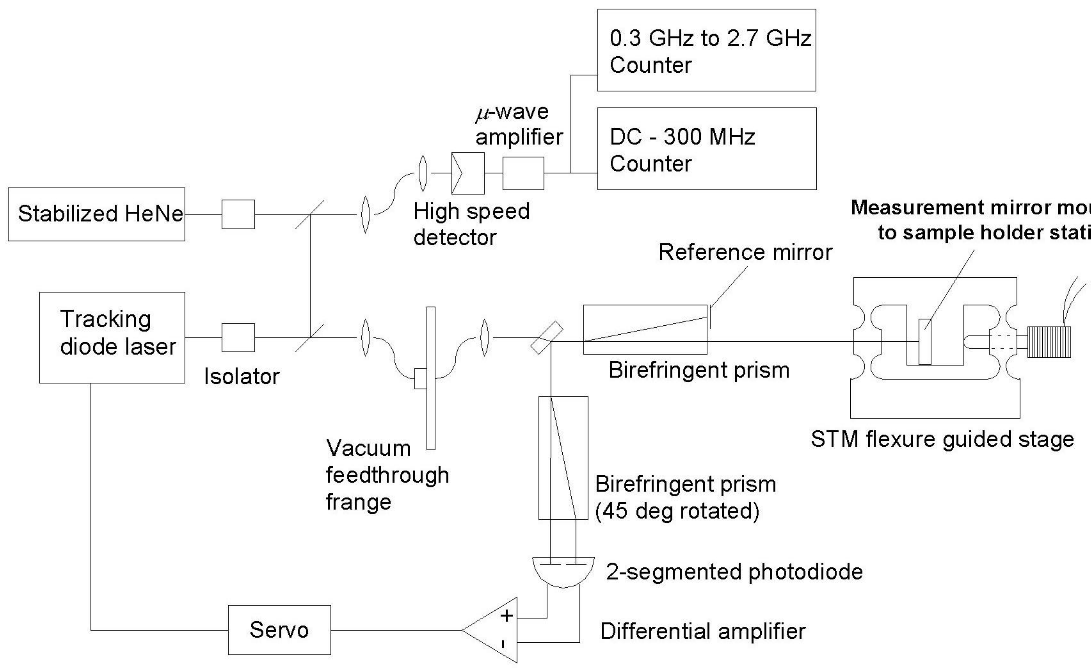

Figure 6. General methodology for tracking the measurement mirror motion. The interaction between the reference HeNe laser and diode measurement laser is shown.

The bicell output signal is logged and monitored for use in the PID control loop of the diode laser output frequency. The diode laser input control signal is continuously changed to lock the diode laser output frequency to a null point measured at the bicell detector. As the measurement 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 45° rotated birefringent prism. The HeNe reference beam and the diode laser beam come together in the reference measurement paths with different polarization states. The two beams are then appropriately rotated so that they interfere and the beat frequency can then be monitored. This combined beam travels through lenses and a collimator before being fed to a microwave amplifier and time interval analyzer (TIA). This nominally 2 MHz signal then gives direct measure of the output diode laser frequency relative to a stabilized HeNe reference signal which was been appropriately calibrated and tested. The output signal from the TIA is logged and synchronized with the STM Z height data. Post processing of the TIA data yields the X displacement of the sample [1].

GRAPHICAL PROGRAMMING

Two programs designed in LabView* allow the user to define the nano-scale structure to create and control the large-scale motion of the system. The first program, called

NanoLith, allows the user to draw on the screen to describe the desired structure. The second program, called MacroMot, allows the user to move the macro motion system to a desired region of the sample.

The main STM control computer is from Digital Instruments* and runs their script language called NanoScript. This script language allows the user to describe the desired motion of the STM tip as a series of lines as well as define certain parameters of the STM scanning operation. By using a specified bias voltage for the STM tip and this desired path, the STM tip can be made to "write" along a given path creating nano-scale structures. The NanoLith software allows the user to avoid the tedious job of hand-coding the script file and creating it directly from the users graphical input. The interface to the NanoLith software is shown in Figure 7.

The other piece of software, MacroMot, communicates directly with the macro motion system and moves the actuators to position a particular portion of the sample under the STM tip. This allows the STM to image large regions of the sample by actually imaging many small regions and piecing together the results for a grid of small images.

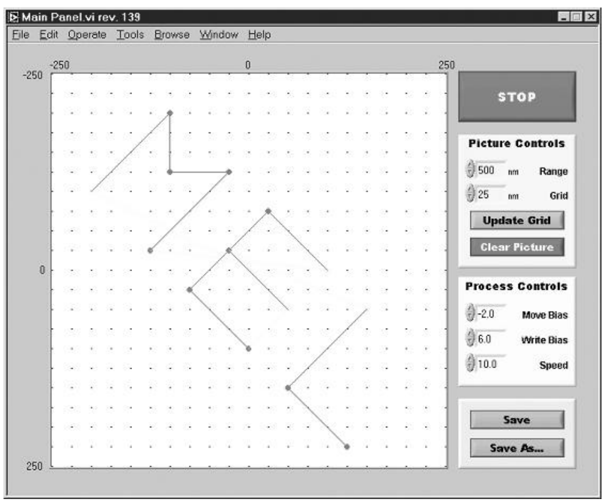

Figure 7. NanoLith Software Interface

RESULTS AND PROGRESS

At the moment, the overall system discussed in this paper is still in development. Most of the system components have been either designed or fabricated, but the entire system has not been fully assembled. The vibration isolation system has been designed and the parts are currently in production. The interferometer and micro motion systems have been fully constructed and are currently undergoing testing in air. The NanoLith software has been developed and structures have been constructed in UHV. Figure 8 shows an atomic resolution scan (250 nm x 250 nm field of view, with feature dimensions nominally 10 nm) taken of the letters MEL written using the initial STM nano-lithography system. In a short time, all of the systems will be put together so that the entire design can be tested under its intended conditions.

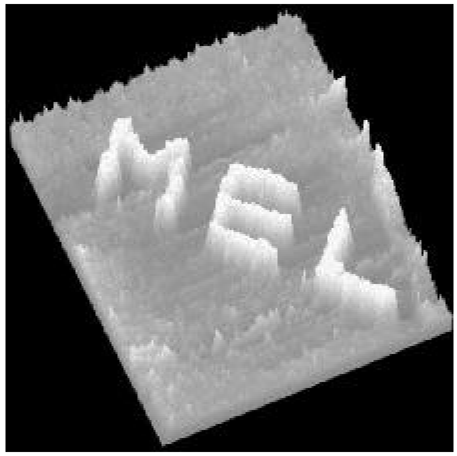

Figure 8. Atomic Resolution Image of the letters MEL written by Nano-Lithography (250 nm x 250 nm field of view, with feature dimensions nominally 10 nm)

SUMMARY

Nano-lithography has grown in complexity from the initial stages of proving a concept to now trying to develop real nano devices. With the increased emphasis in government and industry on nano-technology, it is necessary to develop improved techniques for creating these devices. NIST's goal is to develop a system capable of creating large-scale nano devices by using a combination of off-the-shelf products with custom equipment.

The new frame structure improves the stability and frequency characteristics of the overall frame design. The macro-micro motion system increases the overall range of the STM. The new atomic-resolution tunable diode laser interferometer allows the system to measure down to atomic resolution over a large range of motion. The programming environment gives the user the capability to design the system graphically instead of typing in a text-file. All these systems combine to form the initial steps toward coordinated closed-loop control of the STM.

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