Short Papers

Automated CAD/CAM-Based Nanolithography Using a Custom Atomic Force Microscope

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Abstract—We report the development of a novel nanolithographic system that combines the design capabilities of computer-aided design/computer-aided manufacturing (CAD/CAM) software with the nanolithographic abilities of the atomic force microscope (AFM). The AFM is a powerful tool for research at the nanoscale and can be used to perform a variety of serial nanolithographic techniques. A custom-built three-axis AFM system, designed to execute nanolithography, has been constructed and interfaced with a CAD/CAM design environment. This technique utilizes the CAD/CAM software to create, in a virtual design environment, the desired nanoscale patterns. Then, using a G-code interpreter and software algorithms to control the three-dimensional motion of the system, the design is replicated automatically by using conventional nanolithographic procedures. In this report, AFM-based anodization lithography on a silicon wafer and subsequent AFM imaging is used to confirm the successful automatic replication of the desired nanoscale patterns.

Note to Practitioners—The impetus for this research was based on the desire to create a custom nanolithographic platform that could be changed and manipulated as per the users specifications and operated easily by anyone. Commercial atomic force microscopes (AFMs) that are used for nanolithography and other studies have their own specific software that enables little or no change to the workings of the system, rendering prototyping of new research techniques to be difficult. These closed AFM instruments can be difficult to operate and are user unfriendly. This report delineates our construction of an AFM system and how we have incorporated very familiar software environments and common computer-aided-design programming language to conduct nanolithography. A brief verification of how our system performs is included; we have deposited and imaged a series of surface features in a direct write fashion on a silicon surface using a common lithographic technique that exists in the research environment.

Index Terms—Atomic force microscopy (AFM), computer-aided design/computer-aided manufacturing (CAD/CAM), lithography, nanotechnology, oxidation.

I. INTRODUCTION

The precise deposition, removal, and manipulation of materials at the nanometer length scale, commonly called nanolithography, has gained much interest in the research environment in the past half decade. As the current nanotechnological surge in both academic and industrial research settings continues, the need for improvement concerning the associated tools, processes, and instrumentation is warranted. The atomic force microscope (AFM) allows for physical interaction with materials and molecules at the nanoscale. An AFM platform can serve many functions, including but not limited to surface metrology, force spectroscopy of molecular species, and nanolithography [1]–[8]. As with

any other instrument available in a research setting, one primary concern is ease of use. If an instrument is not user friendly, production and efficiency are often sacrificed. Often, commercial AFM systems utilize custom-designed software that is unfamiliar to researchers and allows for little or no user control and modification potential during operation of the instrument. This leads to difficulty during prototyping of new research methods. For the execution of AFM-based nanolithographic techniques, we have incorporated conventional computer-aided design (CAD) software. By utilizing G-code, a programming language/interface typically used in macroscale computer numeric control (CNC) milling machines, we are able to command the motion of the AFM tip at the nanoscale. This has created an AFM-based nanolithographic platform that utilizes conventional software and hardware which seamlessly incorporates pattern design with automated nanolithographic execution.

II. BACKGROUND

AFM-based nanolithography is a powerful nanofabrication tool that utilizes the tip of an AFM cantilever. By using macroscale machine language, specifically G-code, the AFM tip can be commanded to move at the nanoscale.

A. Atomic Force Microscopy

At the forefront of nanoscale instrumentation is the AFM. The AFM enables the researcher to visualize and quantify forces and displacements on the order of piconewtons and angstroms. The concept of an AFM instrument was first realized by monitoring the displacement of a thin cantilevered beam interacting with particles at the molecular level [9]. An optical AFM reflects a laser signal off the surface of a micro-cantilever with an inverted pyramidal tip as it interacts with a surface. The motion of the reflected laser signal is monitored by a quadrant photodetector, and a tip-sample distance is maintained through piezoelectric actuators.

Advancements in piezoelectric flexure stage positioning and sensing have taken nanopositioning to new levels. AFM systems are typically able to position a cantilever tip with resolutions on the order of angstroms. With resonant frequencies on the order of hundreds of hertz to a few kilohertz, these stages can be moved to a specific position in a matter of milliseconds.

B. Nanolithography

Nanolithography involves the deposition, removal, and/or alteration of materials and chemical species at the nanometer length scale. Serial nanolithography, thought of as a single “tool” manipulating material includes techniques such as electron beam lithography (EBL) and AFM-based dip-pen nanolithography (DPN), anodization lithography (ANL), and other less common methods, such as nanoshaving and physical scratching [6], [8], [10], [11]. Most pertinent to the work presented here is ANL. The first scanning probe microscopy (SPM)-based surface anodization of semiconductor surfaces used the tip of an STM to create surface features on an H-passivated silicon substrate [12]. Surface anodization is the creation of a local oxide layer on a semiconducting or metallic surface. It was later first applied to an AFM setup to create surface features in native and thermally grown oxide layers on silicon and combined with wet etching to create features in the underlying silicon layer [6]. Fig. 1 depicts a typical AFM-based ANL

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Fig. 1. Scheme depicting the ANL process. An AFM cantilever tip in contact with a substrate in a semihumid environment creates a liquid bridge. The voltage bias applied between the tip and substrate provides the excess electrons that facilitate the formation of an oxide layer on the surface. The result is a raised local oxide layer above the surrounding native oxide layer.

scheme. The principle behind local ANL is relatively simple and the basic mechanism is described in the literature [13]. A metallized or semiconductive AFM cantilever is used to supply emission current to a sample via an applied bias voltage between the tip and the substrate, creating a concentrated electric field. When this electric field interacts with silicon in the presence of water from the atmosphere in the form of a meniscus between the tip and sample, a local silicon-oxide layer is grown. Typical heights for contact ANL (AFM cantilever tip in constant contact with the substrate) are around 1 nm–4 nm and widths are usually 50 nm–200 nm. These characteristics depend on applied voltage, dwell time, and chemical composition of the electrolyte bridge (meniscus) for a given tip and sample [13], [14].

C. G-Code

G-code is traditionally attributed to the computer numeric control (CNC) machine tool platforms. When CNC milling machines were first invented, G-code was the programming language that was designed for motion control. A user would manually write code containing the appropriate G-code commands. The program would then be loaded into the machine to dictate the motion of the bit as it created lines, arcs, and circles of varying depths in the material, controlled coolant addition, and changed machining bits. Even more recently, CAD/CAM software has been used to create pieces in a virtual environment. Before tooling even begins, simulations can be run that follow the proposed tooling scheme, and potential problems can be addressed before the actual cutting of material takes place, saving time and money. These programs are capable of outputting the appropriate G-code commands and can be directly incorporated with CNC milling machine platforms to automatically create the desired piece.

III. CUSTOM AFM NANOLITHOGRAPHIC PLATFORM

A custom AFM system has been assembled and designed specifically to execute nanolithography. The following sections highlight an overview of the system, describe the controller design and performance specifications, and discuss the incorporation of CAD/CAM-based design and subsequent CNC-based G-code command interpretation to automatically control the trajectory of the AFM tip.

TABLE I
PARAMETERS FOR PI CONTROLLERS, RESULTING MARGINS, AND EXPECTED PERFORMANCE (3% SETTLING TIME WITH MINIMAL OVERSHOOT)

	x	y	z
K_p	9.0×10^{-3}	6.0×10^{-3}	8.0×10^{-4}
T_i	2.0×10^{-7}	2.0×10^{-7}	1.0×10^{-5}
GM (dB)	11.1	13.7	127.2
PM (deg)	72.7	80.0	93.7
t_s (ms)	16.2	19.4	5.2

TABLE II
TRANSIENT RESPONSE CHARACTERISTICS FOR THE CLOSED-LOOP AFM SYSTEM

	x	y	z
t_d (ms)	4.7	7.3	1.0
t_r (ms)	10.4	25.5	2.4
t_p (ms)	16.0	27.4	3.0
M_p (%)	5.2	2.6	3.0
t_s (ms)	24.2	27.4	3.0
RMS (nm)	1.3	2.8	0.29

A. Controller Design

To control the location of the tip in three dimensions, independent feedback control loops are implemented on each axis. By using a real-time digital interface (PCI data-acquisition (DAQ) board, dSPACE Inc., Novi MI) with associated software and MATLAB to implement the feedback control scheme, the cantilever tip can be positioned in a $70 \times 70 \times 12 \mu\text{m}$ volume with nanometer precision. For the control algorithm, a proportional-plus-integral (PI) control scheme was used

$$K(s) = K_p \left(1 + \frac{1}{T_i s} \right). \quad (1)$$

In order to design the appropriate values for the controllers, time-domain system identification was performed to obtain a model that captured the dynamics of the piezoelectric stack actuators. Loop shaping was utilized to design the appropriate controller in all cases. To determine the final values for K_p and T_i , a balance between performance and robustness was maintained. This was accomplished by monitoring the phase and gain margins while the parameters were adjusted to minimize the 3% settling time with minimal overshoot of a step response ($1\text{-}\mu\text{m}$ step input). The values for gain and phase margin limits used were 10 dB and 30° , respectively. Table I shows the chosen values for the PI control parameters on each axis. The gain and phase margins for the z axis are large (127.2 dB and 93.7°) due to the addition of a notch filter at the resonant frequency of the piezoelectric stack actuator. The filter was included in order to minimize the resonance, increasing both the phase and gain margins as a result.

B. Performance

Once suitable controller parameters were selected, the focus then turned to implementation on the actual system and analysis of the resulting performance. On each axis, a step input of $1 \mu\text{m}$ was applied to the reference signal. After analyzing the data, the step response characteristics of delay time (t_d), rise time (t_r), peak time (t_p), percent overshoot (M_p), and 3% settling time (t_s) were obtained. Table II highlights the performance characteristics of the closed-loop system. Also included in the table is a root mean square (rms) position calculation of the three axes from 20 s of data over the bandwidth of the sensor output (30-Hz cutoff). This frequency was chosen because it resides significantly above typical scanning speeds for AFM experimentation, which are typically in the range of 0.25 Hz–5 Hz.

C. G-Code Implementation and Execution

The advantage of such a setup lies in the fact that our system can be tailored to meet design criterion for nanolithography through specific programming algorithms. By having an open system, modifications that enhance performance are readily implemented. Specifically, we have programmed our AFM system to process DXF output files created using conventional CAD software (SolidWorks). The DXF file is then converted to G-code using a converter downloaded from the Internet [15]. The system interprets the data contained in the G-code file and, along with algorithms designed to control the motion of the three stages, automatically directs the motion of the tip.

To decrease the overall time for the process to complete, translation speed is greatly increased while the tip and sample are separated. A faster speed is used for motion to a new location and a slower speed is used for surface modification. With our system, complex arrays and patterns can be produced automatically with no user input or monitoring necessary. Parameters, such as tip-sample voltage bias, speed, and contact force are controlled and varied automatically based on the representative CAD features.

IV. EXPERIMENTAL

A. Sample Preparation

The substrates used in the ANL process were cut from 100-mm diameter $\langle 100 \rangle$ silicon wafers (Montco Silicon, Spring-City, PA). 1 cm² samples were cut from the wafer (scoring with a diamond cutter and then cleaving) to fit in the AFM. Before ANL, the surfaces were cleaned in a solution of 5:1:1 v/v/v of H₂O : H₂O₂ : NH₄OH for 10 min at 80 °C. The samples were then rinsed with ethanol and dried under a stream of nitrogen.

B. Cantilevers

The cantilevers used were contact Si tips (Nanosensors, Switzerland). These tips have a length of 450 μ m, a stiffness of 0.3 N/m, and a tip R_c of less than 10 nm.

C. Anodization Nanolithography

An ANL scheme used in the confirming experiments followed the same basic procedure. The desired paths were first designed in the CAD environment. The tip was then loaded into the AFM platform, brought into contact with the target substrate, and then backed off $\sim 1 \mu$ m using manual adjustment positioning screws. Once the desired tip and substrate location were aligned, the AFM system was set for G-code input. The design was then sent through the g-code interpreter and used to command the AFM system. The ANL schemes were performed in an ambient environment of 70 °F and 40% relative humidity.

D. AFM Imaging

After ANL deposition, the samples were imaged on both the custom-built AFM system as well as a commercial AFM system (Asylum MFP3D).

V. RESULTS

The letters D, U, K, and E were spelled out in the CAD/CAM design environment (Fig. 2). The force setpoint was set at 1 nN, the tip writing speed was 1 μ m/s, and the bias voltage was 8 V. These lithography parameters were chosen because they provide adequate aspect ratios suitable for imaging. Looking at the result (Fig. 3), the desired letters

Fig. 2. CAD environment displaying designed features to be automatically deposited using ANL. The grid spacings are 1 μ m. The letters D, U, K, and E, spelled out in the design environment are to be deposited automatically at the nanoscale.

were successfully transferred to the substrate. Total execution time to complete the lithography was ~ 2 min. No noticeable drift is evident due to the closed-loop nature of the positioning system.

By analyzing the line profile of Fig. 4, feature characteristics with an average height of 0.609 nm and width of 106.1 nm were determined. These feature dimensions were calculated using an average of 20 line profile samples taken from the resulting images. Also, a representative profile used in the calculations is shown. The height values used were from top to bottom and the widths were taken as full width at half maximum (FWHM), which is a typical measurement technique to account for tip geometry convolution. The standard deviations for height and width were 0.135 and 22.3 nm, respectively.

In order to further confirm the capabilities of the custom system, a series of connected arcs and semicircles (Fig. 5) was deposited using ANL and then imaged. The deposition parameters and tip used were the same as in Fig. 3, but the voltage bias was increased to 12.5 V so the resulting features were expected to be taller. The substrate was then scanned over a 4.5- μ m area at 1 Hz. As can be seen from Fig. 6, the custom system can depict the deposited features with qualitative accuracy.

VI. CONCLUSION

A nanolithographic platform has been constructed that can automatically produce surface modifications at the nanometer length scale. By incorporating conventional CAD/CAM-based software, a nanoscale design environment is created to facilitate the creation of surface features. Taking advantage of CNC milling machine control language, namely G-code, the design environment is seamlessly integrated with the nanolithographic platform. By incorporating conventional software and designing control algorithms that suit the system, the instrument can be tailored to the users specific requirements and modified when necessary. As proof of performance, lines, arcs, and the letters D, U, K, and E, have been deposited on a silicon substrate using ANL. Experimental parameters, such as voltage application and tip scan speed, were optimized in order to obtain a high contrast image. This technique for position control need not be isolated to AFM systems. Other nanoscale lithographic systems, such as near-field scanning optical microscopy (NSOM), will find this technique useful. Future research will involve the modification of the system to use three-dimensional CAD models as an input to the system and have the heights and widths of these features automatically replicated at the nanoscale using nanolithographic techniques.

Fig. 3. AFM contact mode image of the deposited D, U, K, and E features from ANL using an Si cantilever. The applied force was 1 nN, the speed was 1 $\mu\text{m/s}$, and the voltage bias was 8 V. The shaded scale bar (lighter is taller) is 1 nm for height reference and the solid scale bar is 4 μm for lateral reference.

Fig. 4. AFM contact images and a representative line profile obtained from the AFM vertical piezoelectric position during imaging. Twenty line samples were taken from these two images for analysis. The shaded scale bar (lighter is taller) is 1 nm for height reference and the solid scale bar is 2 μm for lateral reference. The features have an average height of 0.609 nm ($\sigma = 0.135$) and an average width of 106.1 nm ($\sigma = 22.3$).

Fig. 5. CAD environment displaying designed features to be automatically deposited using ANL. The grid spacings are 0.5 μm .

Fig. 6. Image acquired when scanning the resulting surface after ANL deposition using the custom AFM platform. The height colormap range is 5 nm, dark to light, and the solid scale bar is 1 μm .

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