Atomic-force lithography with interferometric tip-to-substrate position metrology

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Inadequacies in lateral tip stability and registration presently limit lithographic applications of scanning probes. The authors describe a tool they constructed to write sub-10-nm features with 1 nm pattern registration. The tool utilizes an interferometric metrology technique called interferometric-spatial-phase imaging (ISPI) to continuously measure tip position relative to a substrate. Direct tip-to-substrate position measurement permits correction for the multitude of error sources encountered in the long mechanical path between a tip and a substrate. Experimental results indicate that the lateral tip position is stabilized by ISPI to $3\sigma=0.3$ nm, and pattern placement accuracy in a two-dimensional (2D) grid array is $3\sigma=0.2$ nm. According to ISPI measurements, 2D closed figures written in a polymer are overlaid to <1 nm. Analysis of patterns written by the tip while under ISPI control provides an error bound that is in good agreement with the ISPI measurements. © *2007 American Vacuum Society.* [DOI: 10.1116/1.2787794]

I. INTRODUCTION

Sub-10-nm features, including 2.9 nm full width at half maximum features, were written previously in polymers using a scanning tip.[1] To take advantage of few-nanometer resolution for lithography of arbitrary pattern geometries, it is essential to suppress drift and other spurious influences that would corrupt pattern registration at the nanometer level.

In scanning-probe microscopy or lithography, a long-standing problem is that the lateral position of the tip relative to the substrate is subject to perturbations due to thermal expansion and other distortions in their long mechanical connection. Shortening the mechanical path to improve tip registration would limit a scanning probe to small substrates. Stiffening the mechanical connection has limited effectiveness. In either case, the tip-to-substrate position is unknown until scans are performed, and, as a result of the finite time required to complete a scan, mechanical distortions of tip-to-substrate position typically are evident between the completion of the scan and the subsequent positioning of the tip.

In this work we apply an interferometric position metrology technique, called interferometric-spatial-phase imaging (ISPI), to directly and continuously measure and control tip-to-substrate position in a scanning-probe system and demonstrate use of tip-to-substrate control for nanometer-precision lithography.

II. ADAPTATION OF ISPI TO A SCANNING-PROBE SYSTEM

Simple modifications were made to adapt ISPI to a commercially available atomic force microscope (AFM) (Veeco Dimension 3000), as shown in Fig. 1. A super-Invar framework, whose coefficient of thermal expansion (CTE) is near zero, attaches a small (4 mm diameter) fused silica reference flat ($\text{CTE}=4\times10^{-7}\ \text{K}^{-1}$) to a standard tapping-mode tip holder (Veeco DAFMCH) (Fig. 2). The reference flat contains ISPI marks which are used to detect displacement in X and Y, relative to the corresponding marks on the substrate. Two ISPI microscopes are mounted on the AFM superstructure, directly attached to the large XY travel-range wafer stage and to the monolithic AFM scanner support, both of which are mounted on a granite slab.

The microscopes are individually adjusted to focus on the appropriate ISPI marks on the reference flat. The reference flat is moved in its super-Invar holder in Z, as well as θ_x and θ_y, to make it parallel to the substrate. The height of the flat is set to be $\sim$20 μm above the substrate during lithography. The ISPI marks are separated from the tip by 29 mm to obtain clearance from the piezoscanner housing. Since the only mounting points to the standard piezoscanner are on the tip holder, no modifications to the scanner are required to use this tip holder/ISPI mark apparatus with the AFM.

The ISPI mark design consists of gratings and checkerboards of two slightly different periods, p_1 and p_2, as described in a previous article.[2] The gratings are written by e-beam on the reference flat and the checkerboards are e-beam written and etched into the substrate. When illuminated with oblique-incidence spatially coherent light, interference-fringe patterns are produced by multiple diffractions from marks on the flat and the substrate. These fringes are imaged by oblique-incidence dark-field microscopes, and detected by high-resolution complementary metal oxide semiconductor sensors. The spatial-phase relation of interference-fringe sets determines position in X and Y to the subnanometer level, within a coordinate reference system attached to the substrate.

The substrate is held on an XYZ piezostage (Physik Instrumente P-363.3CD) with an internal, capacitive-sensor-

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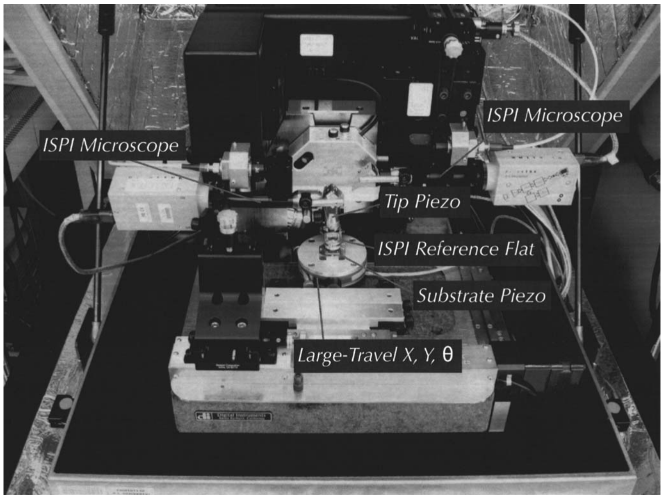

FIG. 1. Photograph of the ISPI-modified AFM. The additional ISPI hardware consists of microscopes for measuring the X and Y positions, and a custom super-Invar tip holder with ISPI marks. A closed-loop piezostage replaces the substrate chuck.

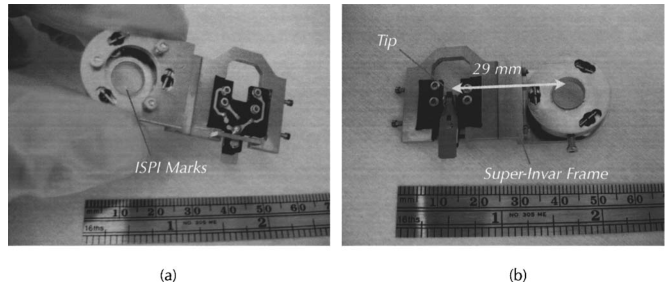

FIG. 2. Photographs of the (a) top and (b) bottom sides of a custom tip holder used with ISPI. A standard Veeco holder is used for the tip, which is coupled to a fused silica flat containing ISPI marks via a super-Invar framework with nominally zero thermal expansion coefficient.

based feedback loop that can maintain the substrate position to <1 nm, within the frame of reference of the piezostage. The open-loop AFM tip scanner from the Dimension 3000 remains operational, and the two piezos can be scanned independently, with or without ISPI control. This arrangement permits comparison of lithography performed in three modes: open loop (using the Dimension 3000 piezo to scan the tip over the substrate), closed loop to an internal reference system (using the PI stage to scan the substrate under a nominally stationary tip), and closed loop to a tip-substrate-based reference system (using ISPI tip-to-substrate measurements to control the PI stage motion).

III. EXPERIMENTAL VERIFICATION OF TIP-TO-SUBSTRATE REGISTRATION

A. Position stability at a single point

Data taken from ISPI microscopes while attempting to maintain a constant tip position are shown in Fig. 3, first using the open-loop piezo [Fig. 3(a)], then using the stage with an internal closed loop [Fig. 3(b)], and finally, using the ISPI measurements to feed back the detected position to correct for position errors [Fig. 3(c)]. Position drift with the open-loop piezo in this case is $\sim$20 nm in X and Y. Position control is improved along the X axis using the stage closed-loop piezo. However, approximately the same magnitude drift is observed in the Y direction as with the open-loop piezo, suggesting the degree of drift that occurs along the mechanical connection from tip to substrate. (These results are particular to our system and the multitude of factors, such as variations in temperature, pressure, humidity, etc., that was present during the 10 min data-collection intervals. They are generally nonrepeatable and will vary from system to system, but provide a suggestion of typical uncertainties in tip-to-substrate position.) As illustrated in Fig. 3(c), ISPI is able to lock the position between the ISPI reference mark and the substrate within $3\sigma=0.3$ nm in X and $3\sigma=0.4$ nm in Y.

The ISPI marks are separated from the tip by 29 mm of super-Invar, fused silica, and portions of the standard tip holder. An indication of drift in the tip position can be gained by lowering the tip and observing the impression left on the polymer. During such tip impressions taken while using ISPI

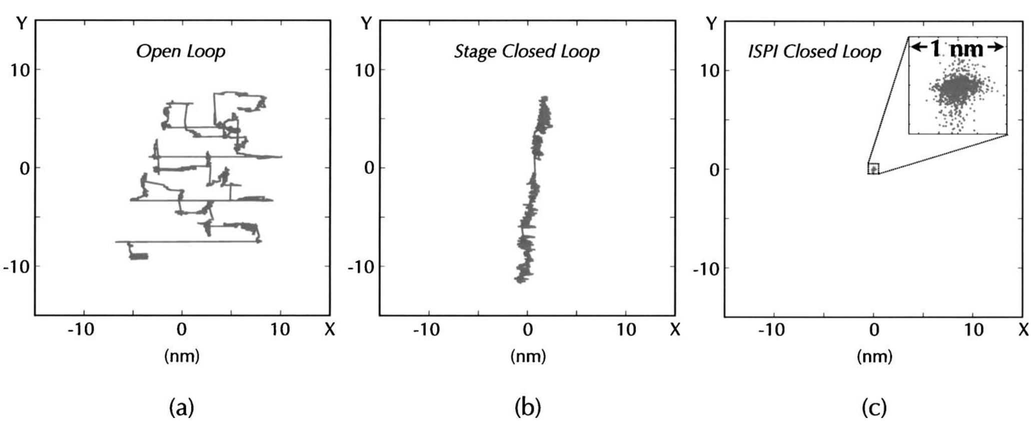

FIG. 3. ISPI measurements of tip-to-substrate position while attempting to hold the tip at a single point over the substrate using (a) an open-loop piezo, (b) a closed-loop piezo stage, and (c) ISPI to feedback control tip-to-substrate position. Although both open-loop and closed-loop piezostages permit drift of more than 10 nm for 10 min, ISPI measurements indicate elimination of tip-to-substrate drift within $3\sigma=0.3$ nm in X and $3\sigma=0.4$ nm in Y.

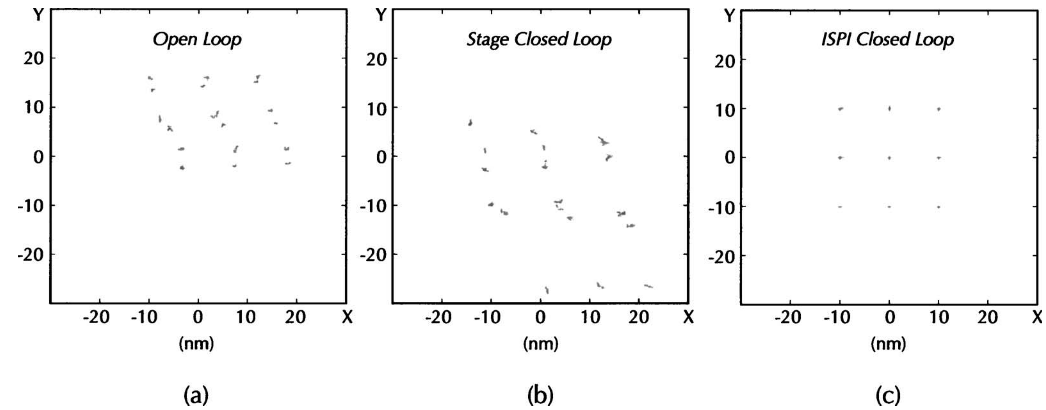

FIG. 4. ISPI measurements of attempts to position a tip on a 3×3 grid with 10 nm period. Data were taken using the (a) open-loop piezo, (b) closed-loop piezo, and (c) ISPI feedback control. In each case the tip was held at an intended position for 2 min, and then moved to the next point, following a serpentine scan, starting at the lower left point. The grid scan was repeated in the reverse order, as shown by the second set of points that are intended to overlay upon the first set. Errors amount to several nanometers, or tens of nanometers, with either open-loop or stage closed-loop operation. Data using ISPI control for the two grid scans are overlaid and are indistinguishable, as shown in (c).

position locking, we found no evidence of lateral motion, indicating an upper bound of a few nanometers on a possible tip-to-ISPI mark position disparity.

B. Pattern placement and repeatability

The ability to hold the tip-to-substrate position at an array of points was tested using ISPI. Figure 4(a) shows a set of measurements taken using the open-loop piezo to move the tip from point to point in a 3×3 array with 10 nm grid period and hold it at each position for 2 min, starting at the lower left point and ending at the upper right point. The procedure is repeated in the reverse order with a second 3×3 array of points. The total duration of the experiment was 36 min. In Fig. 4(a), using the open-loop piezo, the maximum error in pattern overlay was 4 nm, which is a significant fraction of the 10 nm grid period.

The experiment was repeated using the closed-loop stage to position the substrate under the tip. As indicated in Fig. 4(b), distortion of the grid pattern, as well as maximum overlay errors (17 nm), is greater than with the open-loop positioning. Drift in the Y direction is consistent with the drift observed using the closed-loop piezo to hold at a single point.

Control of the substrate position by means of the ISPI measurements is shown in Fig. 4(c). Points from both grid

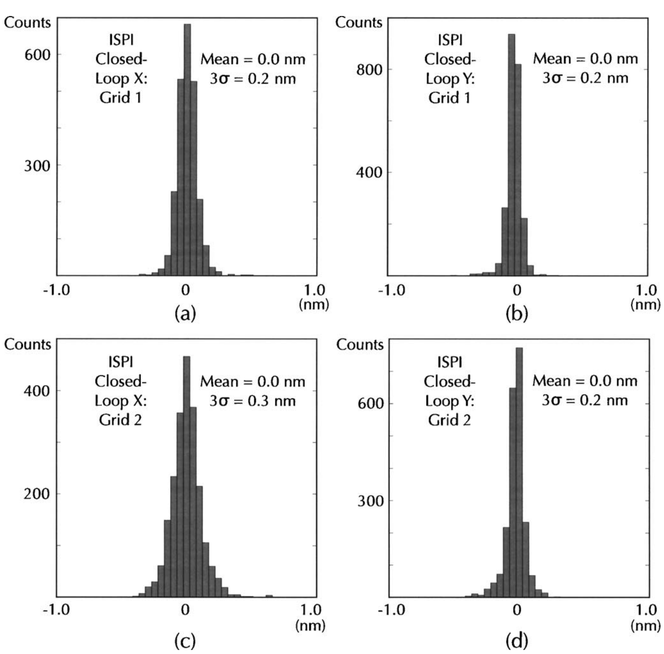

FIG. 5. Plots of the disparity of ISPI positioning from the intended pattern placement taken during position locking of the tip in the two successive grid scans shown in Fig. 4(c). [(a) and (b)] ISPI control results in positioning at grid points with overlay disparities of $3\sigma=0.2$ nm in X and $3\sigma=0.2$ nm in Y. In the second grid scan [(c) and (d)], the deviation from the desired positions was $3\sigma=0.3$ nm in X and $3\sigma=0.2$ nm in Y. The data show good placement accuracy within each grid scan, as well as good repeatability between successive scans. The mean position deviation was 0.0 nm in each scan.

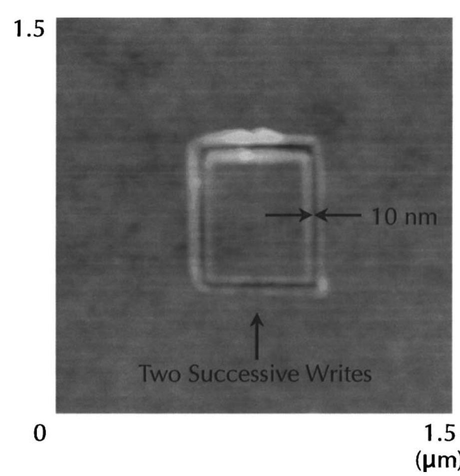

FIG. 6. AFM scan of patterns written in polymethyl methacrylate (PMMA) showing overlay of two patterns using ISPI control. The double-patterned scan employing ISPI is indistinguishable from a single-patterned scan, indicating an upper bound on the overlay (<10 nm) that is limited by the lateral detectivity of the AFM (256×256 data points in a 1.5×1.5 μm^2 scan).

patterns are overlaid. The disparity between the desired coordinates and the measured coordinates is indicated in Figs. 5(a) and 5(b) for X and Y, respectively. The deviation of the actual and intended positions is mean=0.0 nm, 3σ=0.2 nm in X and mean=0.0 nm, 3σ=0.2 nm in Y. Similar measurements showing good repeatability for the second grid are in Figs. 5(c) and 5(d): mean=0.0 nm, 3σ=0.3 nm in X and mean=0.0 nm, 3σ=0.2 nm in Y.

C. Overlay of two-dimensional closed figures

Figure 6 illustrates overlay of successive two-dimensional closed figures written using ISPI position locking. Overlaid box patterns written while employing ISPI display no discernible difference in linewidth or sidewall shape, compared with a single iteration of the pattern, indicating that overlay of tip position is at least in the sub-10-nm regime and may approach the ISPI-measured overlay in the sub-1-nm regime. Residual tip placement error can be reduced by shortening the distance from the ISPI marks to the tip, including mark placement on the cantilever or the silicon base of the cantilever.

IV. CONCLUSIONS

This article describes the use of ISPI metrology to improve scanning-probe tip positioning and registration to the 1 nm level and below. Insight into the tip behavior is obtained using ISPI measurements, which indicate drift of tens of nanometers or more using either open-loop or stage closed-loop piezoscanners. ISPI measurements are used for closed-loop tip-to-substrate position control. Pattern registration, according to ISPI measurements, achieves single-point positioning to 3σ=0.3 nm and pattern placement accuracy with 3σ=0.2 nm. AFM scans of tip impressions in a polymer establish bounds on single-point stability and pattern overlay using ISPI feedback control to be less than the limits of the lateral scan detectivity, i.e., in the sub-10-nm to few-nanometer regime.

ACKNOWLEDGMENT

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[2] E. E. Moon, M. K. Mondol, P. N. Everett, and H. I. Smith, J. Vac. Sci. Technol. B **23**, 749 (2005).