IMAGE VALIDATION OF PARALLEL SCANNING TUNNELING MICROSCOPY WITH A CMOS MEMS PROBE ARRAY

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ABSTRACT

This paper reports on the design and test results from a dual-probe Scanning Tunneling Microscopy (STM) system, suitable for scaling to 1-D array parallel imaging with an eventual purpose for batch-nanofabrication. The 1-D array is fabricated using CMOS-MEMS technology. Each probe is individually addressable, equipped with an electrothermal (ET) microactuator for tip vertical deflection. A hierarchical dual servo system is tested to validate parallel STM operation with two probes on the chip. Dual STM images are obtained on a custom grating calibration sample. A second generation of probe array is being developed, where on-chip ET actuated micro-goniometers are designed for more scalable probe array-sample alignment.

INTRODUCTION

Scanning probe microscopy (SPM) is a powerful tool in surface science. SPM techniques make use of the interaction between the nano-scale sharp tip and the sample surface to study its local properties. Tip-based nanofabrication (TBN) extends the SPM functionalities where the tip is used for direct nanopatterning and modification on the surface [1]. While the minimum feature size has been scaled down to 14 nm using the current state-of-the-art photolithography technique, feature size down to sub-10 nm is achieved via TBN with little difficulty.

Unlike the sample-averaged techniques such as spectroscopy and crystallography, the probe of SPMs interacts with the materials' surface locally, point by point, and therefore provides direct information of material property at atomic and nano-scale that leads to the understanding of the materials in a different way. Yet it is also this nature of reliance on localized interaction of SPMs that make it a much slower surface characterization technique than the sample-averaged ones. It may require a few minutes to scan a few μm^2 areas while it may only take a couple of seconds in SEM.

To overcome the disadvantage of the intrinsic drawback of low-efficiency of SPM, probe arrays are developed. Multiple micro-probes work in parallel on multi-areas of a surface so the efficiency of surface characterization will be multiplied. A variety of 1D and 2D probe arrays have been developed and used in applications like "Millipede" probe-based data storage [2] and dip pen nanolithography [3]. Millimeter-scale parallel imaging in AFM constant force mode has been achieved using a 1×10 CMOS MEMS probe array [4]. In both imaging and fabrication, the array probes are in contact with the examined surface.

In our work, we have developed CMOS MEMS probe array technology intended for non-contact (NC) mode STM-based parallel imaging and nanofabrication. Compared to contact mode SPM operation, only NC mode SPM, like STM or NC AFM tapping mode, may achieve true atomic resolution because it relies on the short range tip-sample interactions that is comparable to the size of the atoms [5]. This indicates that the NC mode SPM may be able to produce an even smaller feature size than the contact mode SPM.

We previously demonstrated the parallel STM imaging via a dual CMOS-MEMS probe array system on a commercial calibration sample [6] along with establishing on-chip switched-capacitor transimpedance amplifier circuitry [7]. The alignment of the probe array and the sample surface was through an external macro

goniometer [6]. In the present work, a custom calibration sample is designed and fabricated for the image validation of the dual probe system. A second generation of CMOS probe array is developed, where the spacing between adjacent probes is reduced by 20 times. On-chip active micro-goniometers are designed for this more scalable probe array-sample alignment.

A HIERARCHICAL DUAL-PROBE STM SYSTEM

The concept and configuration of a hierarchical dual-probe STM system was reported in [6]. The system block diagram is shown in Fig. 1. The CMOS MEMS probe array chip is mounted on the piezoscanner head of a Veeco Dim3000 conventional SPM system. A master servo controls position of the probe chip and its master STM tip relative to the sample and uses the piezoelectric actuator embedded in the conventional system. The second, slave servo controls the second tip relative to the sample while in the frame of reference of the master servo. Slave servo action is performed with the ET bimorph actuator embedded on the probe cantilever. In both servos, the tip current preamplifiers and PI controllers are implemented in custom off-chip analog electronics. For parallel STM image processing, the topography under the master tip is directly constructed from the piezo drive voltage. The topography under the slave tip is extracted by taking the weighted difference of the piezo and ET drive signals, as shown in Fig. 1 (b).

Figure 1: (a) Schematic of master-slave dual probe array system. (b) Slave image constructed by taking the weighted difference of two drive signals [6].

Fig. 2 shows the SEM images of the CMOS probe chip that is used in dual-probe STM system. An array of 5 identical active probes is arranged along one side of the chip, with each probe 329 μm in width. They are equipped with respective ET actuators for individual vertical deflection. The master probe is passive, without on-cantilever actuation mechanisms, and is located on the corner of the probe chip. One from the 5 active probes is used as the slave probe. In principle, the system can be extended to accommodate more active probes as slave probes with corresponding servo electronics. The platinum STM tip shown in the inset is prototyped with electron-beam induced deposition.

Figure 2: SEM images of CMOS probe chip, showing the two probes used in dual probe parallel imaging.

CUSTOM CALIBRATION SAMPLE

Previous characterization of the dual-probe STM system imaged a commercial grating calibration sample where all the gratings assume a same orientation, so the features under the master tip and the slave tip were essentially the same [6]. A custom calibration sample, following the schematic design in Fig. 3 (f) and the process steps in Fig. 3 (a) to (e), provides distinguishable images under different probes during the parallel operation. A series of grating patterns with different orientations and periods are fabricated on the substrate. Grating patterns are first made via e-beam lithography on 950 PMMA A4 resist spun on a 1" Si substrate. Next the patterns are transferred to the Si via anisotropic etch in a Plasma-Therm RIE 790 system. The resist is then washed off, and 5 nm-thick gold is deposited on the substrate bearing the patterns. Fig. 4 shows a representative optical image and an AFM image of the fabricated patterns. The patterns have periods ranging from 200 nm to 600 nm, with pitch depth of ~25 nm.

PARALLEL STM IMAGING OF DUAL-PROBES

In the parallel STM operation of the dual probes, the relationship between the piezo drive voltage and the slave drive power needs to be known for the construction of the image under the slave tip. The relationship is obtained through an *in situ* characterization using a piezo actuator-based STM servo. Fig. 5 describes the measurement method. The probe chip is mounted on the piezo-actuator of the conventional SPM system. One of the active array probes is used as a regular STM end-effector, relying on the piezo-actuator-driven feedback loop to perform the constant current mode STM scanning while the x- and y- direction movement is disabled. When operating in constant current mode, the separation between the tip and the sample surface is fixed at z_0 by the current set point. When using the on-cantilever ET actuator to drive the probe, it moves vertically and the tip-sample distance changes by Δz . To compensate for this distance change so as to maintain the constant current between the tip and the sample, the piezo actuator has to respond accordingly, *i.e.*, the piezo actuator has to drive the probe by Δz in the direction opposite to ET actuator's movement. Fig. 6 shows the obtained relationship, indicating that the travel distance caused by a change of 1 V of drive voltage on piezo scanner is equivalent to that caused by a change of 0.129 mW of drive power on ET actuator. The ET drive sensitivity is 131 nm/mW using the nominal piezo drive sensitivity of 17 nm/V.

Figure 3: Process of fabricating STM calibration sample with custom gratings

Figure 4: Optical and AFM images of the custom-made sample, showing the spacing and pitch of the gratings

Figure 5: Schematic of the measurement of ET drive sensitivity via *in situ* STM scanning: (a) the tip is z_0 from the substrate, keeping a constant current; (b) the tip is lifted up by Δz from the substrate via ET actuation; (c) the piezo drive is extended by Δz to compensate for ET travel distance.

Figure 6: ET drive power vs piezoelectric drive voltage

Figure 7: Dual images when the master probe is on the grating and the slave probe is not. (a) Image under the master tip; (b) Raw image from the slave tip; (c) Real image under the slave tip via the weighted addition of (a) and (b)

The dual probes are scanning on the custom calibration sample for parallel image acquisition. The custom gratings on the calibration sample can be manually moved under either the master probe or the slave probe. In one scenario, the master probe falls on the pattern while the slave probe is scanning on an unpatented area. Fig. 7 shows the obtained dual images. The image under the master tip shows the pattern with a period of around 282 nm. Although scanning on an area with no grating pattern, the slave image directly built from the ET drive power shows a grating that corresponds with that in the master image. Fig. 7 (c) shows the actual topographical image obtained from the weighted difference of the master piezo drive voltage signal and the slave ET power signal. The grating pattern disappears on this difference image, leaving behind only the real features under the slave probe.

In a second scenario, a grating is under the slave probe while the master probe is scanning on an area without gratings. Fig. 8 shows the obtained STM images. No grating patterns appear on the master image. Gratings are identified in the raw slave image and are preserved in the weighted difference image that removes the piezo drive signal.

MICRO-GONIOMETER

In the current version of CMOS-MEMS probe arrays, adjacent probes are spaced 340 μm apart. The lateral scanning range of a peizo-scanner on the commercial SPM system is generally 50 μm or less. It is desirable that the spacing between adjacent probes be smaller than this lateral scanning range so that the individual scanning areas will overlap and combine. When the spacing between array probes is scaled down to tens of microns, it is possible to build an on-chip micro-goniometer which offers a platform to hold an array of probes. It serves to provide the *in situ* fine adjustment of relative height among these probes above the

Figure 8: Dual images when the slave probe is on the grating and the master probe is not. (a) Image under the master tip; (b) Raw image from the slave tip; (c) Real image under the slave tip via the weighted addition of (a) and (b)

sample surface. It will also facilitate the STM operation of probe arrays particularly in an ultra-high-vacuum (UHV) system where a macro-goniometer for tip-substrate parallelization is not easily implementable. To this end, a scaled generation of STM probe array is developed. Fig. 9 shows the SEM image of the STM probe array on a micro-goniometer. It consists of two separate “trunk cantilevers” which can be individually actuated, a leveling beam bridging the trunk cantilevers through two twist beams, and an array of active STM finger probes placed along the leveling beam, with a spacing of 15.1 μm between two neighboring finger probes. Similar to the widely-spaced array probes, the micro-goniometer and finger probes also adopt ET actuation as its driving approach. When the two trunk cantilevers are unevenly heated, *i.e.*, different drive powers are applied on the ET actuators of two trunks, they will have different vertical deflection, so one end of the leveling beam will be elevated higher than the other end, and the relative height among finger probes is therefore changed.

Different drive powers were applied on two trunk cantilevers to measure the tilt of the leveling beam. It is found that a critical power exists. Below the critical power, the tilt of the leveling beam has a linear dependence on drive powers, and the deformation is reversible, *i.e.*, the trunks of the goniometer recover their original shape. Above the critical power, the leveling beam is not straight anymore but bends. Furthermore, irreversible deformation occurs, *i.e.*, the leveling beam tilt remains after the power is removed.

The test started with a freshly released goniometer device. The drive power, which varied between 0 W and 32.2 mW but never went beyond this range, was applied on one trunk cantilever of the goniometer, while the other trunk was not powered. Fig. 10 shows the white light interferometric image when the goniometer is unevenly powered at 32.2 mW. Upon heating, the heated trunk bends downwards, and assumes a lower position than its counterpart on the other side. The leveling beam is tilted by 1.19°. The tilt angle is linearly dependent on the power and has a drive sensitivity of 0.038°/mW.

Figure 9: SEM image of the micro-goniometer showing its structure

Figure 10: Tilt of the goniometer when a power of 32.2 mW is applied on the right trunk cantilever: (a) 2D contour. (b) The tilt of the leveling beam. (c) 3D contour. (d) Tilt dependence on the drive power below critical point.

Furthermore, irreversible deformation is introduced after a high enough drive power is applied and then removed from the trunk cantilever. To examine the time and power dependence of irreversible deformation, a freshly-released goniometer with no previous heating history and hence no irreversible deformation was tested. A fixed drive power was applied to its right trunk cantilever, maintained for different durations and the leftover deformation was measured after the power was removed. The process is akin to annealing, *i.e.*, heating the material to above a critical temperature, maintaining for a certain amount of time and then cooling. It is found that the heated trunk that experiences annealing restores to a higher position than its non-annealed counterpart after the removal of the power. Fig. 11 (a) shows the evolution of the tilt of the leveling beam with annealing time at three different drive powers. At a fixed power, the tilt angle increased with the annealing time, showing a logarithmic time response up to 1000 s. Fig. 11 (b) shows the tilt angle dependence on the power. Irreversible deformation occurs at around 28.4 mW, as extrapolated from the graph. No higher power than 66.7 mW was applied on the trunk cantilever during the test to avoid any possible damage from melting of the aluminum in the goniometer structure.

Figure 11: (a) Irreversible tilt angle vs. annealing time at different powers. (b) Irreversible tilt angle introduced by different powers. The annealing time is 1000 s for each power.

CONCLUSION

The custom grating calibration sample was successfully employed to verify the functionality of a hierarchically driven dual-STM servo system. Two simultaneous STM images were obtained, where the pseudo-features on the raw slave images introduced by the master servo are successfully removed by differencing the image signals. The measured drive sensitivity relationship between the ET actuator and the piezo actuator provides the weighting factor for this difference, validating the fundamental understanding of the system operation.

A second generation of scaled probe array is developed, which is placed on a micro-goniometer. That a permanent tilt angle can be introduced by asymmetrical annealing of the two trunk cantilevers indicates that continuous power is not needed to maintain a desired tilt angle, which is favorable in terms of power scaling for a large system. Besides, thermal coupling between the ET actuated goniometer and ET-actuated finger probes can also be avoided.

While operation of only two probes is demonstrated, the active probe technology is available to enable future multiple STM images obtained by a larger array of probes to be stitched together to make a large-area STM image. On-chip circuits such as in [7] will be desirable to scale the system to tens or even hundreds of probes.

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