Nanometer-Scale Lithography using an Atomic Force Microscope

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Abstract:

With the current development of nanoscale mechanisms, the necessity to create < 50 nm features on surfaces is becoming an important ability for researchers to have. Current lithography tools are either too inadequate or too expensive, e.g. optical and electron-beam lithography, for modest researchers to employ, which has led to the development of Atomic Force Microscope (AFM) Lithography. AFM lithography is an emerging technology praised for its cost-efficient potential to create < 50 nm (as low as 10 nm) features on silicon and other substrates. However reproducibility issues have plagued researchers in reaching this tool's potential. During our research we have discovered key methods to resolve these issues to make AFM lithography a robust tool.

These methods include using non-contact mode microscopy during oxidation to reduce AFM tip wear and increase control of oxide size. Controlling variables such as tip voltage, scan height, scan speed and humidity enable the user to systematically calibrate the size of the oxide written. Through these methods, we were able to consistently produce oxide lines 50 nm in width, 1 nm in height and several microns in length, and were able to reproduce these lines over 30 times without sign of tip decay.

Introduction:

AFM lithography uses anodic oxidation to create features on the target surface using electrically conductive tips. Due to atmospheric humidity, an ambient layer of water exists on the surface of the substrate which provides the oxygen species necessary for oxidation. A meniscus forms between the tip and sample due to the small distance (around 5 nm) between them. A voltage bias is applied to the tip to generate a strong electric field on the order of 10^9 V/m, which causes hydroxide-ion diffusion and drives hydroxide ions from the water meniscus to the surface.

From our studies, it can be seen that using non-contact mode during oxidation promotes long tip life and reproducible data. Feature width (and height) is primarily linked to voltage bias. Width can also be varied with scan speed, average tip height, and humidity. We have also found that surface conditions play a key role in the reproducibility of data. It was found that using a hydrophilic tip and a hydrophobic substrate produced the best results.

We have also found that the thinnest features can be produced by oxidizing a series of dots, rather than lines, on the surface. This can be done by positioning the tip close to the surface to form a water bridge between the tip and surface. This water bridge can be stretched to confine hydroxide-ion diffusion thus resulting in smaller features [1].

Procedure:

Each AFM tip was imaged using the FEI Sirion SEM before and after oxidation to examine the effect of tip wear during oxidation. The tip is then placed on the microscope and engaged on the surface (usually silicon). We used the Digital Instruments Nanoscope IV for every experiment. After we realized contact lithography was too erratic, we conducted every experiment thereafter in non-contact mode. We oxidized the surface by drawing a series of lines. This is done by scanning the tip across the surface at a steady height and steady speed, with a voltage bias always on.

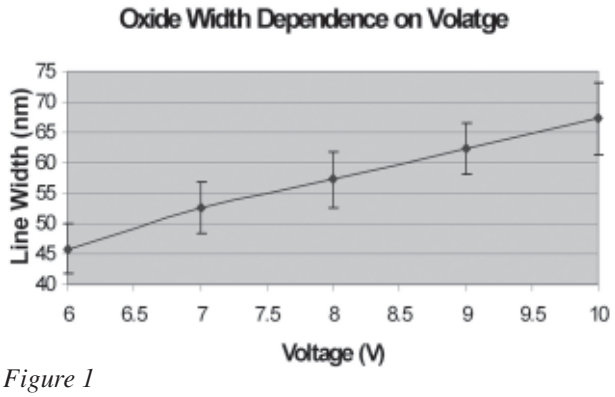

Figure 1

We experimented systematically with various parameters, mainly tip voltage bias, scan speed, and amplitude set point (AS). The latter determined the amount of damping the oscillating tip underwent when engaged. From later experiments, we could derive a relationship between AS and average distance from surface (AS increases as z-distance increases). We also experimented systematically with surface conditions of tip and substrate, i.e. hydrophilic nature.

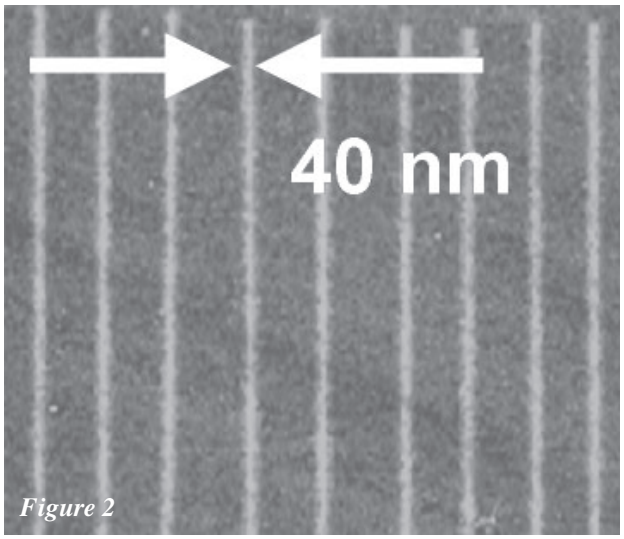

Figure 2

Results and Conclusions:

Of the three main parameters, we found that voltage bias was a first-order parameter; oxide height and size were primarily linked to voltage (Figure 1). Higher voltage bias produced taller and wider oxides. For our tests, we ranged the voltage from -6V to -12V, scan speed about 0.1 μm/s, and average z-distance roughly 7-8 nm. Each tip was calibrated using these parameters to achieve best results. We could consistently reproduce lines 1 nm high and 50 nm wide, and as small as 30 nm wide (Figure 2). Also, we found that because non-contact mode was used, virtually no tip was broken or worn unless mistreated.

For this type of non-contact lithography, a.k.a. line drawing, we found best results with hydrophobic surfaces. This is because as the probe moves across the surface, the water meniscus between the tip and sample must always exist for oxidation to occur. Because the surface is hydrophobic, the meniscus can easily slide across the surface, as opposed to a hydrophilic surface, where the meniscus is attracted to the surface. If the meniscus is attracted to the surface, there will too much tension on the meniscus and it will break, causing irregularities.

Likewise, best results arise when the tip is hydrophilic because the meniscus tends to follow the tip. Also, due to contact angles, the shape of the meniscus will be smaller with a hydrophilic tip, resulting in a narrower oxide (Figure 3).

For future experiments, we found it promising that instead of "drawing lines", smaller oxide widths can be achieved by connecting series of small dots. We will use a hydrophilic surface, because we are no longer "dragging" the tip along the surface, but rather positioning the tip above the surface, applying a voltage to oxidize, and repeating. In other words, voltages will be pulsed as opposed to being continuous. Because of this, we can use a hydrophilic surface to achieve the smallest possible meniscus width, again due to contact angles (Figure 4).

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References:

[1] Calleja, Garcia, Roher, Appl.Phys. 86, 1899, 1999.
[2] Keller, Franke, Surf. Sci., 294, 409, 1993.

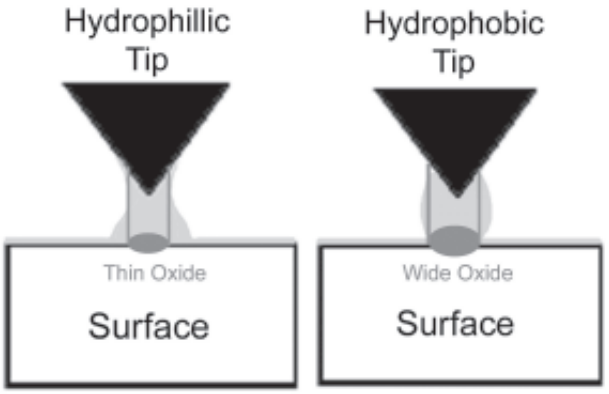

Figure 3

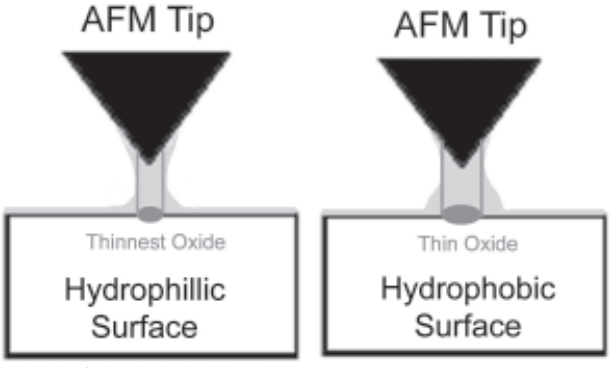

Figure 4