TappingMode Imaging Applications and Technology

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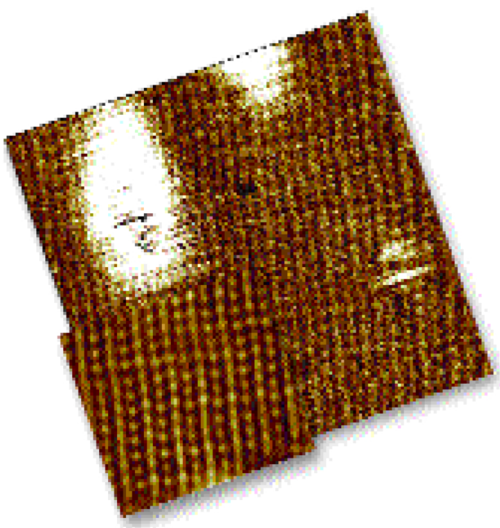


Figure 1. TappingMode image of purified collagen monomer and oligomer molecules without telopeptides. 2μm scan courtesy Advanced Surface Microscopy, Indianapolis, IN.

Introduction

TappingMode™ imaging is a key advance in atomic force microscopy (AFM). This patented technique allows high resolution topographic imaging of sample surfaces including on surfaces that are easily damaged, loosely held to their substrate, or otherwise difficult to image by other AFM techniques. Specifically, TappingMode overcomes major problems associated with friction, adhesion, electrostatic forces, and other tip-sample related difficulties that can plague other AFM scanning methods. The technique has proven extremely successful for high resolution imaging of the widest variety of samples in gases and liquids including:

- silicon wafers
- thin films
- metals and insulators
- photoresist
- polymers
- life sciences

and numerous others. TappingMode makes imaging these surfaces routine and is by far the most popular AFM technique.

Two conventional scanning modes — contact mode and non-contact mode — have been used for some time with varying success. Each has limitations.

Conventional Methods

In contact mode AFM (Figure 2), the probe tip is simply dragged across the surface and the resulting image is a topographical map of the surface of the sample. While this technique has been very successful for many samples, it has some serious drawbacks. The dragging motion of the probe tip, combined with adhesive forces between the tip and the surface, can cause substantial damage to both sample and probe and create artifacts in the image.

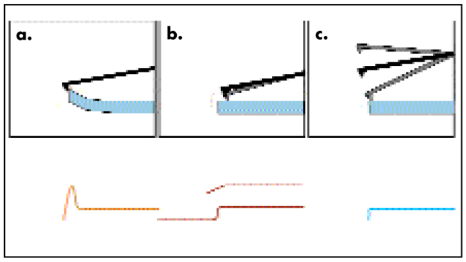


Figure 2. Comparison of contact mode (a.), non-contact mode (b.) and TappingMode (c.) scanning techniques. Contact mode imaging is heavily influenced by frictional and adhesive forces which can damage samples and distort image data. Non-contact imaging generally provides low resolution and can also be hampered by the contaminant layer which can interfere with oscillation. TappingMode imaging eliminates frictional forces by intermittently contacting the surface and probe oscillating with sufficient amplitude to prevent the tip from being trapped by adhesive meniscus forces from the contaminant layer. The graphs under the images represent likely image data resulting from the three techniques.

Under ambient air conditions, most surfaces are covered by a layer of fluid (condensed water vapor and other contaminants) which is typically several nanometers thick. When the scanning tip touches this layer, capillary action causes a meniscus to form and surface tension pulls the cantilever down into the layer (Figure 3). Trapped electrostatic charge on the tip and sample can contribute additional adhesive forces. These downward forces increase the overall force on the sample and, when combined with lateral shear forces caused by the scanning motion, can distort measurement data and cause severe damage to the sample, or just move surface features.

Some researchers have overcome the problems associated with the adhesive forces by operating AFMs with the sample immersed in liquid. When scanning in liquids, the overall forces in contact mode are lower than in ambient air. However, because hydrated samples are sometimes softer than dried samples, tracking forces can still cause reduced image quality and sample damage due to deformation and/or movement of the sample by the scanning probe. In addition, many samples, such as semiconductor wafers, may not be immersed in liquids.

An attempt to avoid this problem is the non-contact mode in which the probe is held a small distance above the sample (Figure 2). Attractive Van der Waals forces acting between the tip and the sample are detected, and topographic images are constructed by scanning the tip above the surface. Unfortunately, the attractive Van der Waals forces are substantially weaker than the forces used by contact mode — so weak in fact that the tip must be given a small oscillation so that AC detection methods can be used to detect the small forces between tip and sample. The attractive forces also extend only a small distance from the surface, where the adsorbed fluid layer may occupy a large fraction of their useful range.

Hence, even when the sample-tip separation is successfully maintained, non-contact mode provides substantially lower resolution than either contact or TappingMode. In practice, the probe is frequently drawn to the sample surface by the adsorbed fluids' surface tension, resulting in unusable data and sample damage similar to that caused in contact mode.

TappingMode Imaging in Air

TappingMode imaging overcomes the limitations of the conventional scanning modes by alternately placing the tip in contact with the surface to provide high resolution and then lifting the tip off the surface to avoid dragging the tip across the surface. TappingMode imaging is implemented in ambient air by oscillating the cantilever assembly at or near the cantilever's resonance frequency using a piezoelectric crystal. The piezo motion causes the cantilever to oscillate with a high amplitude (the "free air" amplitude, typically greater than 20nm) when the tip is not in contact with the surface. The oscillating tip is then moved toward the surface until it begins to lightly touch, or "tap" the surface. During scanning, the vertically oscillating tip alternately contacts the surface and lifts off, generally at a frequency of 50,000 to 500,000 cycles per second. As the oscillating cantilever begins to intermittently contact the surface, the cantilever oscillation is necessarily reduced (Figure 4) due to energy loss caused by the tip contacting the surface. The reduction in oscillation amplitude is used to identify and measure surface features.

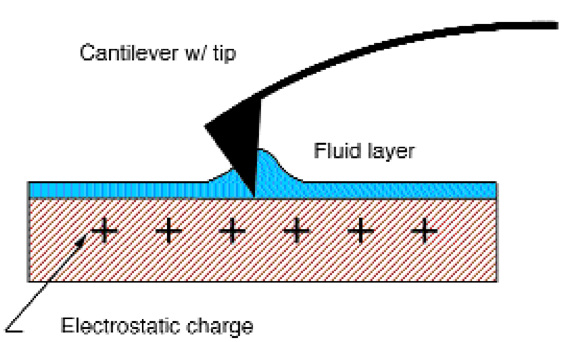


Figure 3. In contact AFM, electrostatic and/or surface tension forces from the adsorbed fluid layer to destructive lateral shear tip sample forces.

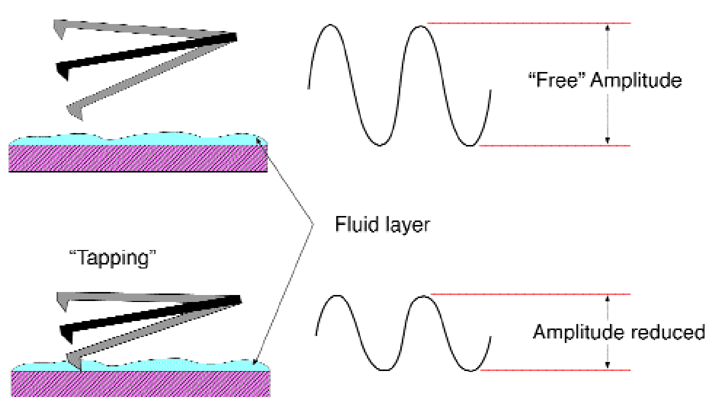


Figure 4. TappingMode cantilever oscillation amplitude in free air and during scanning.

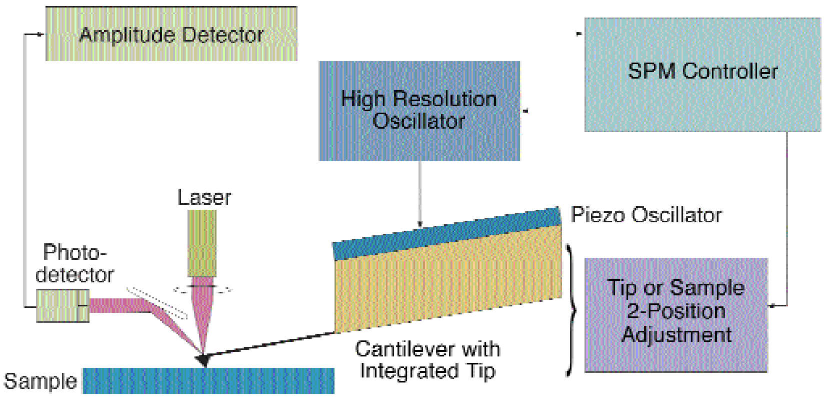


Figure 5. Block diagram for TappingMode operation.

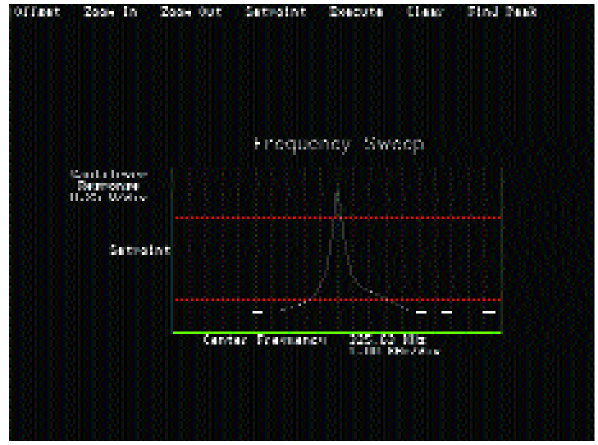


Figure 6. The cantilever tune screen assists the operator in selecting the optimum TappingMode oscillation frequency.

During TappingMode operation, the cantilever oscillation amplitude is maintained constant by a feedback loop (Figure 5). Selection of the optimal oscillation frequency is software-assisted and the force on the sample is automatically set and can be maintained at the lowest possible level (Table 1 and Figure 6). When the tip passes over a bump in the surface, the cantilever has less room to oscillate and the amplitude of oscillation decreases. Conversely, when the tip passes over a depression, the cantilever has more room to oscillate and the amplitude increases (approaching the maximum free air amplitude). The oscillation amplitude of the tip is measured by the detector and input to the SPM controller electronics. The feedback loop then adjusts the tip-sample separation to maintain a constant amplitude.

TappingMode inherently prevents the tip from sticking to the surface and causing damage during scanning. Unlike contact and non-contact modes, when the tip contacts the surface, it has sufficient oscillation amplitude to overcome the tip-sample adhesion forces. Also, the surface material is not pulled sideways by shear forces since the applied force is largely vertical (see sidebar on page 6 for additional discussion of tip-sample forces).

Another advantage of the TappingMode technique is its large, linear operating range (Figure 7). This makes the vertical feedback system highly stable, allowing routine reproducible sample measurements. Several references which discuss TappingMode imaging are listed at the end of this application note.

Drive Frequency Range	*10KHz to 1MHz*
Drive Amplitude and Frequency Adjustment	*Software control and display of TappingMode parameters allows fast, semi-automated on-screen optimization*
Detector	*RMS-to-DC amplitude detector provides phase-independent amplitude signal; Noise level > 0.5Å RMS*
Cantilevers	*Etched silicon cantilevers with or without coatings for specialized applications; typically 50-500KHz resonant frequencies*
Tip-Sample Approach	*Motorized approach automatically brings cantilever into TappingMode operation at low tracking force*

Table 1. TappingMode Specifications.

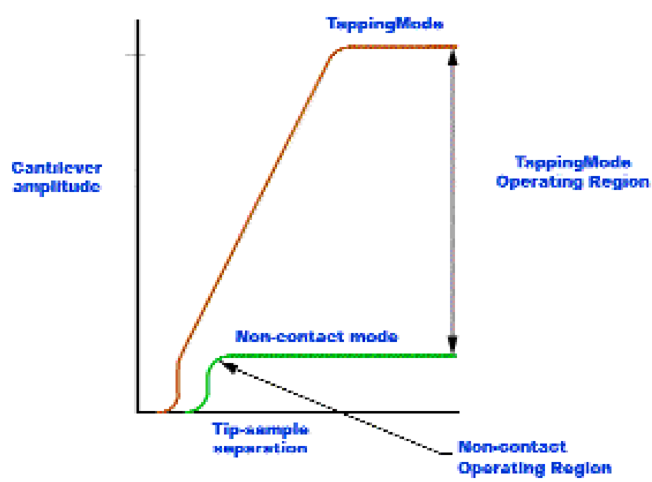


Figure 7. Comparison of large linear operating range for TappingMode vs. small operating range for non-contact mode.

TappingMode Imaging in Liquids

Similar advantages are realized with TappingMode operation in liquids. In this case, however, the liquid medium tends to damp the cantilever's resonance. When an appropriate frequency is selected (usually in the range of 5,000 to 40,000 cycles per second), the amplitude of the cantilever will decrease when the tip begins to tap the sample, similar to TappingMode operation in air.

Once the cantilever is set into oscillation, the SPM feedback system adjusts the position of the tip for samples to maintain a constant oscillation amplitude. Again as in air, the oscillating cantilever eliminates frictional and shear forces on the sample.

Examples

Figures 8 through 14 illustrate the capabilities of TappingMode for imaging a variety of surfaces. Figures 8 through 10 show life sciences imaged in both liquid and air, illustrating the dramatic improvement in image quality for TappingMode relative to contact mode in both environments.

Figure 11 illustrates the capabilities of TappingMode relative to contact modes for harder surfaces, such as in semiconductor and data storage using side-by-side comparisons. Figures 12 through 14 are TappingMode images for a polymer and two thin films.

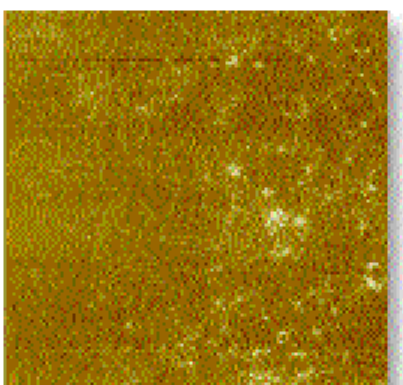


Figure 8. TappingMode image scanned in air of kinetoplast DNA from the trypanozome of a malarial parasite. 2µm scan courtesy Oak Ridge National Labs, Oak Ridge, Tennessee.

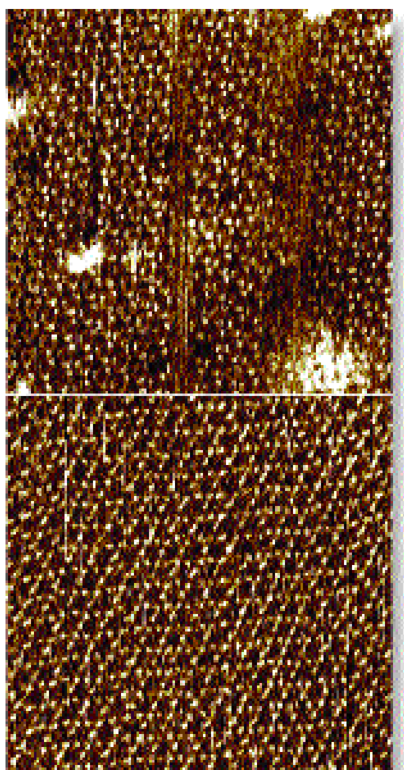


Figure 9. Comparison of contact mode (top) and TappingMode (bottom) images of Bacteriorhosdopsin in liquid (buffer). 100nm scan size.

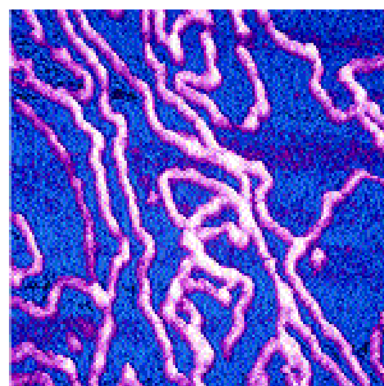
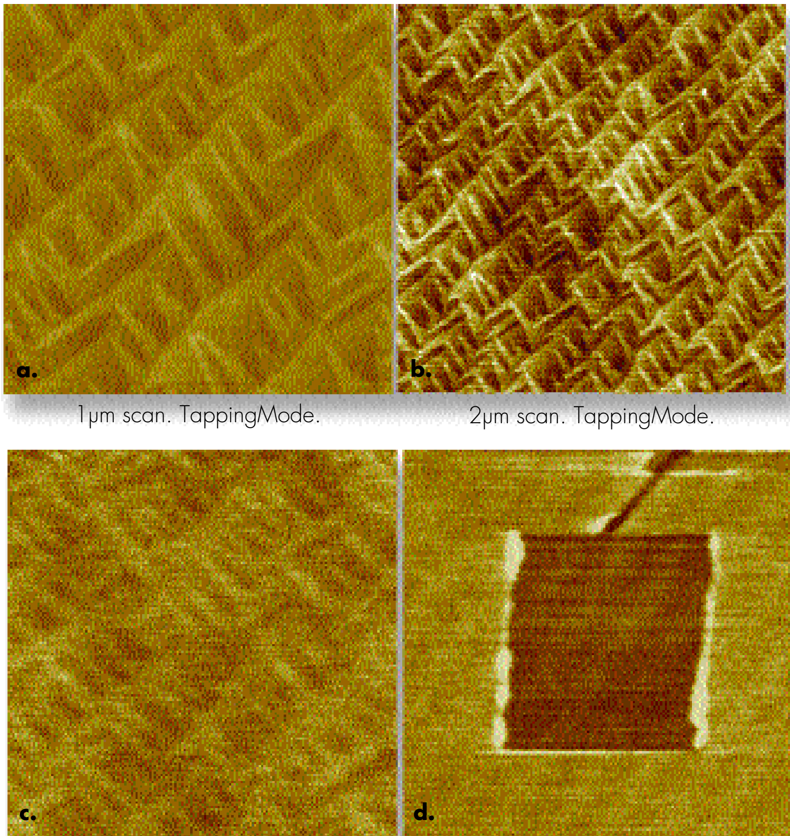


Figure 10. Lambda Hind III DNA imaged on mica with TappingMode in water. The sample was scanned continuously for over one hour without damage. Contact mode scanning of the same material caused damage in less than one minute — before the scan could be completed. 500nm scan courtesy M. Bezanilla, University of California, Santa Barbara.



1µm scan. TappingMode. 2µm scan. TappingMode.

1µm scan. Contact mode. 2µm scan. Contact mode.

Figure 11. Contact and TappingMode images for the same (100) epitaxial wafer. In both cases, the left image was taken first and the scan size was immediately doubled and re-scanned to include the area imaged in the first scan. The TappingMode images show no surface alteration and better resolution. Conversely, the damaged area of the first scan can be easily seen in Figure 11d. Contact mode imaging is extremely inconsistent for silicon surfaces; in this case material has been removed by the scanning tip, while in other cases, additional oxide growth or more subtle changes may occur. This type of surface alteration often goes undetected since most researchers do not check for damage by rescanning the affected area at lower magnification.

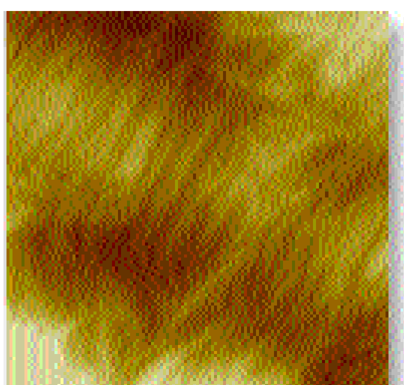


Figure 12. TappingMode image of high density polyethylene from a shopping bag. The structures in the image are the polymer lamellae which are approximately 30nm thick and all oriented in the same direction to increase the tensile strength. This structure could not be seen with contact mode since the features were altered by the tip dragging across the surface. 675nm scan.

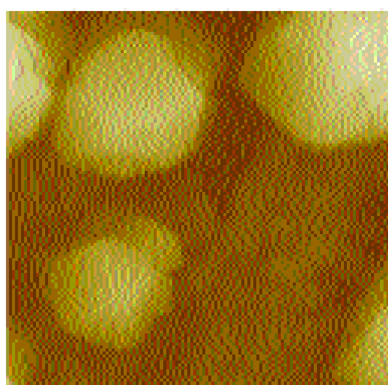


Figure 13. Chemical vapor deposited (CVD) diamond film. During film formation, seed crystals of diamond are placed on a silicon wafer which is then placed in the CVD deposition chamber in which growth is initiated to produce the thin film. This image shows the film at early initiation of growth. The TappingMode technique was used to more accurately profile the crystals and to avoid moving the seed crystals on the surface. 1µm scan. Sample courtesy of Stanford University.

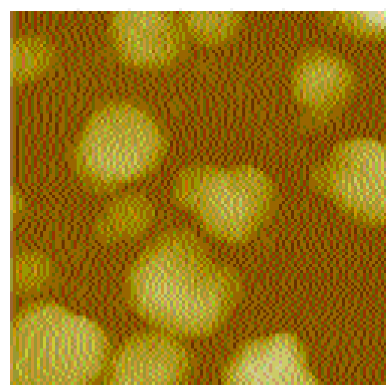


Figure 14. Thermally evaporated gold film, 60Å thick, deposited onto an oxidized silicon wafer. The films were used to build strain sensors with higher strain sensitivity than continuous films. 500nm scan courtesy L. ChunShien, P. Hesketh, and G. Maclay, University of Illinois at Chicago.

Summary

To obtain quality images, it is critical that the microscope tip not damage the surface being scanned but that it contact the surface to obtain high resolution measurements. This is where TappingMode imaging excels. For many materials, this technique provides the highest resolution possible without sample damage.

TappingMode imaging continues to expand the ability of scanning probe microscopy in both materials and life sciences applications, and enables a wide variety of imaging techniques for materials characterization unattainable with Contact Mode. Combined with Phase Imaging, using TappingMode with Veeco SPMs is the key to advancing nanoscience research. For more information about this technique, and the advantages of Phase Imaging, please visit www.veeco.com.

More on Tip-Sample Forces in TappingMode

One of the key advantages of TappingMode imaging over contact AFM is the low tip-sample shear forces generated during scanning. Because the tip only contacts the surface briefly during each oscillation cycle, lateral shear forces applied to the sample by the tip that can tear the sample, distort data, or dull the tips are minimized.

The brief contact force is less than one might expect. In TappingMode the cantilever is oscillated at or near its resonant frequency. Once the cantilever amplitude is stabilized at the desired setpoint, the sample must absorb only the small force due to the increased amplitude during a single oscillation cycle; i.e., the time between two consecutive "taps." Because the cantilevers used in TappingMode have a high quality factor ("Q"), the amplitude gained in one cycle is very small. The force due to this small amplitude increase can be absorbed by the vast majority of samples with no damage to tip or sample. Because of these gentle scanning forces, TappingMode has been used successfully to reproducibly image such samples as polymers, unbaked photoresist and DNA, as well as numerous other fragile samples. Also, we have repetitively imaged the angstrom-level microroughness of the same 1µm region of a silicon wafer continuously over a 24-hour period without degradation of the image or damage to the sample.

Finally, the cantilever is oscillated at frequencies from 50KHz to 500KHz. At these frequencies, many surfaces become stiff (viscoelastic) and can more easily resist forces from the probe tip. This property further reduces the possibility of sample damage for extremely soft samples such as polymers, biological specimens, and others and causes less distortion of the sample due to tip forces.

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