High-Resolution Tip Positioning Facilitates *In Situ* AFM Studies

Application Note

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Introduction

The Agilent 5600LS AFM system features a fully addressable, 200 mm x 200 mm stage to support samples of various sizes. After loading a sample as large as an 8-inch wafer on the stage, any locations (including the wafer edge) can be reached directly by the AFM tip without remounting or rotating the sample. In addition, the 5600LS offers the ability to move the stage with sub-micrometer-scale precision over the system's entire hundreds-of-millimeters translation range, thus enabling high-resolution tip positioning at selected sample locations. This application note provides an explanation, illustration, and how-to guide of high-resolution tip positioning and its role in facilitating *in situ* AFM imaging.

High-Resolution Tip Positioning

The accuracy of tip positioning originates from the stage move and stage control mechanisms. Coupled with ceramic motors, the stage is actually driven by high-resolution piezoelectric devices. With specially designed ceramic geometry and electrical drive, simultaneous excitations of longitudinal extension and transverse bending of the piezo in the motor result in a driving force being exerted on the stage to make it move. The periodic nature of the excitation drive at a frequency much higher than the mechanical resonance of the stage allows a continuous, smooth stage motion. Due to the intrinsic characteristics of the piezoelectric effect (i.e., applied high voltages correspond to a nanometer-scale change in the physical dimensions of piezoelectric materials), these ceramic motors offer an attainable resolution better than 100 nm.

Besides its fine shift capability, the stage is also equipped with optical encoders that have a sub-100nm detection resolution. Stage moves are regulated via closed-loop servo control. Therefore, the 5600LS can deliver accurate location positioning with better than 500nm reproducibility. The example provided in Figure 1 demonstrates this ability. A grating sample is first immobilized on the stage at a selected location close to the edge and the stage is then manually shifted to make sure the AFM tip is right above the sample. After tip approach and engagement, the grating sample is initially imaged by AFM (Fig. 1, left). Next, the tip is withdrawn and the stage is programmed to travel in such a way (a closed triangle loop with the two turning points also close to the stage edge) that the stage will move almost fully in both X and Y directions and return to its starting point at the end. Once the programmed move is finished, the sample is imaged again by AFM (Fig. 1, right). Using a particular surface feature (e.g., the hole at the location approximately corresponding to 4 μm in the X axis and 2 μm in the Y axis) as the reference mark, it can be observed that the displacement of the tip positioning is <200 nm.

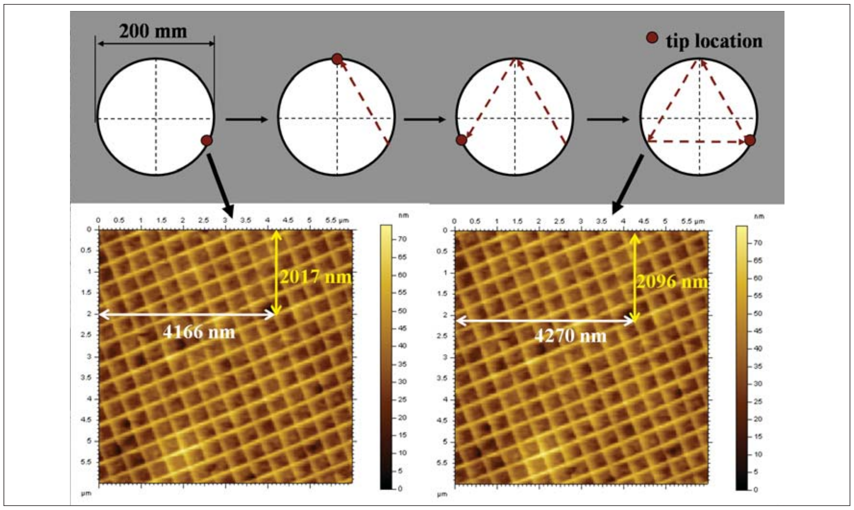
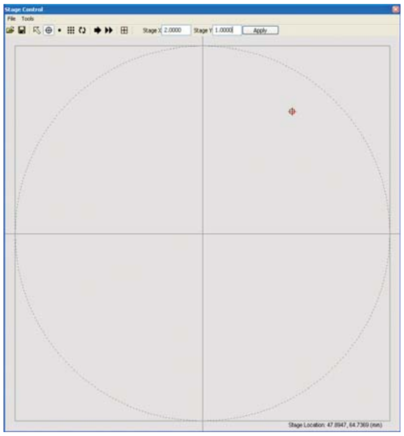
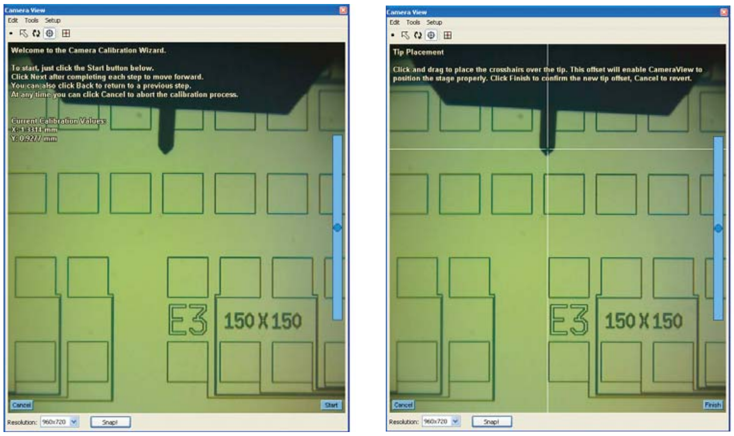


Figure 1. This example demonstrates the sub-500nm accuracy of 5600LS stage moves. A grating sample is imaged via AFM before the stage move (left) and after a programmed, closed-loop stage move to return to the original position (right).



Stage X 2.0000
Stage Y 1.0000
Stage Location: 47.8947, 64.7369 (mm)

Figure 2. The graphic user interface "Stage Control" in the software is used for stage move control.



Welcome to the Camera Calibration Wizard.

To start, just click the Start button below.
Click Next after completing each step to move forward.
You can also click Back to return to a previous step.
At any time you can click Cancel to abort the calibration process.

Current Calibration Values:
X: 1.3314 mm
Y: 0.9277 mm

Resolution: 960x720

Tip Placement

Click and drag to place the crosshairs over the tip. This offset will enable CameraView to position the stage properly. Click Finish to confirm the new tip offset, Cancel to revert.

Resolution: 960x720

Figure 3. The graphic user interface "Camera View" in the software is used for camera view calibration (left) and tip placement (right).

The graphic user interface "Stage Control" (Figure 2) in the software allows easy control of stage moves. Among the main menu options (near the top of the "Stage Control" window), a preferred stage location can be accurately defined by direct input of values (up to ten thousandths of a millimeter to meet the requirement for sub-micrometer accuracy control) for the "Stage X" and "Stage Y" parameters. After that, a simple click on the "Apply" button will direct the stage to the planed position.

The ability to move the stage with extremely high resolution via easy software control dramatically benefits AFM investigations in the following two ways:

1. It enables *in situ* AFM imaging.

   Tip positioning at a desired sample location is quick and easy because the sample move can be achieved directly through software control, which is more accurate than manual operation. In addition, the current stage position is always displayed in real time at the bottom of the "Stage Control" window (e.g., "Stage Location: 47.8947, 64.7369 (mm)" in Figure 2). Therefore, once a sample location of interest is identified, the corresponding stage position (i.e., "Stage Location" numbers) can be tracked and used later to be inputted as the "Stage X" and "Stage Y" values to direct the stage move to guarantee the tip positioning at or near the same sample location.

2. It enables the AFM scanner to operate at its full-range capability and under optimized conditions.

   Fine control of stage moves can completely substitute for the offset function of a scanner, thus allowing the AFM to preserve its maximum scan size. (Using scanner offset to achieve tip repositioning carries the tradeoff of decreased scan size.) Furthermore, because scanner calibration is typically performed with zero offset, operating the AFM with minimum scanner offset can result in more accurate measurements by eliminating possible distortion when the scanner is pushed to its limit.

Optical View-Based Automatic Tip Positioning

An optical microscope incorporated in an AFM system allows direct visualization of both the tip and the surrounding sample area. This optical view can help users search for or locate surface features of interest and guide the subsequent sample move in such a way as to bring those targets right underneath the tip. Typically, however, users need to shift the sample slowly and carefully in a manual fashion (or drive the sample move via software control if a motorized sample stage is available) while closely watching the optical display in the monitor. This process can be time consuming and frustrating. Furthermore, the accuracy of tip positioning is affected by the fact that when targeted surface features are brought very close to the tip position they will be blocked by the cantilever itself in the optical view. This difficulty arises because most AFM tips are not located at the very edge of the cantilever, thus making it extremely hard to judge whether or not the tip is positioned exactly above the target.

The 5600LS AFM system provides a new software feature, point-and-shoot, that enables automatic and accurate tip positioning at selected sample locations purely via software control. Its working principle is based on the fact that 5600LS stage moves are high resolution at the sub-micrometer scale and can be directed completely through software. The operating procedures of the point-and-shoot feature are relatively straightforward:

1. Calibrate the camera view.

   A camera calibration wizard is available in the software (Fig. 3, left) and provides step-by-step instructions for the entire process, which includes selecting a visible surface feature as the reference mark, defining its initial location in the camera view, moving it via shifting the stage, and then redefining its "afterwards" location in the camera view. 5600LS stage encoders can detect and accurately quantify the stage move (in both the X and Y directions) and the calibration of the "Camera View" window can be achieved by correlating measured stage position variations to the corresponding position change of the reference mark in the camera view due to the stage move.

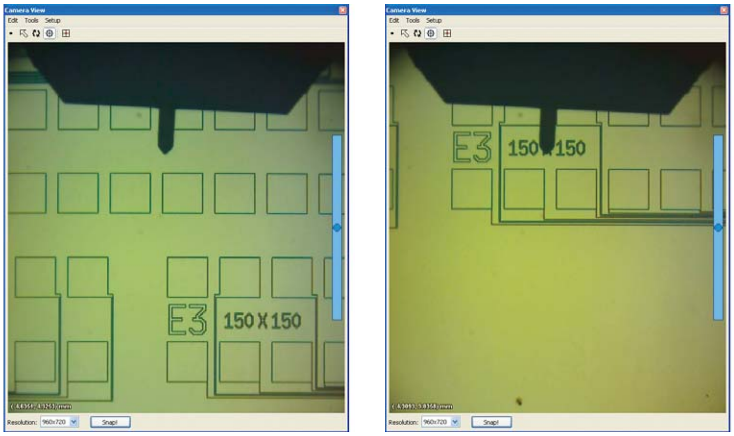


Figure 4. This example demonstrates the automatic stage move directed by point-and-shoot.

2. Define the AFM tip position in the camera view.

   This can be done directly by clicking and dragging to place the crosshairs at the current tip location (Fig. 3, right).

3. Select the target location from the camera view.

   Once the camera view is correctly calibrated and the current AFM tip location is defined, simply clicking the sample feature of interest in the camera view can direct the stage to move automatically and bring the selected target location exactly underneath the tip. Figure 4 presents an example demonstrating point-and-shoot performance. Here, a particular location corresponding to the center of the "X" (between two "150" numbers) near the right bottom corner (Fig. 4, left) is chosen. It shows (Fig. 4, right) that the stage directed by point-and-shoot moves exactly as expected, putting the center of the "X" directly under the tip.

Accurate Tip Positioning for *In Situ* AFM Studies

In this section of the application note, a practical case will be used as an example of achieving easy, accurate tip positioning based on the above-mentioned 5600LS hardware performance and software functionality. It would be difficult to locate the target feature quickly and perform an *in situ* AFM study using any other AFM instrument or technique.

The sample under investigation is a special optical fiber made with undisclosed materials. One of the primary interests is to quantitatively measure the mechanical properties of this optical fiber. Therefore, the sample is first probed via nanomechanical scratching with an Agilent Nano Indenter G200 system. The diamond tip of an indenter is scanned across the sample with precisely controlled loads and speeds to produce trenches along different directions at a chosen location on the surface. In order to calculate the mechanical properties, both the lateral width and vertical depth of the fabricated trenches are critically needed. It is highly desirable for the same fiber to be subsequently characterized *in situ* by a high-resolution AFM to measure the physical dimensions of these target features.

In this multi-technique study, however, the same sample must be transferred from one instrument to another instrument. This requirement places a high premium on the ability of the AFM system to position the tip accurately at a preferred site (i.e., to "find" the previously produced features). To make things even more challenging, the fiber is composed of a material that is not optically reflective, thus leading to a situation in which none of the sample-related surface features (not to mention the nanometer-scale fabricated trench lines) can be identified in the resultant optical image. With almost no landmarks in the optical view to serve as the reference mark, typically the best approach for this kind of sample is to use a large AFM scanner to search at different locations until the feature of interest is found. It will be extremely challenging to guarantee the correct tip positioning in the first AFM image, particularly if a small scanner is used (i.e., scan size less than 10 µm x 10 µm).

The only useful points of reference that can be relied upon are the relative positions of the indentation pattern with respect to the center of the fiber. Figure 5 is the draft revealing both the pattern geometry (two crossed red lines in the picture) and its location in the designed indentation experiment. Detailed definitions such as the orientation of the longer red line (with a 50 degree angle from the vertical green line) and distances from the center to each line (12 µm for the longer red one and 7.6 µm for the shorter one) are provided.

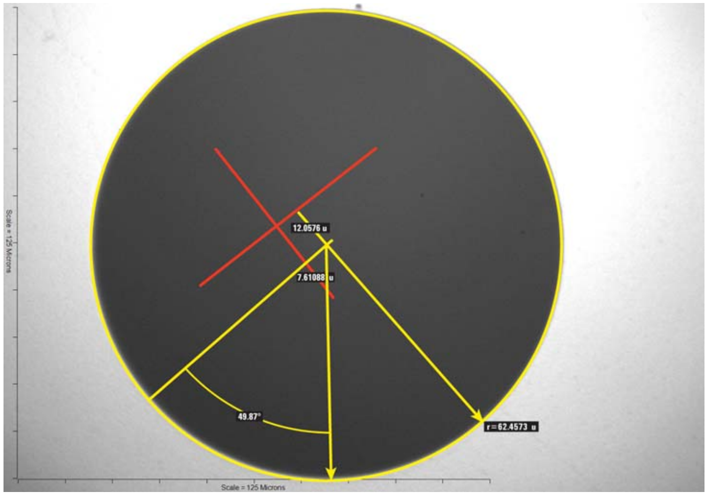


Figure 5. The draft showing both the scratch geometry and location in the indentation experiment.

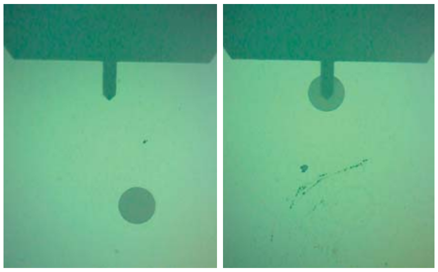


Figure 6. Quick tip positioning at the fiber center using point-and-shoot.

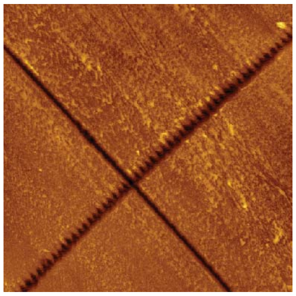
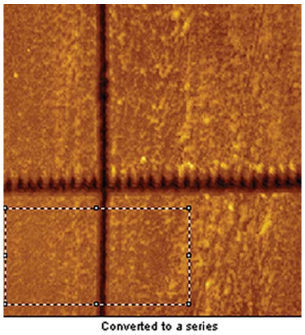


Figure 7. AFM image after tip positioning at the targeted scratch pattern.



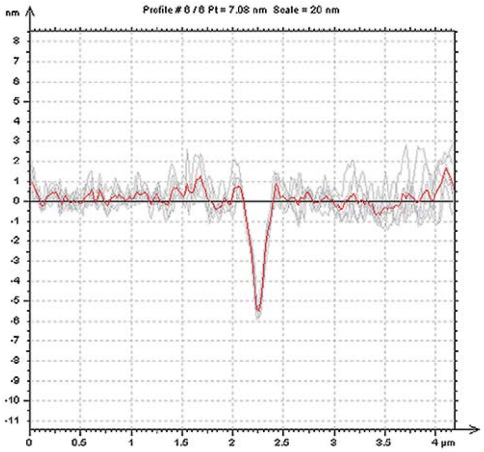


Figure 8. Quantitative measurements of the scratch pattern based on the AFM study.

With this quantitative information, the relative position of the crossed point of the two red lines with respect to the fiber center is approximately 15.5 µm on the left side in the X direction and 3.5 µm above in the Y direction. The tip positioning for the fiber sample, therefore, can follow a two-step approach. First, point-and-shoot quickly brings the tip right above the fiber center as shown in Figure 6. Then the stage can be directed to move exactly 15.5 µm along the -X direction and 3.5 µm along the +Y direction by inputting -0.0155 mm as the Stage position X value and 0.0035 mm for the Stage position Y value in the "Stage Control" window.

After this designed stage move, the fiber is immediately imaged by the AFM. In the first resultant AFM image, Figure 7, the indented pattern is present and the crossed point is close to the image center. The only manual involvement with the sample during the entire AFM operation is to place it on the stage and within the optical field of view. After that, quick and accurate tip positioning can be achieved by software control. Thus, the ability of the 5600LS to provide high-resolution tip positioning and facilitate *in situ* AFM studies is clearly demonstrated in this example.

Several quantitative measurements based on the AFM data are listed in Figure 8. For instance, the average scratch depth and width within the specified area are ~5.5 nm and ~294 nm, respectively (Fig. 8, right).

Summary

The Agilent 5600LS AFM system offers accurate, quick tip positioning through fine control of stage moves. The system's point-and-shoot software function provides an easy, automatic way to move the tip to a selected target feature based on the optical view. The high-resolution tip positioning of the 5600LS greatly facilitates *in situ* AFM studies.

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