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Crystal Scanner for Nano-Metrology Applications

Paul West, Zhiqiang Peng, Natalia Starostina
Pacific Nanotechnology, Inc.
pwest@pacificnanotech.com

Introduction

Traditionally a scanning probe microscope (SPM), such as the atomic force microscope (AFM), affords spectacular images of surfaces at the nanometer scale. With advanced developments in scanner design, probe manufacturing and force sensor technology it is now possible to make quantitative metrological measurements with an SPM. Quantitative metrological measurements that are possible include: a) dimensional measurements of micro/nano fabricated structures, b) surface texture of surfaces having RMS values of only a few angstroms, and c) measurements of the number of grains, and particles on a surface as well as grain and particle sizes, areas, volumes, and distributions.

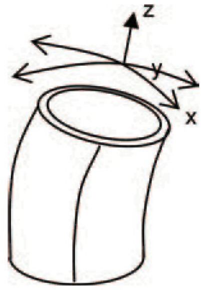


Figure 1: A piezoelectric ceramic in the shape of a tube is often used in AFMs for generating 3-D motion. Electrodes are deposited on the inner and outer surface of the tube. By sectioning the outer electrode in four quadrants, and using the inner electrode, 3-D motion is possible. There is a variant of the tube scanner design that has a separate Z ceramic at the end of the tube; however, there are serious coupling issues between all three of the axis in all tube scanner designs.

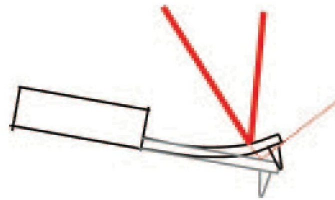


Figure 2: In the light lever force sensor a laser beam is reflected of the backside of a cantilever. There are two problems with this approach, first the cantilever is at an angle to the surface, and the deflection of the cantilever causes a change in the probe/sample angle.

The design of the crystal scanner is optimized for metrological measurements. The force sensor is small and permits use of advanced flexure stages, which are orthogonal and have minimal out of plane motion. Further, the probes used in the crystal scanner may be constructed from any type of material such as tungsten, silicon, or even glass.

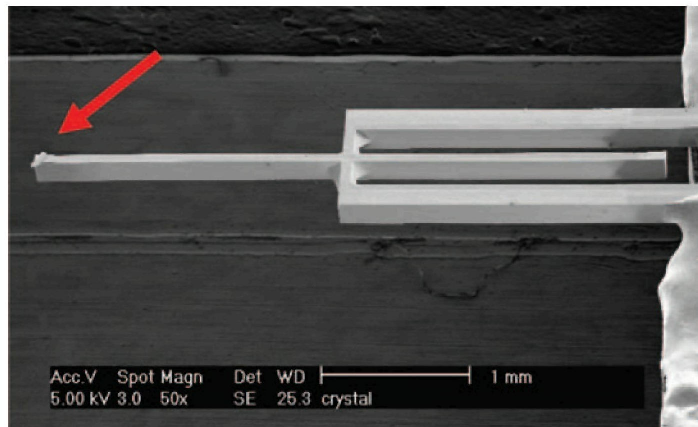


Figure 3a: This SEM image shows the cross quartz crystal resonator used in the crystal sensor. A cantilever, identified by the red arrow, is mounted at the end of one of the resonating beams of the quartz oscillator. The dimensions of the oscillating beams are: 2.1 mm long, 0.09 mm wide, and 0.17mm thick. Electrodes are deposited on two opposing faces of the beams.

Background

Scanners that move the probe in an AFM are typically constructed with piezoelectric ceramics. The three dimensional motions of the scanner are made possible by configuring the ceramics in one of several geometries such as a tube or a tripod. Regardless of the scanner configuration there are problems resulting from the hysterisis and creep of the piezoelectric ceramics. These effects make it difficult to make precise and accurate measurements in all areas of a scanner's field of view. Also, it is tedious to zoom in on a small feature in an initially-viewed, AFM large scan area image.

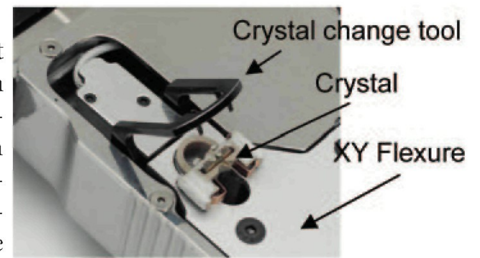


Figure 3b: The crystal sensor is held in the scanner with a zero insertion force mechanism. The crystal change tool is used to remove the force of springs that hold the crystal sensor in the scanner. Changing the crystal sensor takes less than a minute.

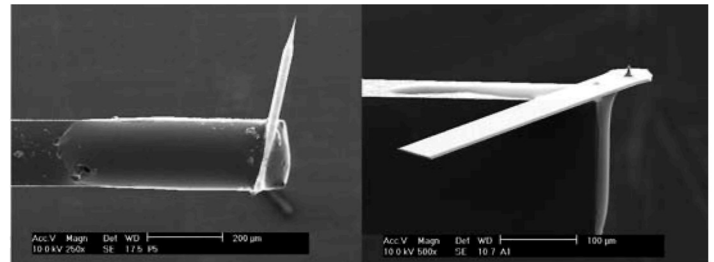
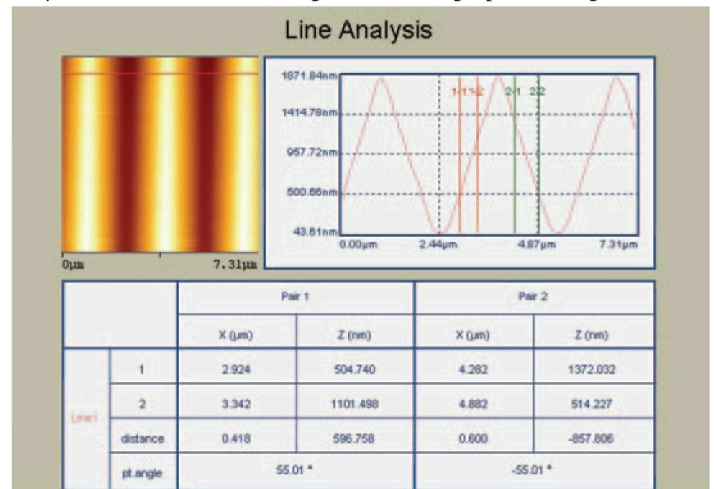


Figure 4: Many types of probes may be used with the crystal sensor. At the right is a tungsten probe and at the left is a silicon probe.

Typically, scanners suffer from crosstalk between the spatial axes scanned. For example, there is unwanted crosstalk between the XZ, YZ, and XY axis, see figure 1. Crosstalk is possible even when the scan axes are fully linear and calibrated. This crosstalk makes the measurement of sidewall angles in structures such as semiconductor devices and DVDs impractical.

Finally, because scanners are designed from tripods or tubes, there is a considerable background bow in the images. Such bow may be removed from images with image processing software;



		Pair 1		Pair 2	
		X (µm)	Z (nm)	X (µm)	Z (nm)
Line1	1	2.924	504.740	4.262	1372.032
	2	3.342	1101.498	4.882	514.227
	distance	0.418	596.758	0.600	-857.806
	pt.angle	55.01 °		-55.01 °	

Figure 5a: XZ and YZ crosstalk is tested using a reference sample having a triangle pattern etched its surface. The angles of the sides of the triangle patterns should be the same, 55 degrees. The line analysis at the right shows the correct angle is measured for both sides of the triangle with the Crystal Scanner.

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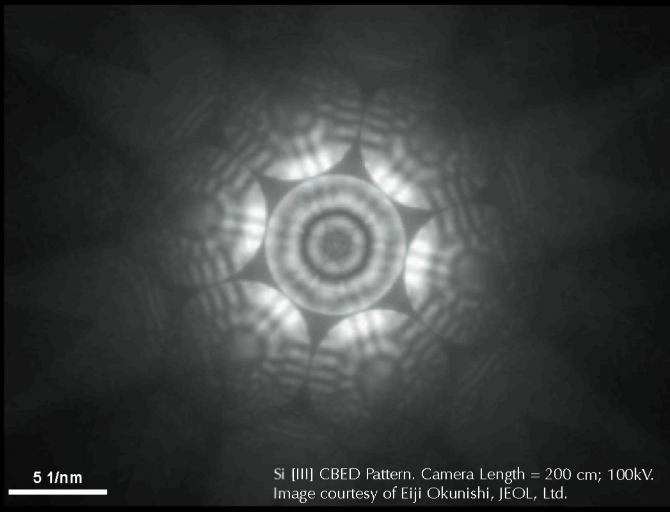
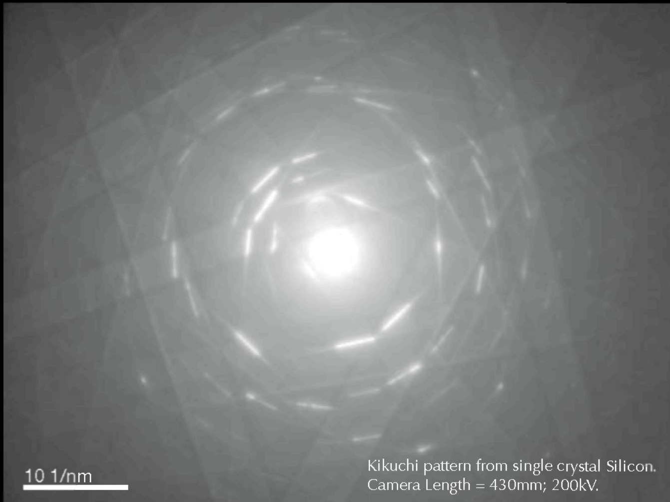
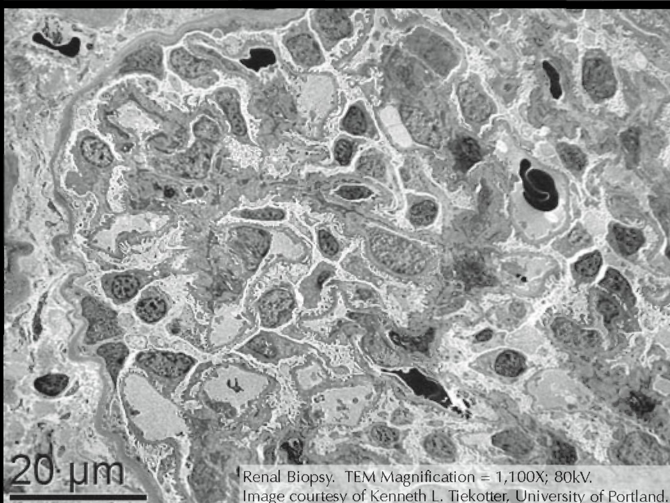


Si [III] CBED Pattern. Camera Length = 200 cm; 100kV.
Image courtesy of Eiji Okunishi, JEOL, Ltd.

Peripheral Nerve. TEM Magnification = 30,000X; 80kV.
Image courtesy of Kenneth L. Tiekotter, University of Portland.



Kikuchi pattern from single crystal Silicon.
Camera Length = 430mm; 200kV.



Renal Biopsy. TEM Magnification = 1,100X; 80kV.
Image courtesy of Kenneth L. Tiekotter, University of Portland.

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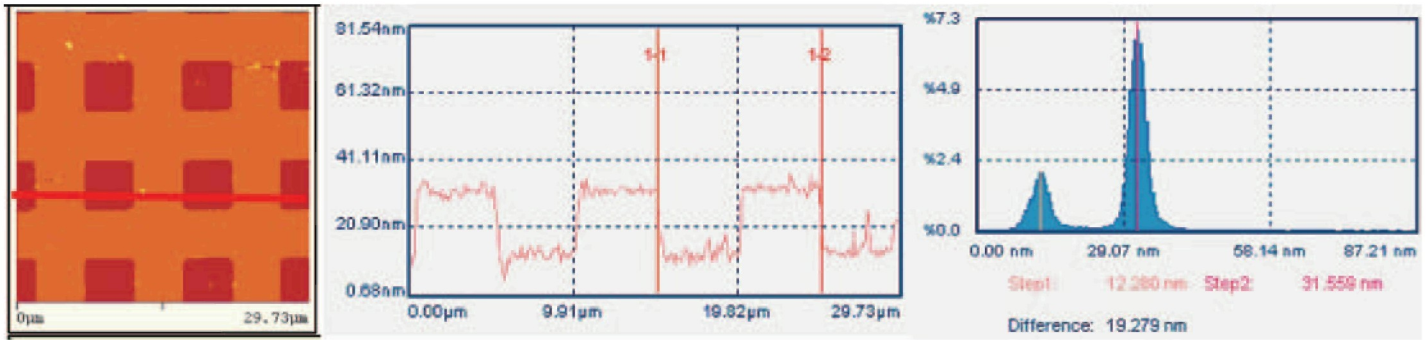


Figure 5b: The calibration in the X-Y axis is verified with a VLSI standard test pattern. The pitch of the standard is measured with a line profile and the result must be within the error margin of the standard. The Z axis is calibrated by measuring the height of features in the standard. A histogram analysis is optimal because the histogram includes the data points from the entire image.

however, such removal can easily add unwanted image processing artifacts.

In many of the first designs of scanning probe microscopes, the sample was scanned while the probe was held fixed. This approach was abandoned because scanning the sample greatly limited the number of sample types that could be scanned. Samples of different weight and sizes required different scan conditions. These unwanted problems are avoided when the probe is scanned in the x, y and z axis and the sample is held stationary.

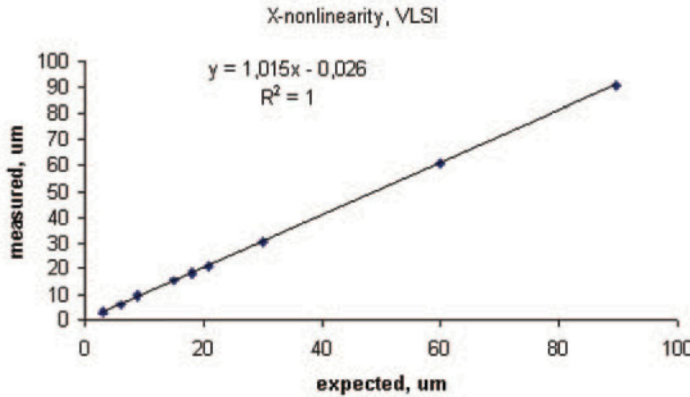


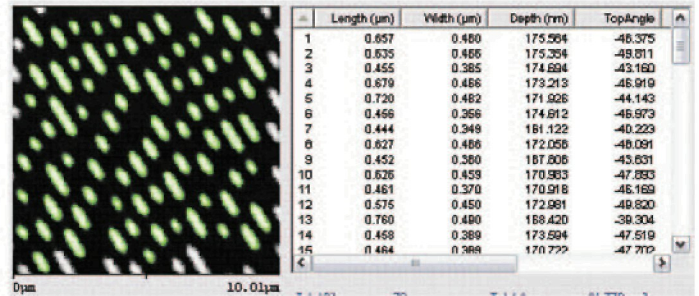
Figure 5c X and Y nonlinearity are determined by comparing the expected position of features on a test pattern with the measured position of features on the test pattern. This figure shows the results form a measurement of the features in the X axis of a VLSI standard.

Probes mounted at the end of a cantilever play a critical role in the ability to make metrology measurements with an atomic force microscope, see figure 2. With the most common type of force sensor, the light lever, the angles between the cantilever and sample is established by the optical path of the light lever sub-system. Typically the probes are at fixed angle, between 5 and 15 degrees, with respect to the surface. Specialized designs have a probe that is mounted at an angle to compensate for cantilever/surface angle. Both types of cantilever/probe result in errors in metrological measurements with an AFM.

Crystal Scanner™

The crystal scanner is designed for making accurate and precise topographic images at the nano-scale. The crystal scanner has two major sub-components: the crystal sensor and the xyz piezoelectric scanner.

Crystal Sensor- The crystal sensor, shown in figure 3, is constructed using a quartz crystal oscillator having a resonance frequency at approximately 640 kHz. Forces between the probe and surface are detected by measuring a change in the vibration



	Length (µm)	Width (µm)	Depth (nm)	TopAngle
1	0.657	0.480	175.564	-46.375
2	0.635	0.466	175.354	-49.811
3	0.455	0.385	174.694	-43.160
4	0.679	0.466	173.213	-46.919
5	0.720	0.482	171.926	-44.143
6	0.466	0.356	174.612	-46.973
7	0.444	0.349	181.122	-40.223
8	0.627	0.466	172.056	-48.091
9	0.452	0.380	187.806	-43.631
10	0.626	0.459	170.963	-47.893
11	0.461	0.370	170.918	-46.169
12	0.575	0.450	172.981	-49.820
13	0.760	0.490	168.420	-39.304
14	0.458	0.389	173.594	-47.519
15	0.464	0.389	170.722	-47.702

Figure 6a: The Crystal Scanner can measure high resolution images of DVD masters, stampers, and replicas. With specialized software the dimensions of each of the DVD bits are easily calculated.

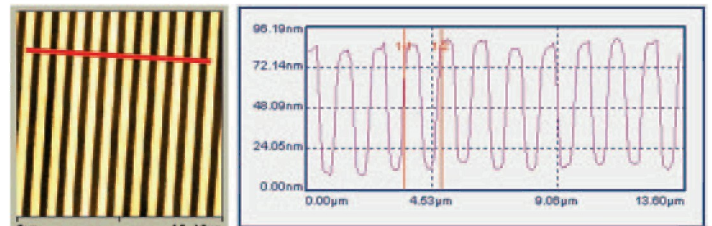


Figure 6b – Single line profiles or automated software is available for measuring pitch of optical media using the Crystal Scanner.

amplitude or phase of the resonating crystal. In typical operation, the vibration amplitude of the crystal is < 0.4 nm and the probe/surface forces are < 300 pN.

The damping force between the probe and surface are a complex combination of vertical and horizontal forces. In operation, the probe in the crystal sensor vibrates horizontally in the *average* plane of the surface. However, because of surface topography, the probe vibrations are damped by the vertical component of the interaction vector. Additionally, the probe vibration damping can occur from interactions with the contamination layer at the surface of a sample.

With the crystal sensor, topography images for all types of samples are measurable and provide exceptional visualization.

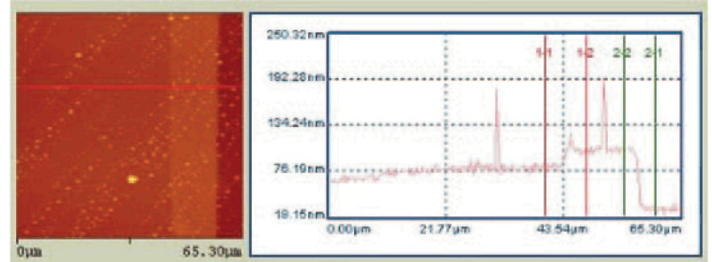


Figure 7 The step height of this structure on a flat panel display is measured with the Crystal Scanner. The step at the left is 20nm and at the right is 80 nm.

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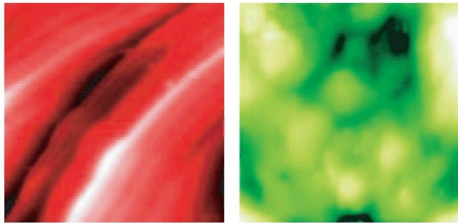

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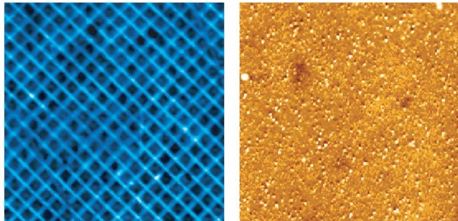

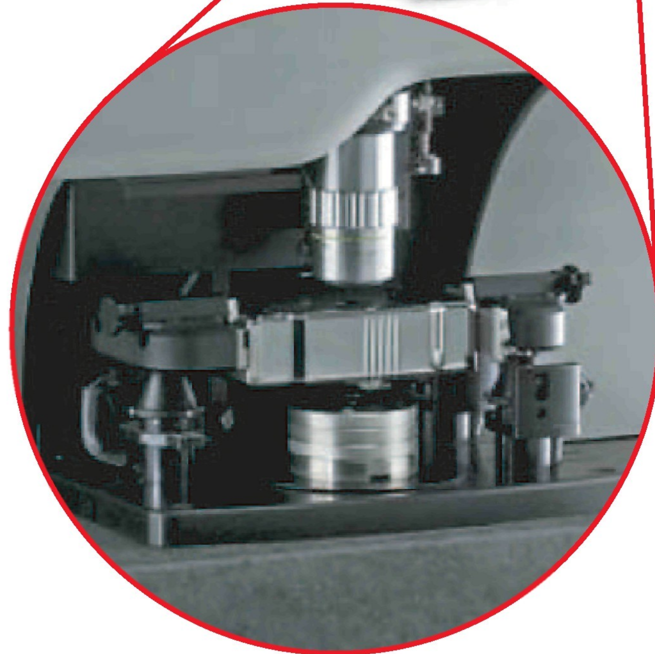

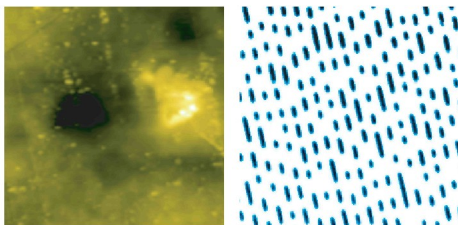

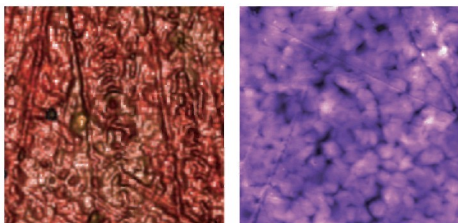

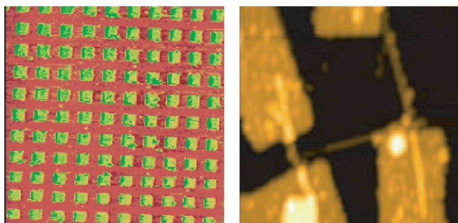

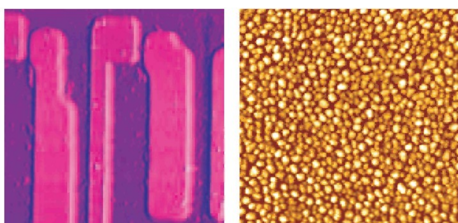

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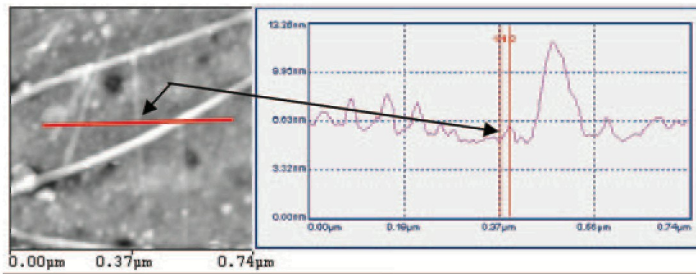


Figure 8a: Crystal sensor image of single and multiwall carbon nanotubes. The single wall nanotube, measured in the line profile, is 1 nm height.

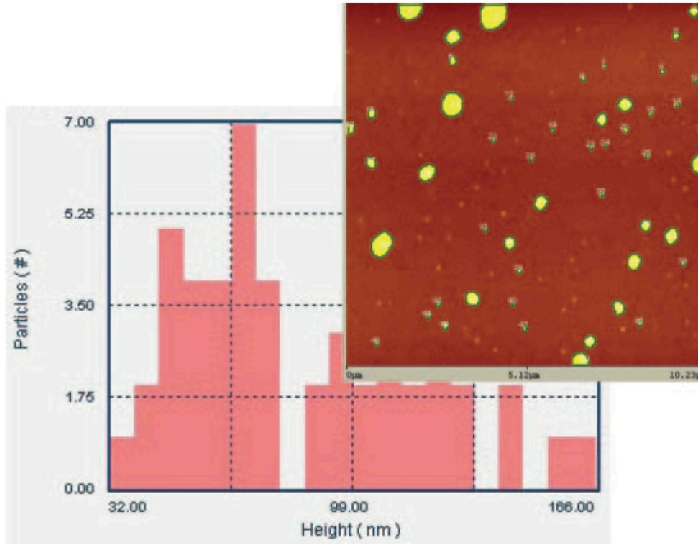


Figure8b With automated software, crystal microscope images of nanoparticles may be analyzed. The number of nanoparticles, the height, the diameter and volume are calculated. On the right is an analysis showing the distribution of particles in the CFM image.

Examples of images obtained with the crystal include polymers, semiconductor devices, and DVD's. Examples of scientific research applications include nanoparticles and DNA.

Scanner Design- Because the crystal sensor is small and modular, it can be mounted on most types of three dimensional piezoelectric scanners. The optimal scanner for X-Y motion, used in the Pacific Nanotechnology Crystal Scanner, uses a flexure for both axes. This is because a flexure scanner has minimal bow, and X-Y crosstalk. In the Z axis, a direct piezoelectric drive is used. The direct drive ceramic facilitates viewing of the probe with a video optical microscope. Figure 3b illustrates the probe mounting fixture in a Crystal Scanner.

Probes- Probes used in the crystal sensor are chemically fastened to the extended tine of the crystal resonator. This means that any type of probe can be used with the crystal sensor. For example, as illustrated in figure 4, a tungsten probe or a silicon probe can be used. In the case of a tungsten probe, the angle of the probe is variable.

Specifications- Specifications for the Crystal Scanner are optimal for making metrological measurements. The specifications are helpful in determining if an application may be possible with the scanner. However, it is important to fully understand the application before the exact application is done. Figures 5a-c show some of the data and images used for establishing the specifications of a Crystal Scanner.

Specifications of the Crystal Scanner are:

Range		
	XY	> 65 microns
	Z	> 8 microns
Integral Linearity		
	X-Y	< 1 %
	Z	< 1 %
Cross Talk		
	XY	< 1 %
	ZX, ZY	< 2 %
Calibration		
	X-Y	< 1 %
	Z	< 2 %
Maximum Out Of Plane		
	ZX	± 30 nm
	ZY	± 30 nm

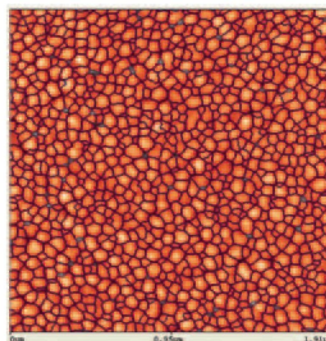
Figure 5c X and Y nonlinearity are determined by comparing the expected position of features on a test pattern with the measured position of features on the test pattern. This figure shows the results form a measurement of the features in the X axis of a VLSI standard.

Metrology Examples

Great care must be taken to properly make metrology measurements with scanning probe microscopes. Knowledge of the scanner specifications and probe geometry are essential for making SPM dimensional or metrological measurements. The metrological measurements such as step heights, surface roughness, particle size, and pitches are required for several types of product development, process development, and research areas.

Technical Applications:

Optical Media – The development of optical storage media, such as digital video disks, requires control of the physical dimensions at the nanometer level. Parameters such as bit sidewall angles, bit width, bit length, and bit height must be critically controlled. Figure 6 shows crystal images of DVD bits and the types of analysis that is possible



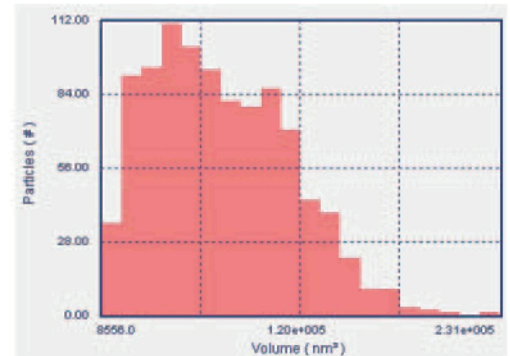


Figure 9: Using specialized software the grains size distribution of this polysilicon sample is measured with the Crystal Scanner. The grain area, perimeter, and volume may be calculated. On the right is a histogram plot for the grain size volume.

Flat Panel Displays – It is important to critically measure and control thin film thicknesses in flat panel displays. Because the Crystal Scanner is calibrated in the X, Y and Z axes, it is ideal for

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step height measurements of films used for flat panel displays, see figure 7.

Semiconductor Devices – Characterizing the geometries of structures used in devices is important for improving device density and performance. The Crystal Scanner is ideal for measuring the geometry of semiconductor devices.

Nano Structure Applications:

Nanotubes – Nanotubes play an ever important role in the evolution of nano-scale science and technology. The Crystal Scanner is ideal for both visualizing nanotubes but also measuring their diameter and their length, Figure 8a

Nanoparticles – Characterizing the size and shape of nanoparticles is often done with FE-SEM or even TEM. The Crystal Scanner affords an alternative to these electron beam techniques. With the Crystal Scanner and special software, the diameter, and diameter distribution of nanoparticles is easily measured, figure 8b

Nano Grains – Grains at the nano-scale play a critical role in the electrical characteristics and mechanical properties of many thin films. Because the images measured with the Crystal Scanner are three dimensional, software can readily count the number and calculate the area and area distributions of grains, see figure 9.

Conclusion

The Crystal Scanner is optimized for making metrological measurements. The types of measurement that are possible include surface texture, dimensional measurements on micro/nanofabricated devices, nanostructure dimensions, and particle/grain analysis. Such measurements are useful in high technology industries, basic industries and research institutions working in nanotechnology. ■

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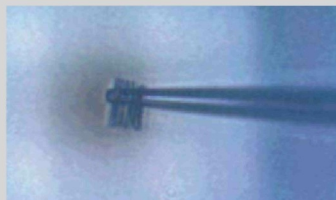

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