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Advanced Nanoscale Metrology with AFM

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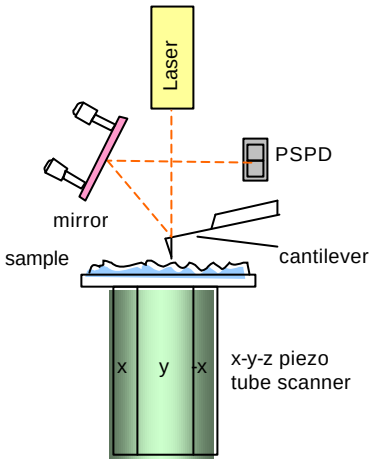
SPM: the Key to the Nano World

- Initiated by the invention of STM in 1982.
  - By G. Binnig, H. Rohrer, Ch. Gerber at IBM Zürich.
- Expanded by the invention of AFM in 1986.
  - By G. Binnig, C.F. Quate, Ch. Gerber at Stanford Univ.
- Numerous modes of SPM was introduced thereafter.

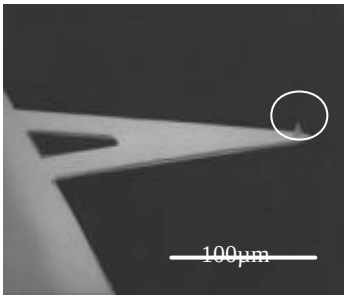
Schematics of AFM

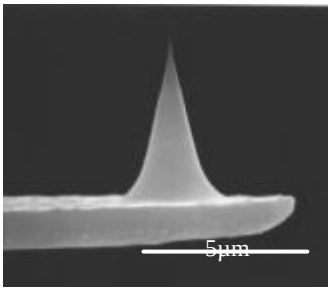
- Deflection of cantilever is measured by baser beam bounce system.



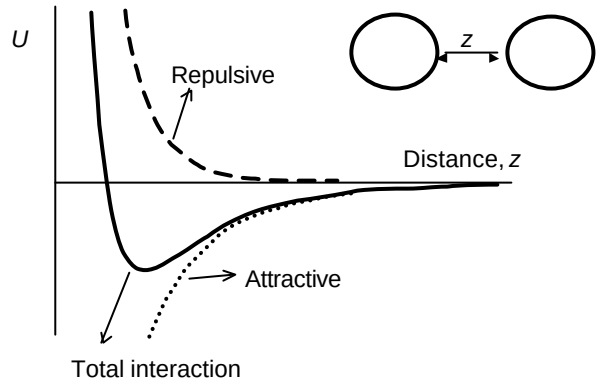
- Laser interferometer
- Piezo resistance
- Quartz tuning fork

Typical AFM Cantilever and Tip

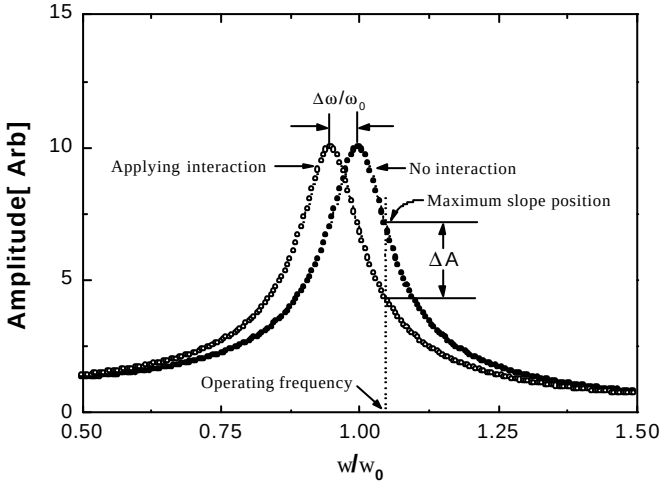




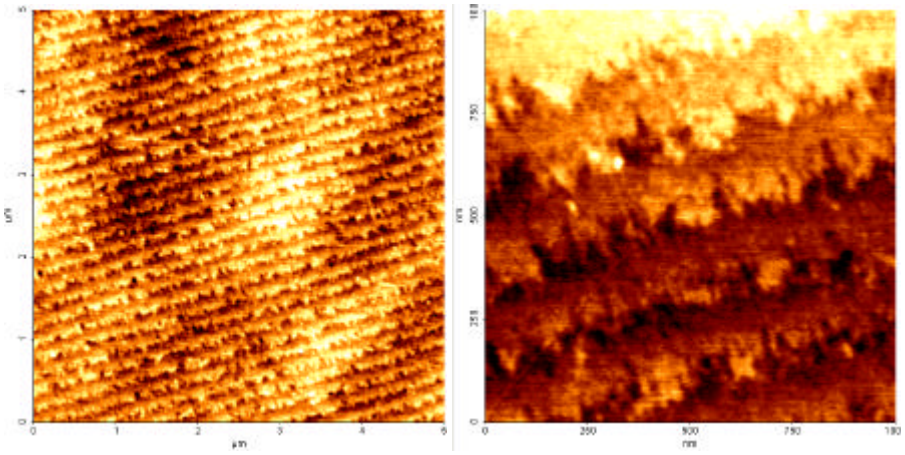
Inter-Atomic Force



Resonance Frequency Change Due to Tip-Sample Interaction

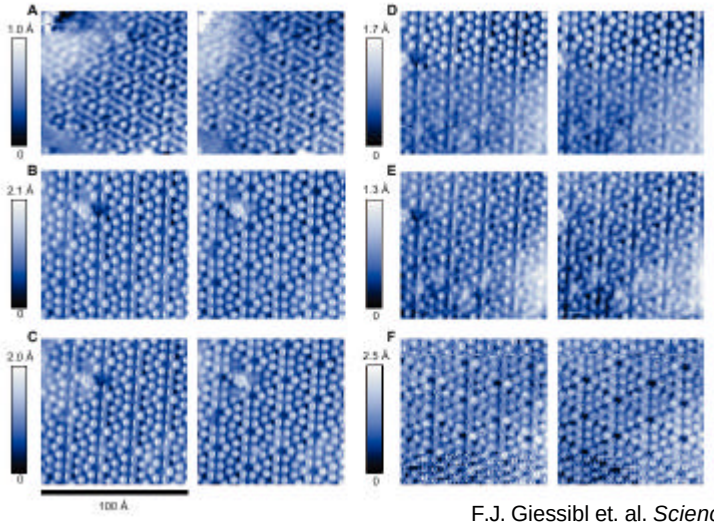


NC-AFM: Mono Atomic Steps on LAO



Scan size: 5 x 5 µm, 1 x 1 µm, z range: 0.5 nm [$LaAlO_3$]

UHV NC-AFM: Si(111) 7x7



FM Detection

Tuning fork

W tip

f_0=16.7kHz

k=1800N/m

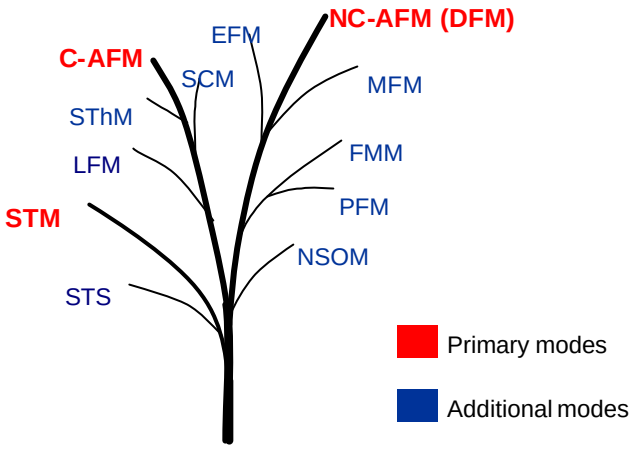
A=0.8nm

F.J. Giessibl et. al. *Science* **289**, 422 (2000).

Advantages of SPM

- High Resolution : ~ 1nm lateral, < 0.1nm vertical.
- Quantitative 3-D information.
- Non-conductors as well as conductors and semiconductors.
- Operates in air, liquid, and vacuum.
- Can measure electrical, magnetic, optical, and mechanical properties.
- Atomic scale manipulations and lithography.

SPM Family Tree

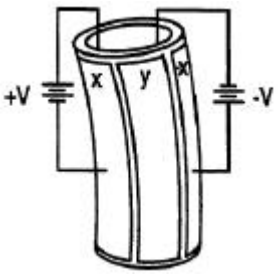


SPM Wish List

- **Speed**
  - z-scanner response
  - NC detection time constant
- **Accuracy**
  - Scan accuracy
  - Tip convolution
- **Resolution**
  - Acoustic and vibration noise
  - Preserving sharp tip
- **Convenience**
  - Easy operation
  - Optical vision

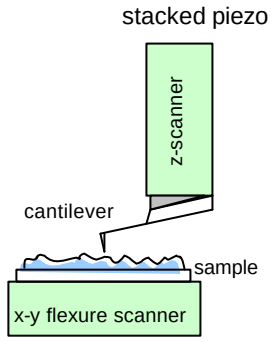
Common Problems in Conventional AFM

- Piezo tube is not an orthogonal 3-D actuator.
- Non-linearity.
- x-y and z cross talk and background curvatures in z.
- Low resonance frequency (f_0 < 1kHz) and low force.



New XE Scan System

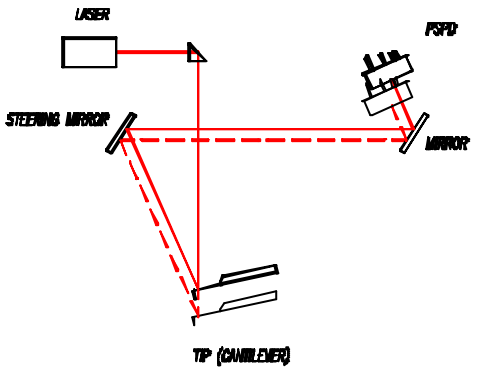
- Separated z scanner from x-y scanner; x-y scanner scans only the sample, z scanner scans only the probe.
- x-y flexure scanner has minimal out-of-plane motion.
- Rigid and high force z scanner can scan much faster (f_0 > 10kHz).



Single module parallel-kinematics x-y scanner

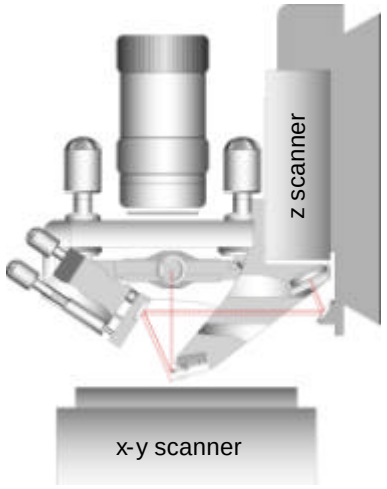
Cantilever Deflection Measurement

- z scanner moves the cantilever and PSPD.
- With a second mirror, the bounced laser beam hits the same point on PSPD regardless of the z scanner motion.

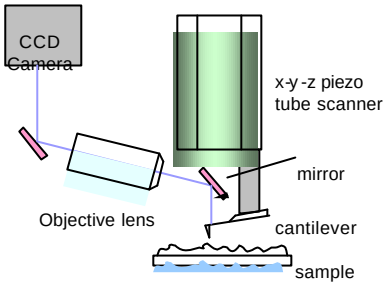


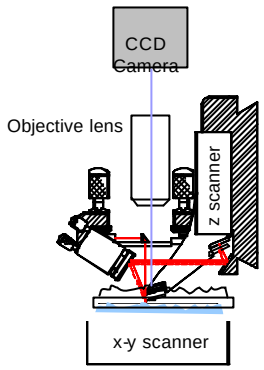
XE Scan System

- Z scanner moves only the cantilever and the detector (PSPD).
- Laser, steering mirror and aligning mechanisms are fixed on the head frame.
- x-y scanner moves only the sample.



On-Axis Optical Microscope



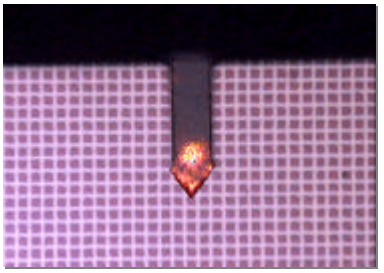


In conventional large sample AFM, an oblique mirror had to be used.

XE scan system allows direct on-axis optical view.

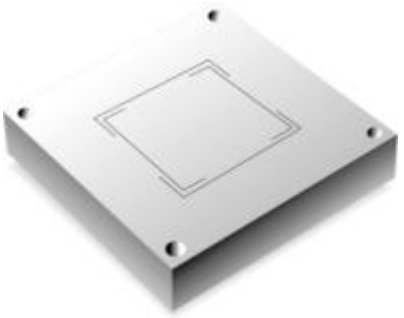
Improved Optical Vision

- All optical elements – objective lens, tube lens, and CCD camera – are rigidly fixed on a single body.
- The whole optical microscope move together for focusing and panning to keep the highest quality intact.
- 1 µm resolution (0.28 N.A.)



x-y Flexure Scanner

- Single module parallel-kinematics stage has low inertia and minimal runout.
- Provides the best orthogonality, high responsiveness, and axis-independent performance.



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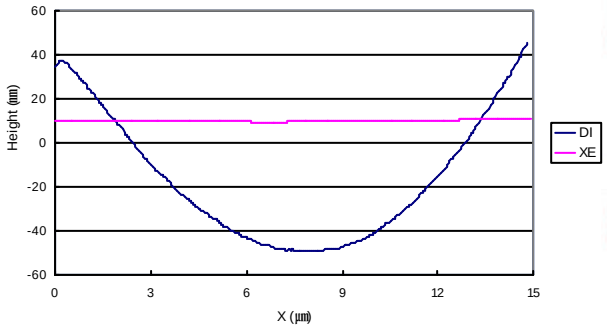
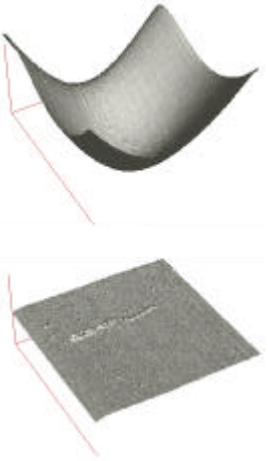
Improved Scan Accuracy

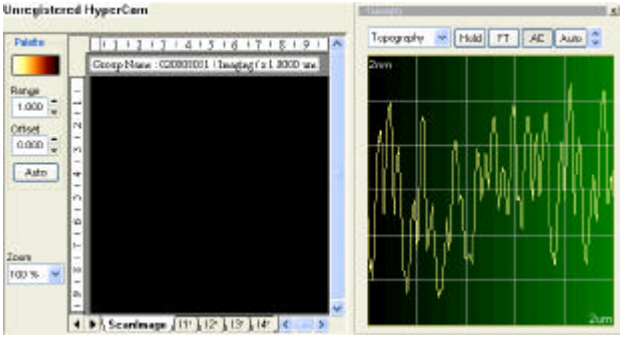




PSIA

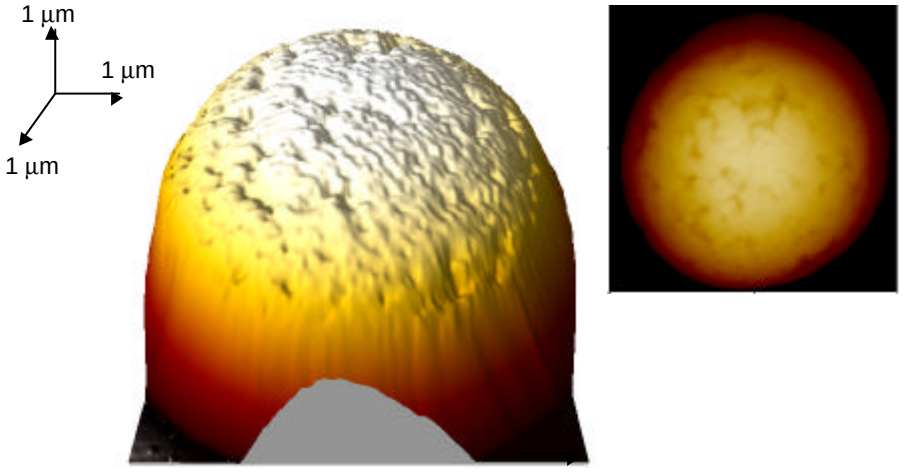
Improved Scan Speed

Contact mode, 10Hz scan, 10 x 10 µm (256 x 256 pixel)



PSIA

Improved z-servo Performance

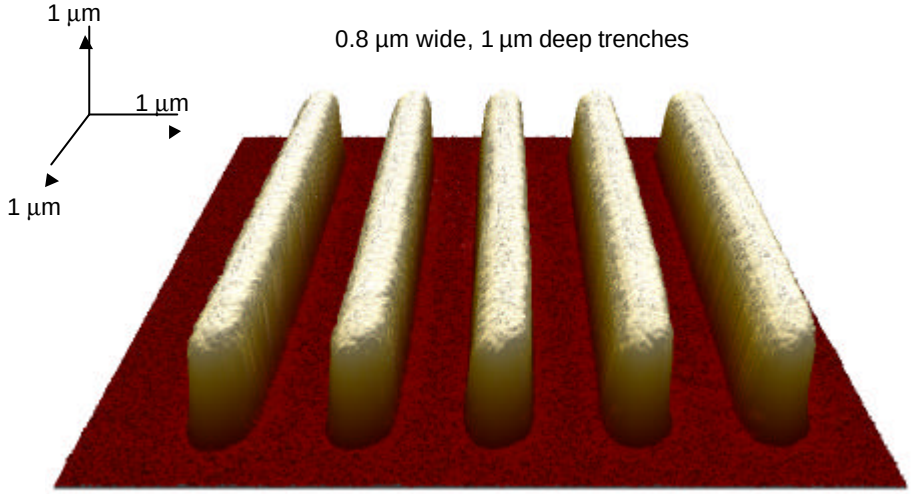


Scan size: 6 x 6 µm, z range: 6 µm NC-AFM [Styrene and Divinyl-Benzen]

PSIA

Improved z-servo Performance

0.8 µm wide, 1 µm deep trenches



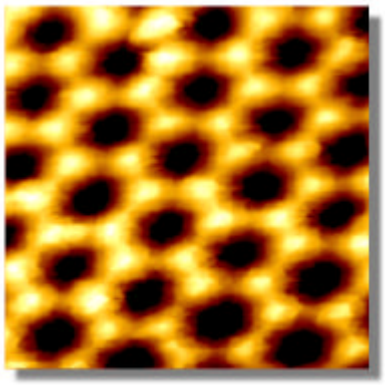
Scan size: 9 x 9 µm, z range: 1.4 µm NC-AFM [Silicon Pattern 0.8 µm width]

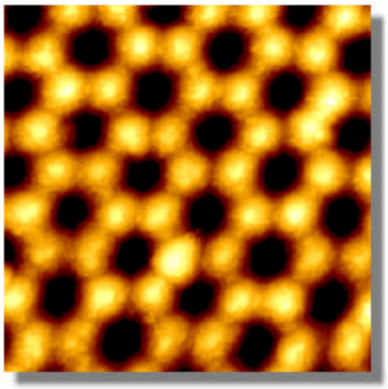
PSIA

Improved Resolution

Conventional AFM tapping mode

XE non-contact mode





Scan size: 500 x 500 nm, z range: 10nm [Anodically generated textured aluminum]

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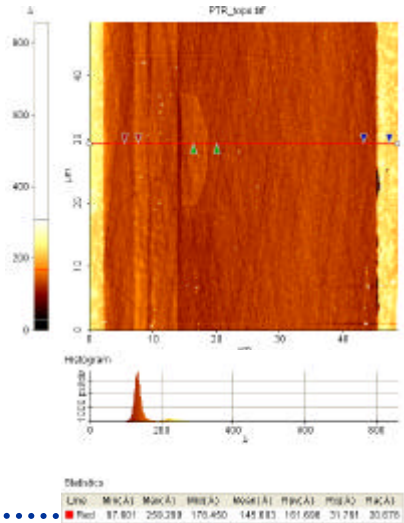
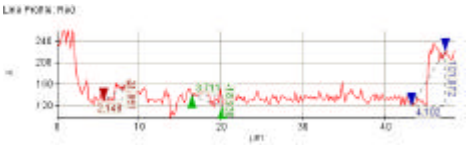
Advanced Metrology with XE: PTR





Pole Tip Recession (PTR) of MR head has been an important subject of nano-metrology, but conventional AFM had difficulty.

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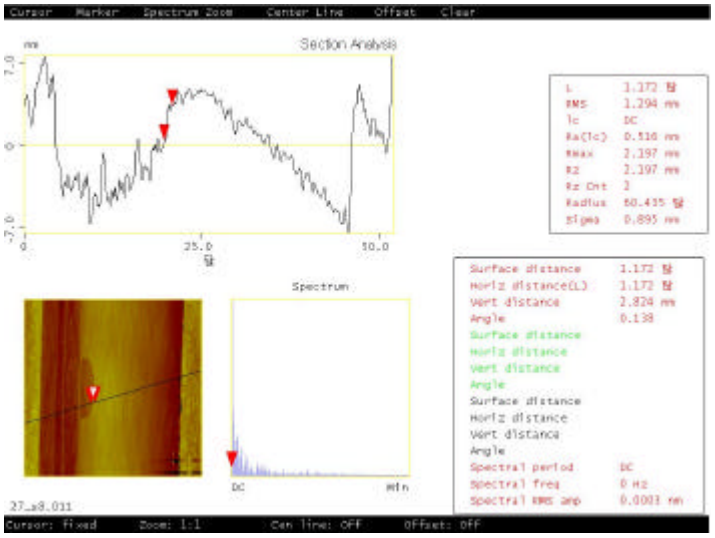
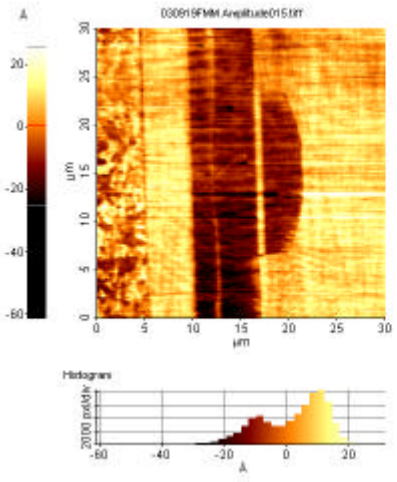
Conventional AFM Tapping Mode



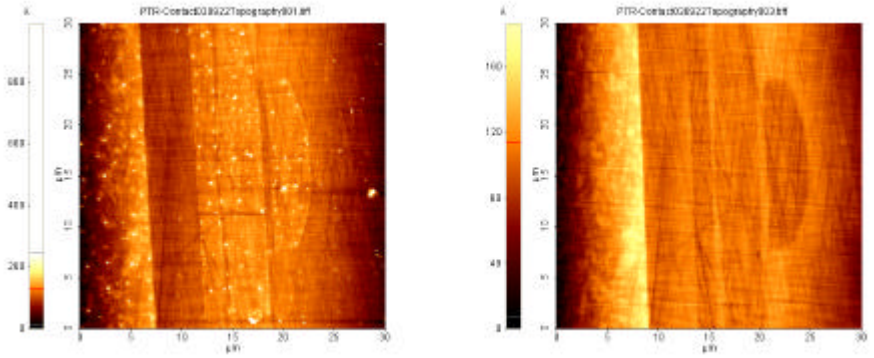
PSIA

Force Modulation Image



File Name	030919FMM Amplitude015.tiff
Head Mode	FMM
Source	FMM Amplitude
Data Width	256 (pxl)
Data Height	256 (pxl)
X Scan Size	30 (μm)
Y Scan Size	30 (μm)
Scan Rate	0.5 (Hz)
Set Point	1.5 (nN)
Data Gain	244.14E-6 (μm/step)

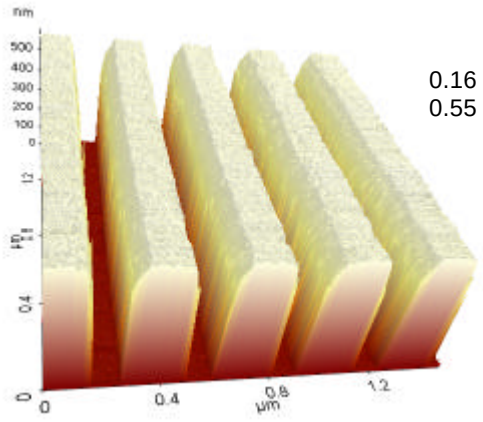
Contact Mode AFM



Small Setpoint Large Setpoint

Tapping force makes indentation on soft pole tip!

CD Metrology

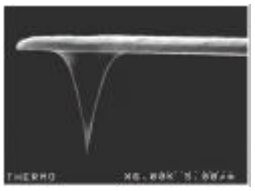


0.16 µm wide
0.55 µm deep trenches

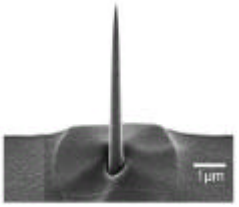
Scan size: 1.5 x 1.5 µm, z range: 0.6 µm NC-AFM

Improved AFM Probe Tips

Conventional conical Si tip

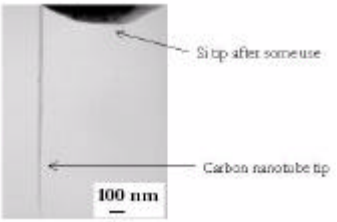


FIB tip (Park Scientific Instruments)



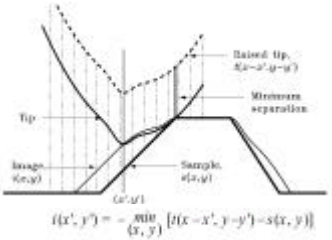
High Density Carbon tip (Nano Tools)

Carbon Nanotube tips (Piezo Max)



Tip Convolution and Deconvolution

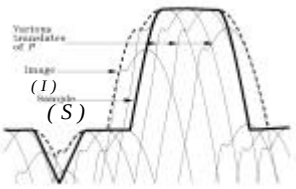
by JS Villarrubia, NIST



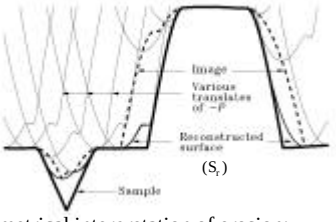
$$i(x,y) = \max_{(u,v)} [s(x-u, y-v) + p(u,v)] \quad \Rightarrow I$$

$$p(x,y) = -t(-x,-y) \quad \Rightarrow P = -T$$

$$I = S \oplus T \qquad S_r = I \ominus P$$

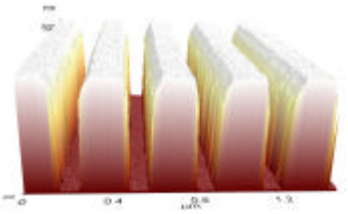


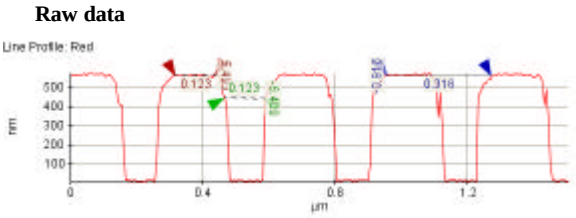
Forming AFM image by dilation

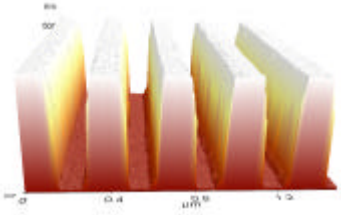


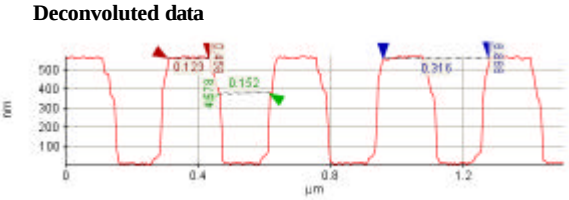
Geometrical interpretation of erosion: Reconstructed image is equivalent to the minimum of tip's envelop

Tip De-convolution









Conclusions

- The performance of AFM has been greatly improved with the new XE design.
  - 2D flexure scanner vs. tube scanner
  - NC-AFM vs. tapping mode AFM
- The new XE AFM can provide nanoscale metrology solutions, which were not possible with conventional AFM.