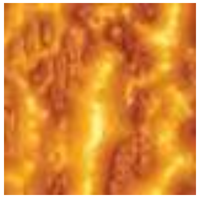
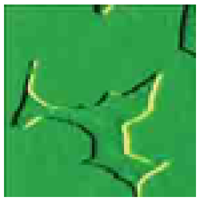
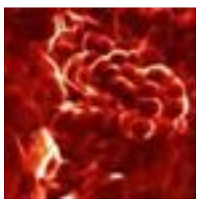
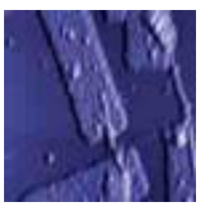
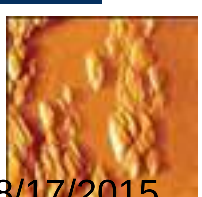

Today's SPM in Nanotechnology

An introduction for Advanced Applications

Qun (Allen) Gu, Ph.D., AFM Scientist, Pacific Nanotechnology

IEEE Bay Area Nanotechnology Council, August, 2007

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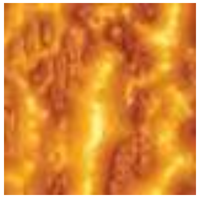
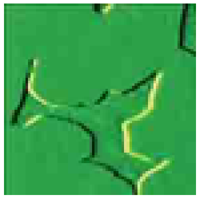
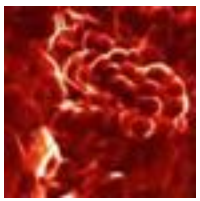
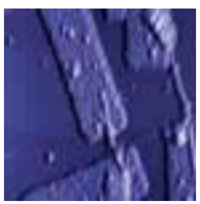
Content

- AFM fundamentals: Principle, instrument, applications
- Field Modes
  - EFM
  - KPM
  - MFM
- Shark Modes (C-AFM, I-V)
- Lithography
  - LAO
  - Scratch
  - DPN



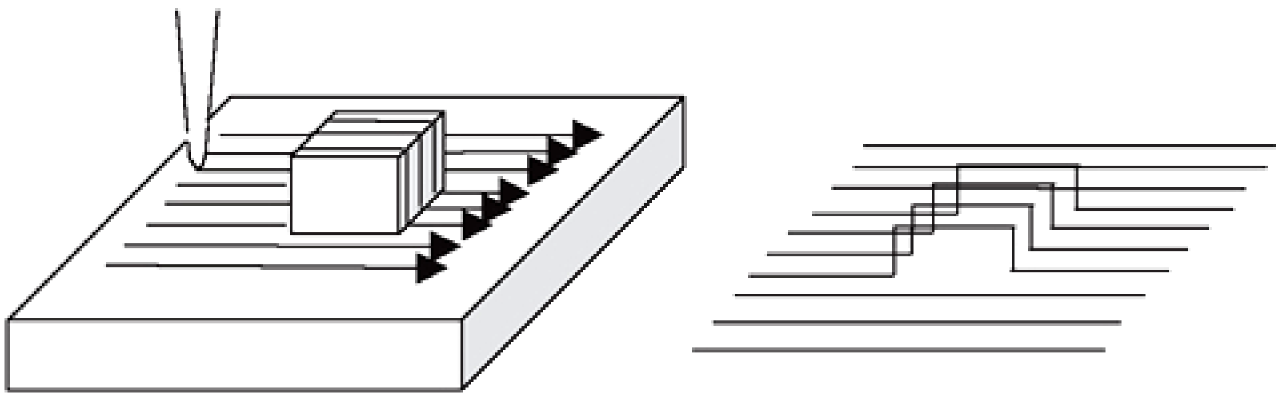




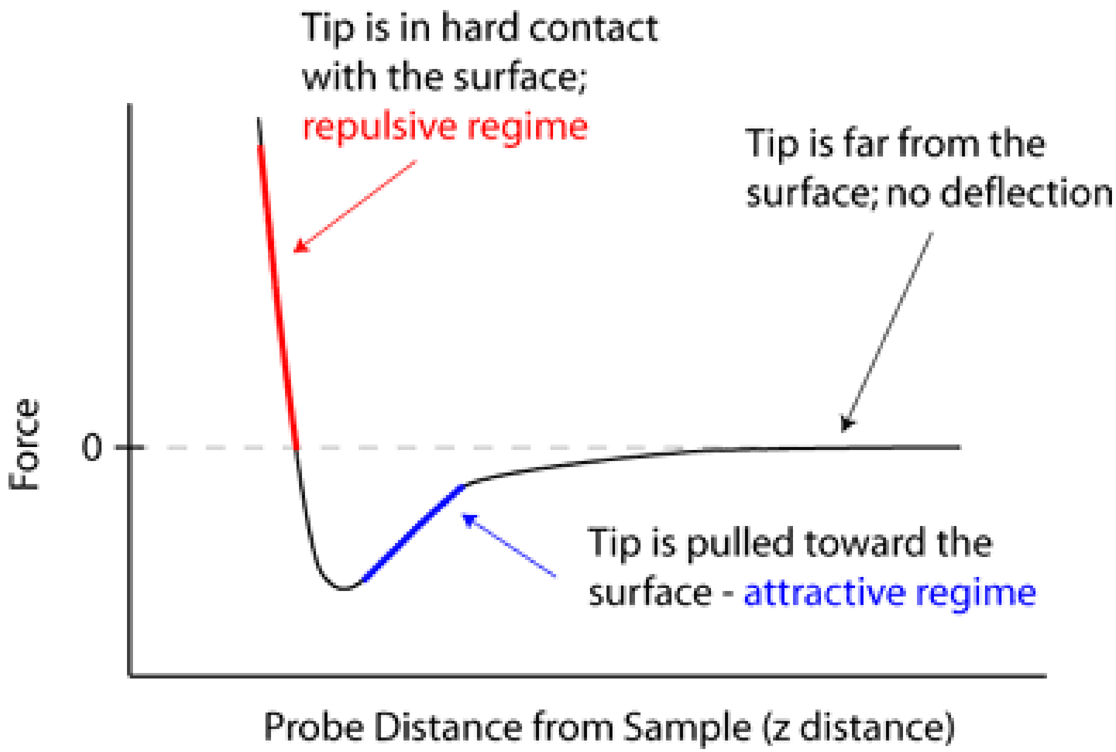


What is an SPM

- An SPM is a mechanical imaging instrument in which a small, < 10 nm in radius, probe is scanned over a surface. By monitoring the motion of the probe, the surface topography and/or surface physical properties are measured with an SPM.



Forces


Tip is in hard contact
with the surface;
repulsive regime
Tip is far from the
surface; no deflection
Force
0
Tip is pulled toward the
surface - attractive regime
Probe Distance from Sample (z distance)

AFM System

Computer
Software for gathering and processing images resides on the computer.

Electronic Controller
Generates electronic signals that control all functions in the stage

Stage
Scanner (laser, PD, PZ), Optical Microscope, sample stage.

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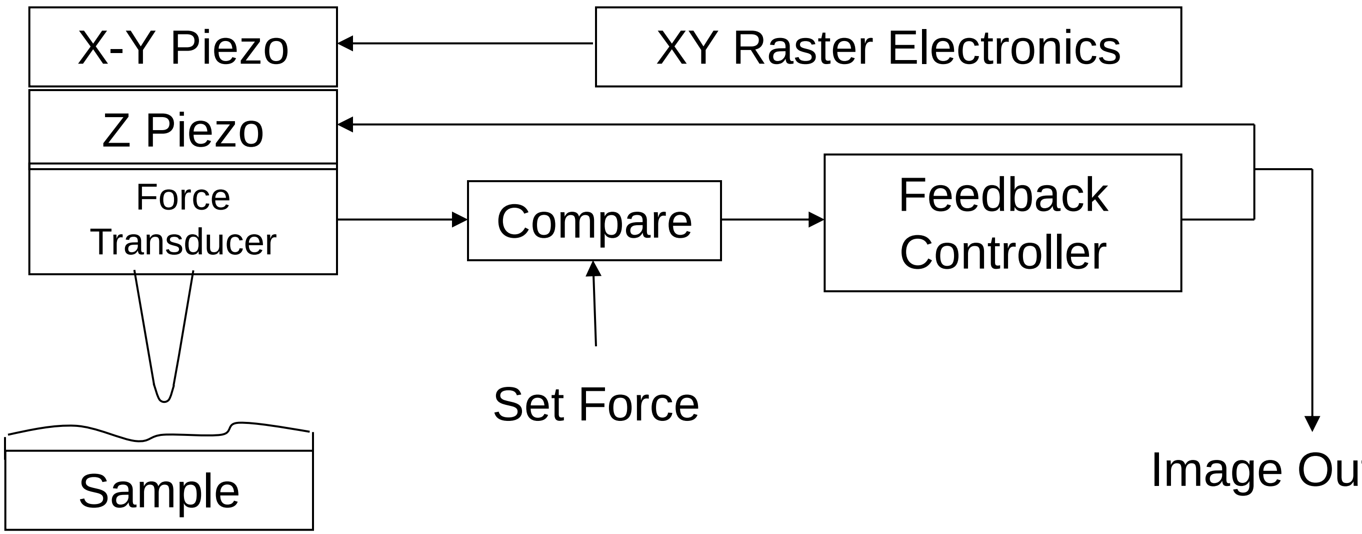
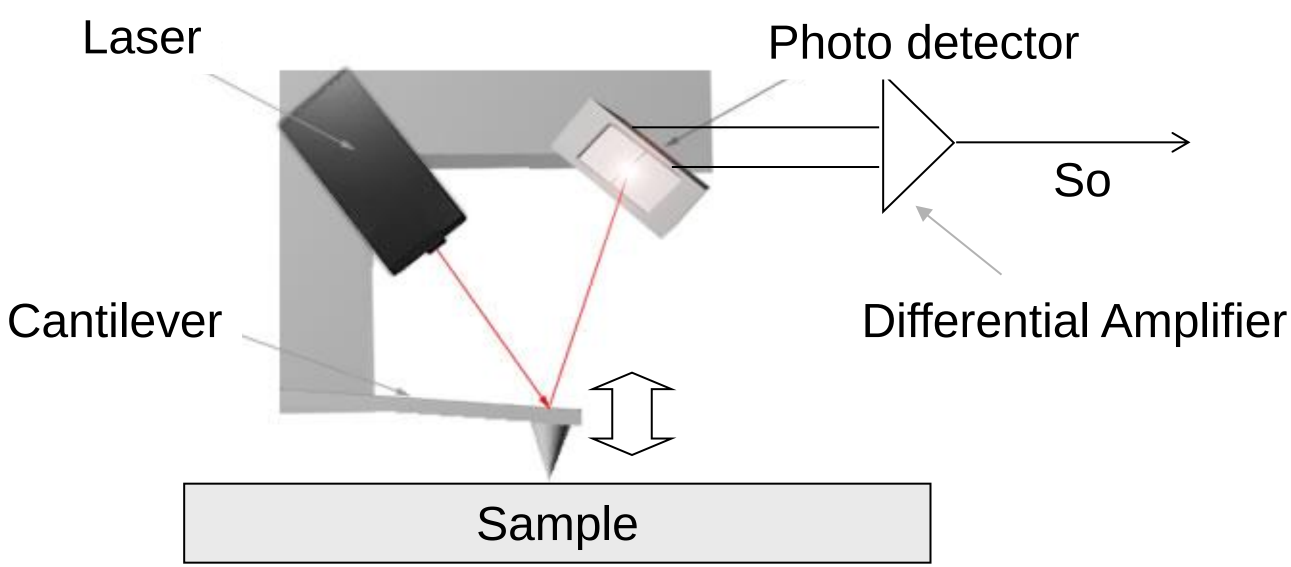
AFM System


X-Y Piezo
XY Raster Electronics
Z Piezo
Force
Transducer
Compare
Feedback
Controller
Set Force
Sample
Image Out

AFM Light Lever

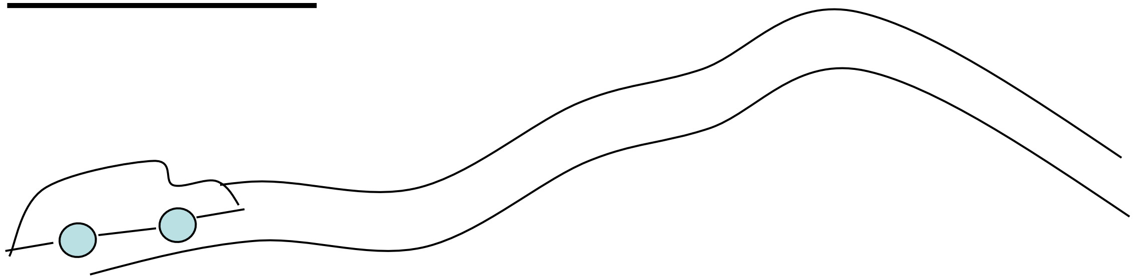


When the cantilever moves up and down, the position of the laser on the photo detector moves up and down.

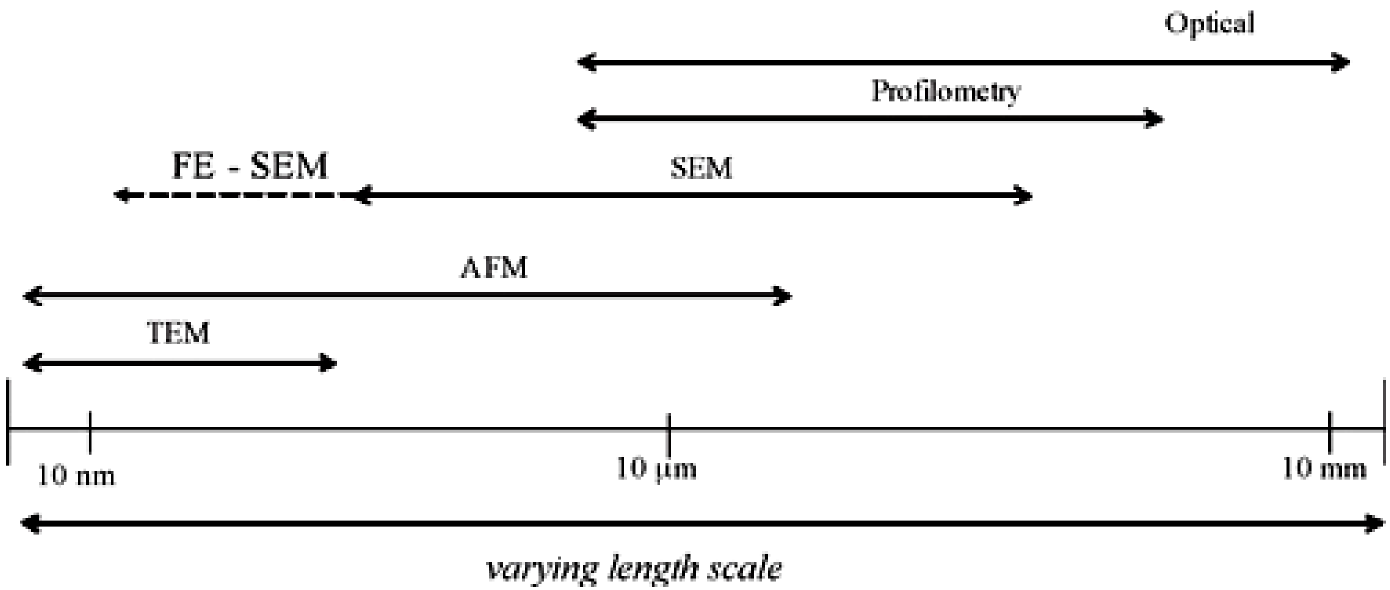
Feedback Control

- A control system which monitors its effect on the system it is controlling and modifies its output.
- Measure, Compare, Update

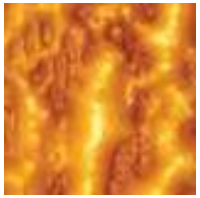
Car on a road



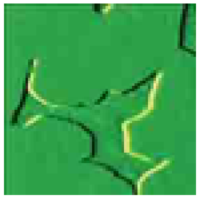
Comparison



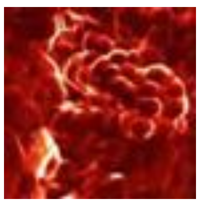
Non-destructive; 3D Magnification; Ambient air; Surface physical property

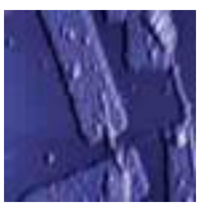


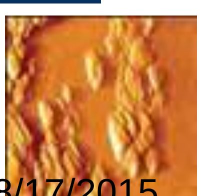
AFM Applications



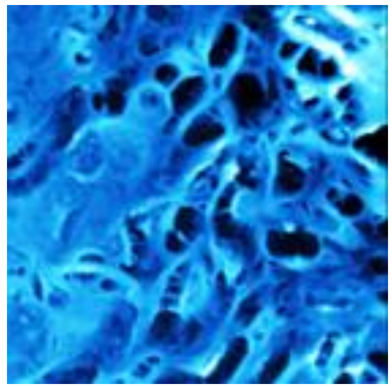
- Life Sciences
  - Cells, Bio-molecules, Biomaterials
- Material Sciences
  - Semiconductors, Ceramics, Polymers
- High Technology
  - Data Storage, Optics, Semiconductors, Biotech.
- Low Technology
  - Paper, Steel, Plastics, Automobile

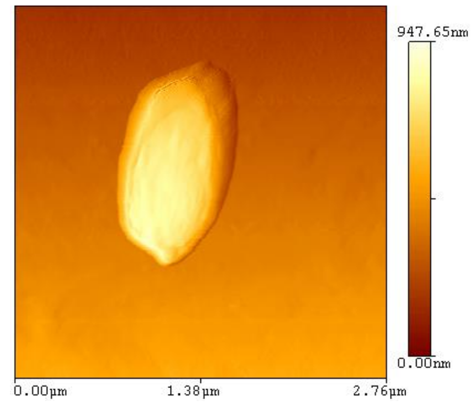


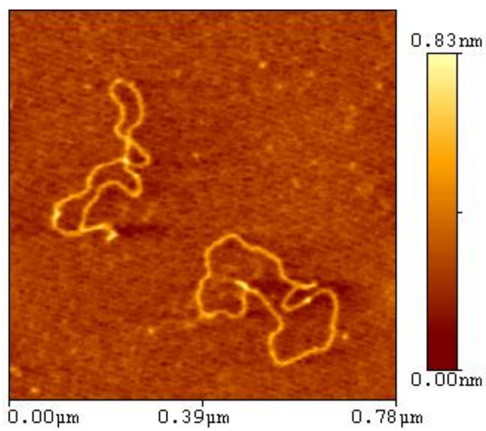


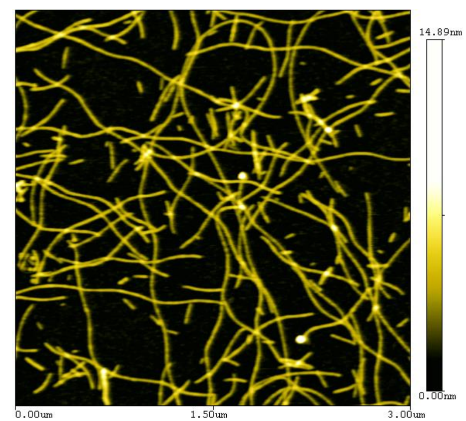


Life Sciences

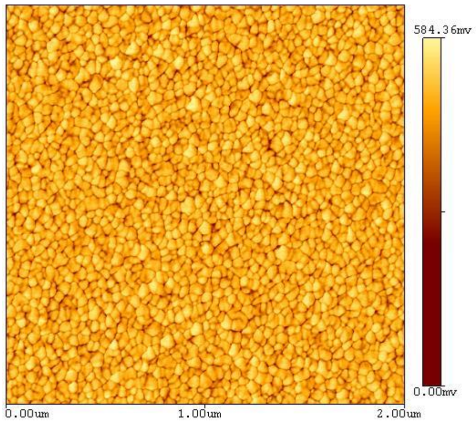


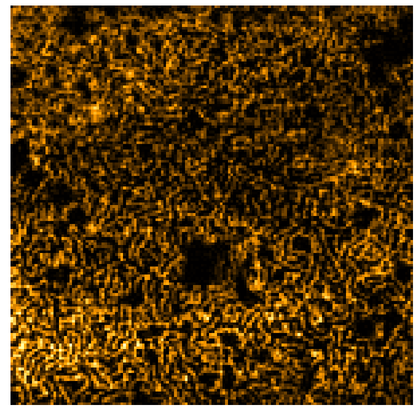


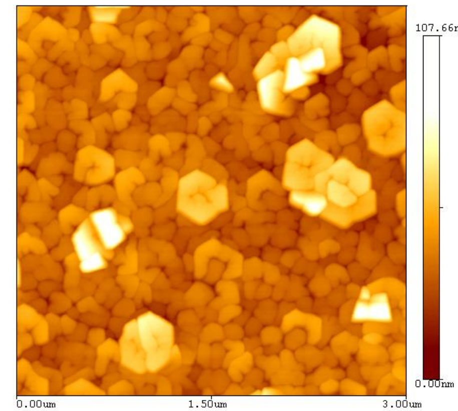


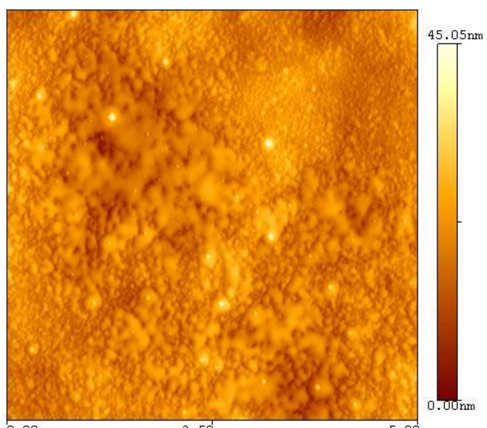


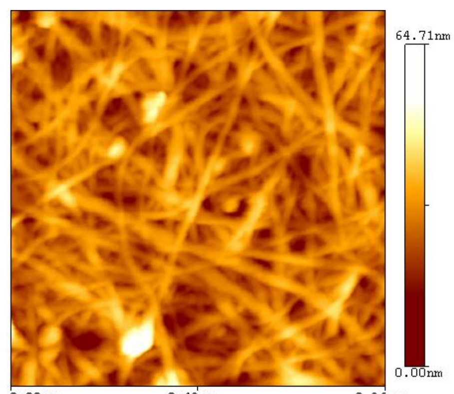
Material Sciences

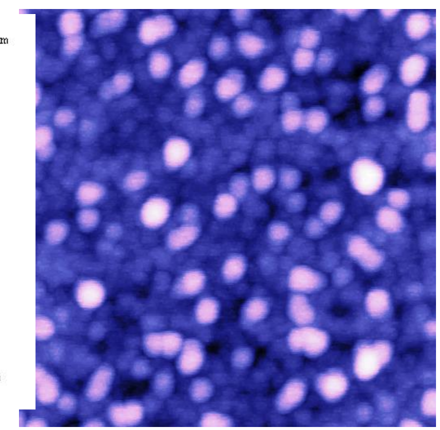












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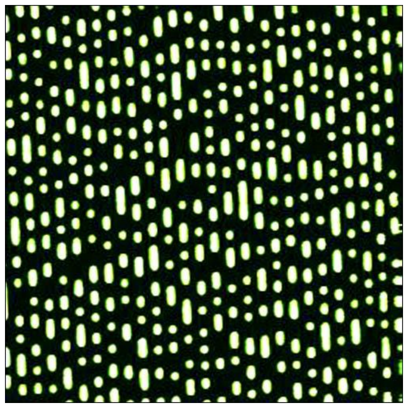
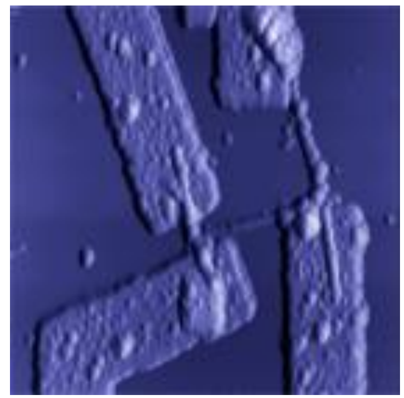
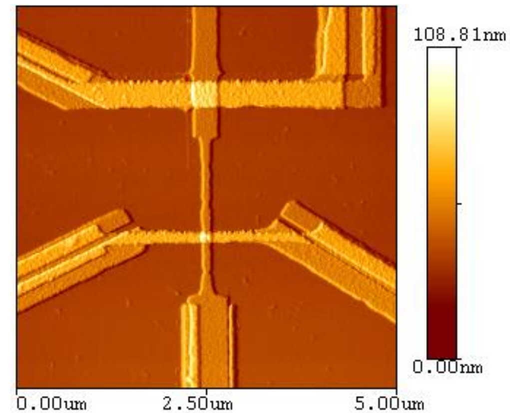
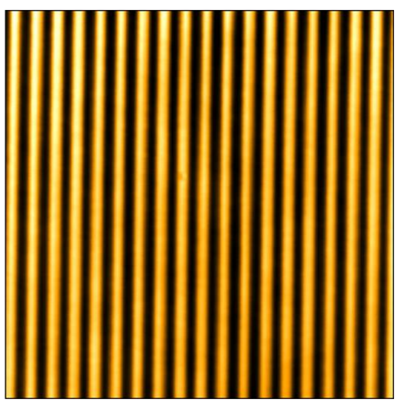
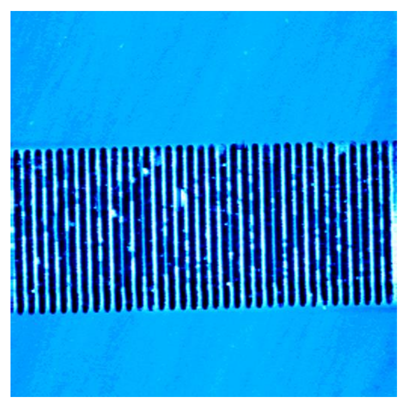
High Technology

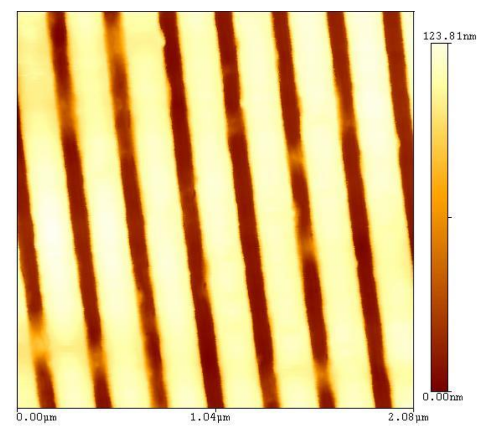












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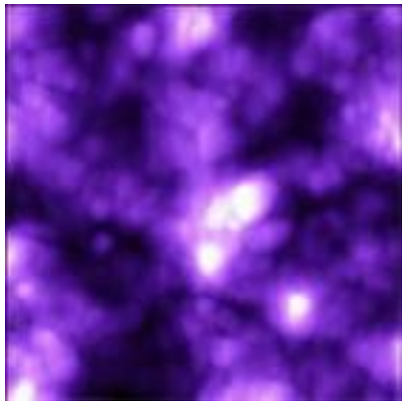
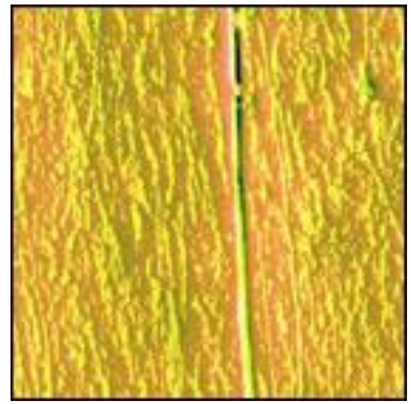
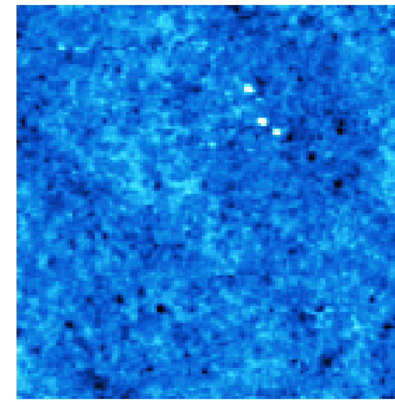
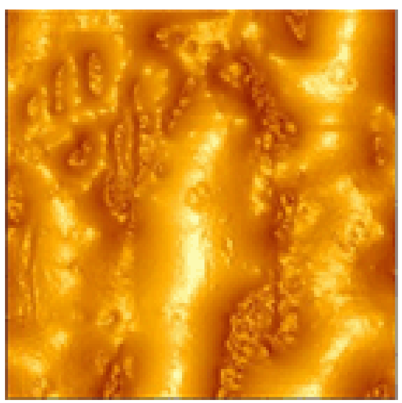
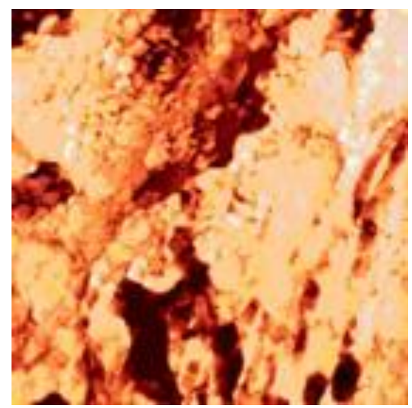
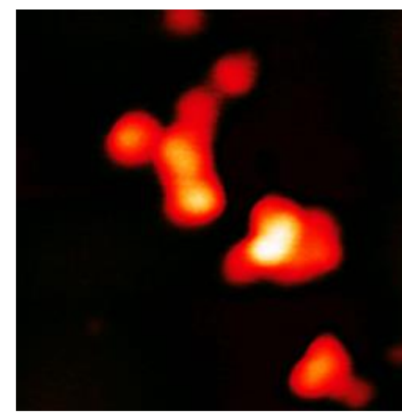
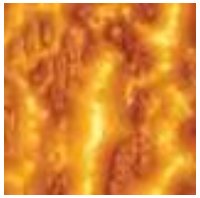
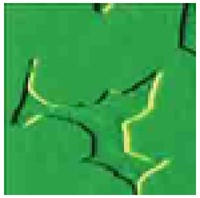
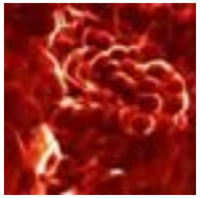
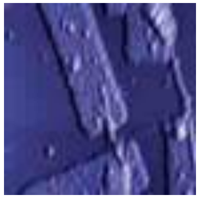
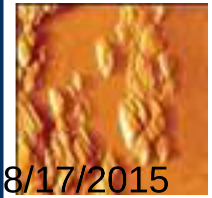
Low Technology

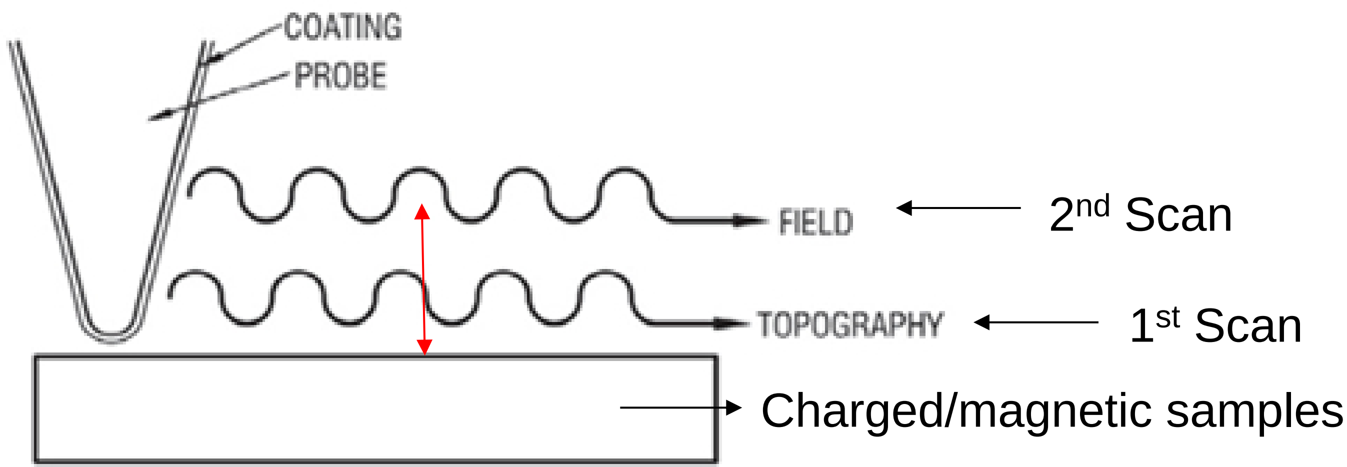
AFM Modes: Advanced Applications

- Field Modes
  - KPM/EFM
  - Magnetic Force
- Electrical Modes (Shark)
- Lithography
  - LAO
  - Scratching
  - DPN
- Material Sensing Modes
  - Lateral Force
  - Vibrating Phase
- Mechanical
  - Force/Distance
  - Indenting
- Liquid

Field Modes

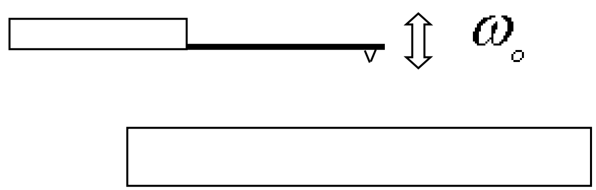
$$F = F_{surface} + F_{electrostatic} + F_{magnetic} + F_{other}$$



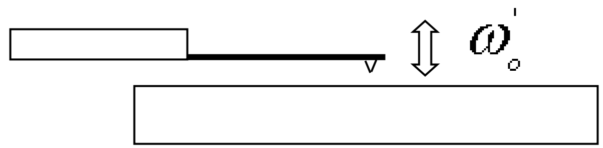
- Electrostatic force/magnetic force interaction (> tens of nm)
- Qualitative/Quantitative
- Resolution depends on sample, probe coating

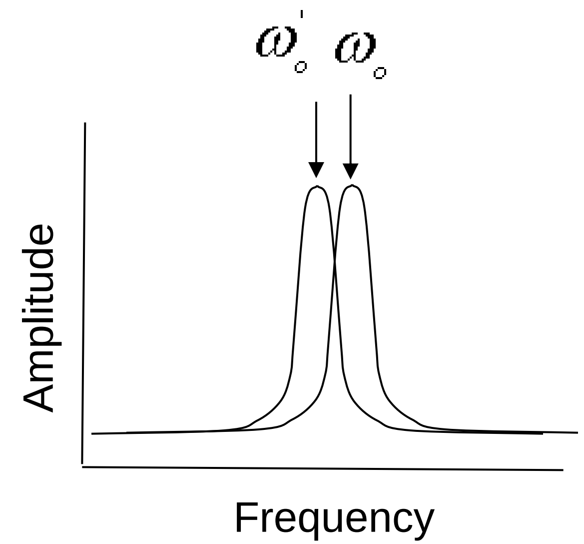
Probe/Surface Interaction

A Free oscillations



B Oscillation damped by a surface





Tip-sample interaction = A spring in series with cantilever

$$\omega_o - \omega_o' \approx \omega_o \, f' / 2k \qquad f' = \frac{dF}{dz}$$ (Linear approximation)

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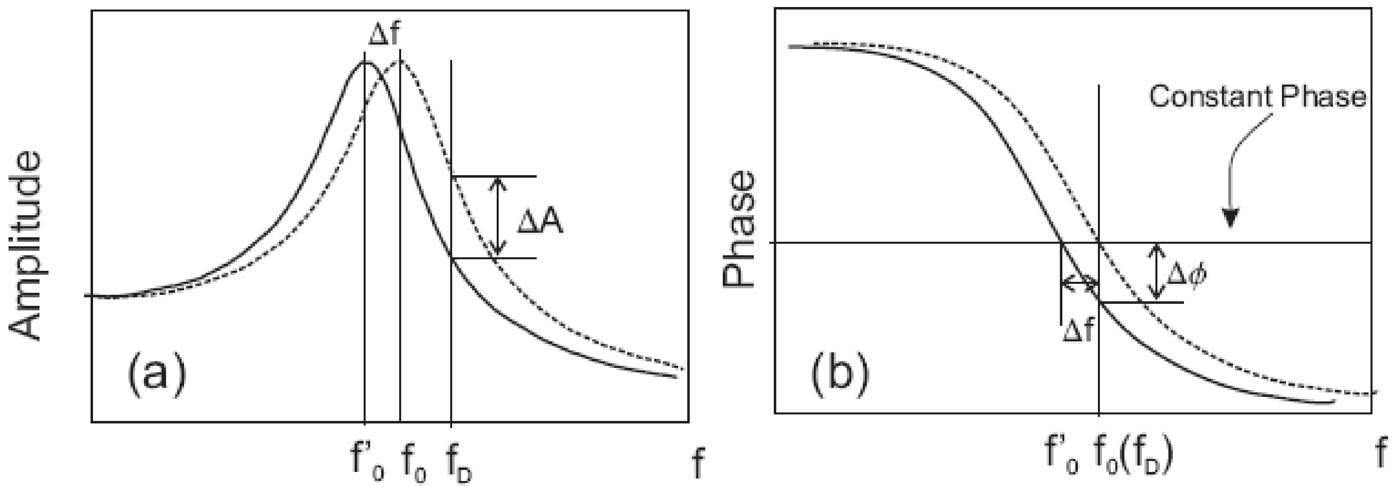
INSTRUMENTATION



1. **Lock-in technique**: at *constant fD,* cantilever Δf results in ΔA (a) and Δ*φ* (b), which can be interpreted as a force signal. (No FB)
2. **Frequency Modulation** (servo controller): Measure Δ*f*: at the constant phase (phase lag is zero in a phased locked loop).

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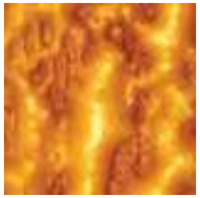
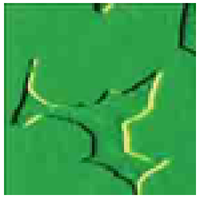
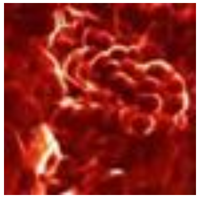
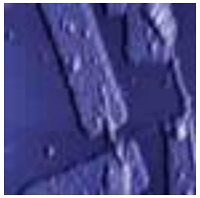
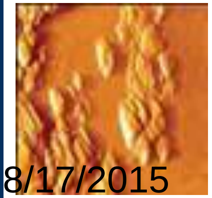




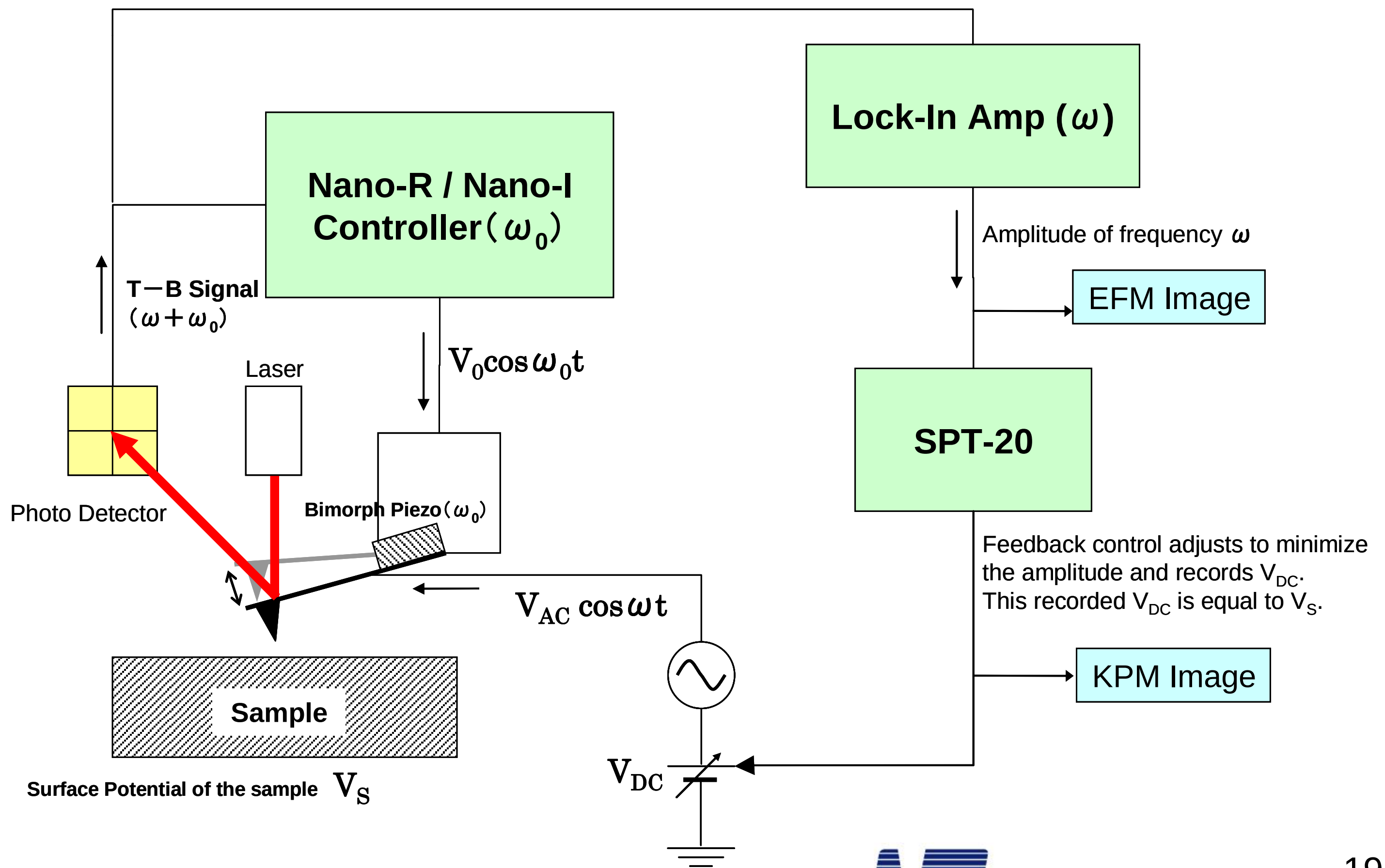






KPM/EFM

Schematic of the EFM･KPM Mode



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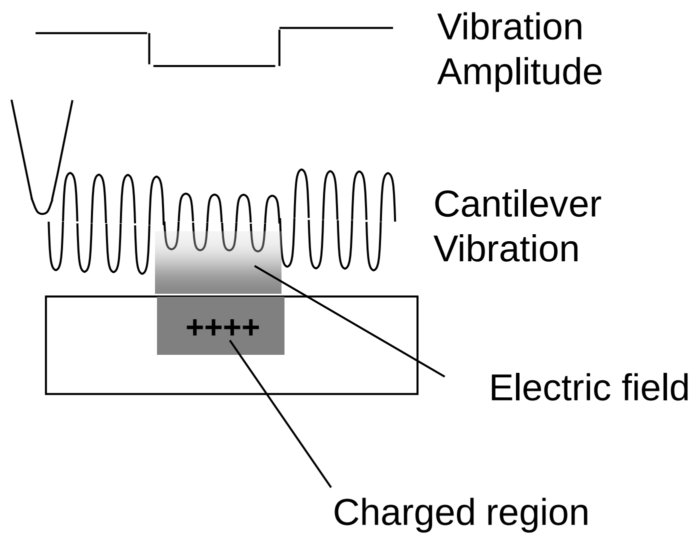
EFM



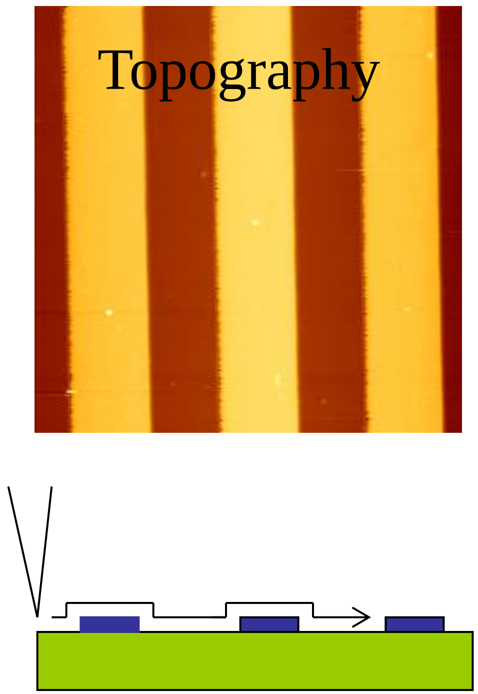
$$\omega_o - \omega_o' \approx \omega_o \, {f'}/{2k}$$

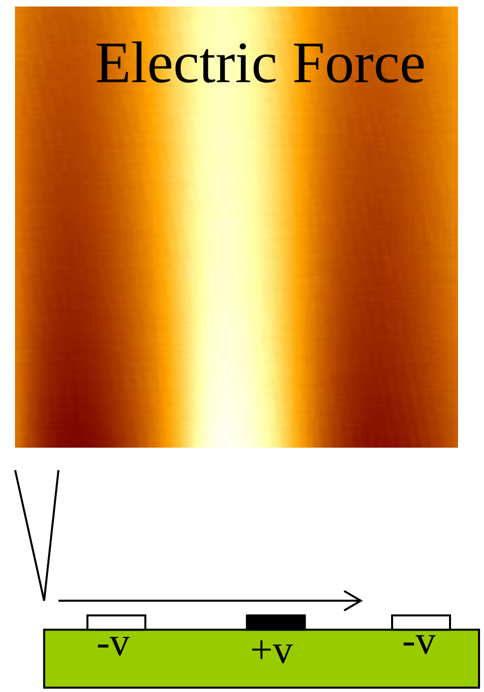
$$f' = \frac{dF}{dz}$$

$$F_{electrostatic} = -\frac{1}{2}\left(\Delta V\right)^2 \frac{dC}{dz}$$

Calculate the change in the resonant frequency(ω): Use Equations for fields above a surface and calculate the derivative of the field.

Electric Forces (EFM)





KPM

$$F_Z = -\frac{1}{2}\frac{\partial C}{\partial z}\left(V_S + V_{DC} + V_{AC}\cos\omega_m t\right)^2$$
$$= -\frac{1}{2}\frac{\partial C}{\partial z}\left\{\left(V_S + V_{DC}\right)^2 + 2\left(V_S + V_{DC}\right)V_{AC}\cos\omega_m t + V_{AC}^2\cos^2\omega_m t\right\}$$

Vs: Contact potential difference or work function difference

- DC component: static attractive force between electrodes (topo)
- ω component: a force between charges induced by AC field (KPM)
- 2 ω component: a force induced to capacitors only by AC voltage (SCM)

Lock-in Amp detects the signal at ω, feedback control minimizes this component by adjusting V_{DC}, so $V_S+V_{DC} = 0$

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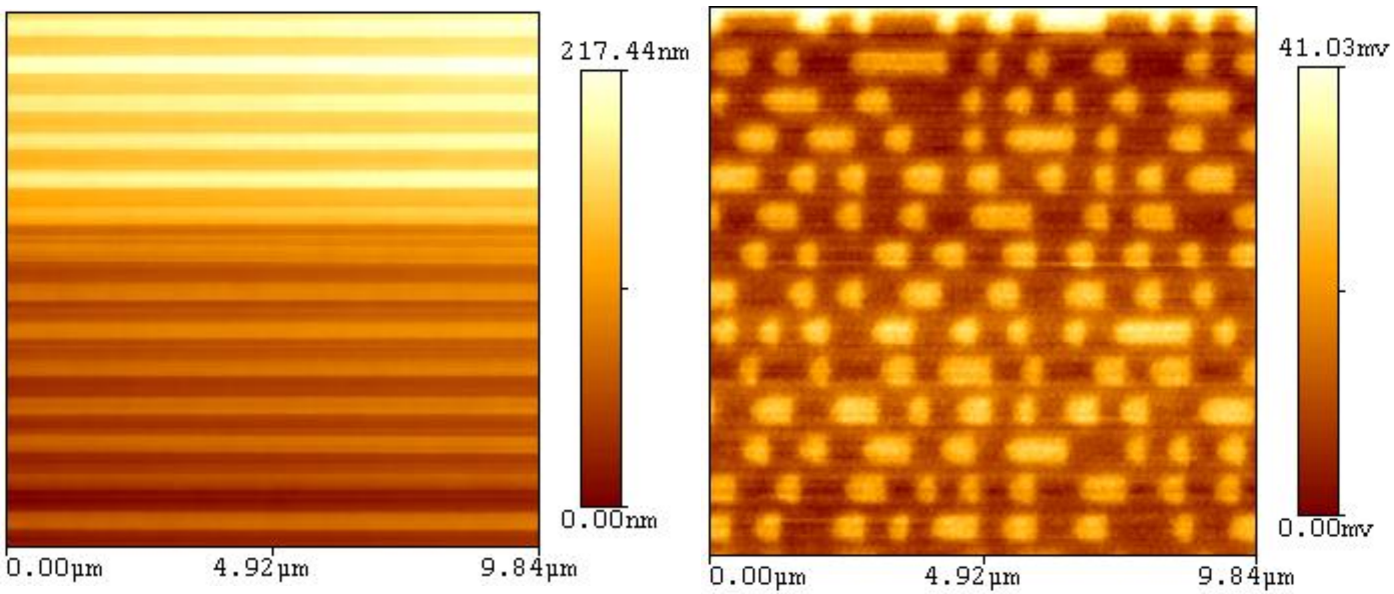
EFM/KPM

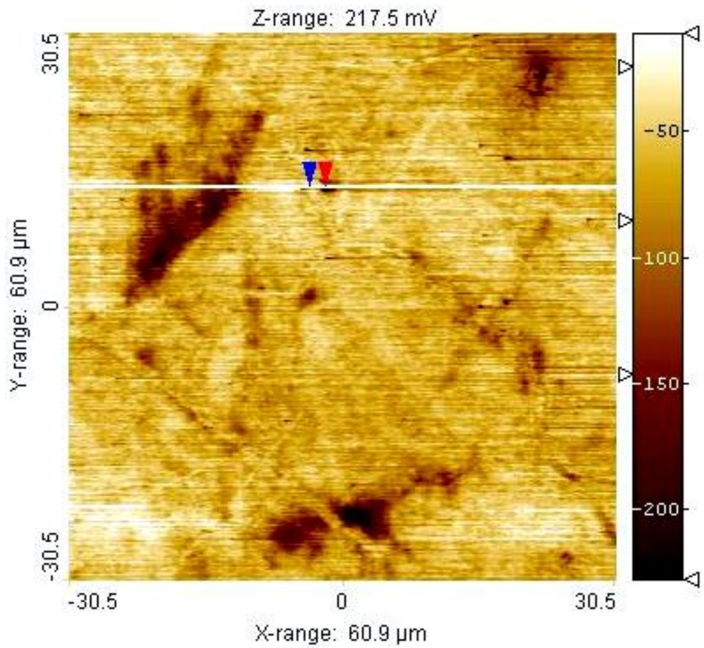
- Surface potential distribution
- Capacitance (C-z, C-V)
- Polarization of adsorbed molecules
- Polarization or piezo effect of ferroelectric
- Charge distribution
- Carrier distribution in semiconductor
- Local work function
- others

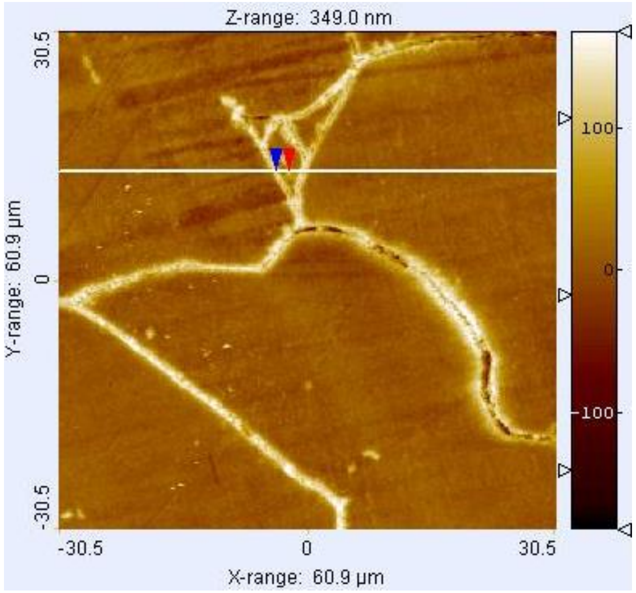
EFM/KPM



10X10 um topography and KPM images of a DVD-RW surface

Corrosion Study





Surface potential mapping for a metal alloy surface: enhanced corrosion (higher cathodic reaction) observed in the boundaries.

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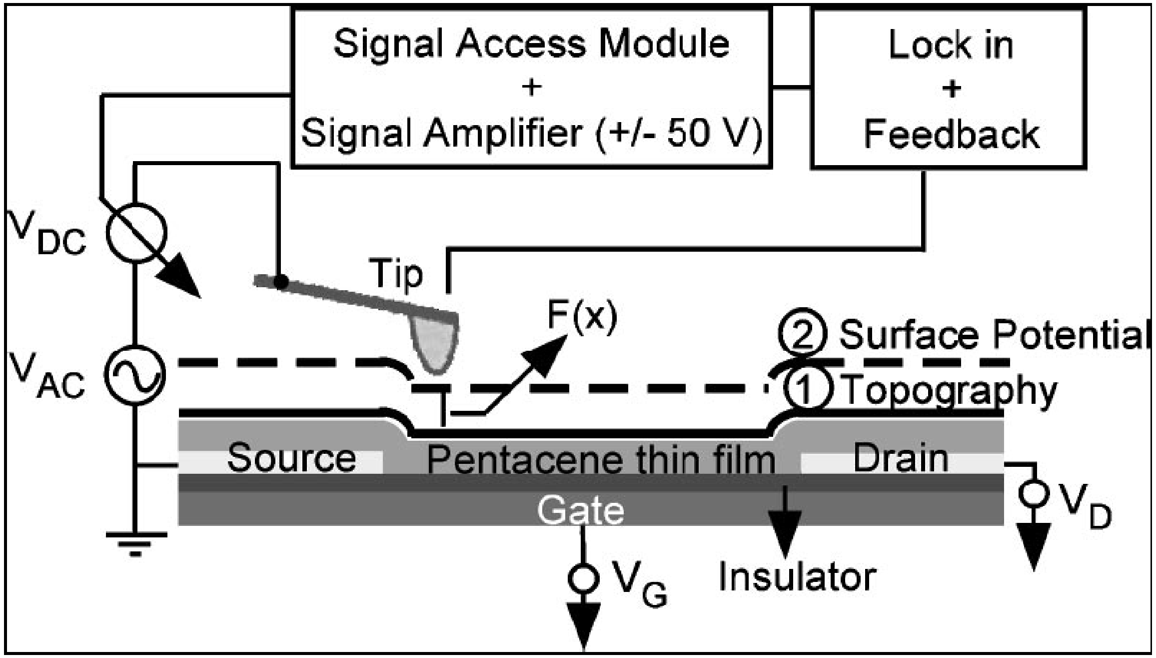
Semiconductor



Puntambekar et al., Appl. Phys. Lett., Vol. 83, No. 26, 29 December 2003

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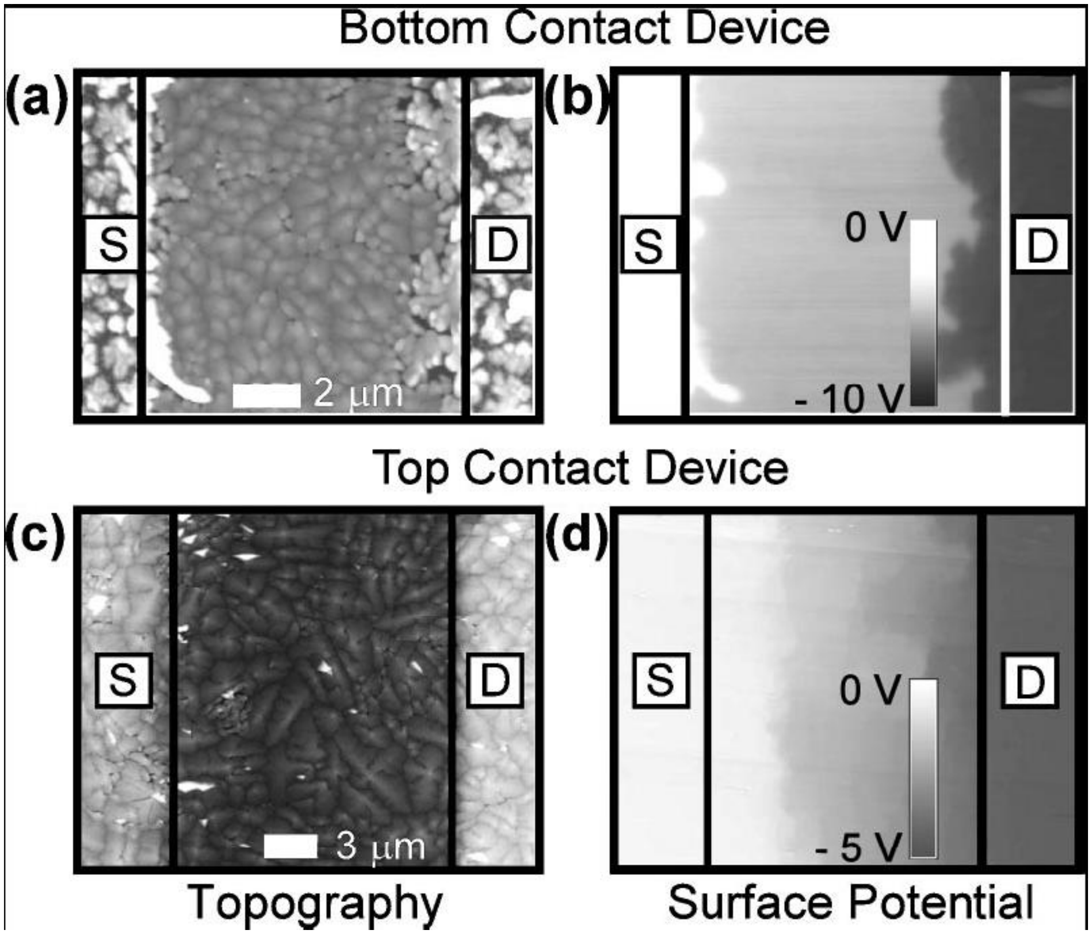
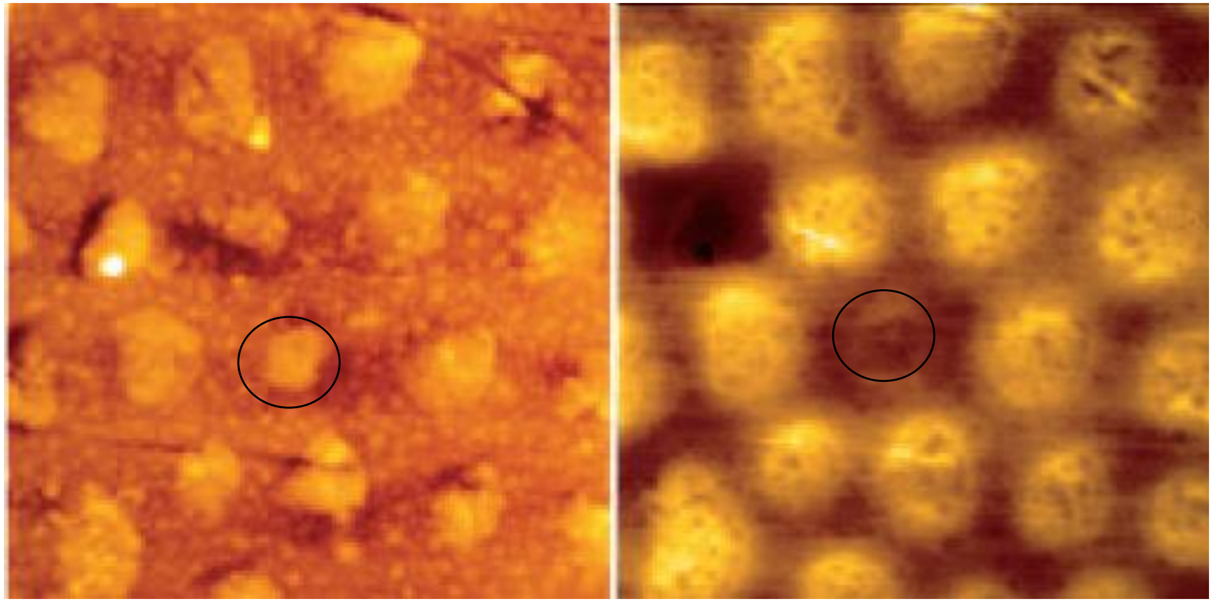
Semiconductor



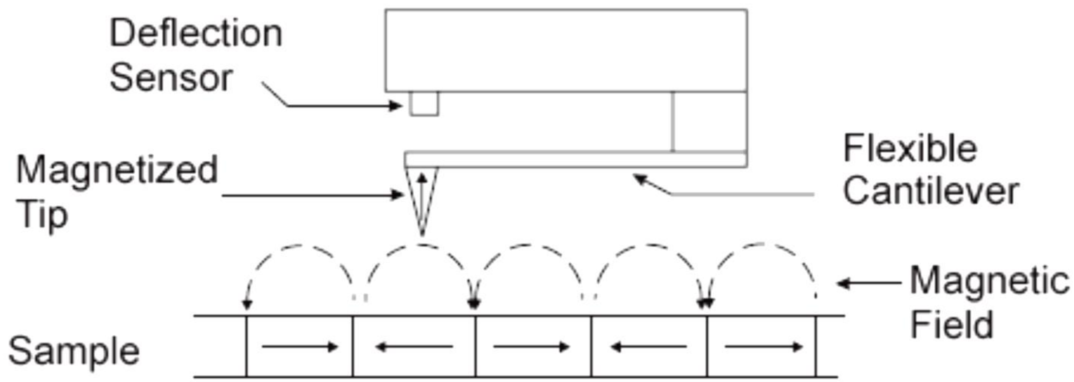
Nanomaterials



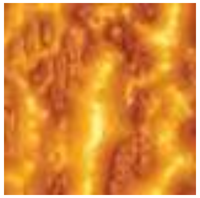
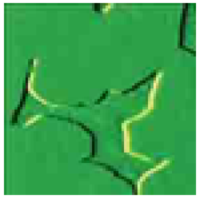
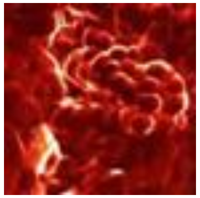
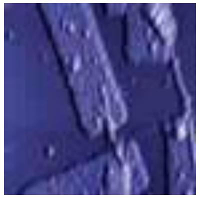
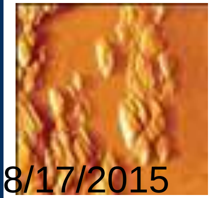
Nanowires embedded in alumina matrix. (Right) EFM images show the electrical discontinuity of the nanowires.

C. A. Huber; *Science*, 263, 1994), pp. 800-802.

MFM



A magnetically sensitive cantilever interacts with the magnetic stray field of the sample. Resulting changes in the status of the cantilever are measured by the deflection sensor, and recorded to produce an image.

MFM

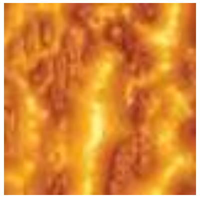
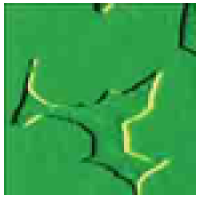
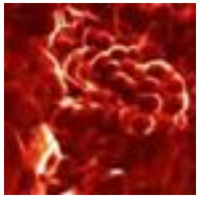
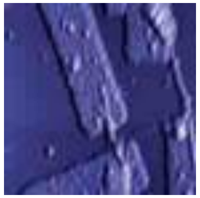
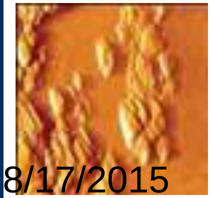
$$F = F_{mag} + F_{elec} + F_{van}$$

$F_{van} = A_H R/6z^2$ $\qquad$ $F_{elec} = \pi \varepsilon V^2 R/z^2$

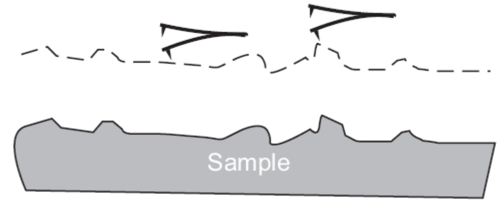
R=10 nm, Z=50 nm, F’elec, F’van ~ 10^{-6} N/m

F’mag ~ 1/(a+z)^2 *a: domain width; z: distance*

Sharp tip and small V, F’elec F’van << F’mag (at Z > 20 nm)

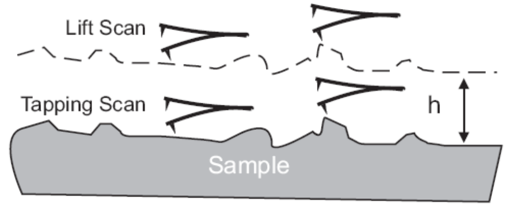






MFM



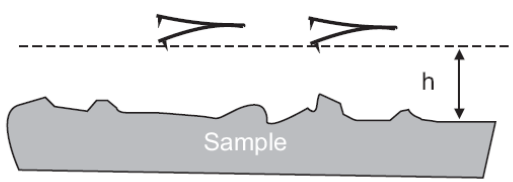
Constant frequency mode:

Maintain the frequency by adjusting z
Topography convolution; AC+DC
Felec as servo force



Lift-mode:

Monitoring fr or the phase shift during 2^{nd} pass



Constant height:

Applying small bias to compensate
Felec by work function difference;
Highest S/N (no FB noise)

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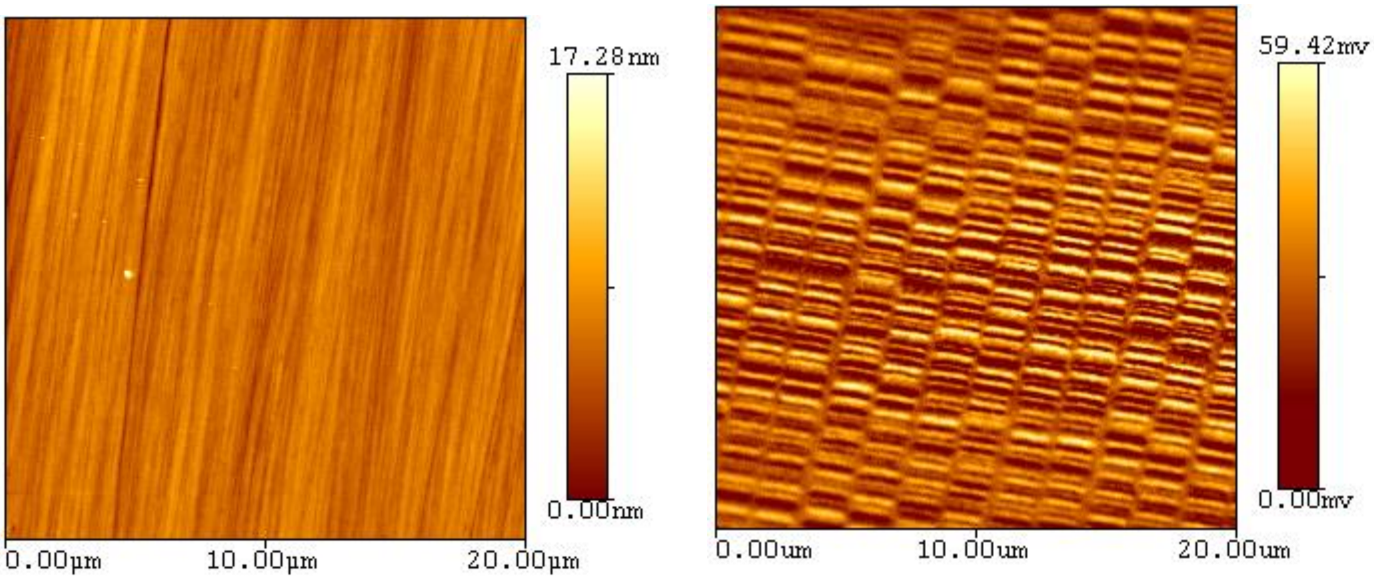
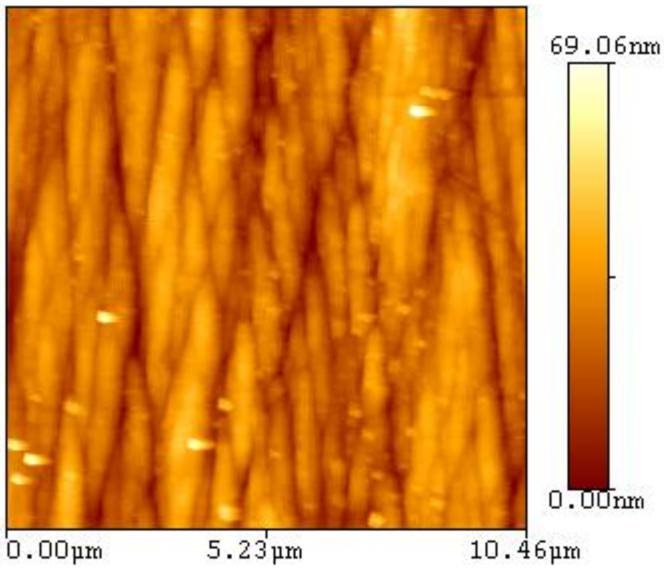
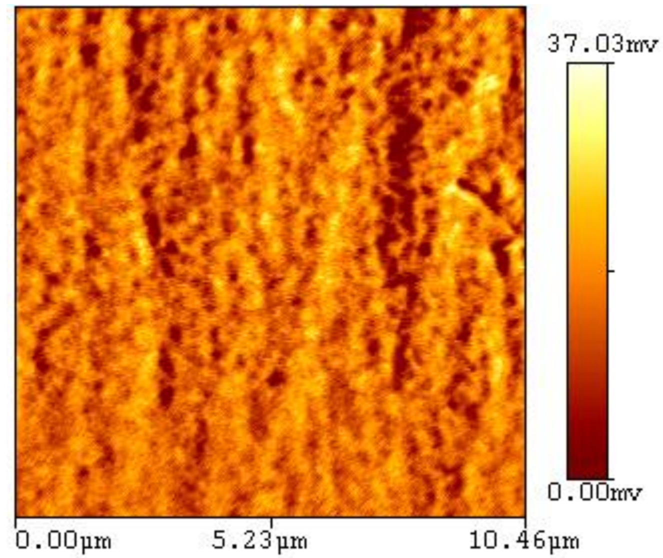
MFM



A topography (left) and MFM image (right) for a hard disk.

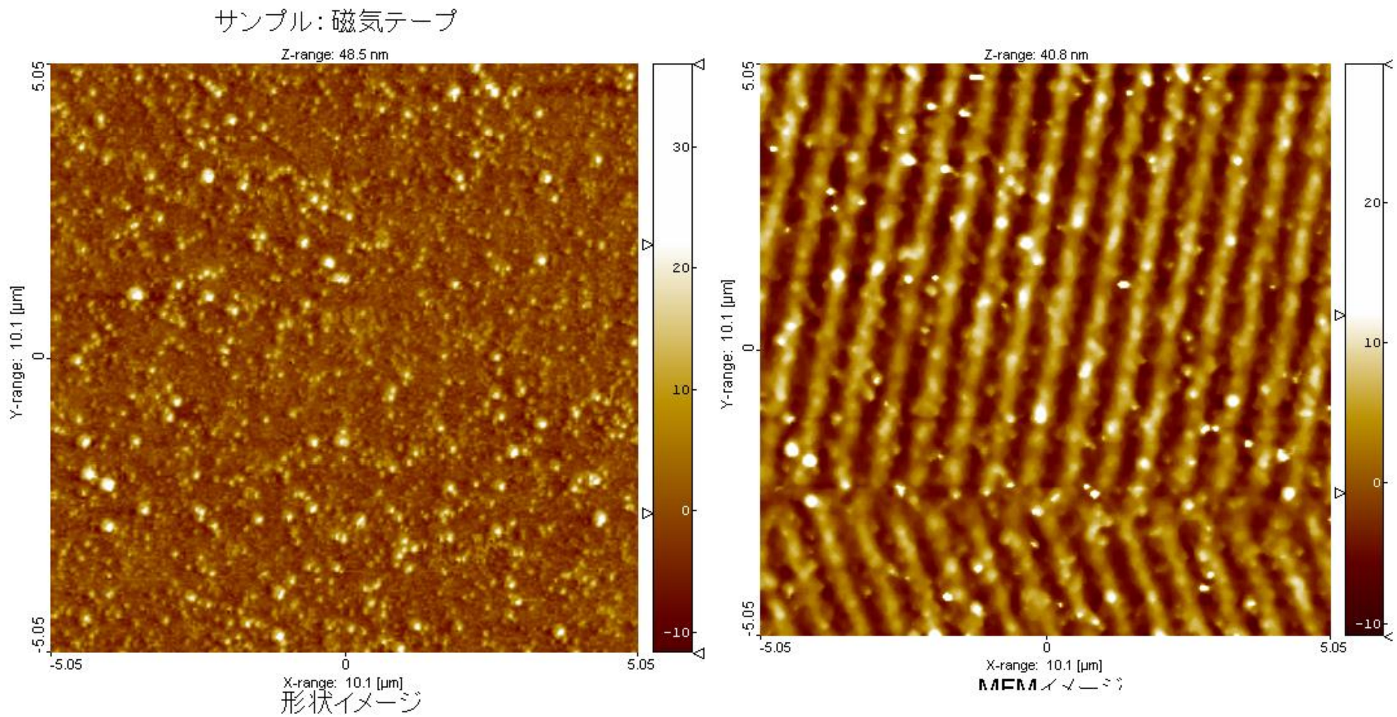
MFM





A topography (left) and MFM image (right) for a degassed hard disk. MFM image acquired by raising the magnetic tip ~80 nm above the surface. The bit microstructures were never found on this sample surface.

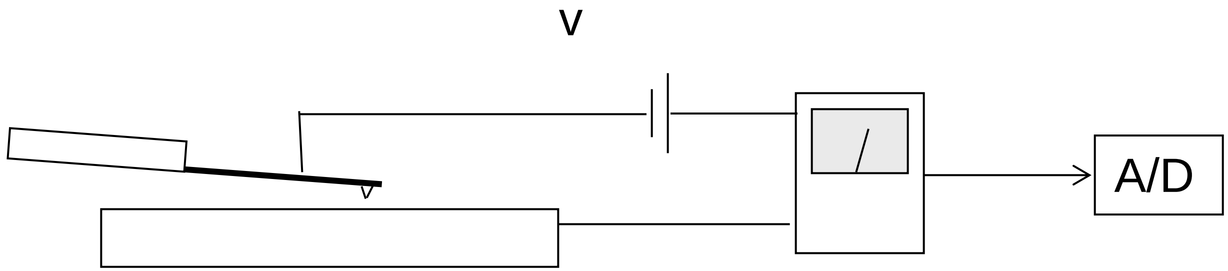
MFM



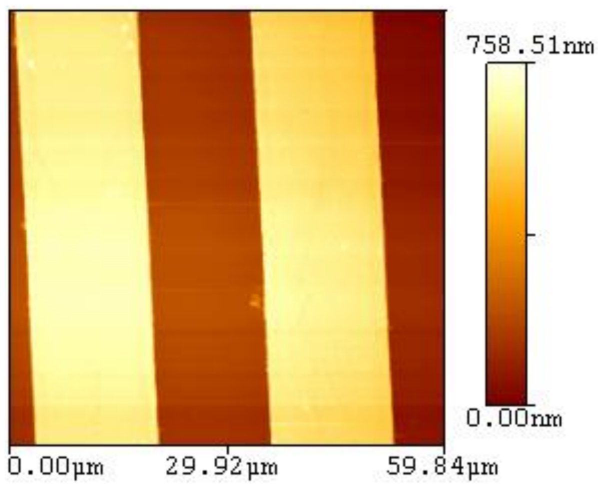
A topography (left) and MFM image (right) for a Magnetic recording tape

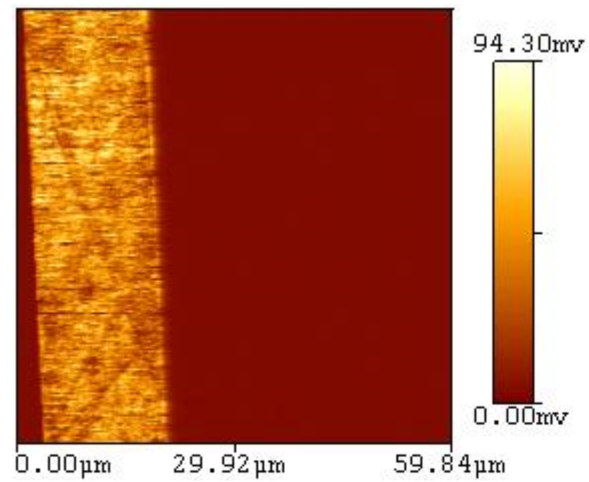
SHARK Mode

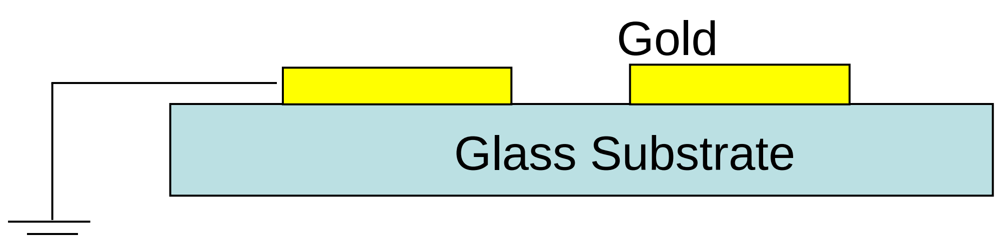
- Monitor Current Between Tip and Sample while scanning in contact mode
- Measure current map and Topography Simultaneously



SHARK Example







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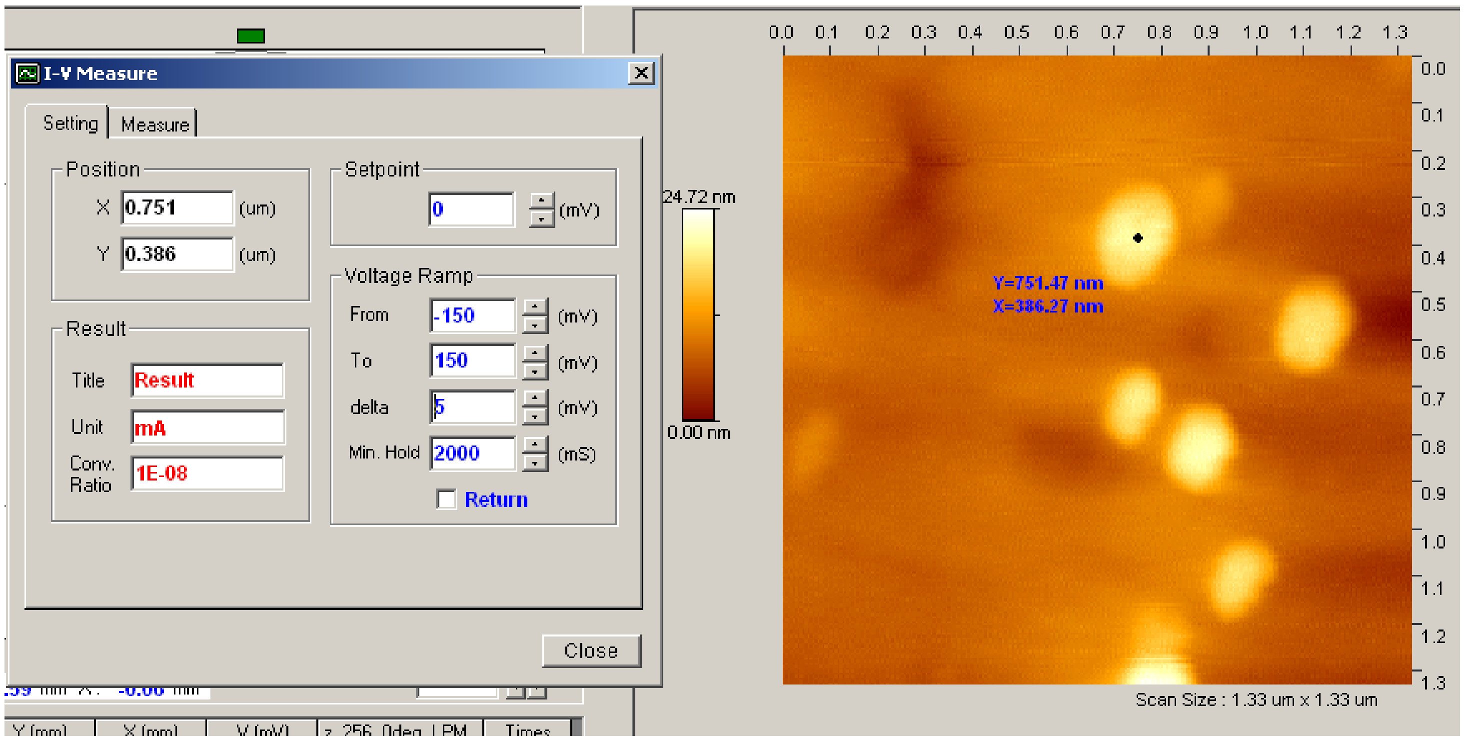
Electrical Test



LPM Software allows probing the sample; SP, Voltage ramping, holding time

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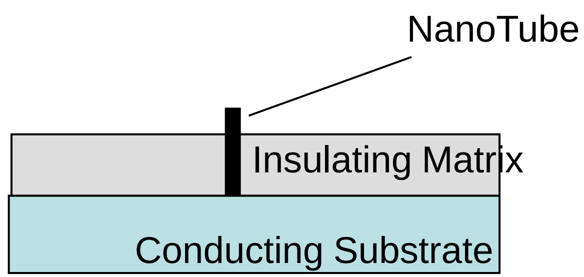
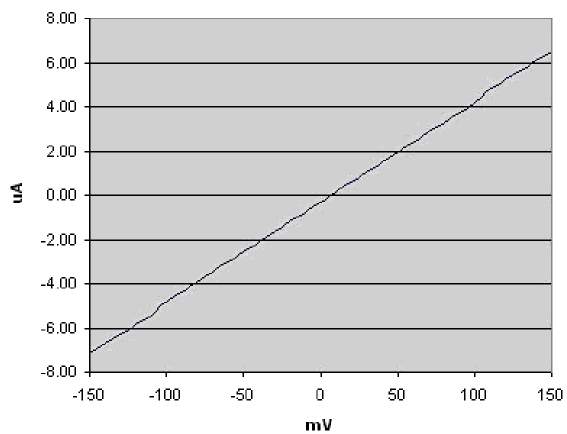
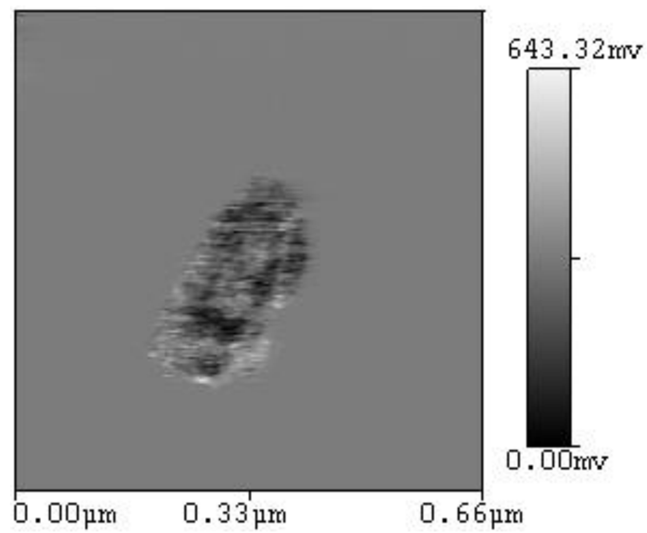
SHARK Example







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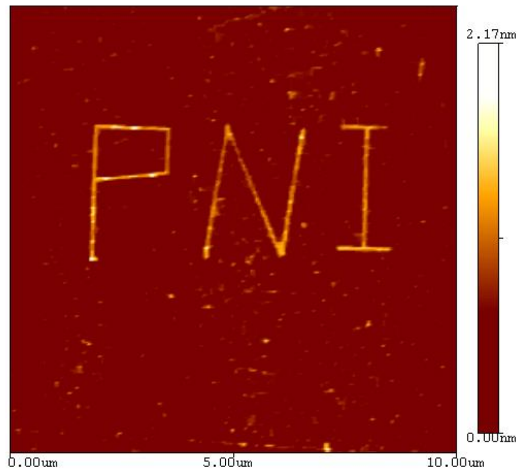
Nano-Lithography



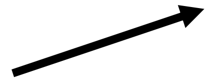
-**Change surface chemical composition**

-**Deposit materials on a surface**

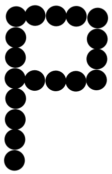
-**Physically scratch surface**

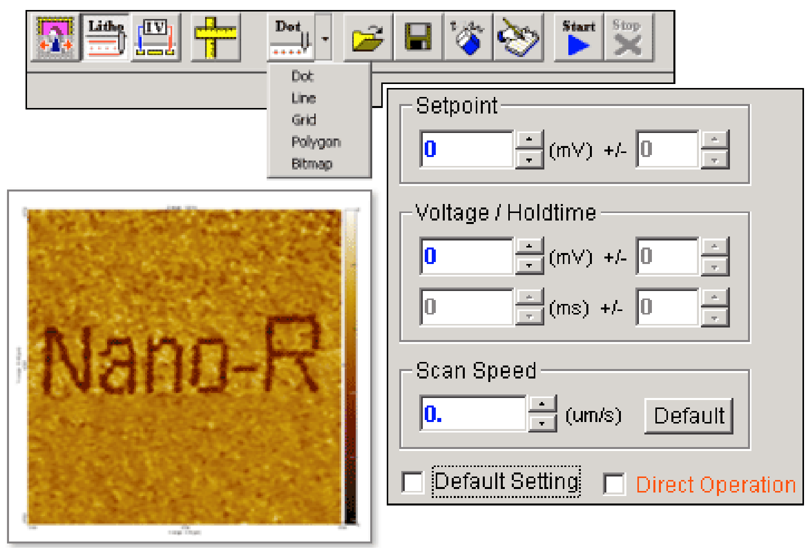
Nano-Lithography

-Draw Line as vector



- Draw an array of dots “dot matrix”





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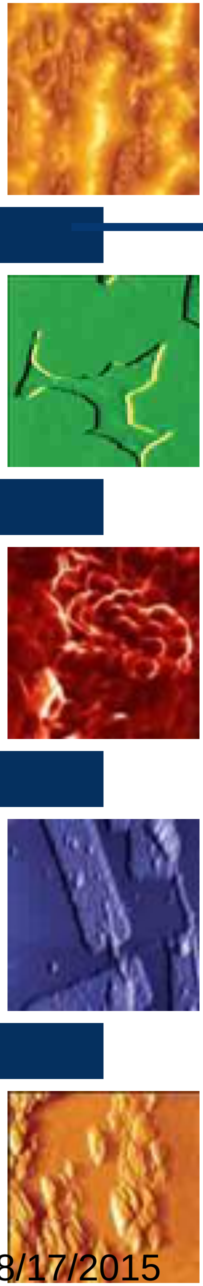
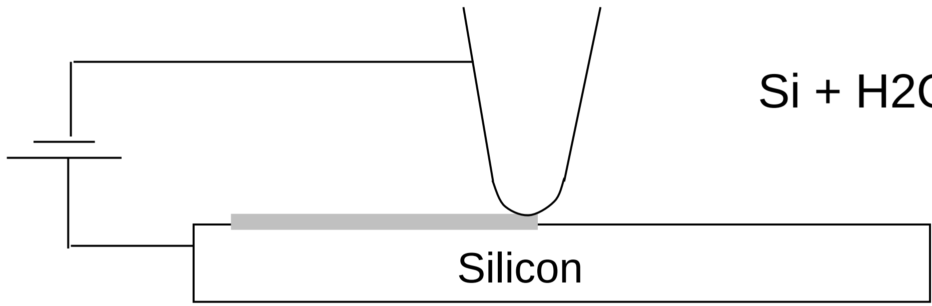
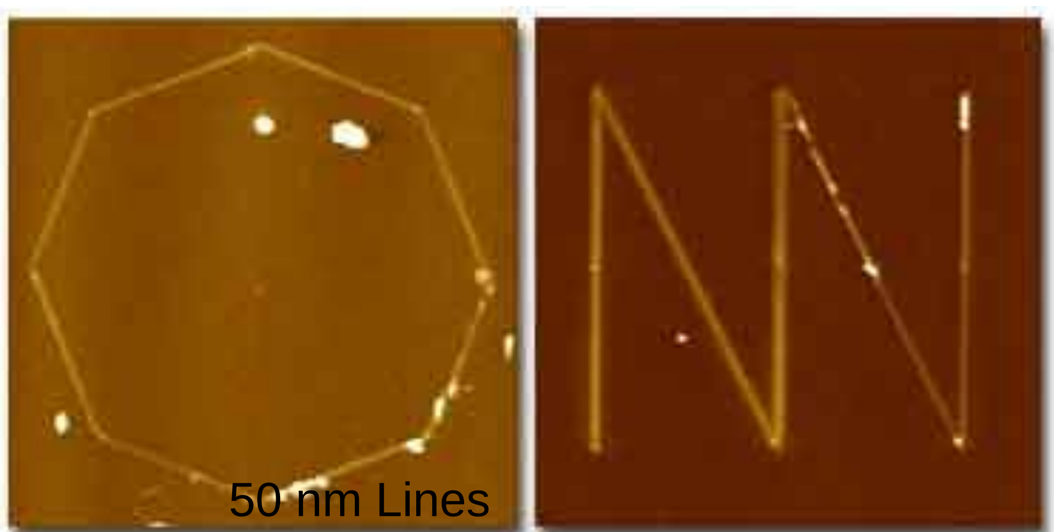


Local Anodic Oxidation

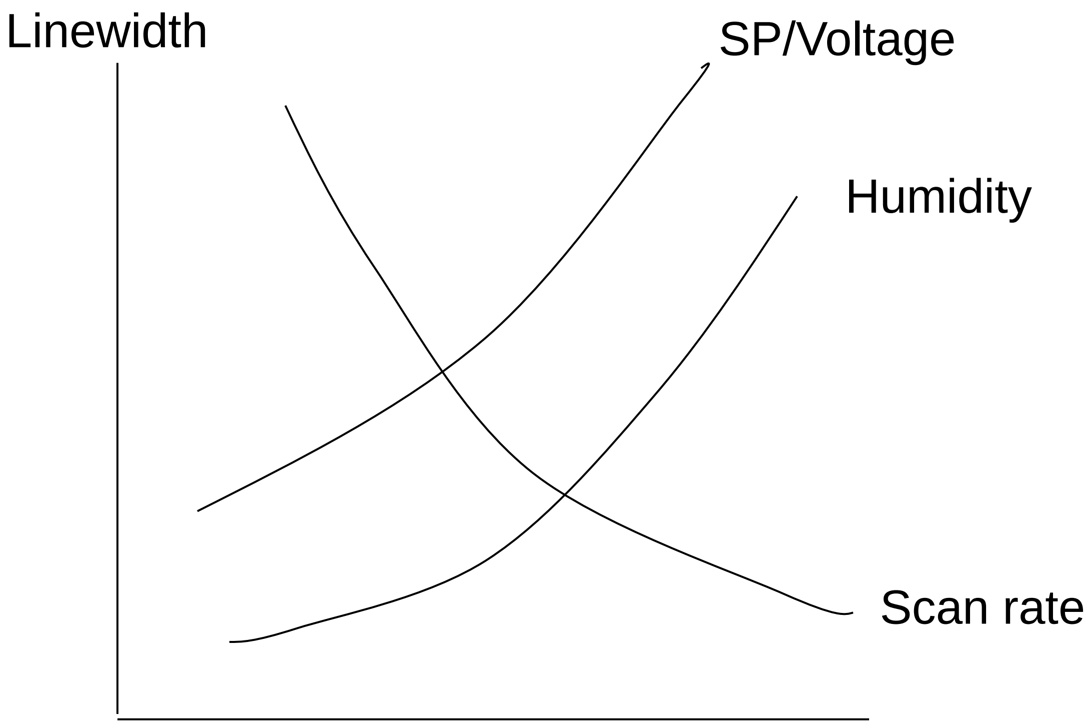


$Si + H2O \rightarrow SiO2 + H^{+}$



50 nm Lines

Local Anodic Oxidation



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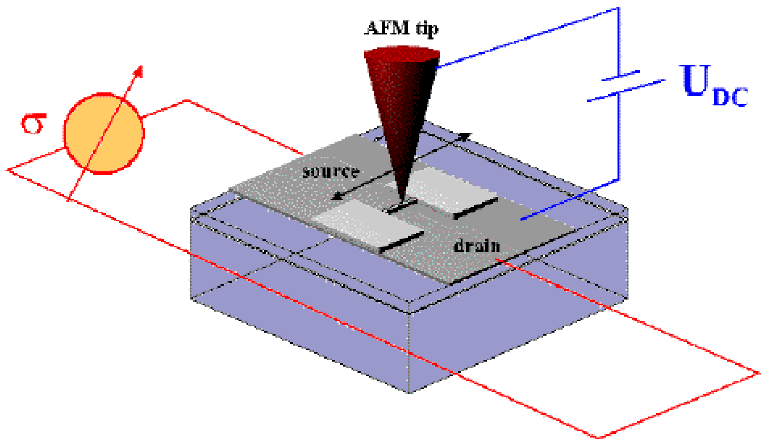
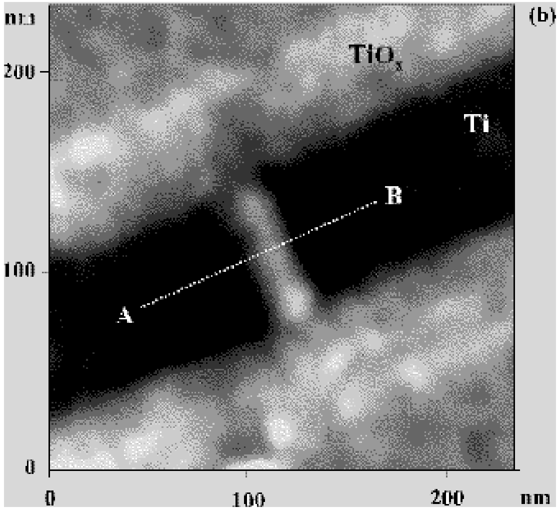
Local Anodic Oxidation

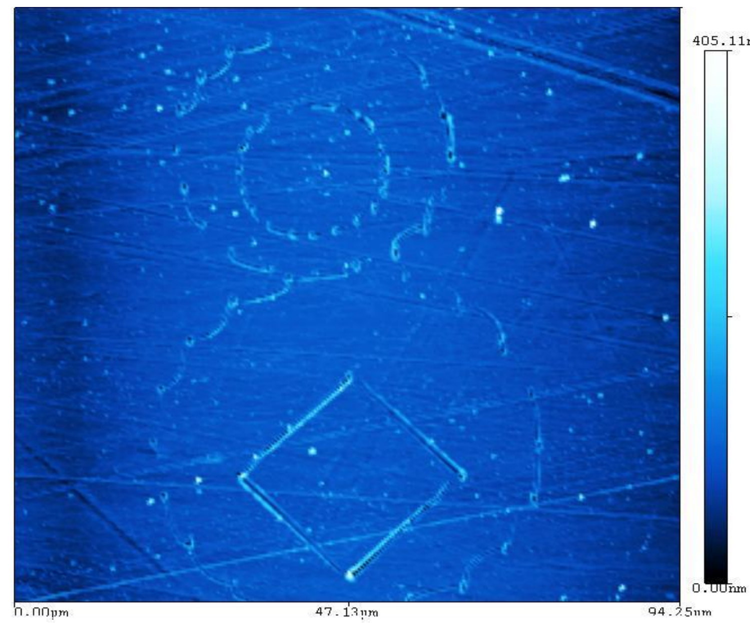


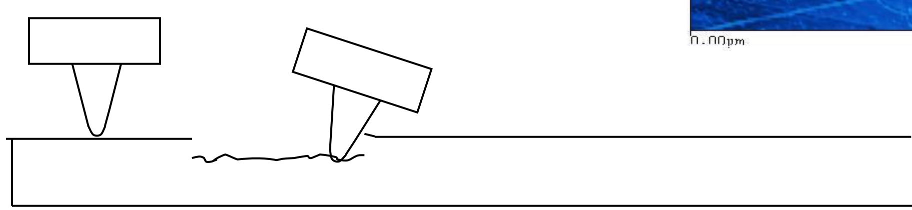


The formation of a single (tunneling) barrier within a thin metal film is shown. The tip repeatedly scans along a single line, monitoring the conductance through the device while oxidising. The image shows the 70nm wide metallic wire(black), defined by AFM induced oxide barrier, 21 nm wide.

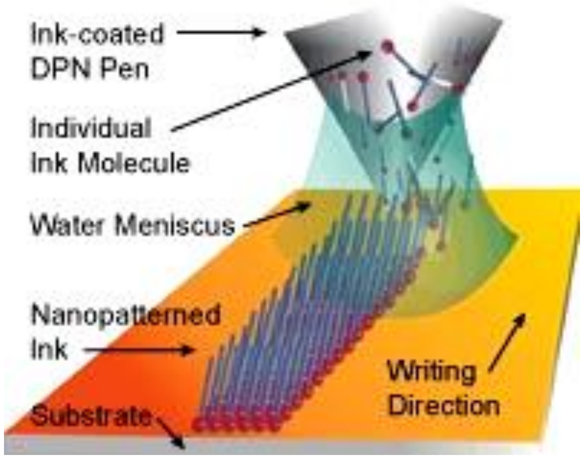
Scratching

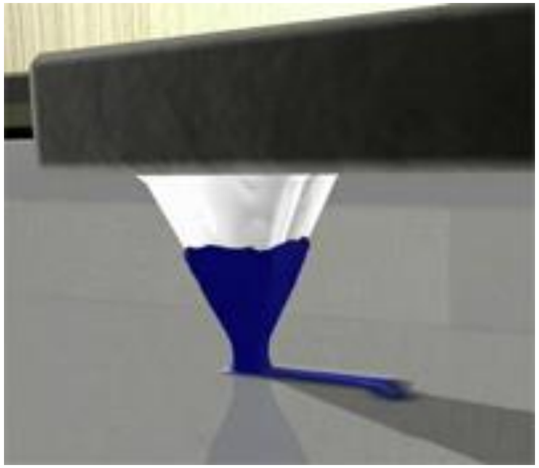
When Scratching With the AFM, there is a torsion on the cantilever so the probe area changes.





DIP-PEN NANOLITH





Transfer ink materials (small molecules) onto substrate in a pre-defined pattern

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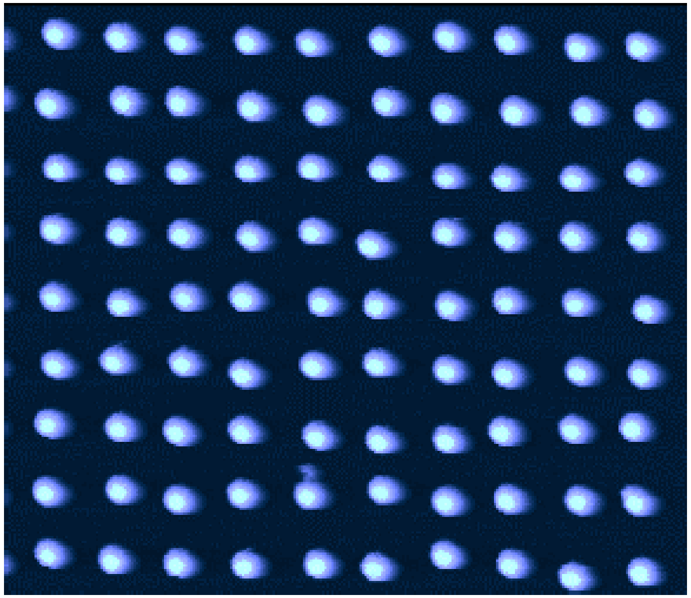
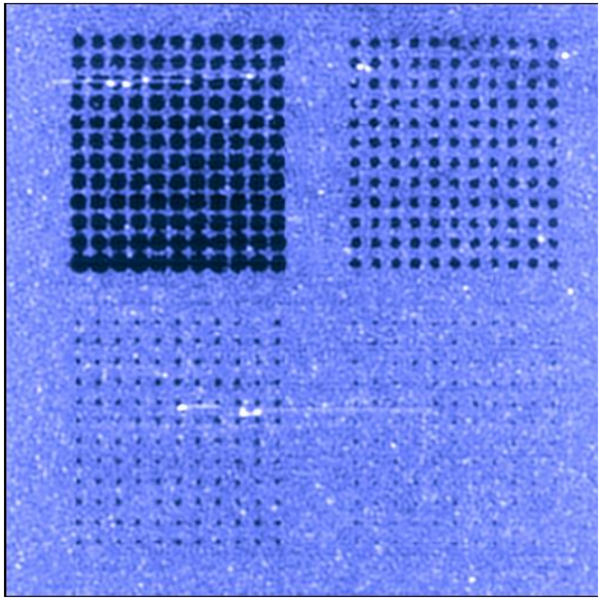
DIP-PEN NANOLITH





(Left) amino-modified polystyrene particles onto carboxylic acid alkanethiol (-) template. (Right) Opposite electrostatic assembly of citrate-stabilized gold nanoparticles onto carboxylic acid alkanethiol (-) surrounding a hydrophobic, uncharged dot array (ODT).

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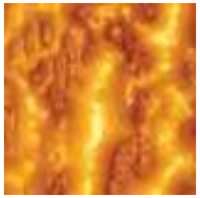
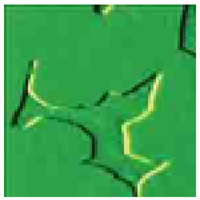
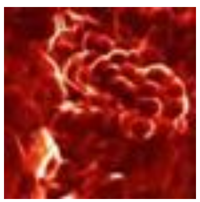


DIP-PEN NANOLITH

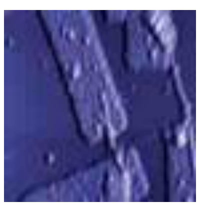


High Resolution and Accuracy:
14 nm linewidths, 5 nm spatial resolution; Automated registry

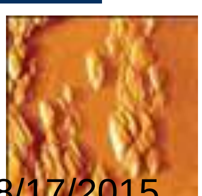


Versatile Chemical and Material Flexibility:
Alkylthiols (e.g. ODT & MHA), Fluorescent dye, Silazanes, Alkoxysilanes, Conjugated polymer, DNA, Proteins, Sols, Colloidal particles, Metal salts

Simple Operation and Experimental Procedures:
Can deposit direct-write, without need for resists; Operates in ambient conditions (no UHV); Patterning and imaging by the same instrument.



Efficient and Scalable:
Patterning and imaging routines are automated via InkCAD;
parallel pen arrays scale to 52 parallel pens;
2D nano PrintArrays™ in development: 2D arrays of 55,000 pens.



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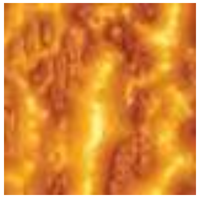
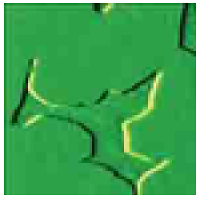
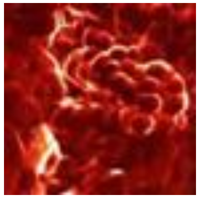
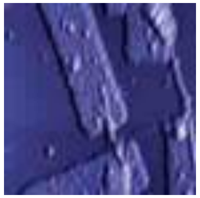
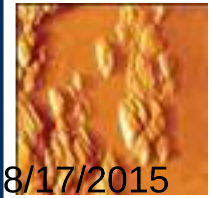

Summary

AFM is a Hot Instrument in nanotechnology applications

- High Resolution: a few nm X/Y, A in Z
- Versatile: Measure electrical/magnetic field, tens of nm
  I-V Curve measurement, conductive mapping
  Nanolithography (LAO/DPN); Force measurement
- Non-destructive, Ambient/water environments, affordable
- Weakness: Limited Z, Low speed, …

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