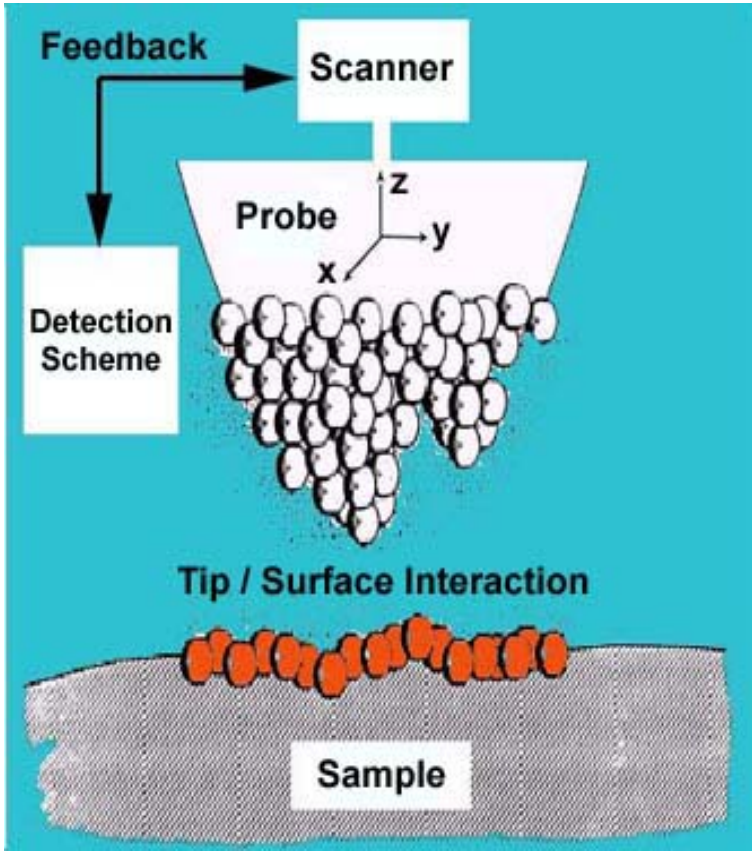
Scanning Probe Microscopy (SPM)



Scanning Tunneling Microscopy (STM)

--- G. Binnig, H. Rohrer et al, (1982)

Near-Field Scanning Optical Microscopy (NSOM)

--- D. W. Pohl (1982)

Atomic Force Microscopy (AFM)

--- G. Binnig, C. F. Quate, C. Gerber (1986)

Scanning Thermal Microscopy (SThM)

--- C. C. Williams, H. Wickramasinghe (1986))

Magnetic Force Microscopy (MFM)

--- Y. Martin, H. K. Wickramasinghe (1987)

Friction Force Microscopy (FFM or LFM)

--- C. M. Mate et al (1987)

Electrostatic Force Microscopy (EFM)

--- Y. Martin, D. W. Abraham et al (1988)

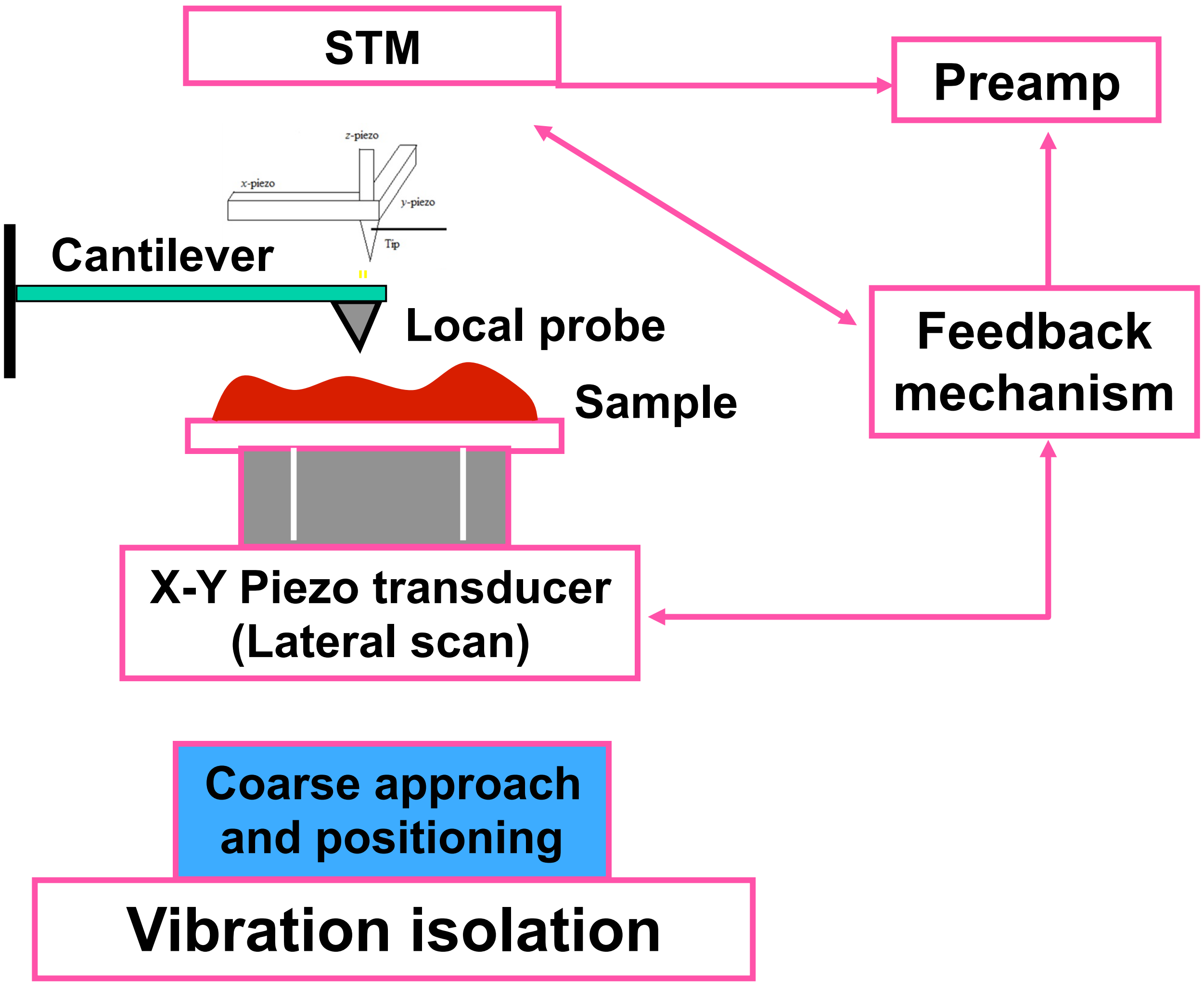
Scanning Capacitance Microscopy (SCM)

--- C. C. Williams, J. Slinkman et al (1989)

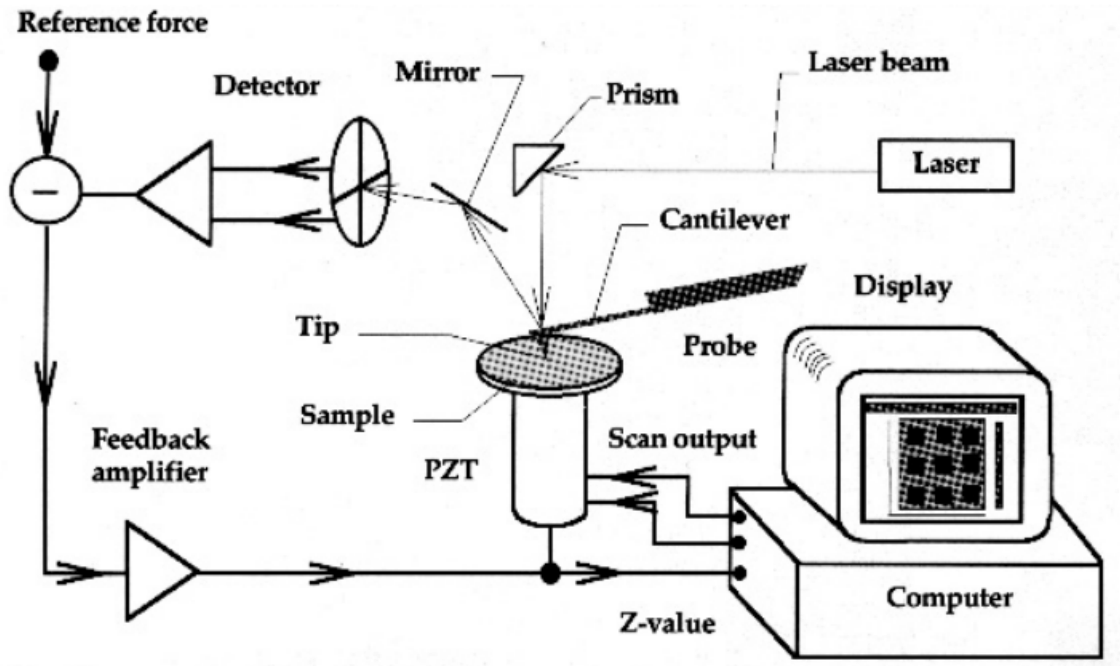
Force Modulation Microscopy (FMM)

--- P. Maivald et al (1991)

Original Structure of AFM



Atomic Force Microscopy (AFM)



$$F = k\Delta z$$

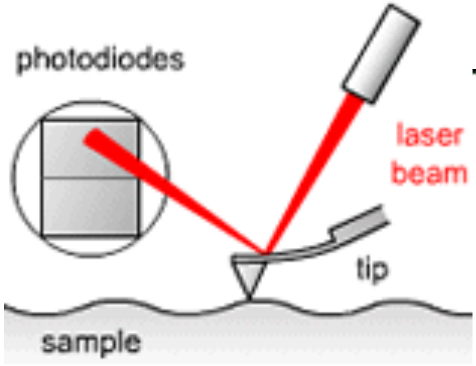
$$F = 10^{-9} – 10^{-6}\ \text{N}$$

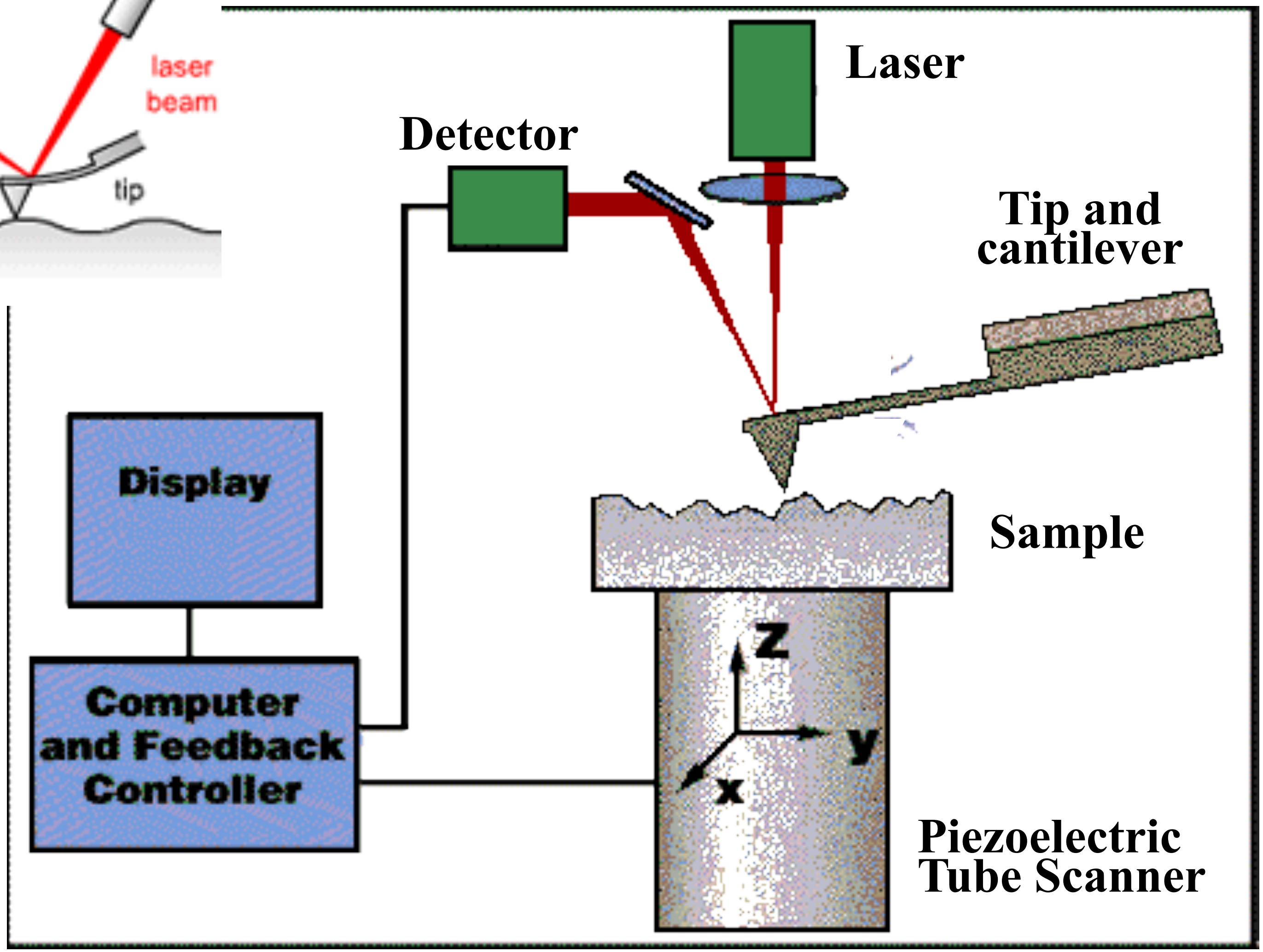
$$k = 0.1 – 1\ \text{N/m}$$

References:

- G. Binnig, C. F. Quate, and C. Gerber, Phys. Rev. Lett. 56, 930 (1986).
- C. Bustamante and D. Keller, Physics Today, 32, December (1995).
- R. Wiesendanger and H.J. Güntherodt, *Scanning Tunneling Microscopy II* , Springer-Verlag, (1992).

Core components of AFM



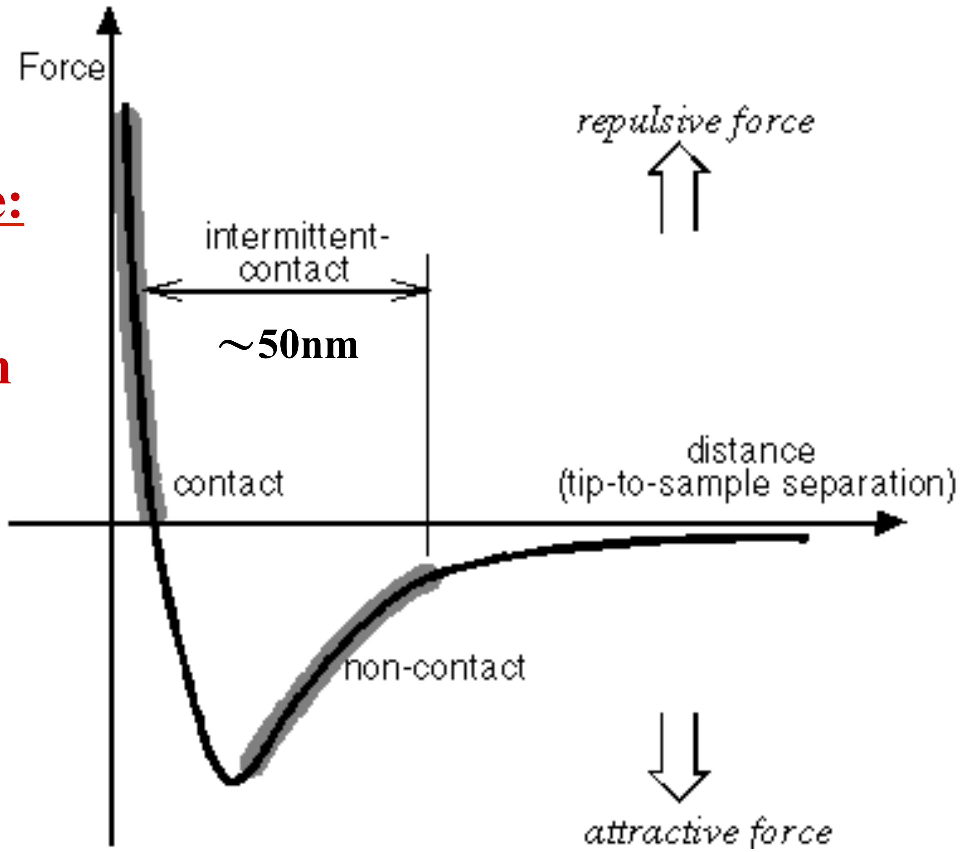


Interaction between the probe and sample

Short-range:

1) Bonding

2) Repulsion



Long-range:

1) Van der Waal

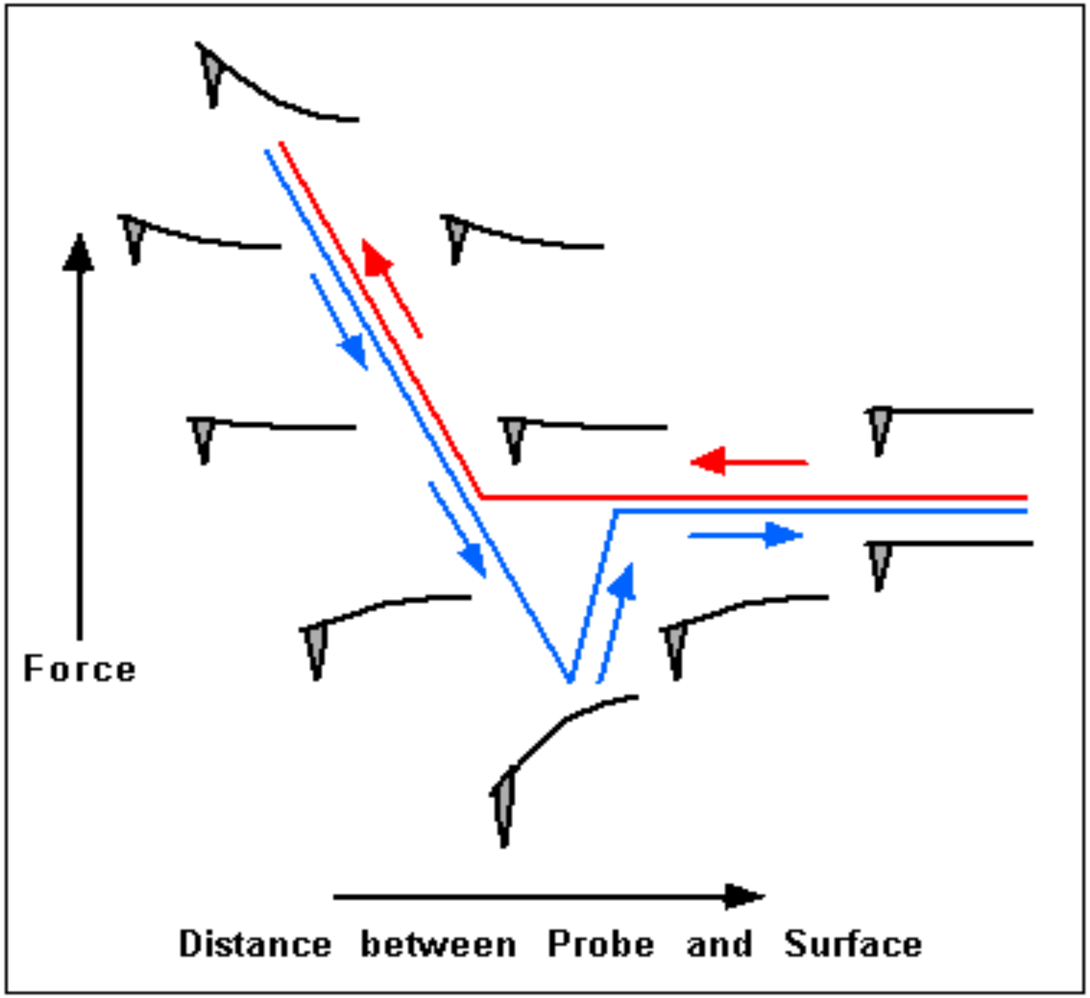
2) Capillary

3) Magnetic

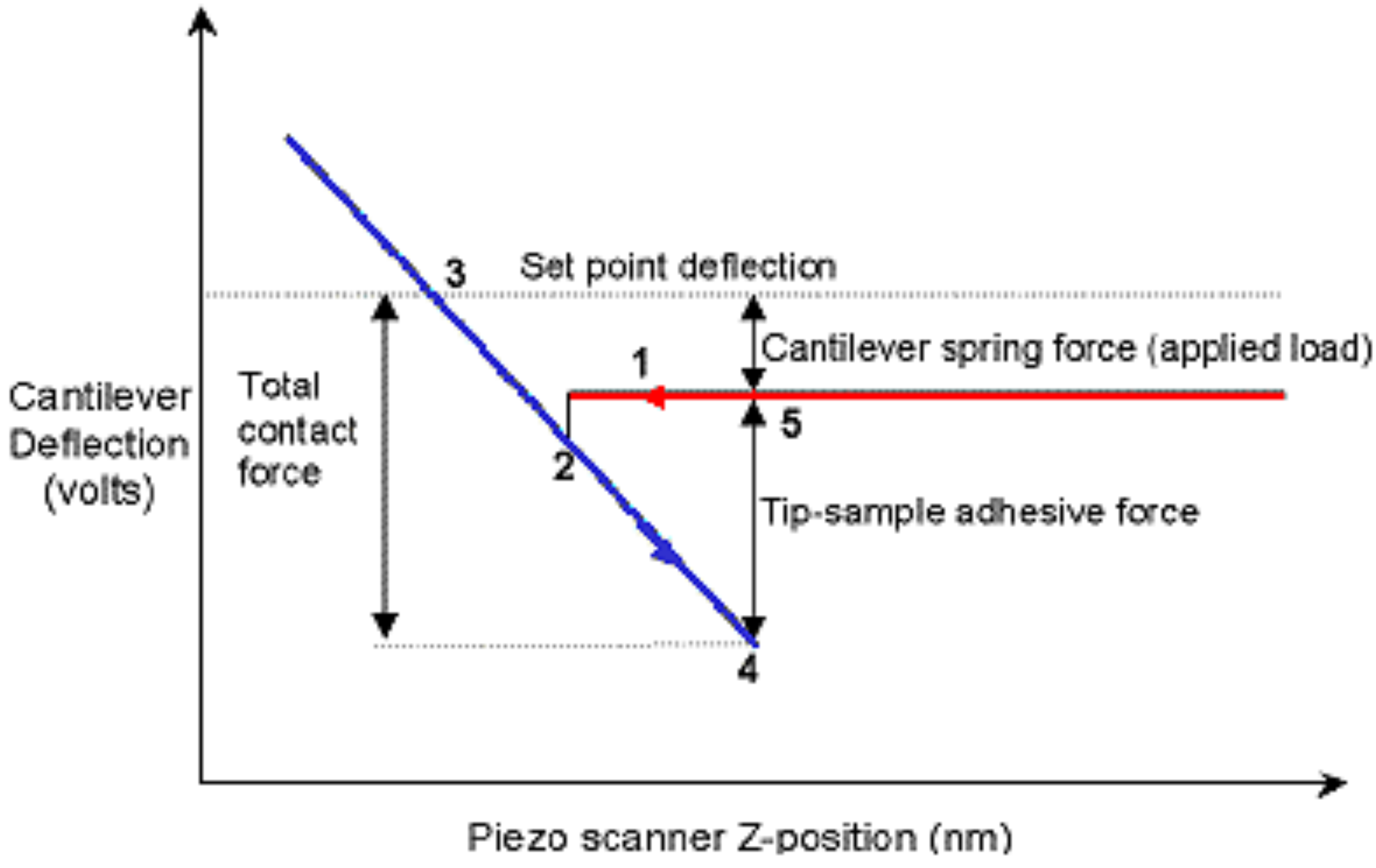
4) Electrostatic

Lennard-Jones potential $\phi(r) = - A/r^6 + B/r^{12}$

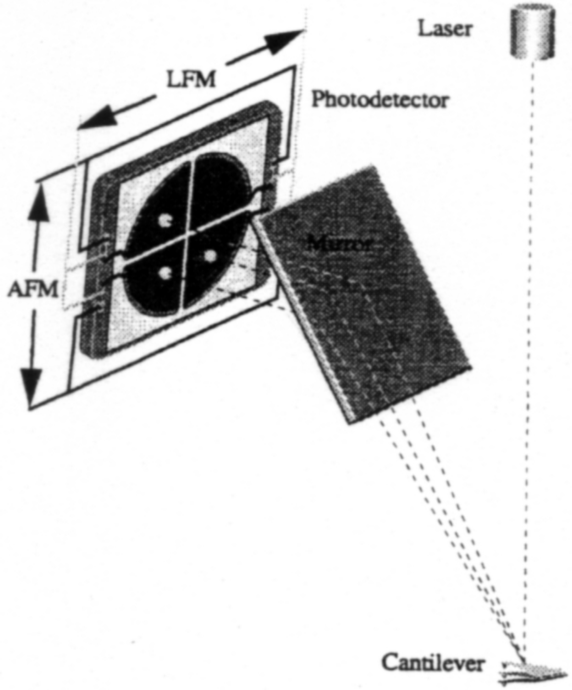
Reaction of the probe to the force

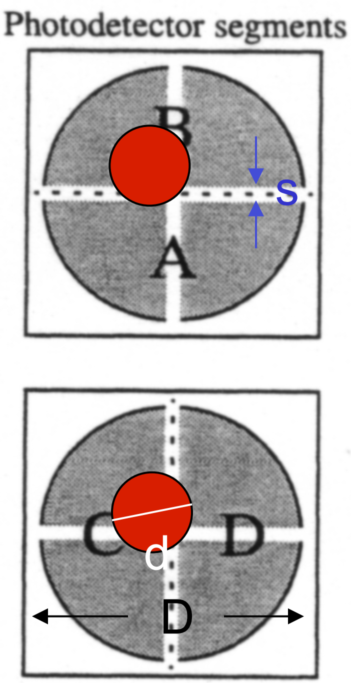


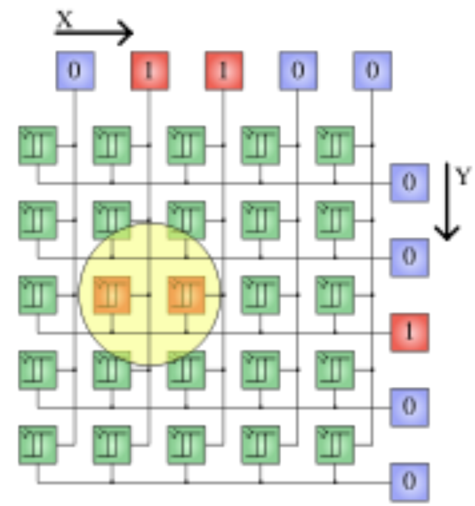
Deflection of Cantilever vs Piezo displacement



Position-sensitive Photo Diode (PSPD)

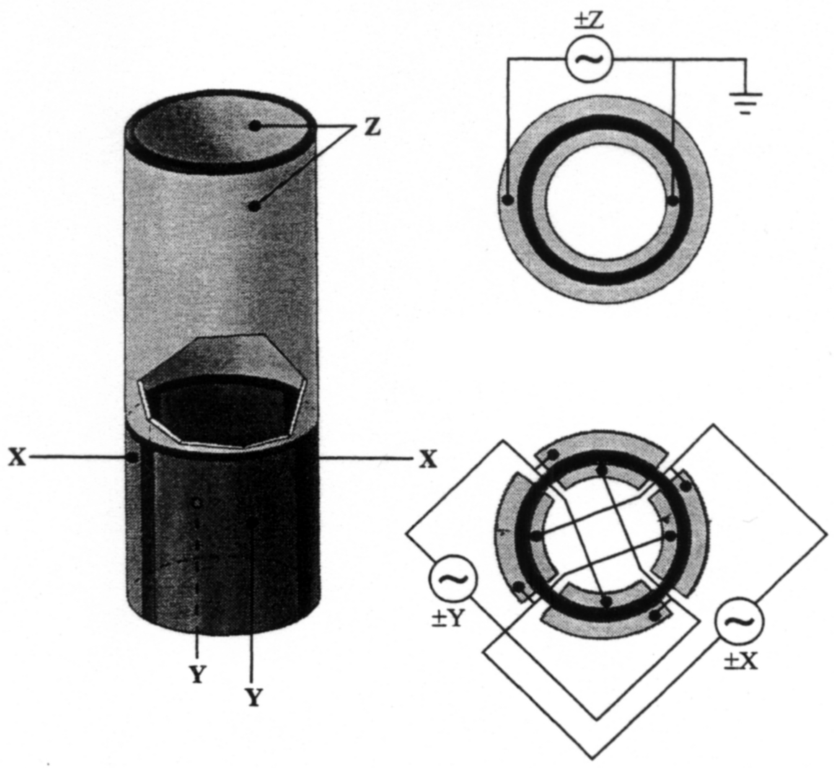


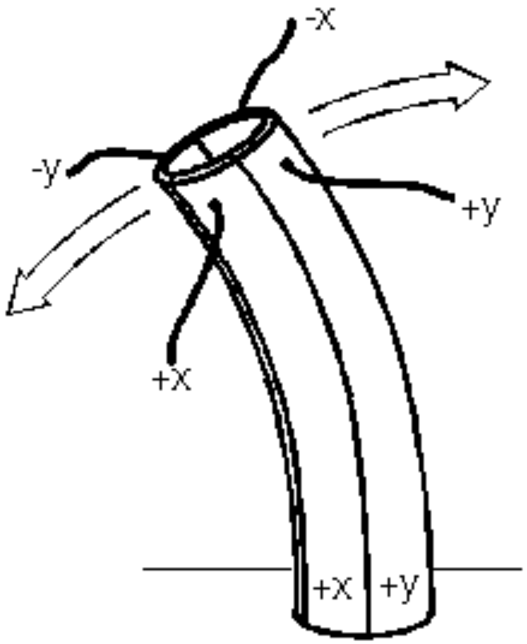




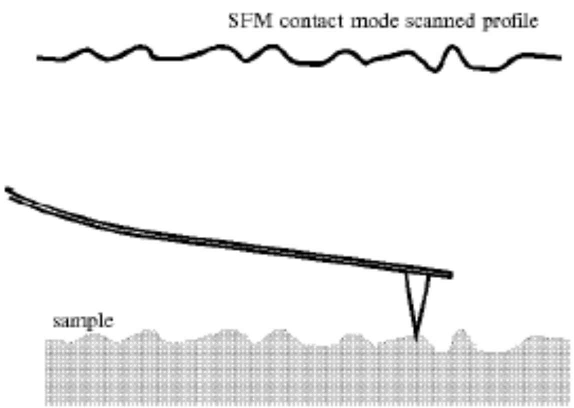
D ~ 10mm   d ~ 1mm   s ~ 0.01mm

Piezo Scanner

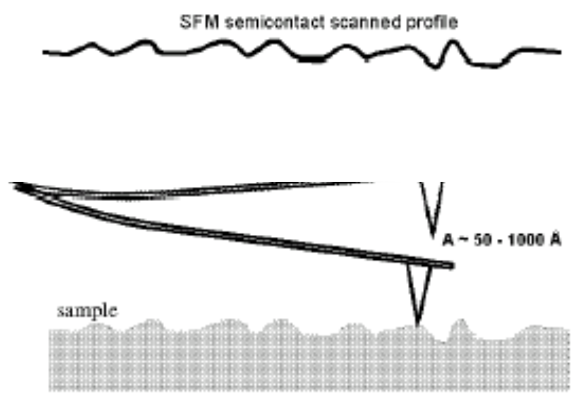




Three scanning modes of AFM

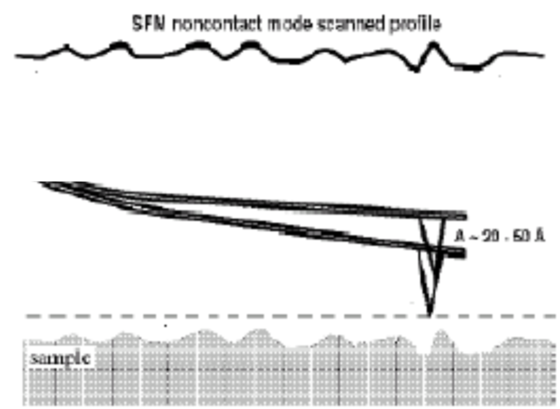


Contact Mode AFM



Semicontact Mode AFM

(Tapping mode)



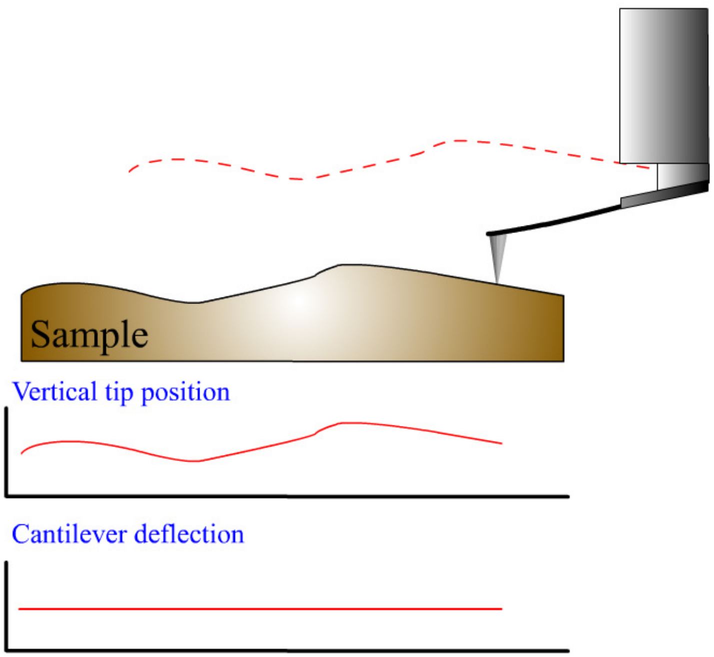
Non-contact Mode AFM

Two imaging methods in contact mode

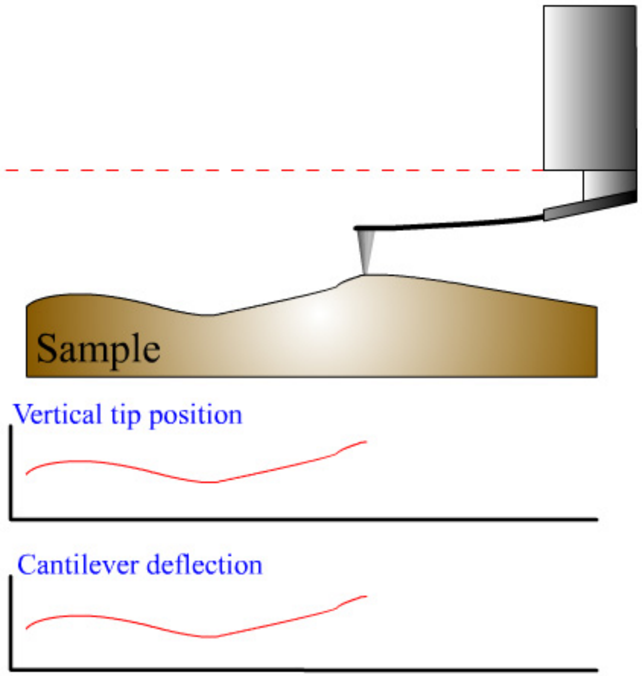
- Constant force method： By using a feedback loop the tip is vertically adjusted in such a way that the force always stays constant. The tip then follows a contour of a constant contact force during scanning. A kind of a topographic image of the surface is generated by recording the vertical position of the tip.

- Constant height method： In this mode the vertical position of the tip is not changed, equivalent to a slow or disabled feedback. The displacement of the tip is measured directly by the laser beam deflection. One of its advantages is that it can be used at high scanning frequencies.

Constant-force scan vs. constant-height scan



Constant-force mode



Constant-height mode

www.ntmdt.com

Constant-force scan vs. constant-height scan

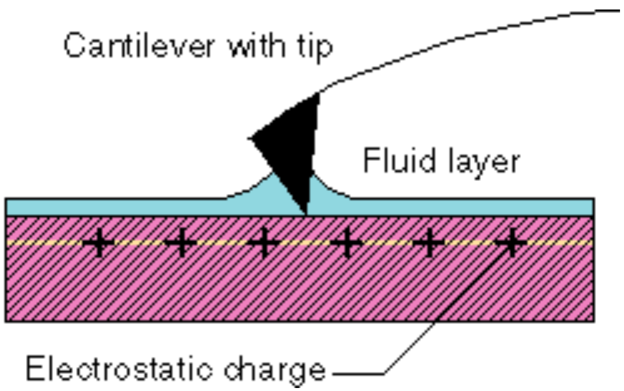
Constant-force

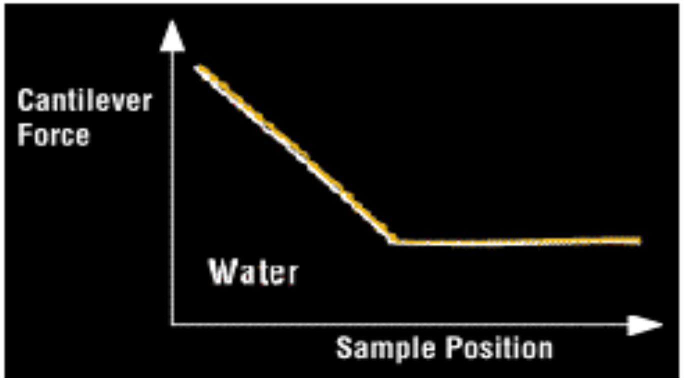
- Advantages:
  - Large vertical range
  - Constant force (can be optimized to the minimum)
- Disadvantages:
  - Requires feedback control
  - Slow response

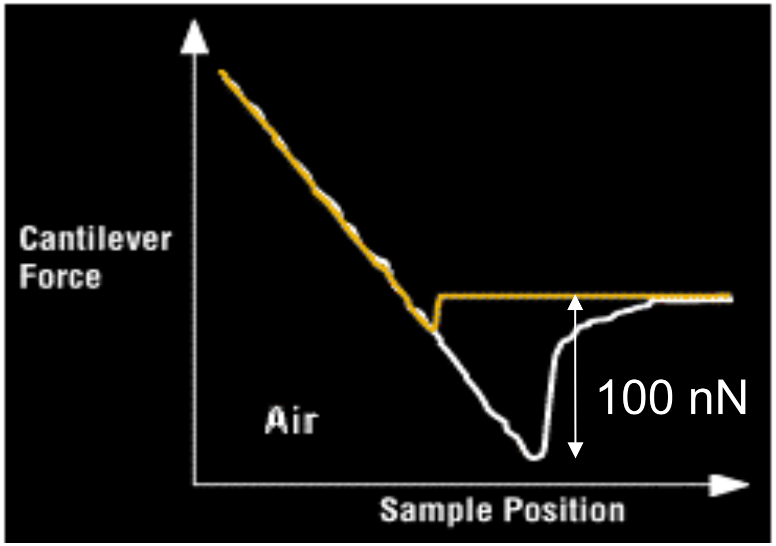
Constant-height

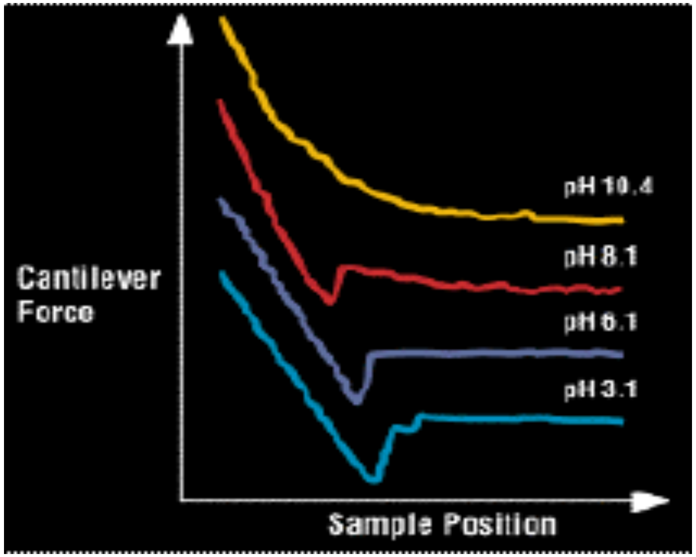
- Advantages:
  - Simple structure (no feedback control)
  - Fast response
- Disadvantages:
  - Limited vertical range (cantilever bending and detector dynamic range)
  - Varied force

Problems with the contact mode

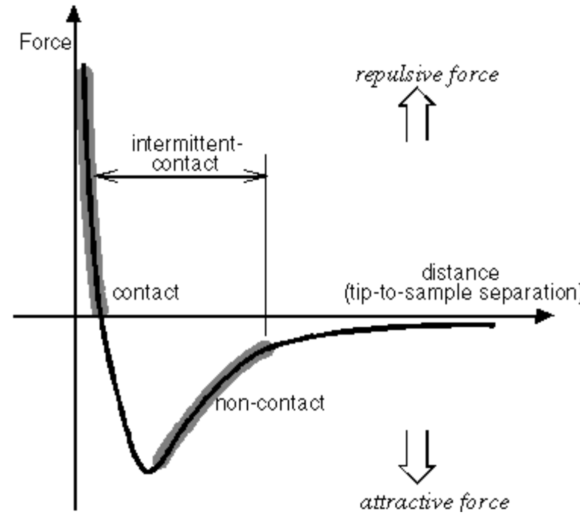




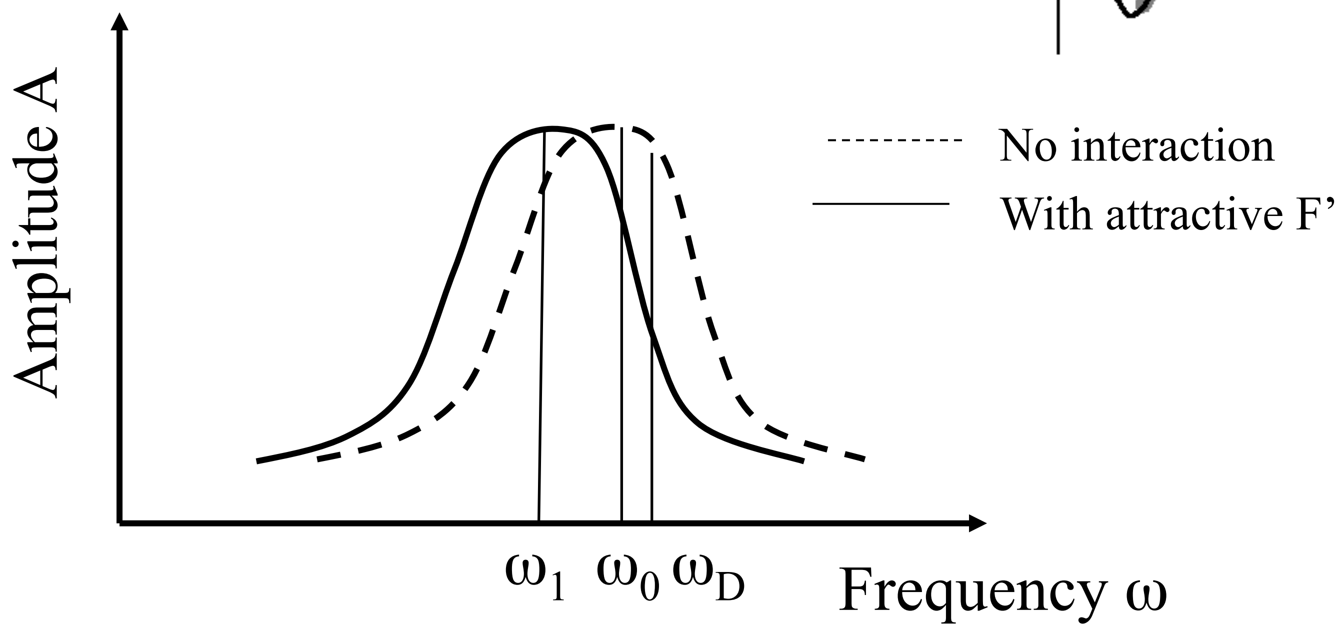




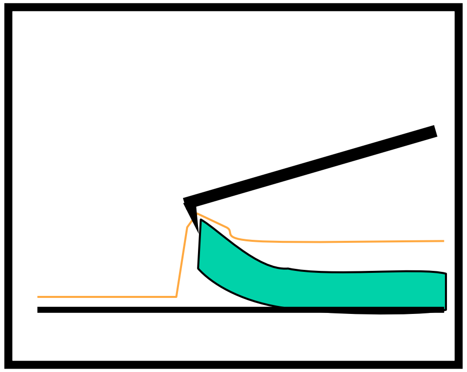
AC imaging mode



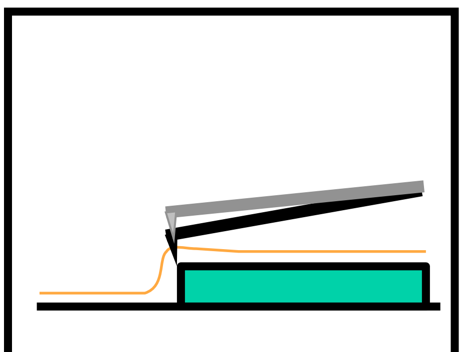
$$\omega_1 = \omega_0 \,(1 + F'/2c)$$



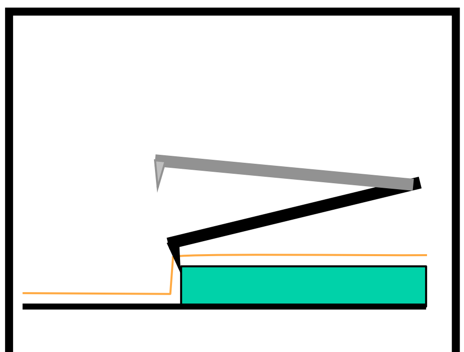
Comparison of three scanning modes



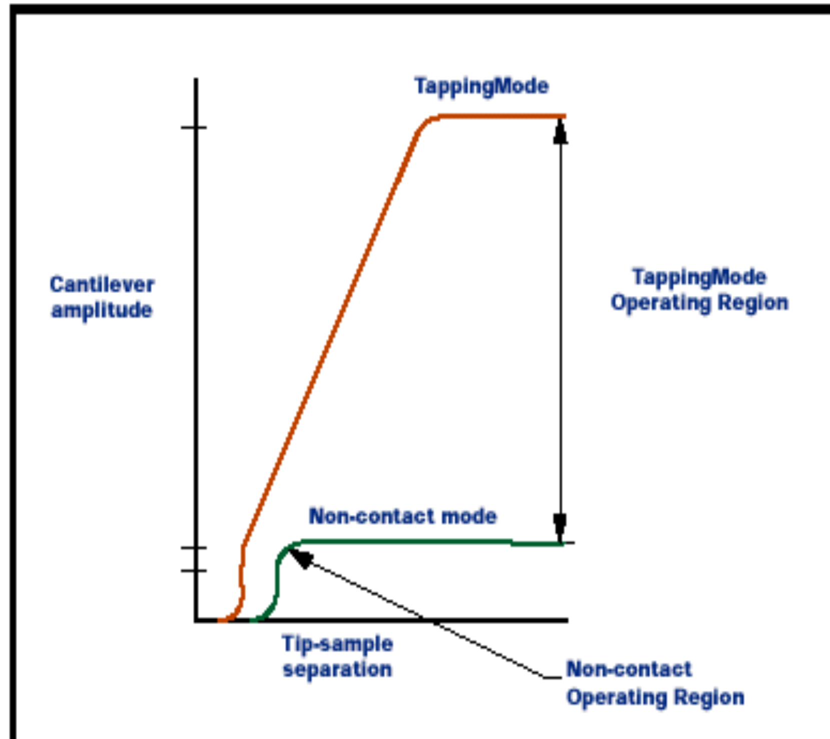
Contact



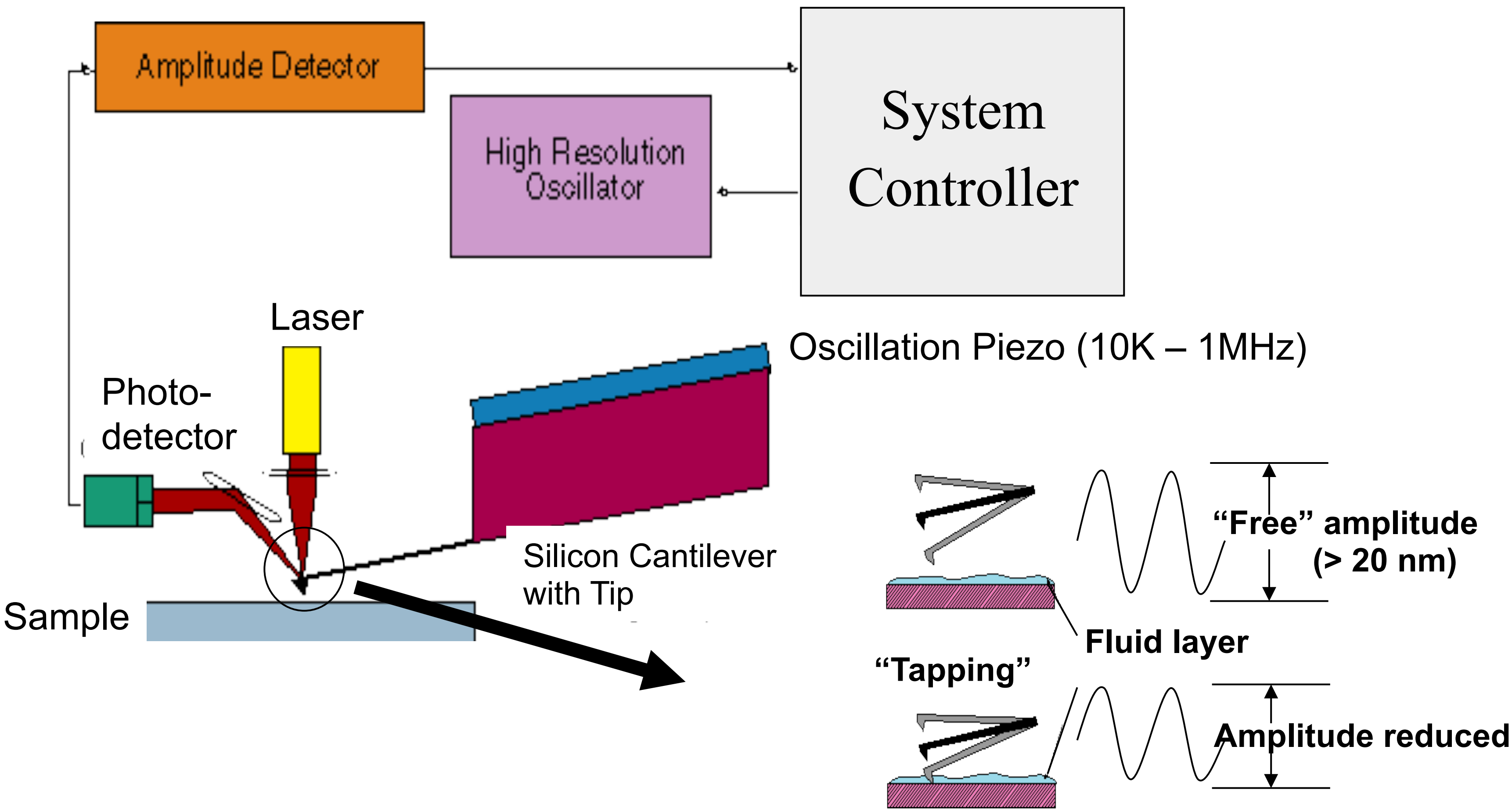
Non-contact



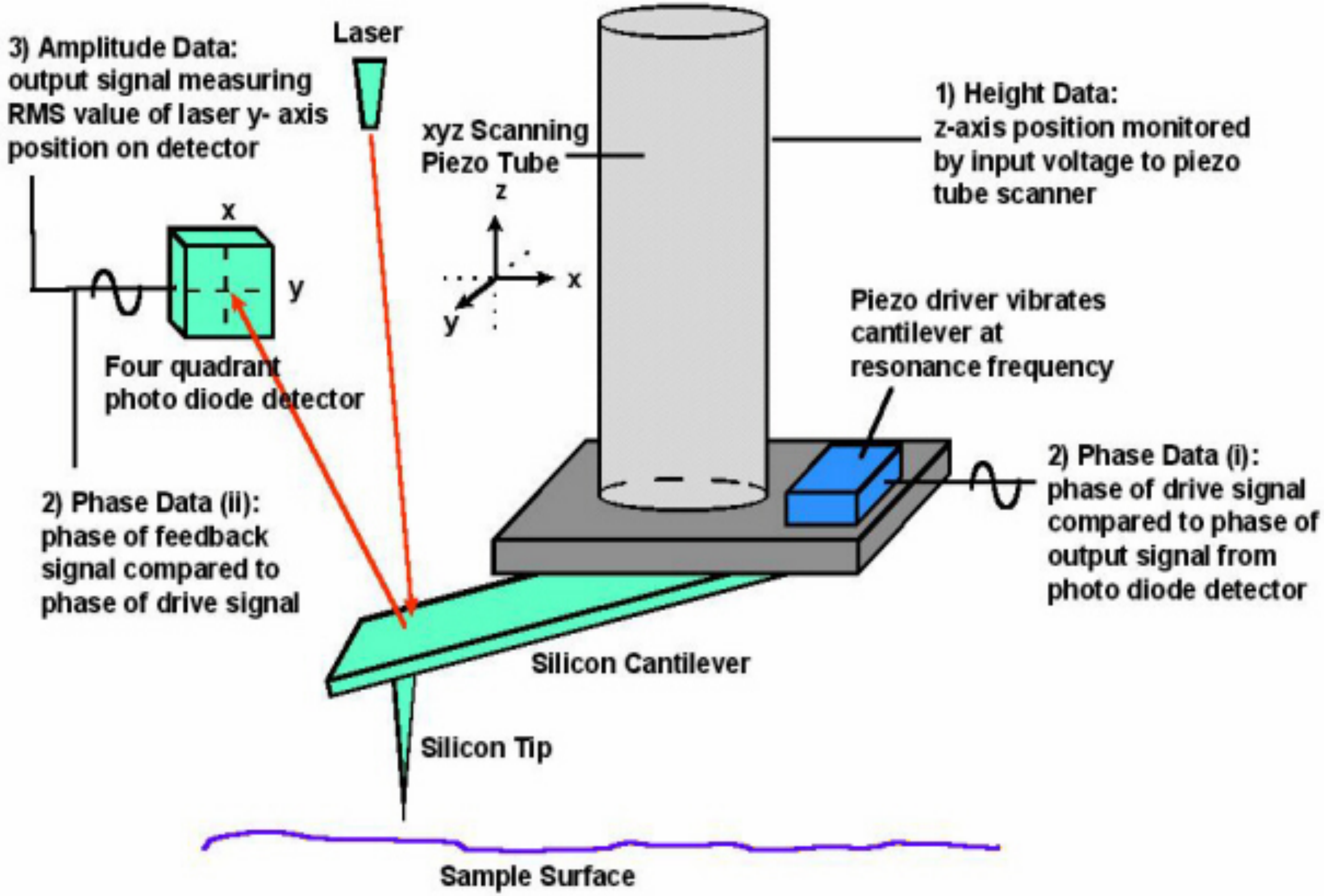
Intermittent-contact



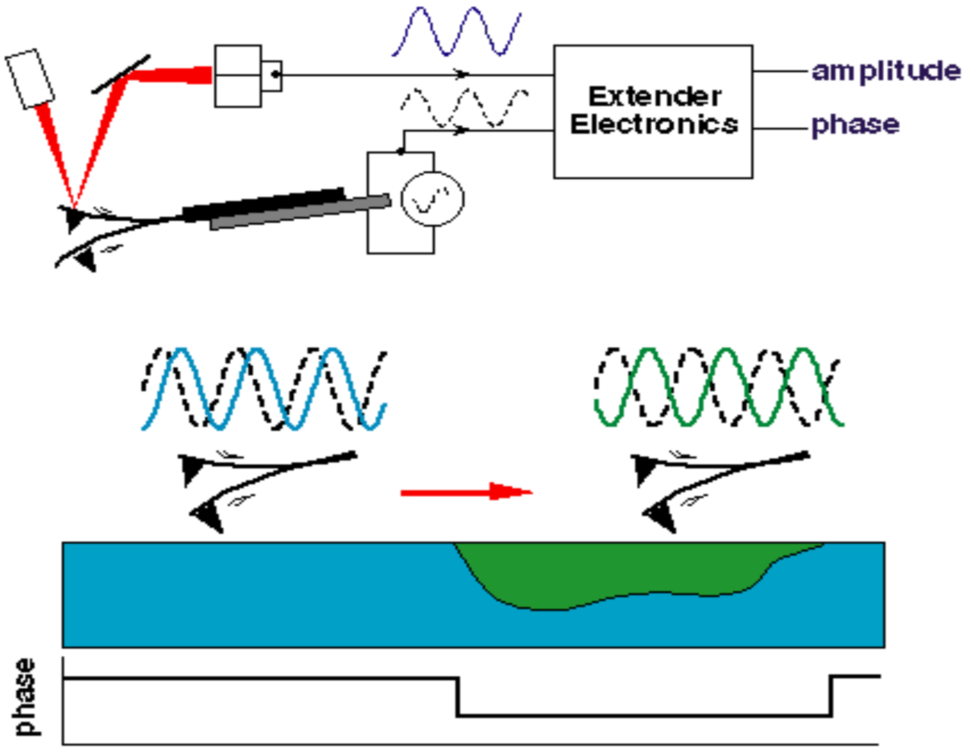
Tapping mode

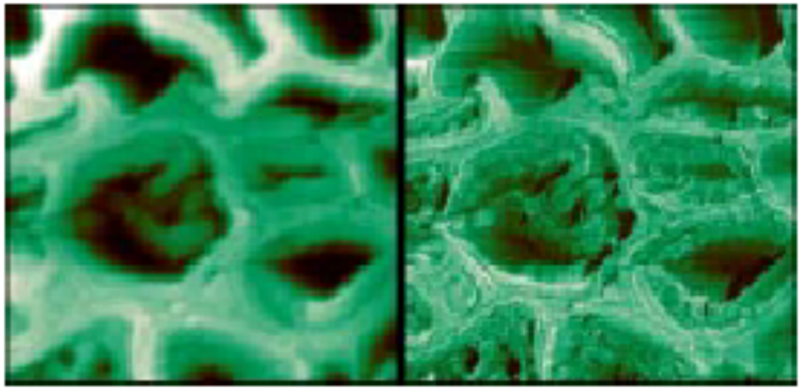


Three Types of Data Collected in Tapping Mode



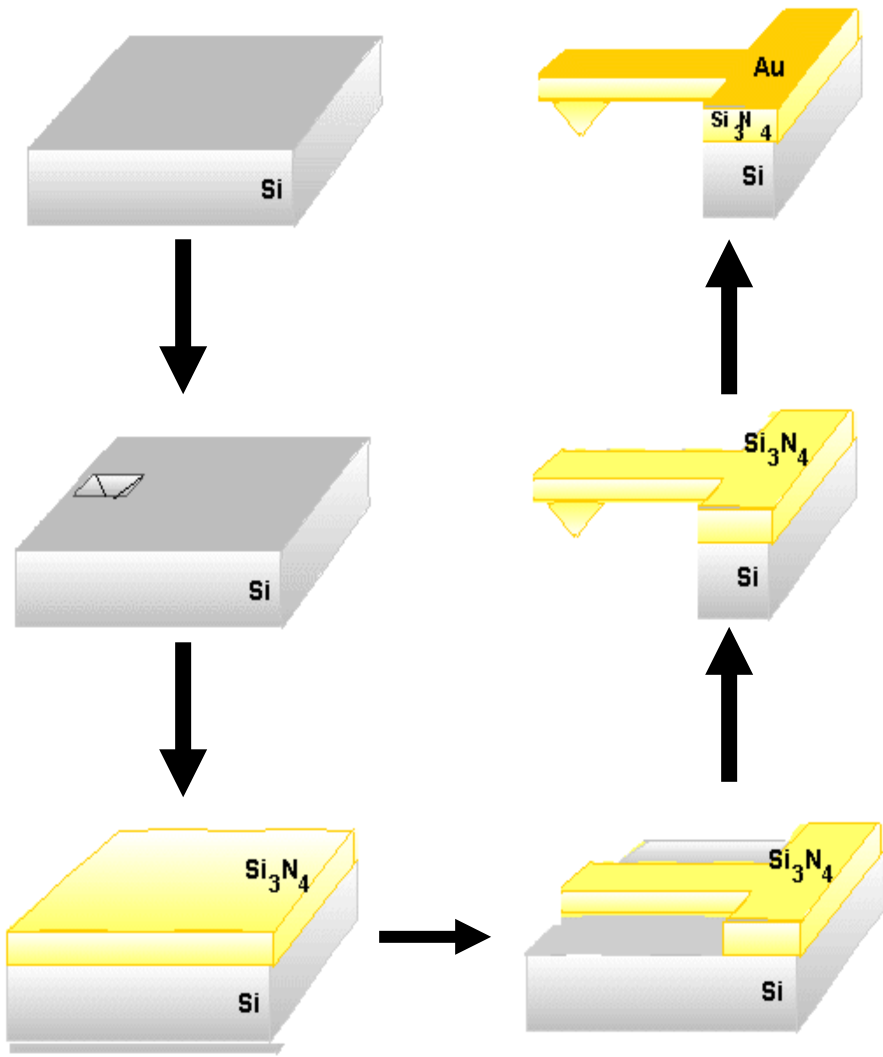
Images by tapping mode

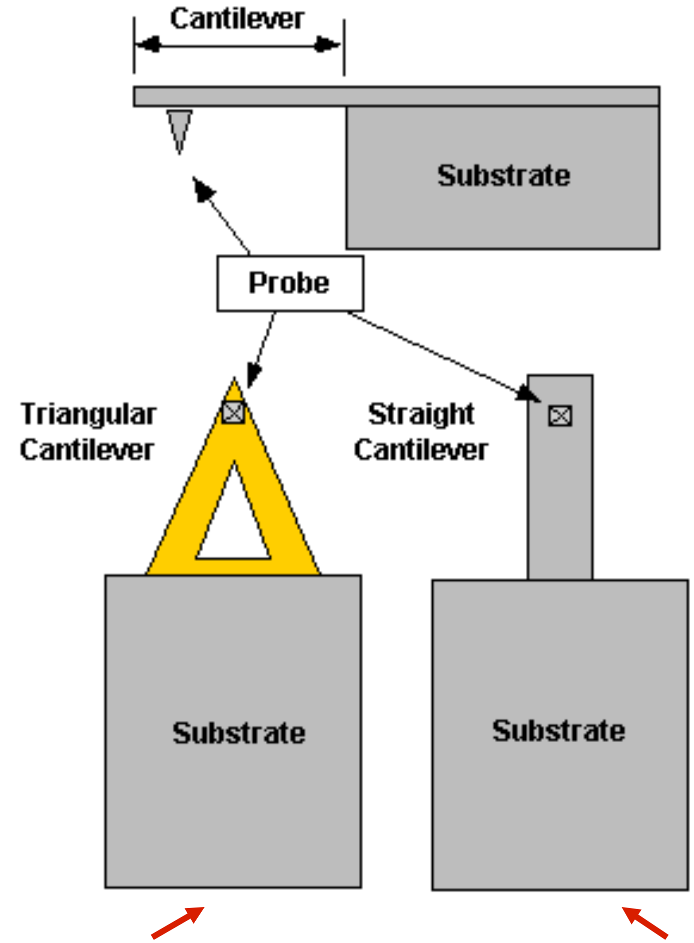




AFM image of a fresh
Alfalfa root section

Fabrication of AFM probes



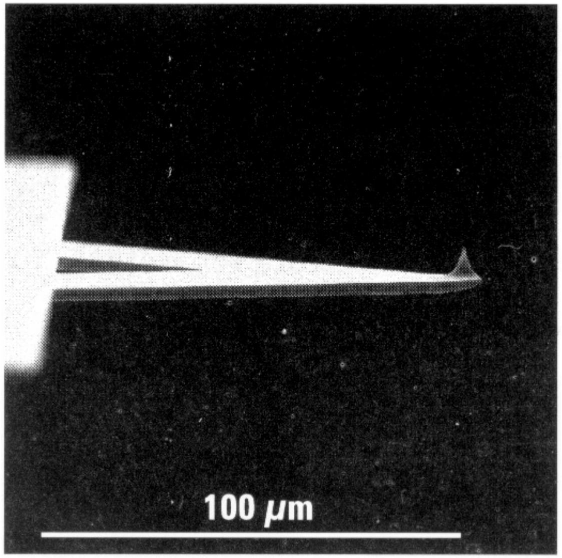


Typical Tip Dimension:
150μm x 30μm x 0.5μm
$k \sim 0.1$ N/m
Materials: Si_3N_4

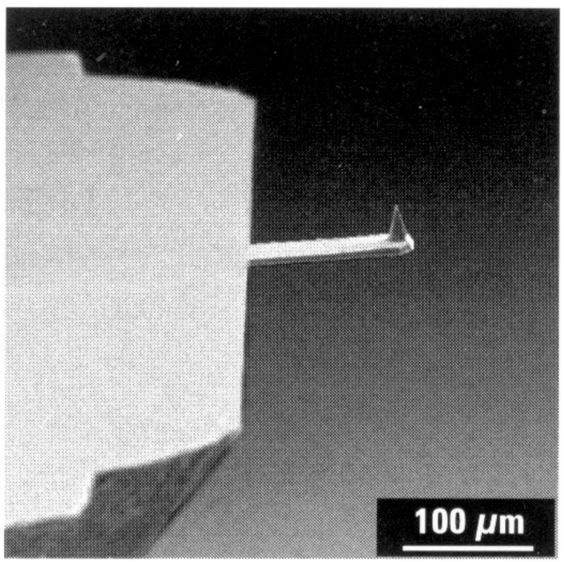
Typical Tip Dimension:
150μm x 30μm x 3μm
$f_r \sim 100$ kHz
Materials: Si

Materials: Si, SiO_2, Si_3N_4
Ideal Tips: hard, small radius of curvature, high aspect ratio

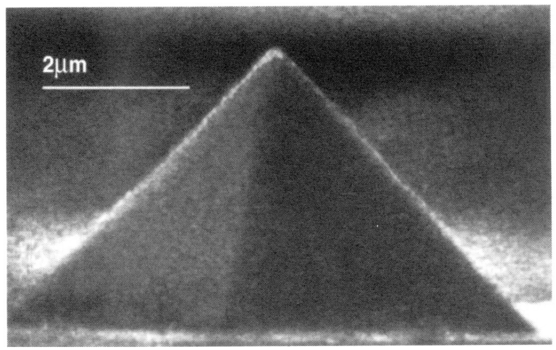
V-shaped



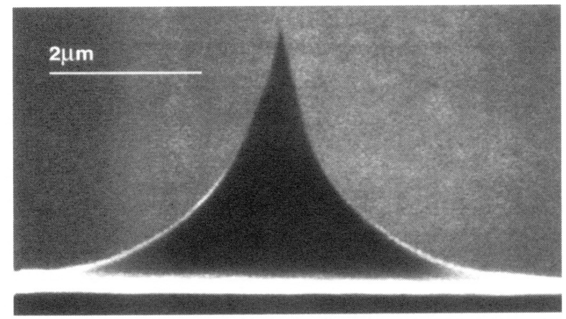
Rectangular-shaped



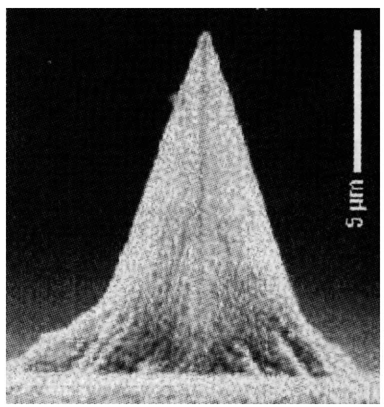
Pyramid Tip

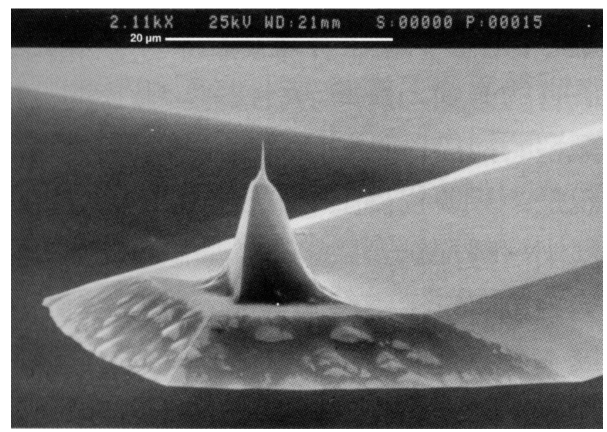


Ultrasharp Tip



Diamond-coated Tip





Criteria for AFM probe

1) Small spring constant (*k*) $F = k\,\Delta z$

To detect force of ~ nN

2) High resonant frequency (f_r) $f_r \propto (k/m)^{1/2}$

To enable scanning and other operations

3) Highly anisotropic stiffness

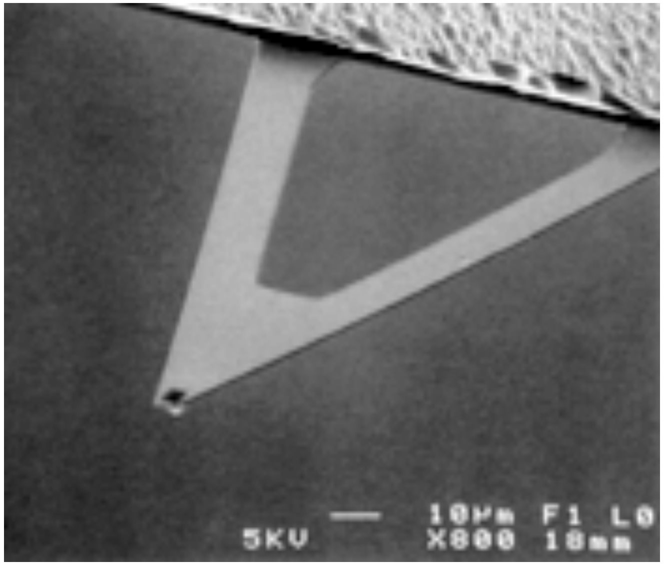
Easy to bent and difficult to twist

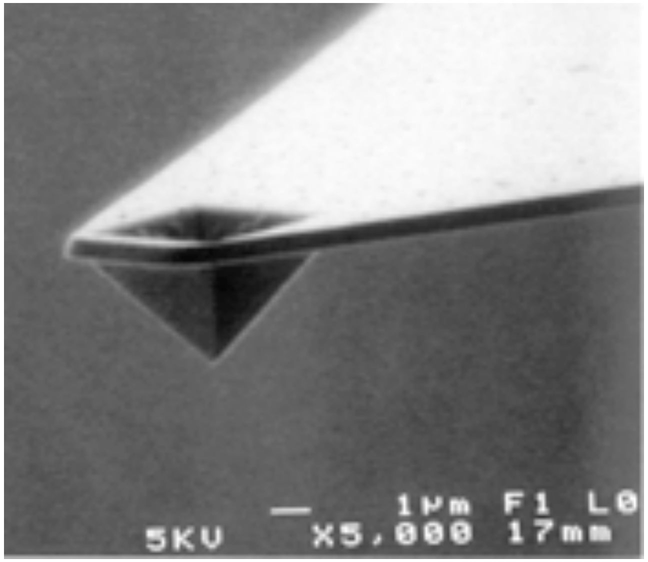
4) Sharp protrusion at the apex

To better define the tip-sample interaction

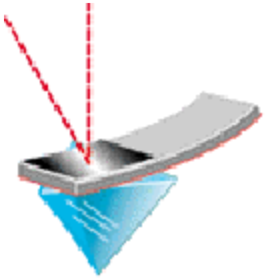
Tip of small shear force

(for Contact mode)



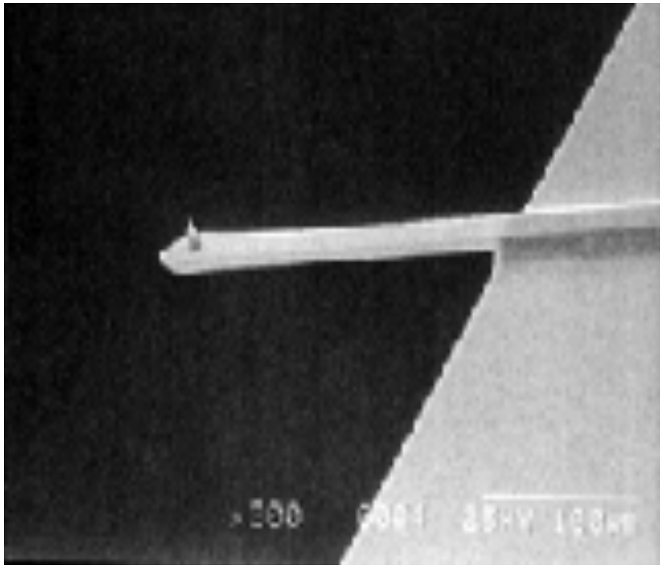


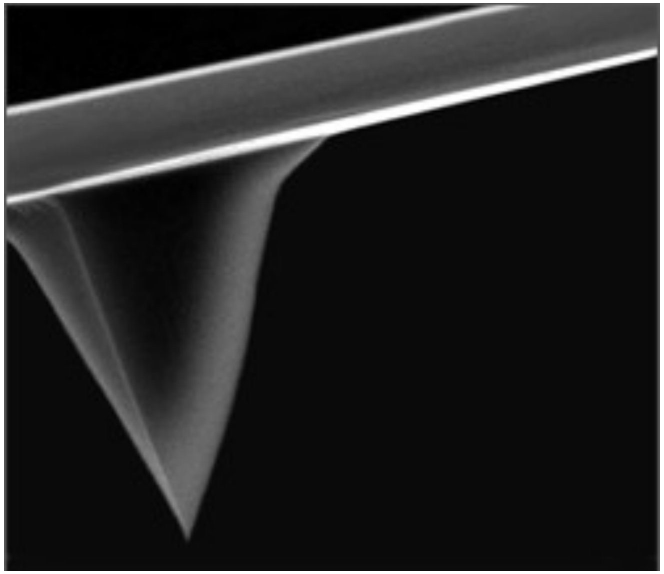
Typical Tip Dimension:
150μm x 30μm x 0.5μm
k ~ 0.1 N/m
Materials: Si_3N_4



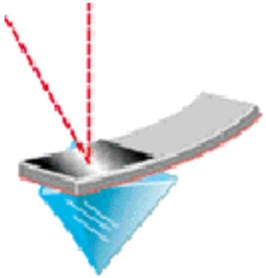
Tip of high resonant frequency

(for Tapping mode)





Typical Tip Dimension:
150µm x 30µm x 3µm
f_r ~ 100 kHz
Materials: Si



AFM versus STM

1. Generally, STM has “better” resolution than AFM.
2. The force-distance dependence in AFM is much more complex when characteristics such as tip shape and contact force are considered.
3. STM is generally applicable only to conducting samples while AFM is applied to both conductors and insulators.
4. AFM offers the advantage that the writing voltage and tip-to-substrate spacing can be controlled independently, whereas with STM the two parameters are integrally linked.

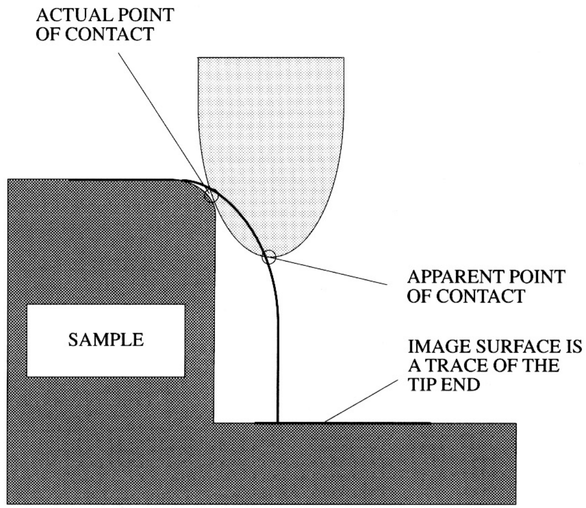
AFM versus EM

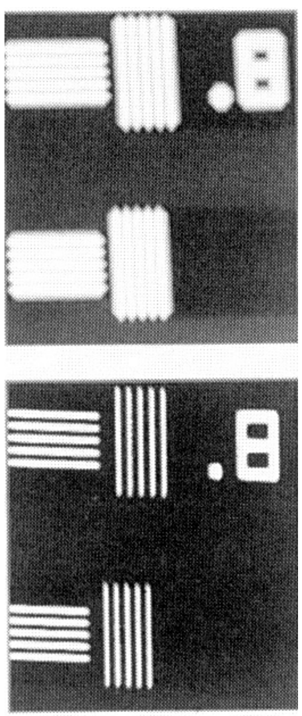
1. AFM only reveal the surface and EM can probe the interior structure of the sample with higher resolution.
2. AFM provides direct topographic measurements and EM provides only 2D projection of the sample structure.
3. No charging effect occurs in AFM. So, for insulating samples, no metallic coating is necessary.

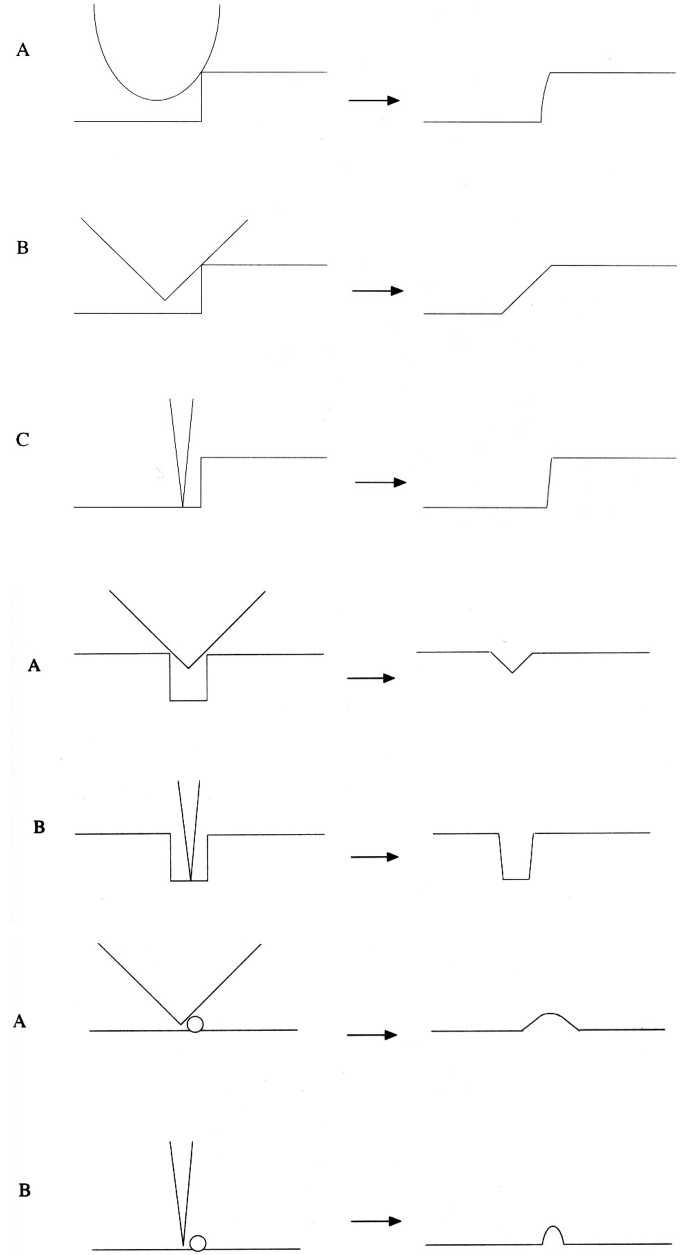
AFM versus Optical Microscope

1. AFM has much better resolution than Optical Microscope (OM).
2. AFM provides unambiguous measurement of step heights, independent of reflectivity differences between materials.
3. OM can be applied to much faster dynamic studies with the pump-probe method.

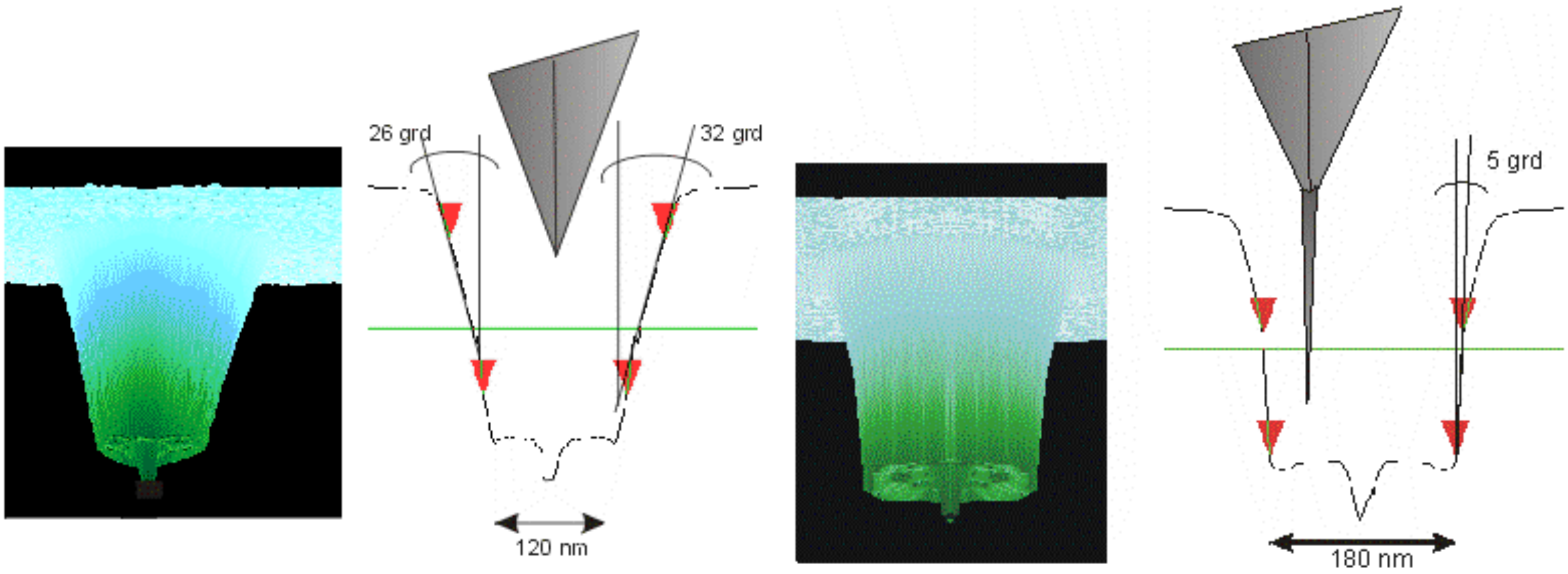
Effects of the Tip Shape



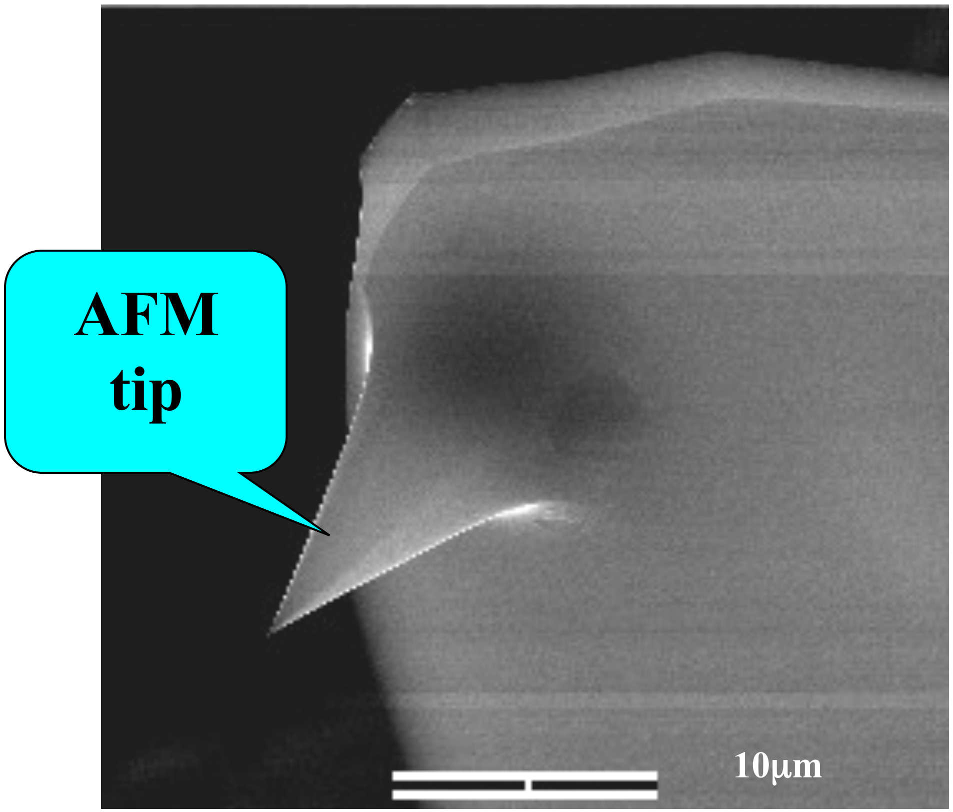




Ultra-sharp tip



AFM Tip + Carbon Nanotube



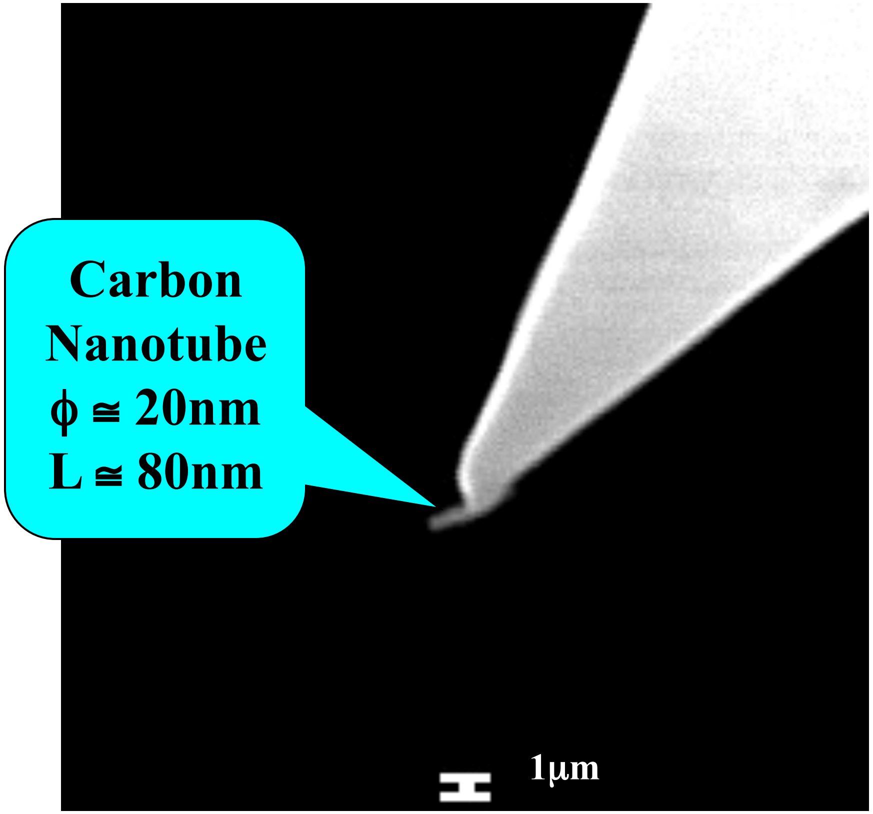
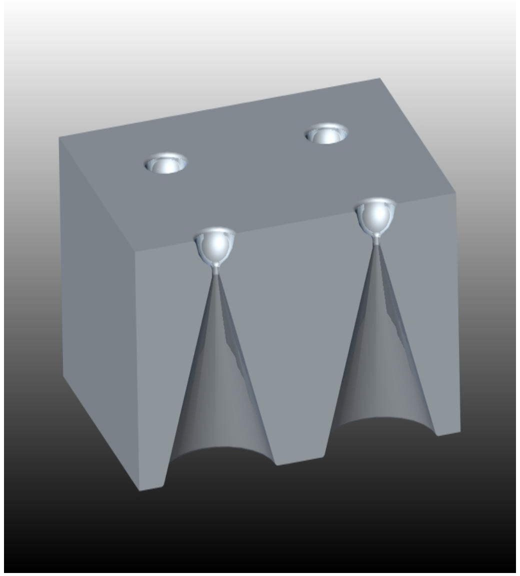
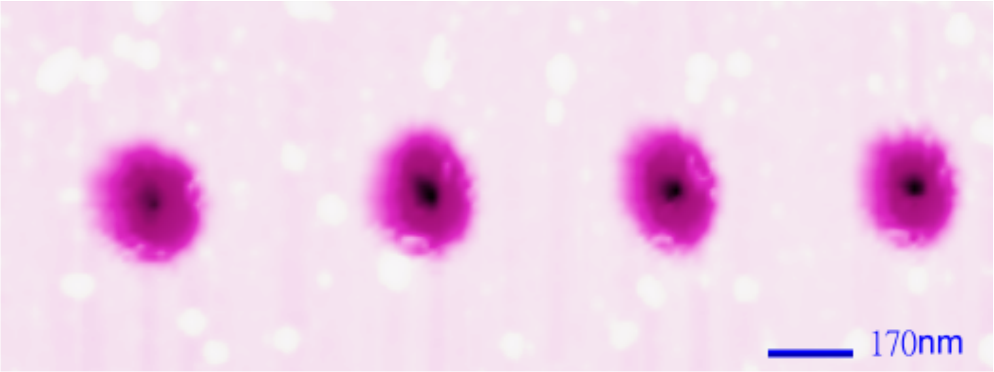


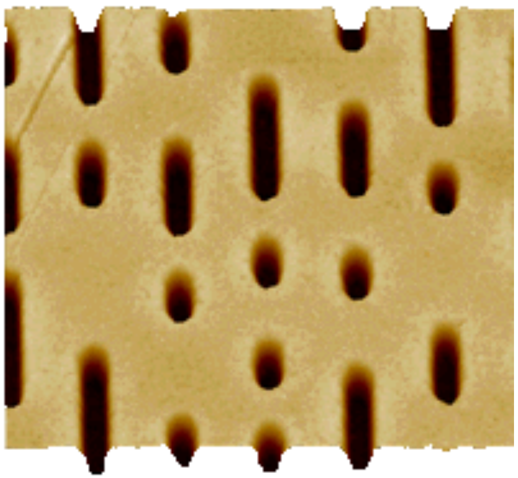
Image of high aspect ratio



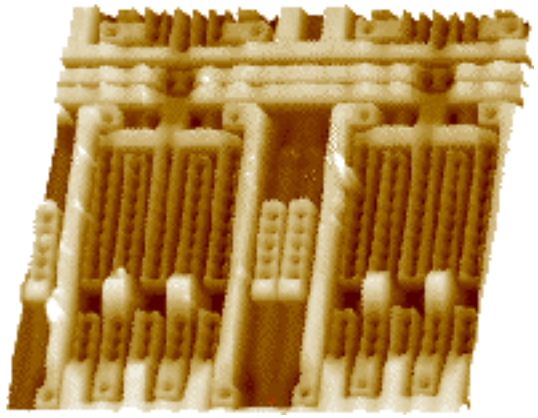


AFM images

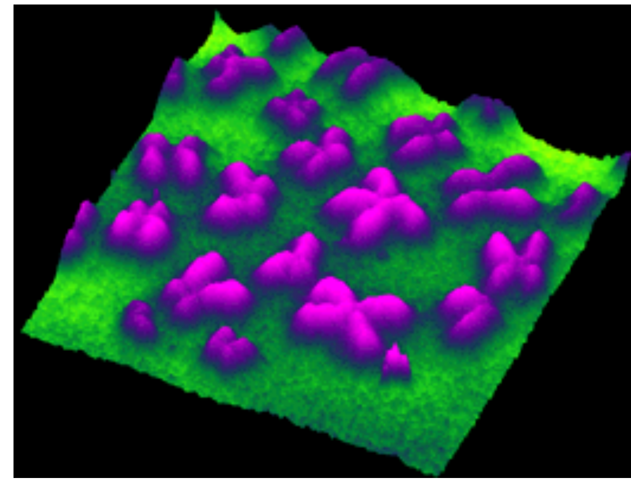
CD pits



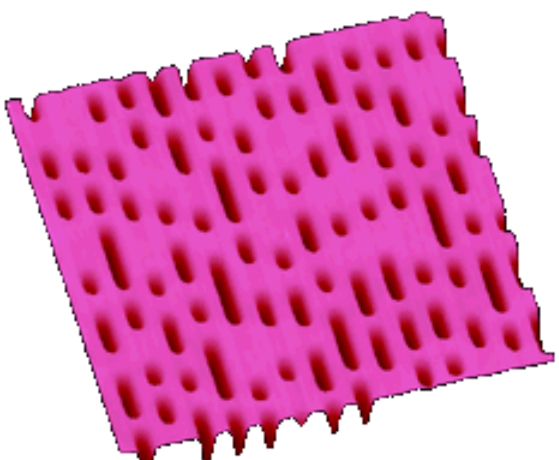
Integrated circuit



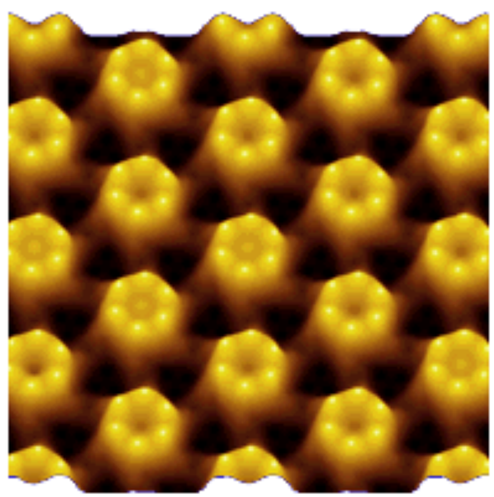
Chromosomes



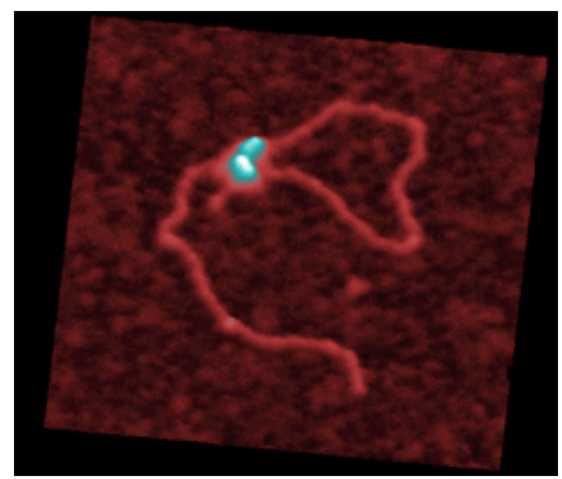
DVD pits



Bacteria



DNA

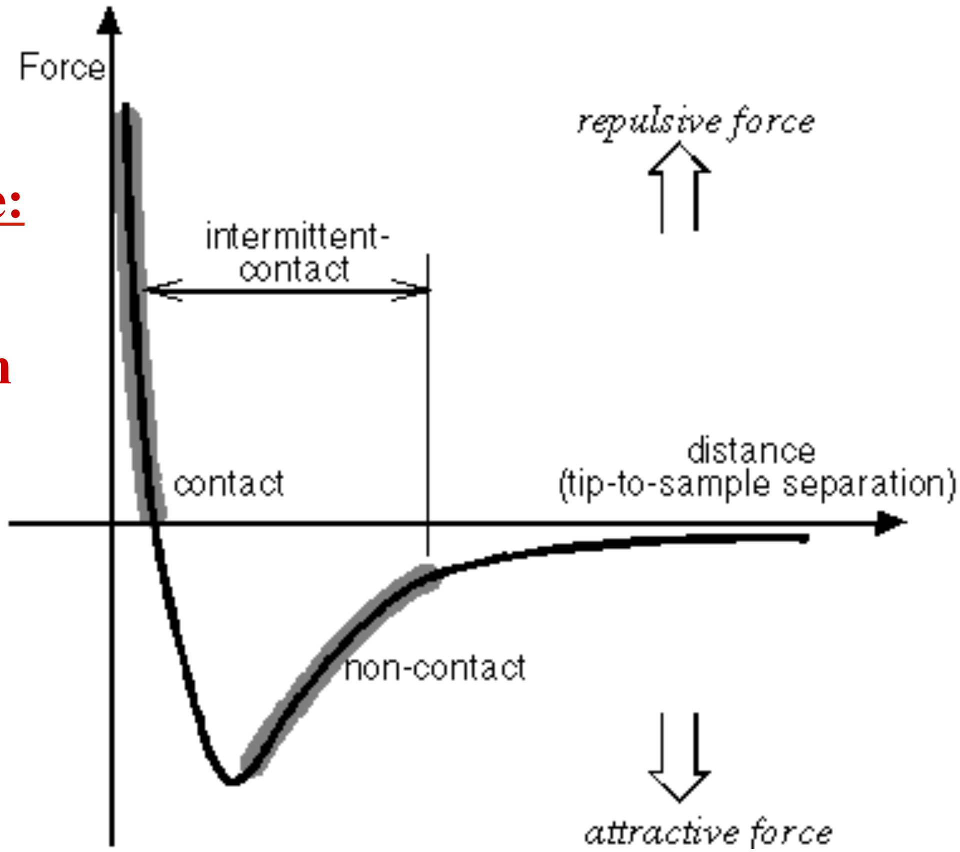


Interaction between the probe and sample

Short-range:

1) Bonding

2) Repulsion



Long-range:

1) Van der Waal

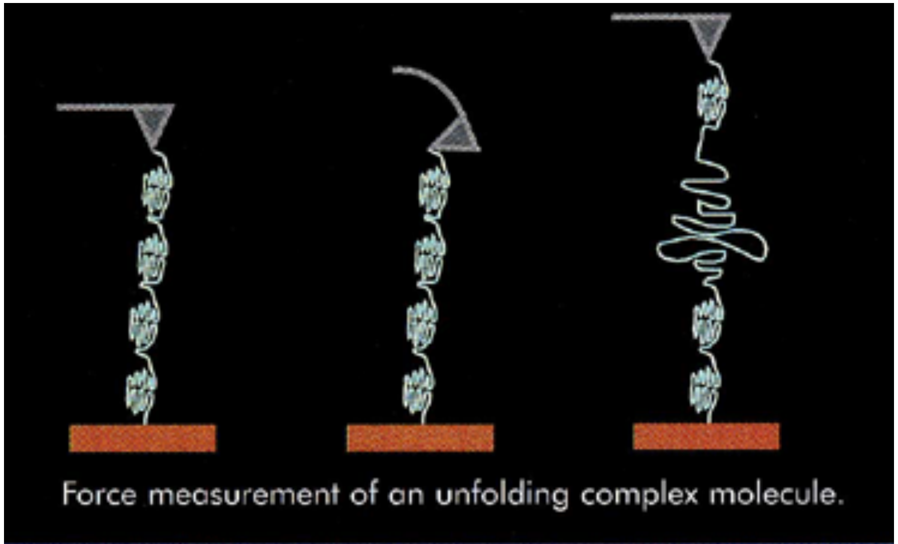
2) Capillary

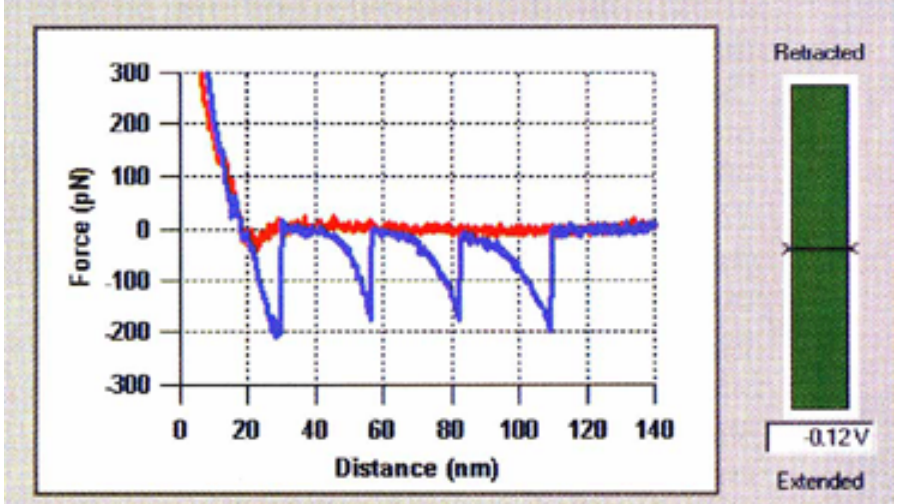
3) Magnetic

4) Electrostatic

Lennard-Jones potential $\phi(r) = - A/r^6 + B/r^{12}$

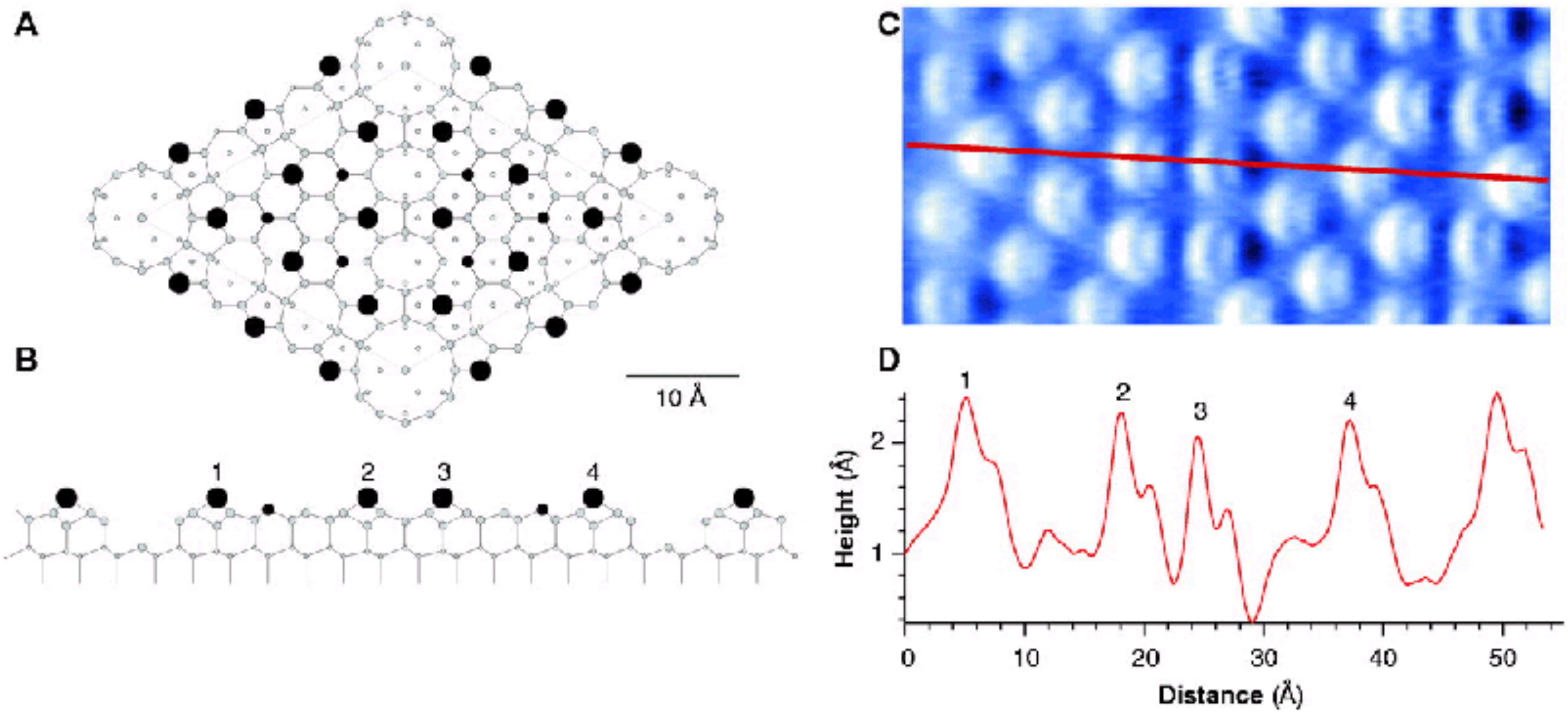
Force spectroscopy by AFM





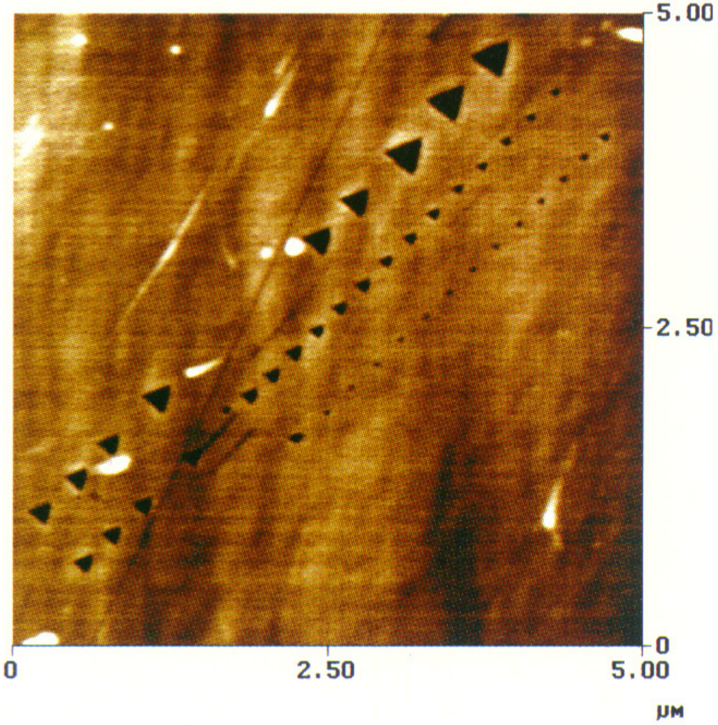
Advanced graphical user interface shows titin muscle molecule force curve.

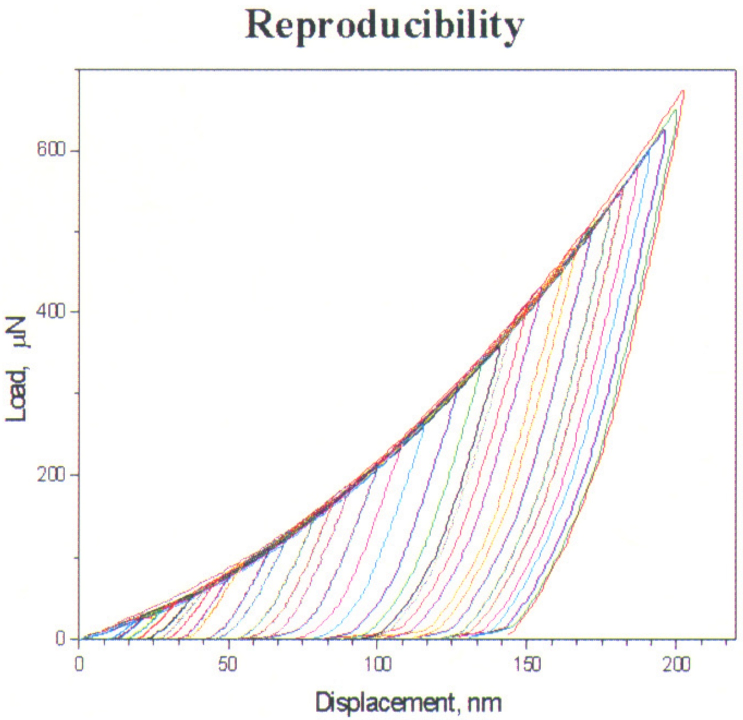
Atomic Image of Si(111)-(7×7) Taken with AFM



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

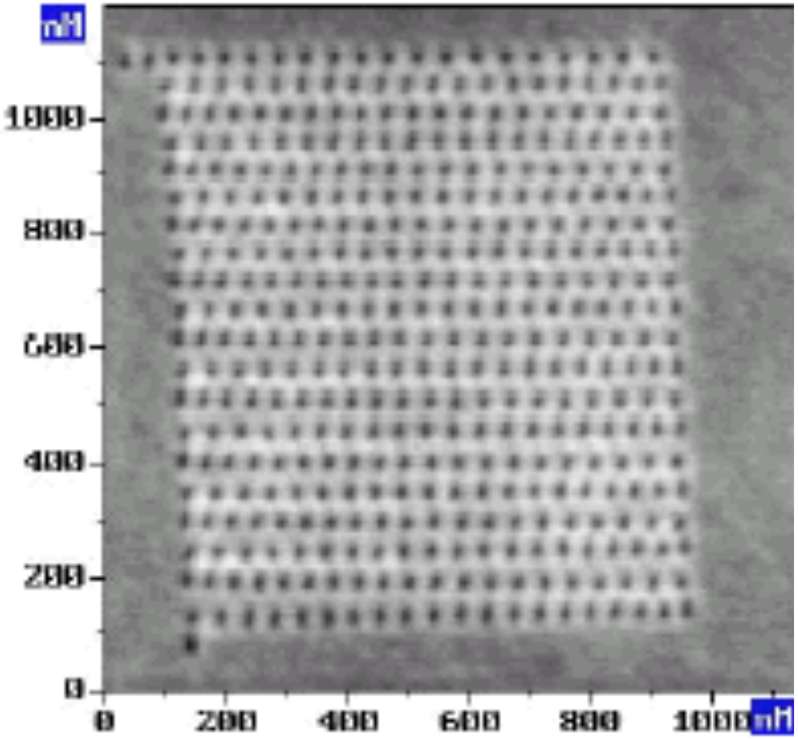
Measurement of Mechanical Properties

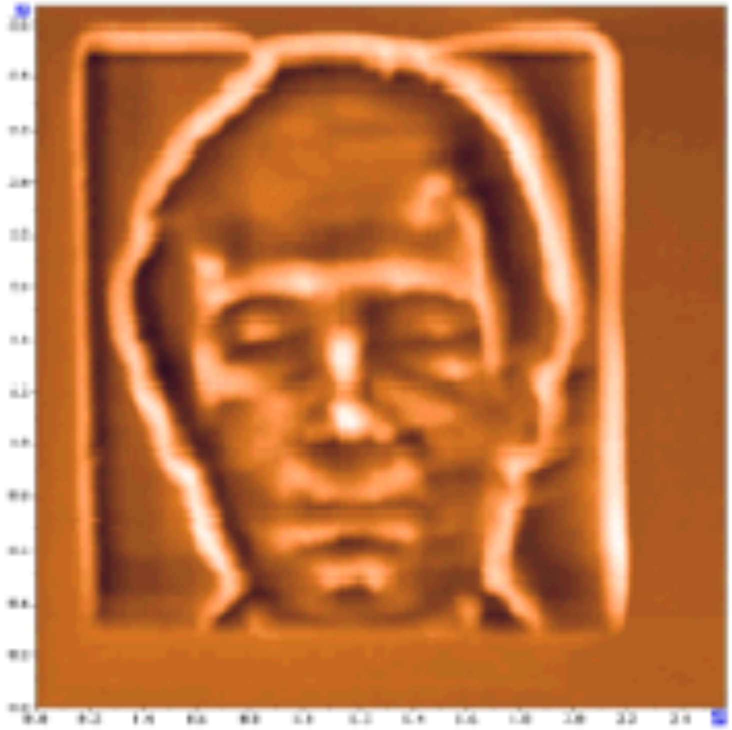




1. The load-displacement curves provide a "mechanical fingerprint" of material's response to deformation, from which parameters such as hardness and young's modulus of elasticity can be determined.
2. In measuring the mechanical properties of thin coated system, the size of contact impression should be kept small relative to the film thickness.

Nanolithography of Tapping-Mode AFM

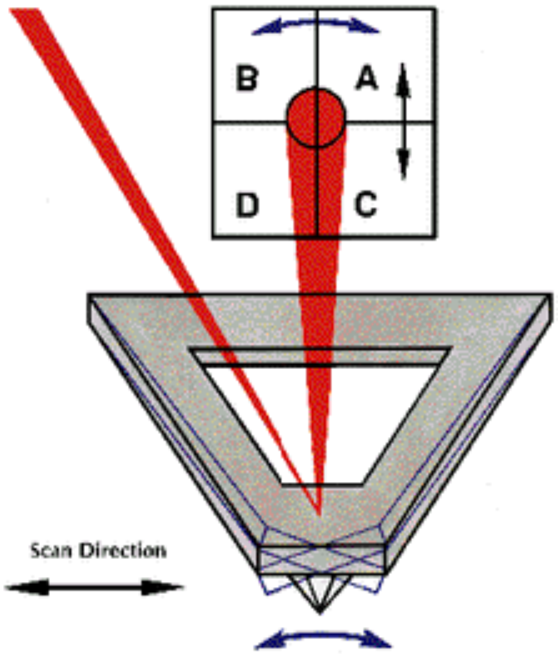




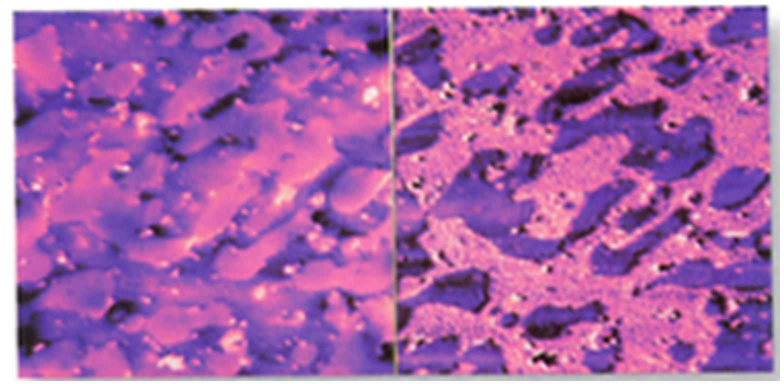
(1.2 μ m× 1.2 μ m) (2.5 μ m× 2.5 μ m)

Image of polycarbonate film on silicon surface

Lateral Force Microscopy

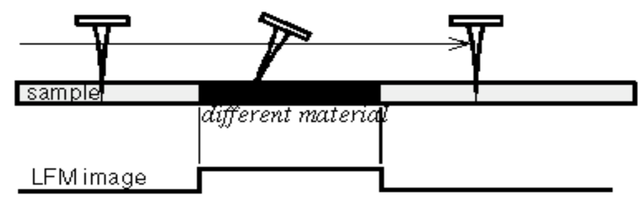


(A+C) – (B+D)

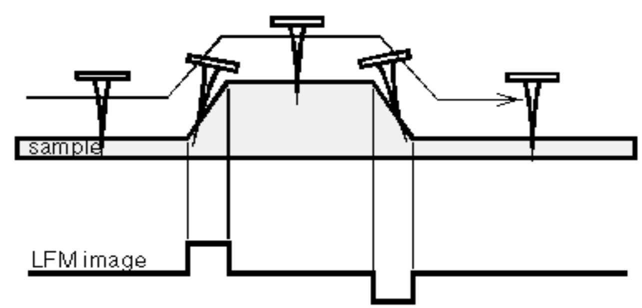


Topography LFM

Nature rubber/EDPM blend



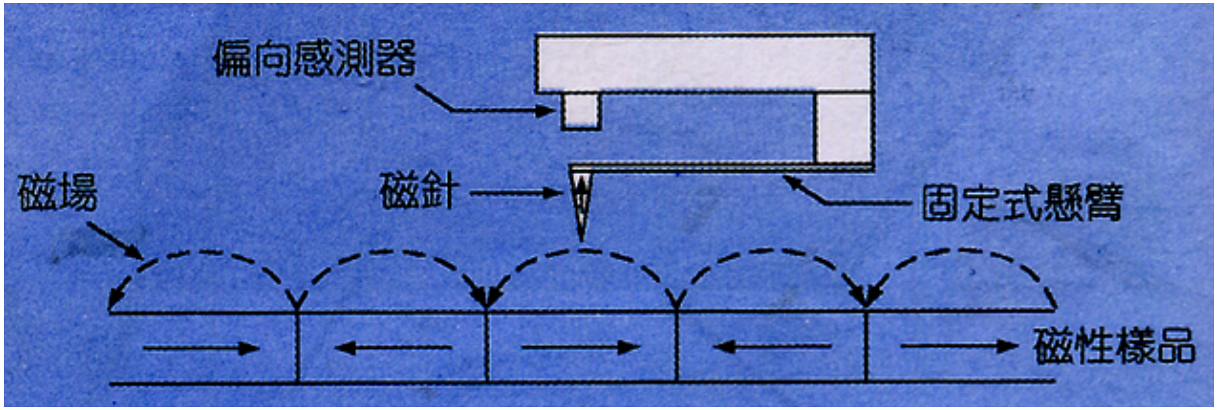
- LFM is sensitive to friction and chemical forces.
- Image contrast depends on the scanning direction.
- Surface roughness will contribute to the contrast.



Chemical Force Microscopy

CFM scan of well-defined regions that terminate in either methyl or carboxylic acid groups. When a carboxylic acid-terminated tip is used for imaging (left), the carboxylic acidterminated regions exhibit greater frictional force (lighter color) than the methyl-terminated regions. When a methylterminated tip is used (right), the friction contrast is reversed. No differences are revealed by the topographic AFM scan (not shown) since the functional groups are structurally quite similar. Image courtesy of Dr. C. Lieber, Harvard University.

Magnetic Force Microscopy (MFM)



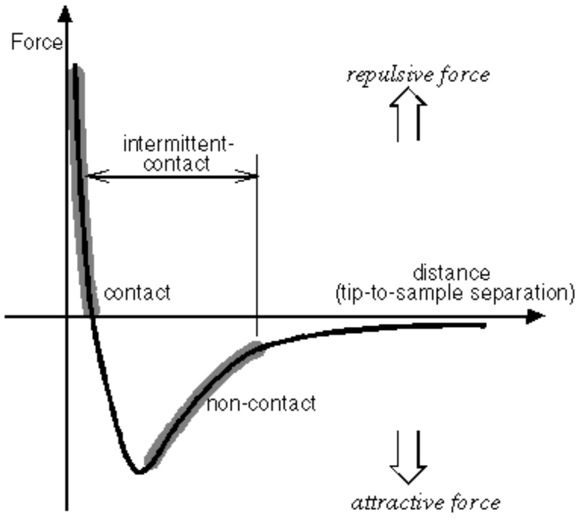
$$F = \nabla(m \cdot H)$$

Tips: silicon probes are magnetically sensitized by sputter coating with a ferromagnetic material.

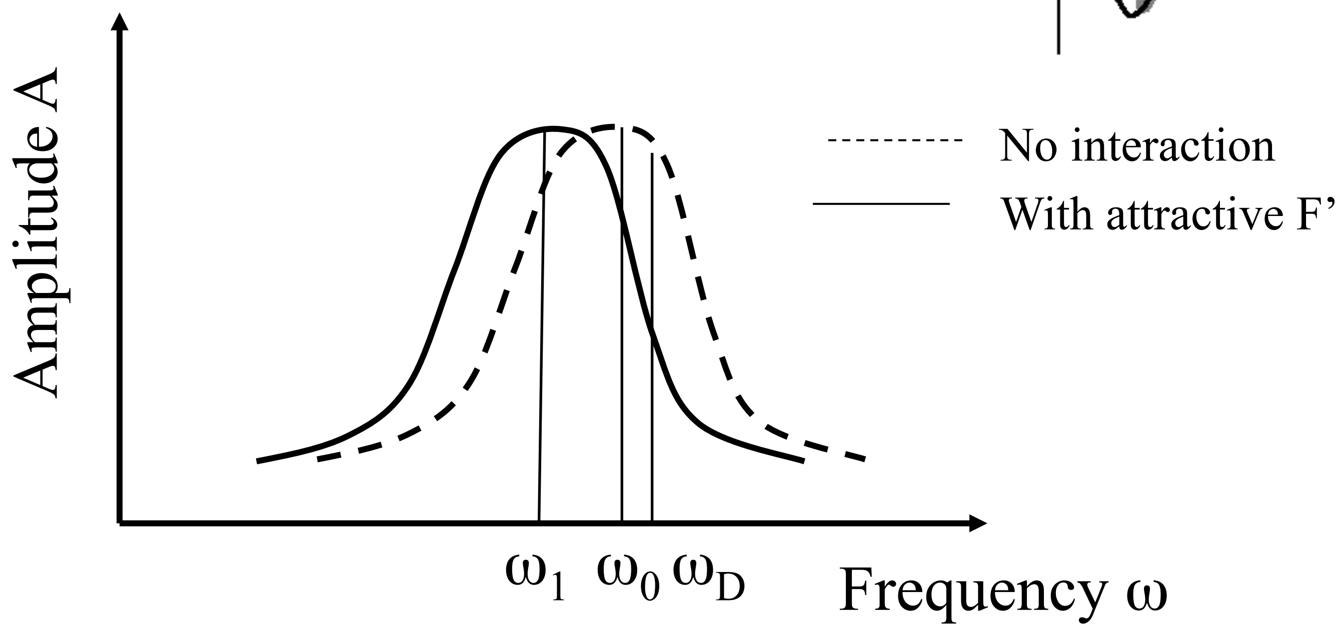
Resolution: 10 ~ 25 nm.

Applications: hard disks, magnetic thin film materials, micromagnetism.

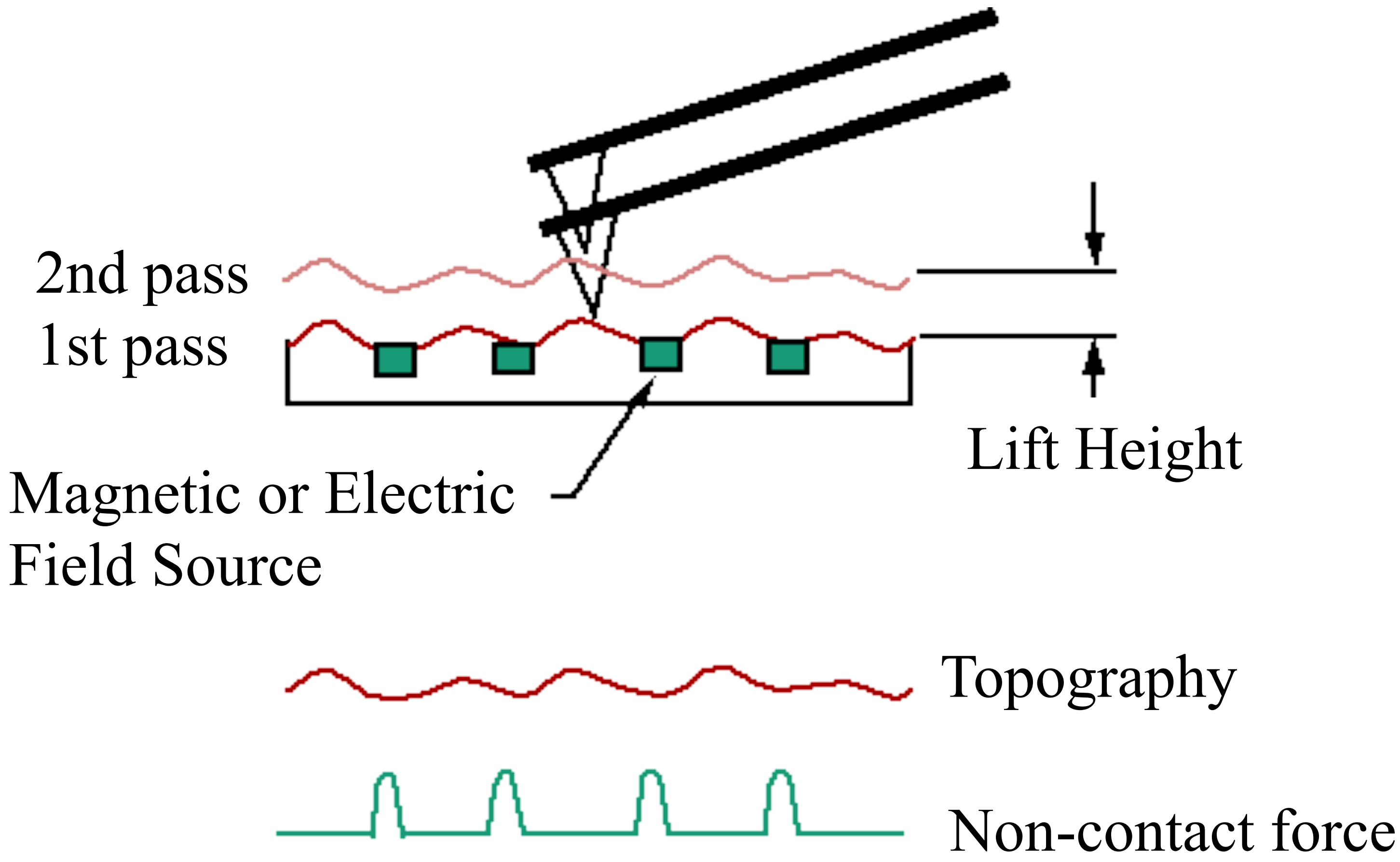
AC imaging mode



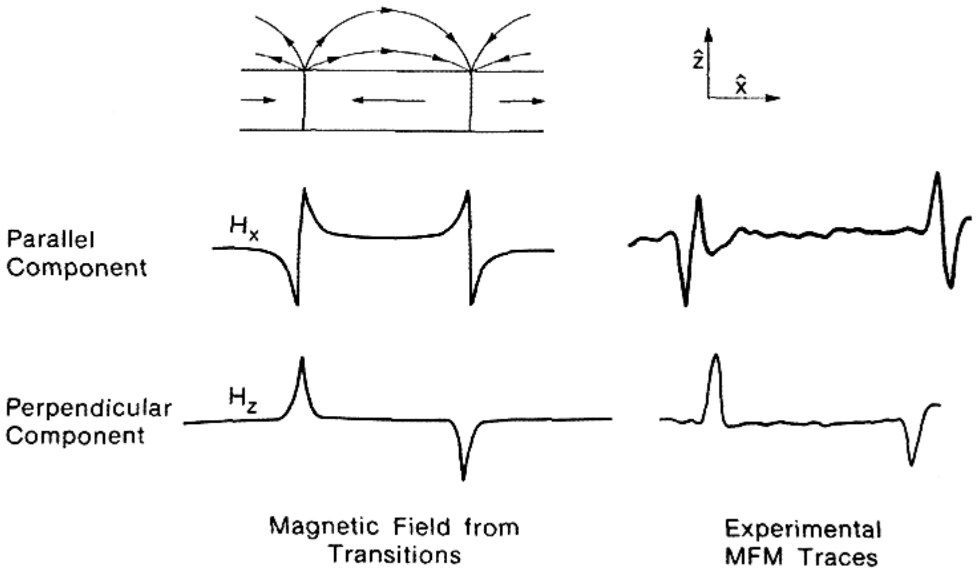
$$\omega_1 = \omega_0 \,(1 + F'/2k)$$

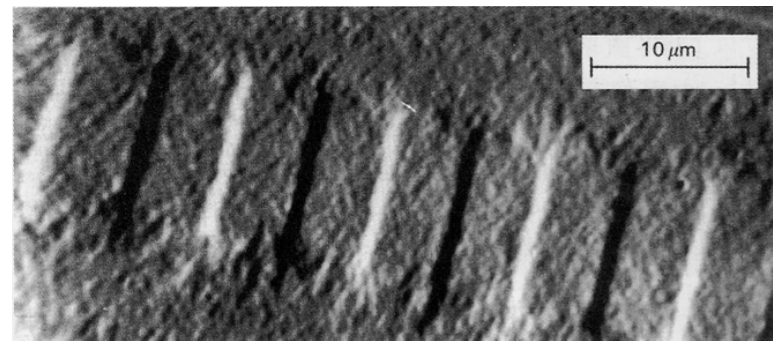


Lift mode of AFM

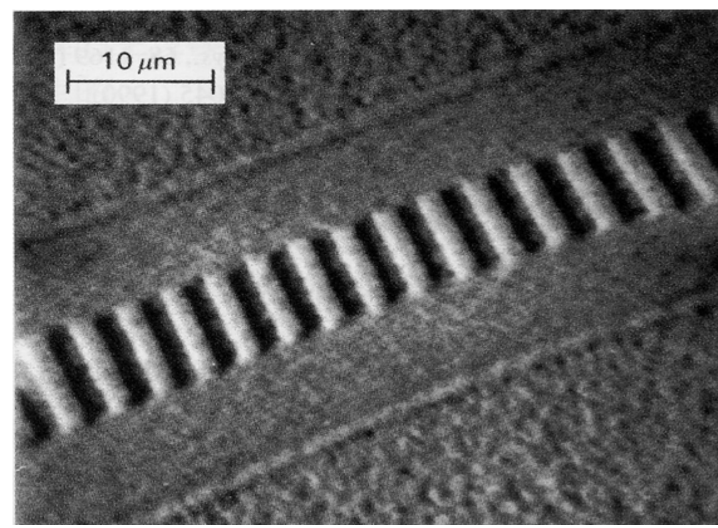


MFM Images





$m^T = m_Z$



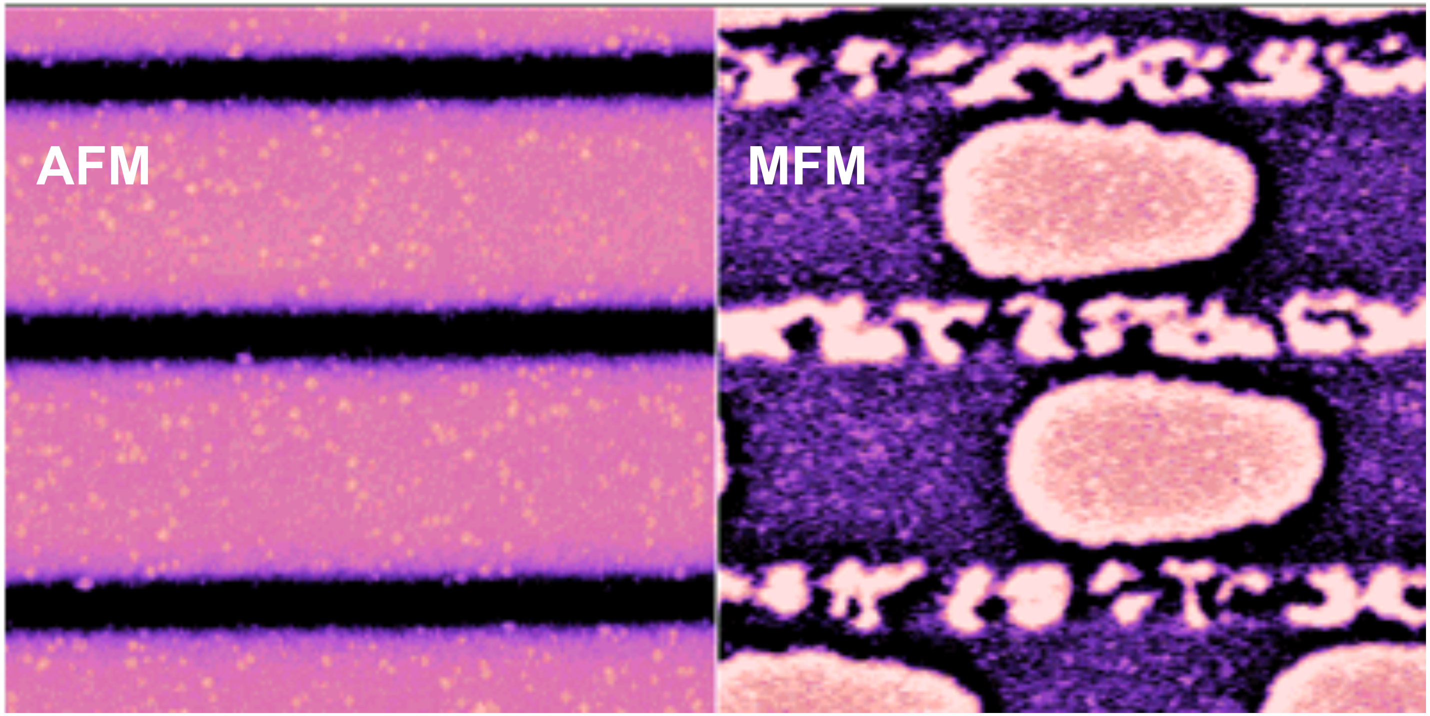
$m^T = m_x + m_z$

Tip as a point dipole

$$F_z = \partial(m_xH_x + m_yH_y + m_zH_z)/\partial z$$

Tip as a long rod

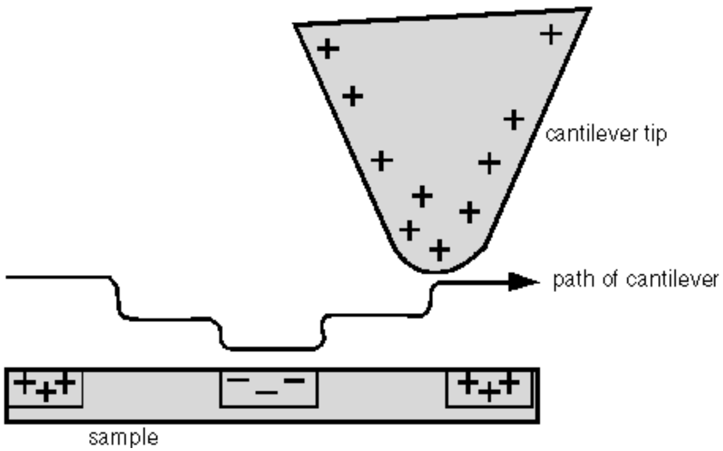
$$F_z = m_zH_z$$

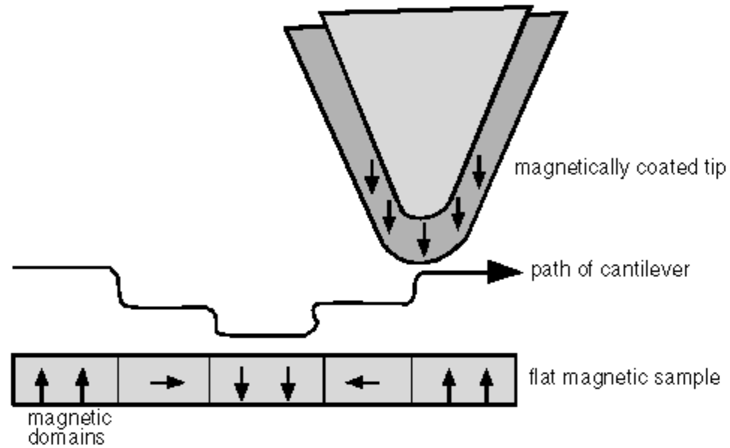


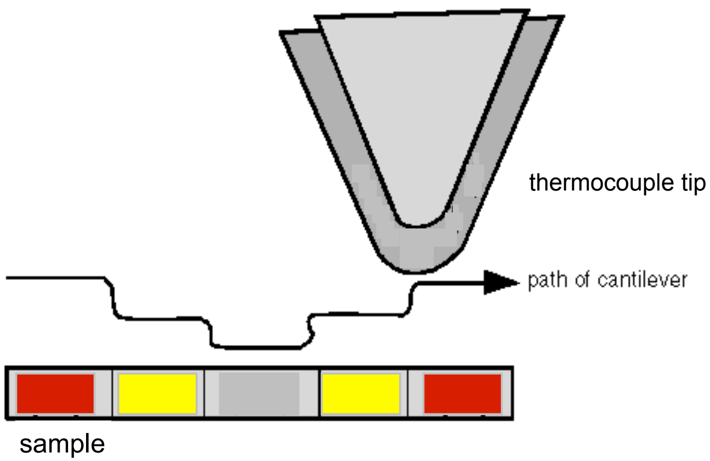
Bits (50 nm) on a magneto-optical disk

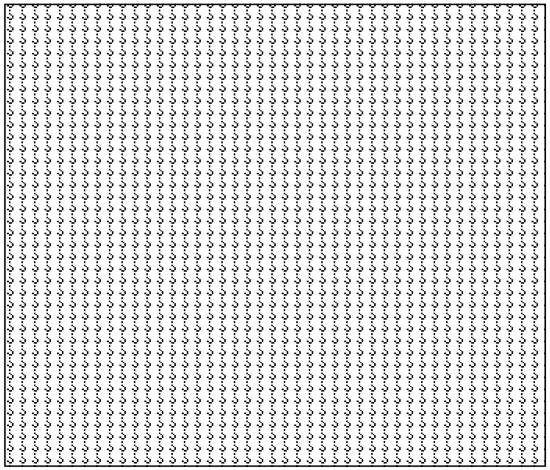
Scan area (5µm× 5µm)

Probes of various functions

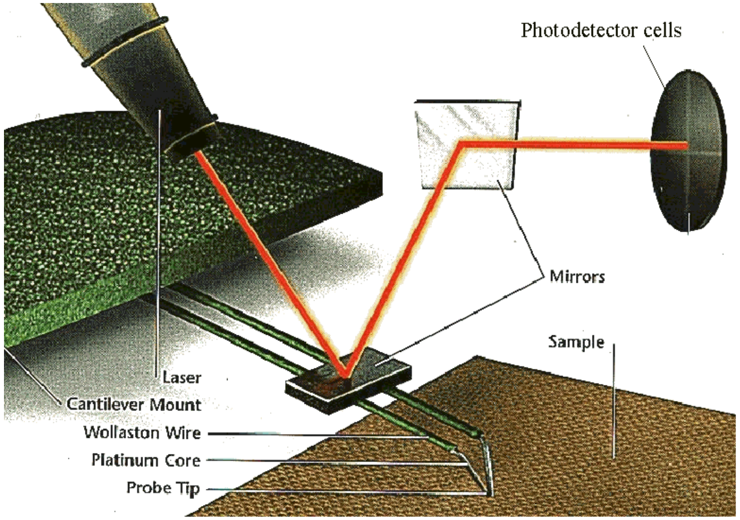


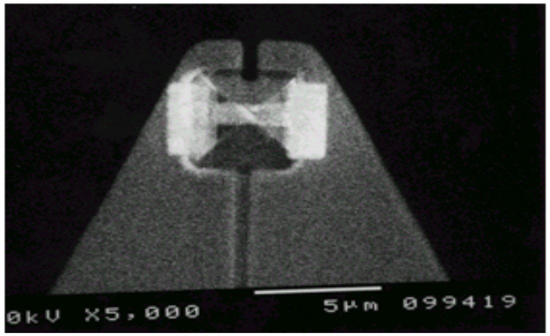


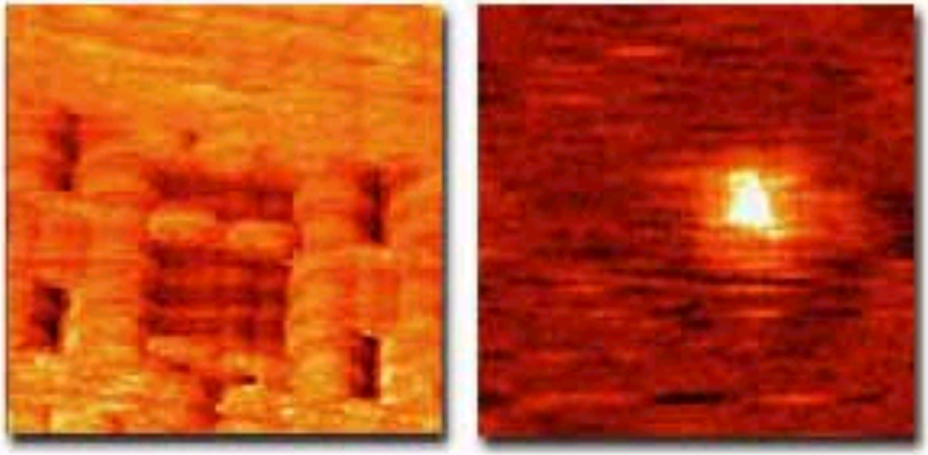




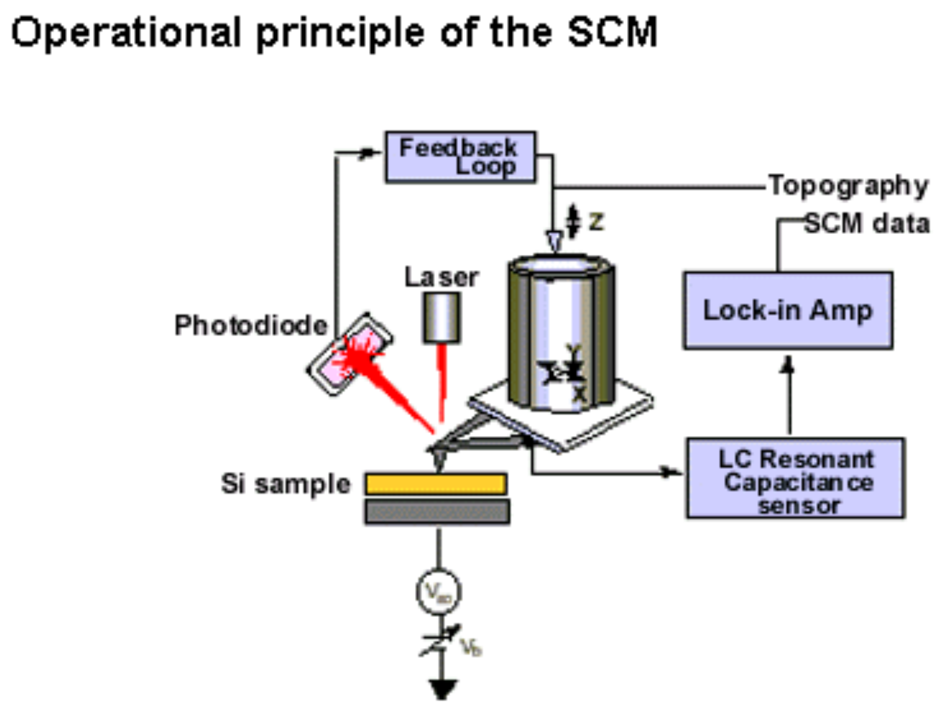
Scanning Thermal Microscopy (SThM)

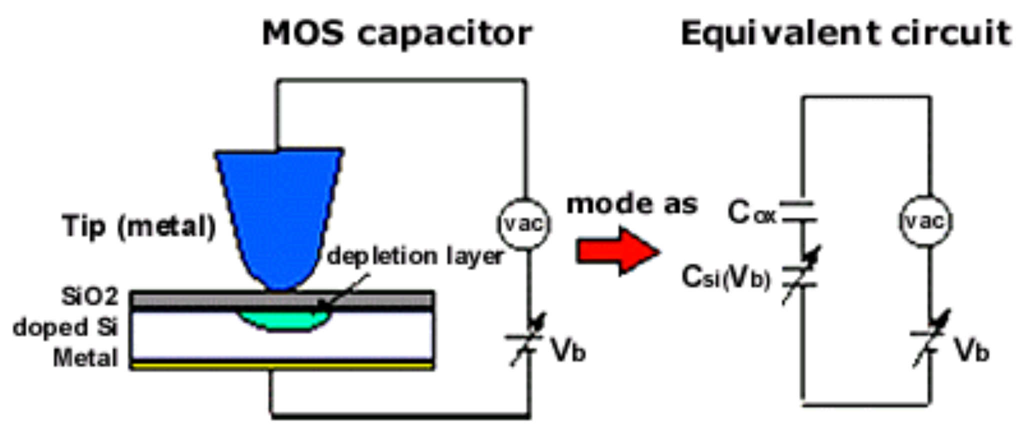




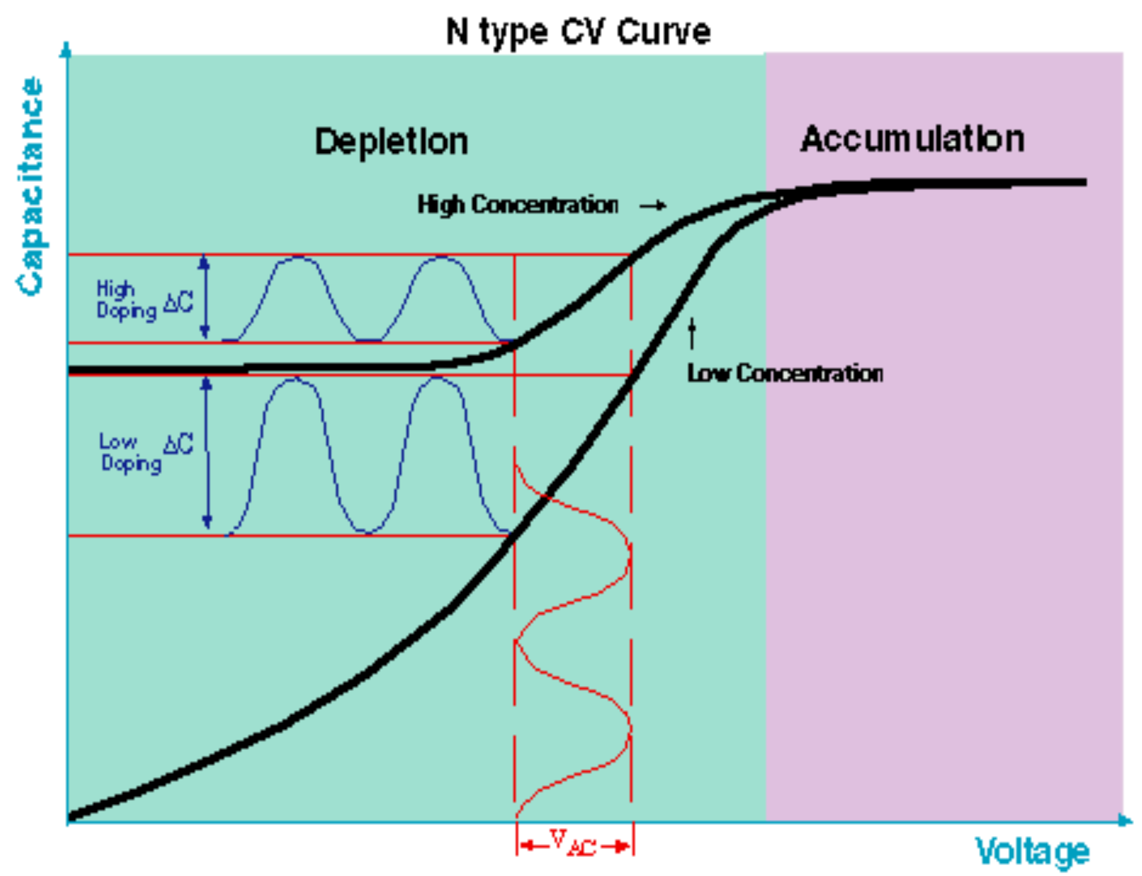


Scanning Capacitance Microscopy (SCM)

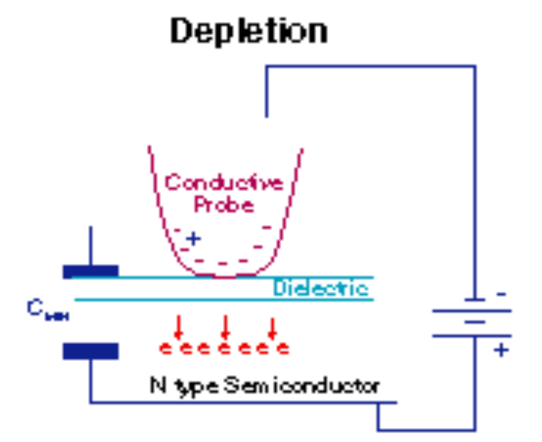




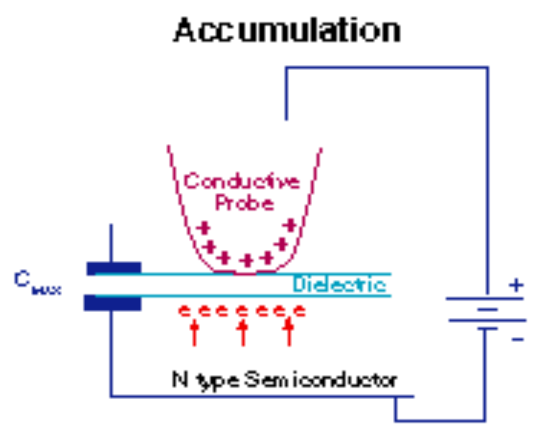
SCM CV Curve



N type CV Curve
Capacitance
Depletion
Accumulation
High Concentration
High Doping ΔC
Low Doping ΔC
Low Concentration
V_AC
Voltage

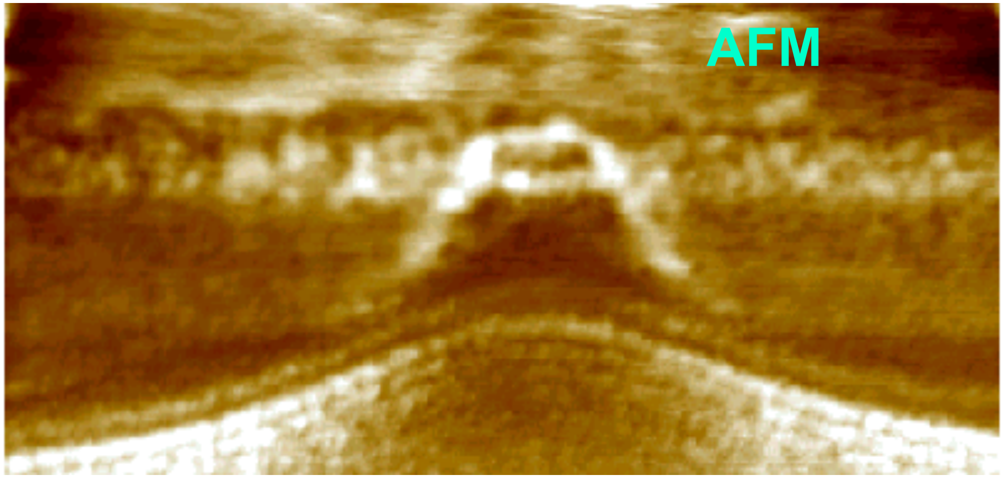


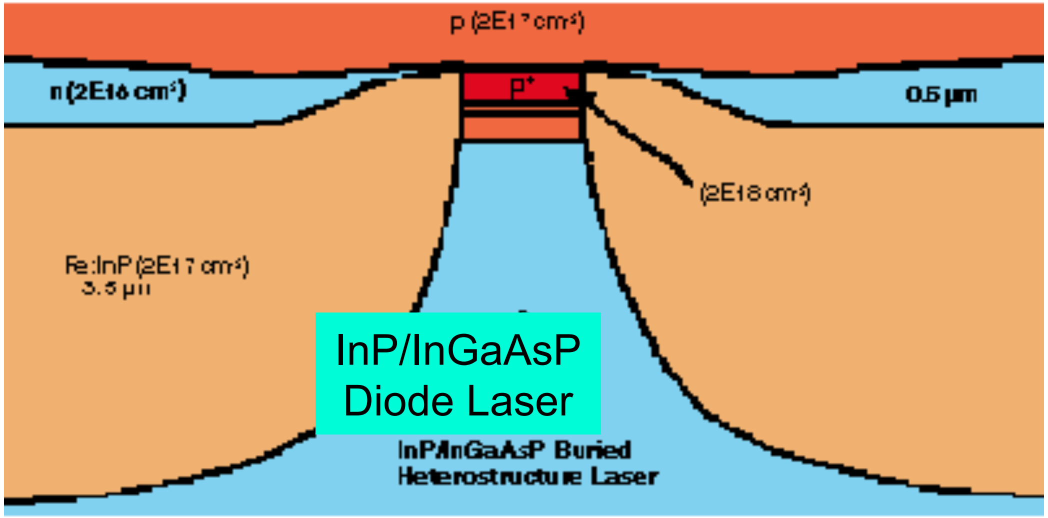
Depletion
Conductive Probe
Dielectric
N type Semiconductor



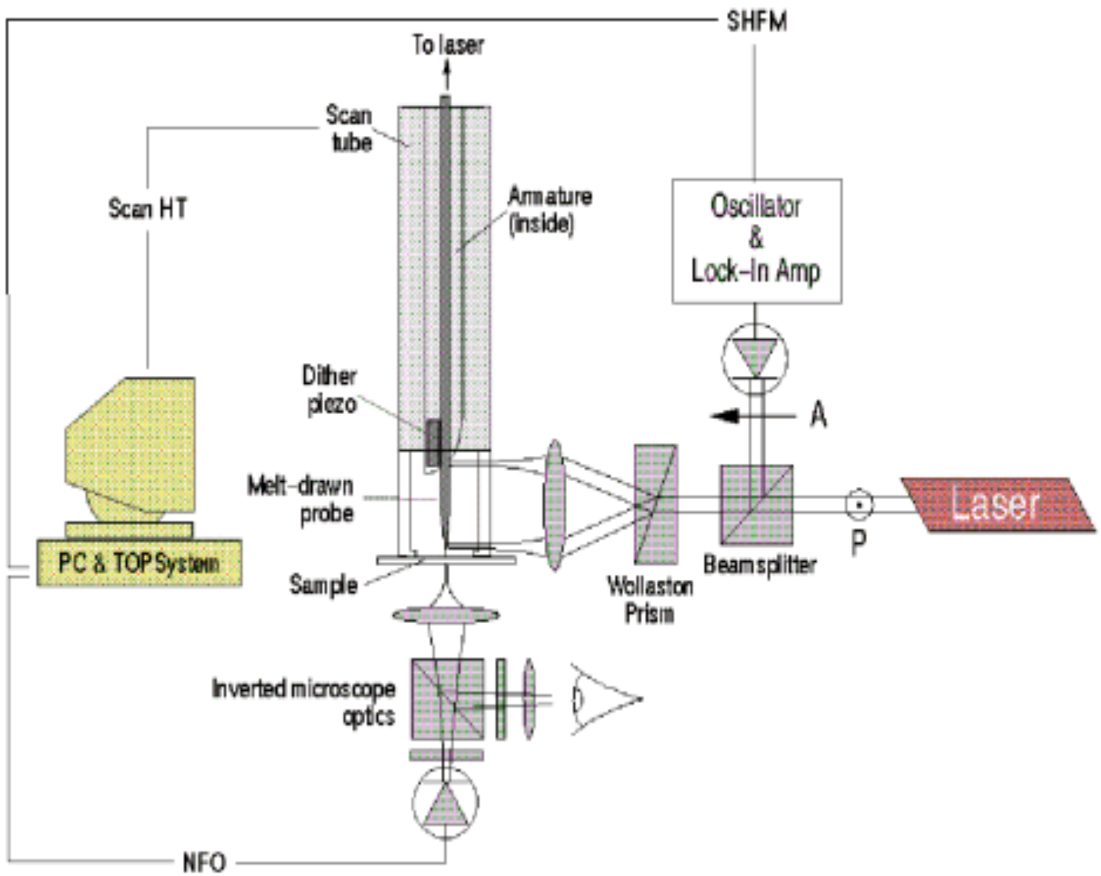
Accumulation
Conductive Probe
Dielectric
N type Semiconductor

Scanning Capacitance Microscopy



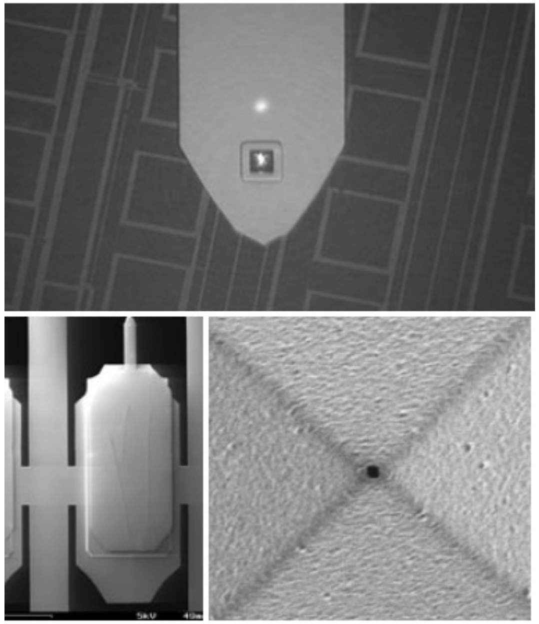


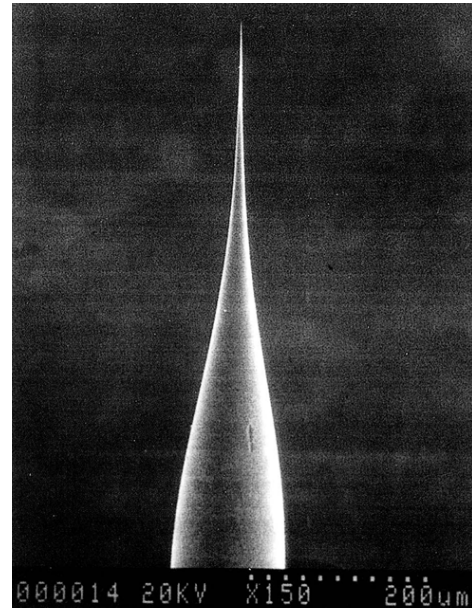
Near-field Scanning Optical Microscopy (NSOM)

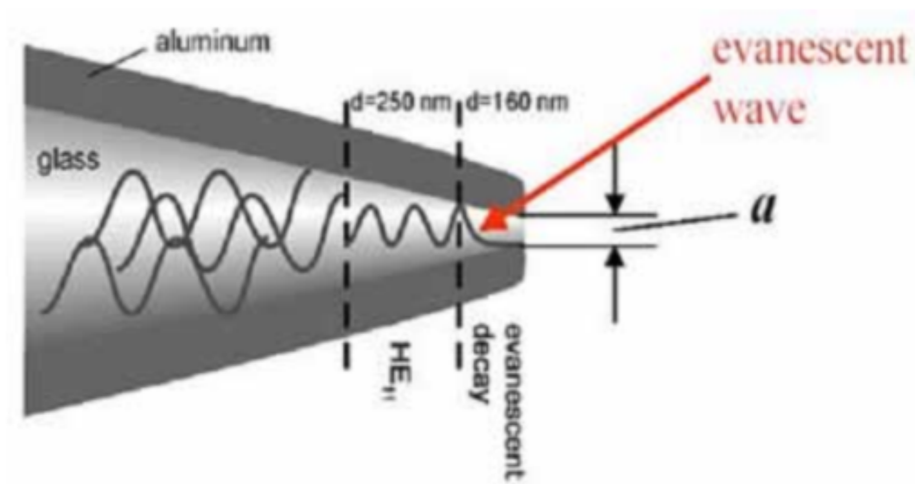


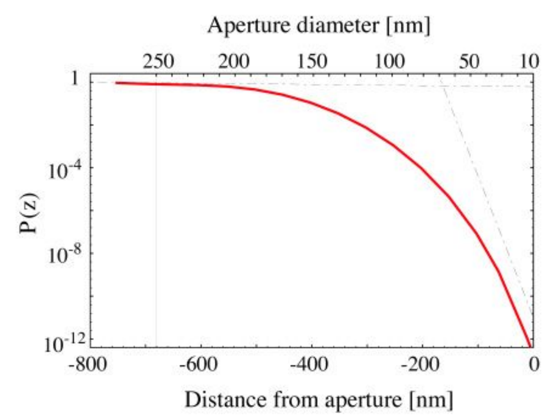
Shear force detection is used to regulate
the tip/sample separation

Probes for NSOM



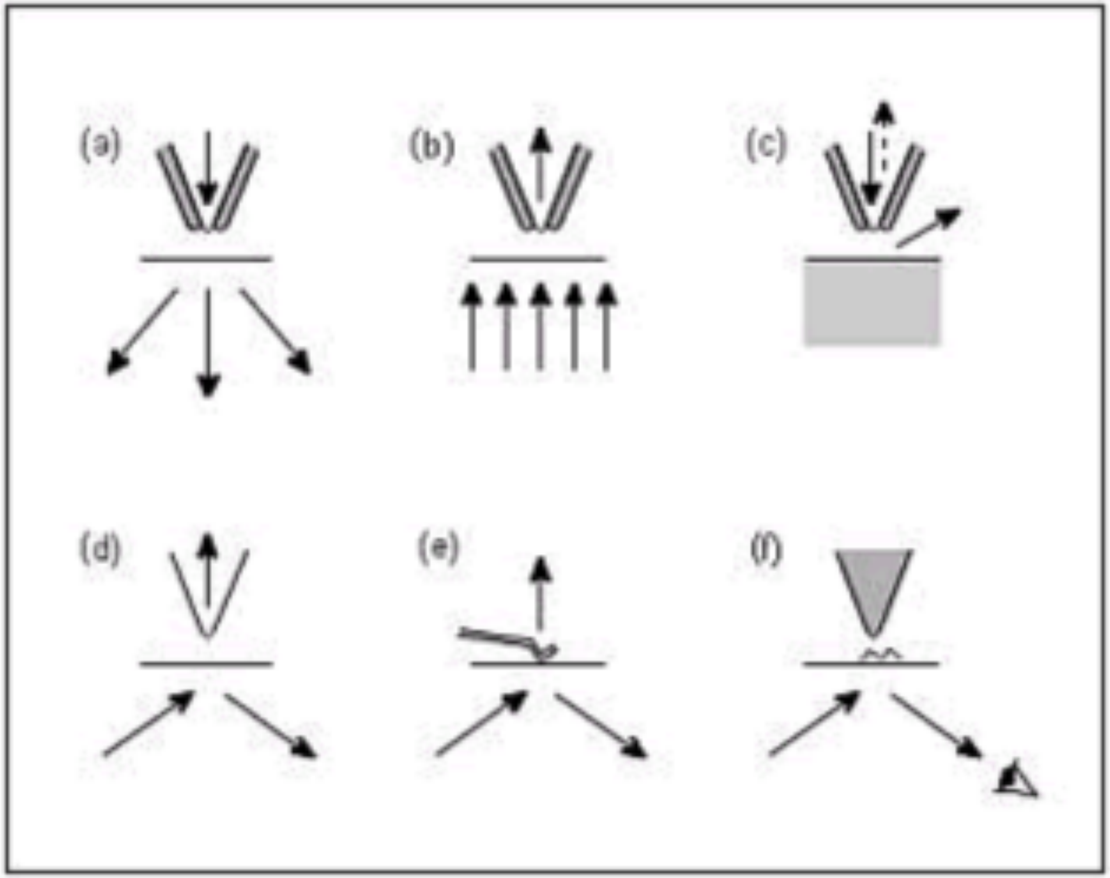




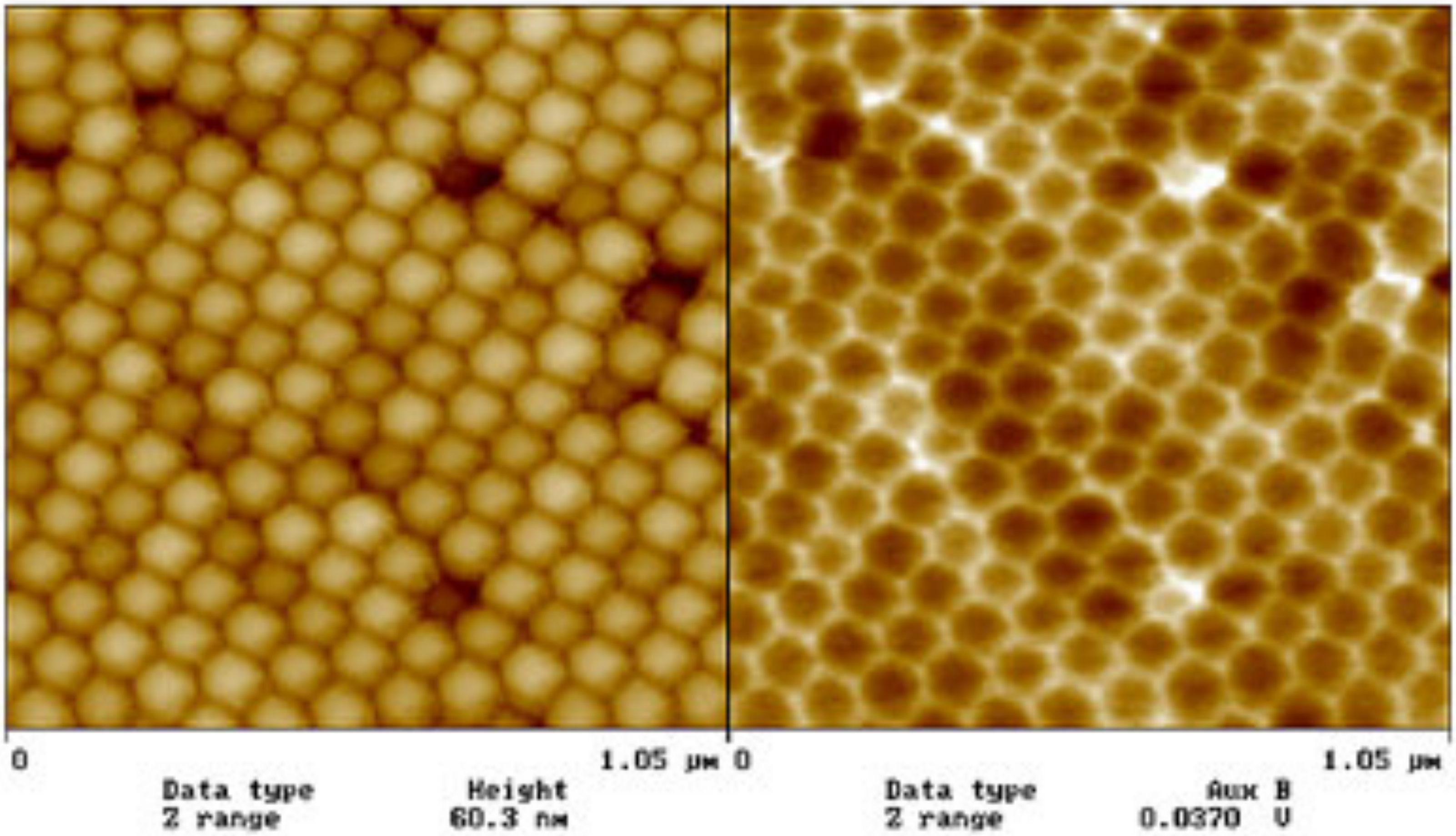


L. Novotny and D. W. Pohl, in *Photons and Local Probes*, NATO ASI Series E, p.21-33, Kluwer Academic, 1995.

Imaging modes for NSOM



Topography | NSOM Image



Polystyrenes of 100 nm on glass

1. **All SPMs are based on the ability to position various types of probes in very close proximity with extremely high precision to the sample under investigation.**
2. **These probes can detect electrical current, atomic and molecular forces, electrostatic forces, or other types of interactions with the sample.**
3. **By scanning the probe laterally over the sample surface and performing measurements at different locations, detailed maps of surface topography, electronic properties, magnetic or electrostatic forces, optical characteristics, thermal properties, or other properties can be obtained.**
4. **The spatial resolution is limited by the sharpness of the probe tip, the accuracy with which the probe can be positioned, the condition of the surface under study, and the nature of the force being detected.**