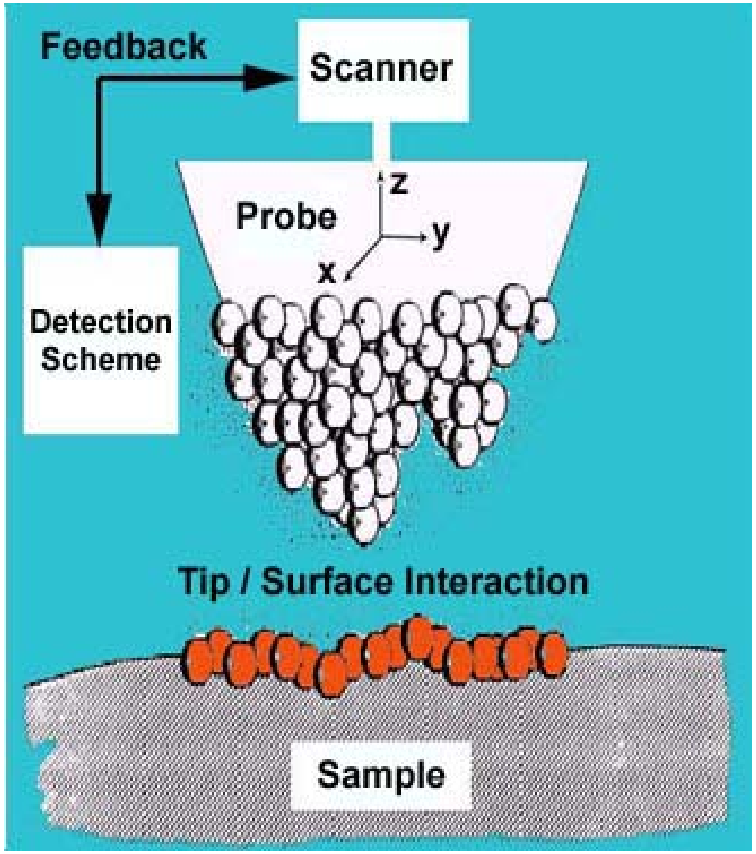
Scanning Probe Microscopy (SPM)



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)

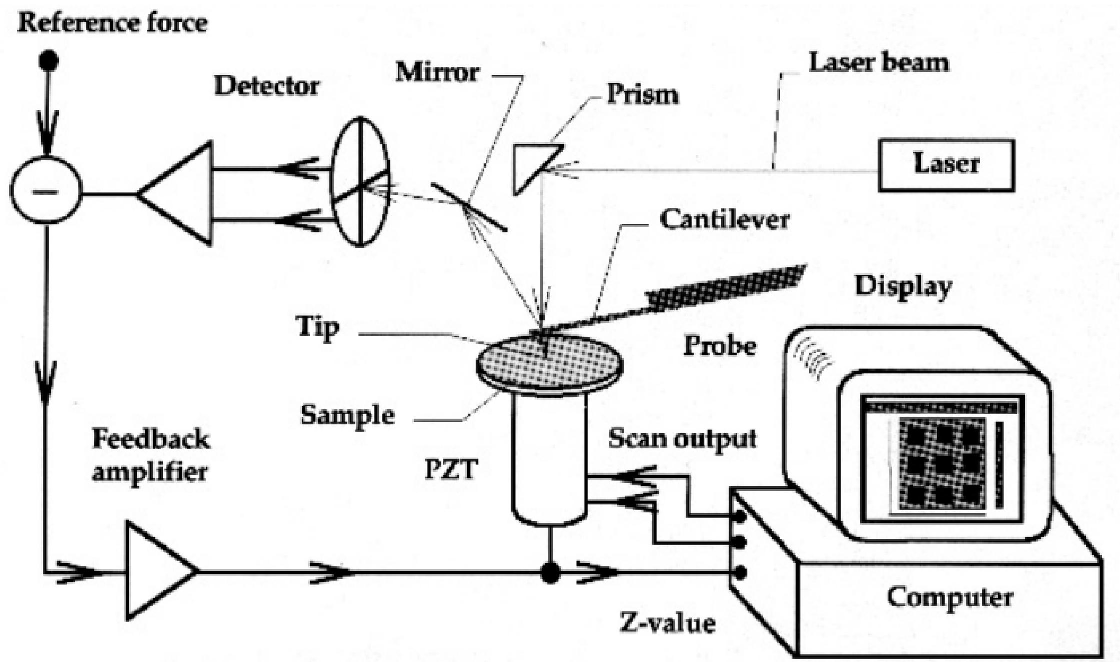
Scanning Capacitance Microscopy (SCM)

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

Force Modulation Microscopy (FMM)

--- P. Maivald et al (1991)

Atomic Force Microscopy (AFM)



$F = k\Delta z$

$F = 10^{-9} – 10^{-6}$ N

$k = 0.1 – 1$ N/m

References:

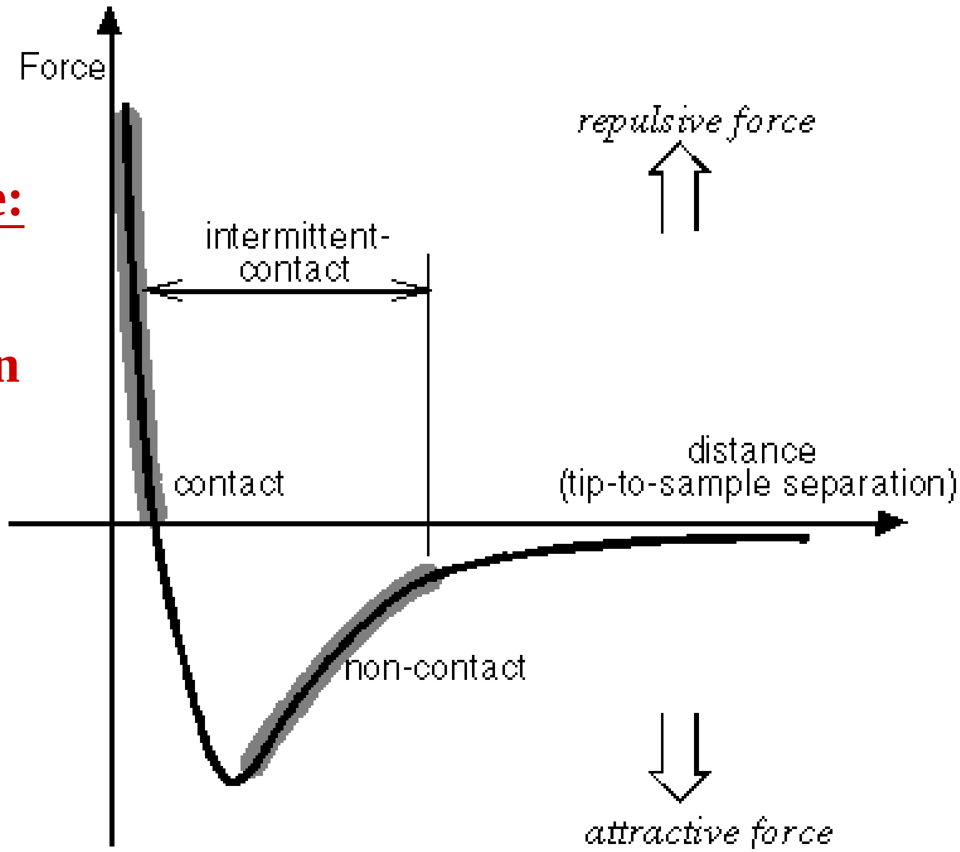
- G. Binnig, C. F. Quate, and C. Gerber, Phys. Rev. Lett. 56, 930 (1986).
- C. Bustamante and D. Keller, Physics Today, 32, December (1995).
- R. Wiesendanger and H.J. Güntherodt, *Scanning Tunneling Microscopy II* , Springer-Verlag, (1992).

Interaction between the probe and sample

<u>Short-range:</u>

1) Bonding

2) Repulsion



<u>Long-range:</u>

1) Van der Waal

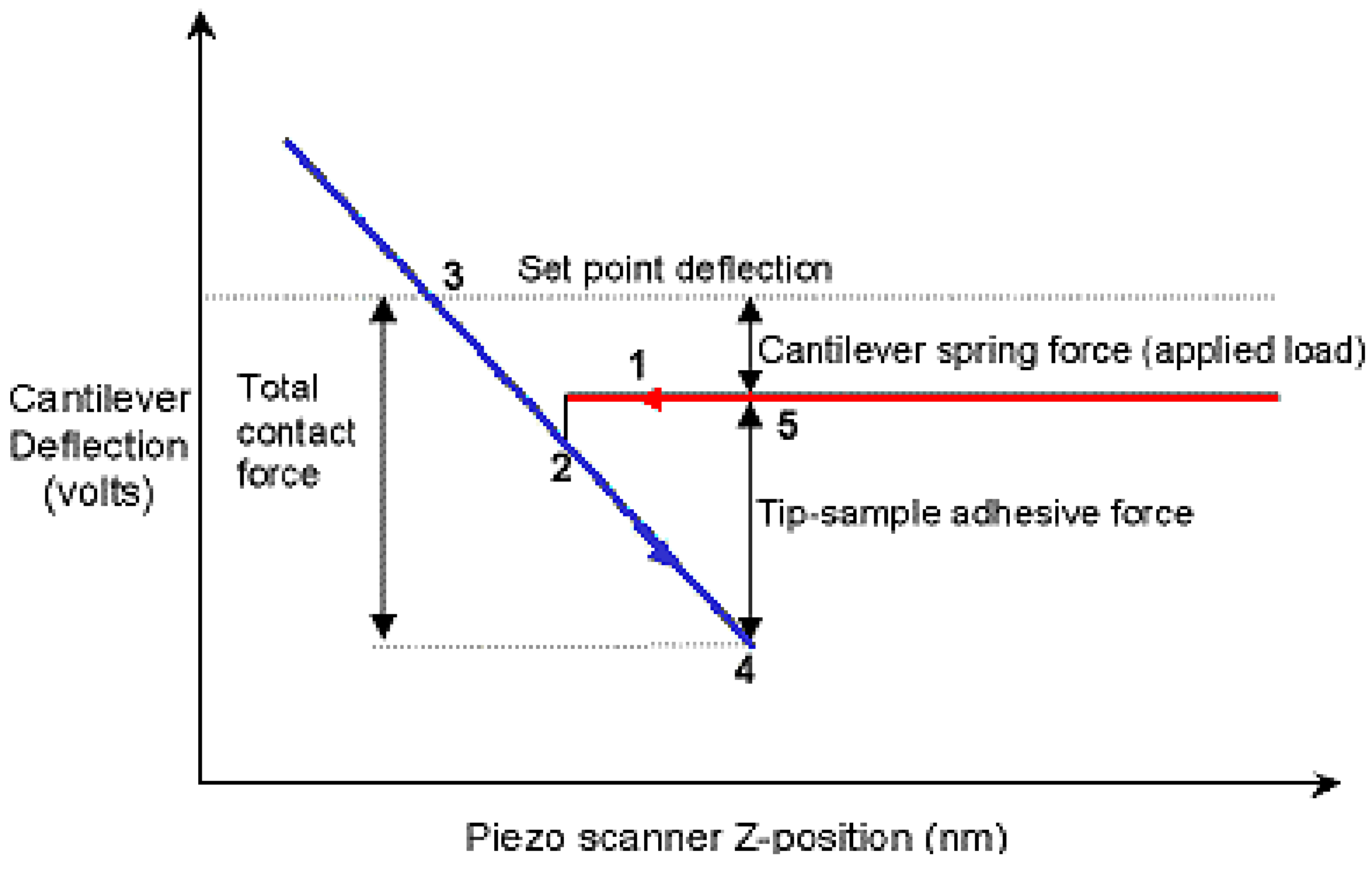
2) Capillary

3) Magnetic

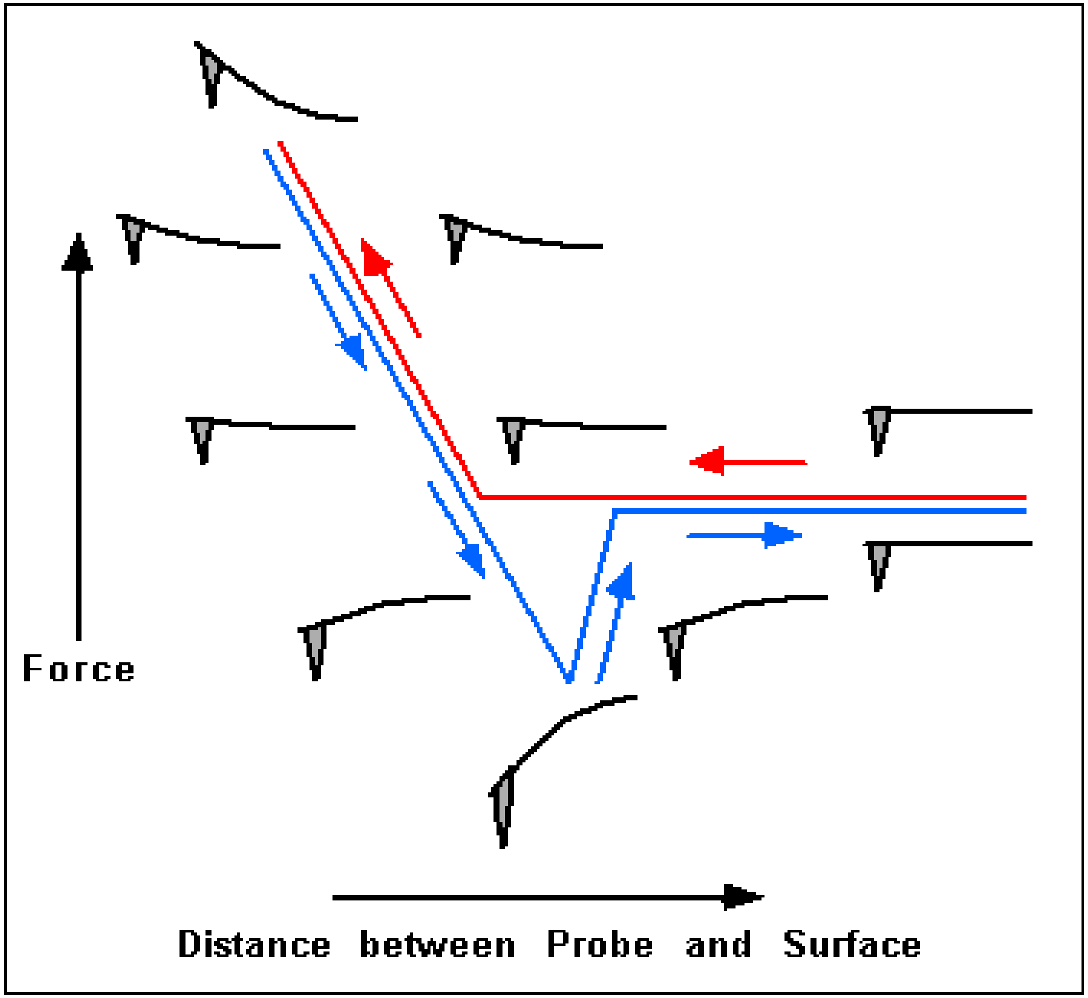
4) Electrostatic

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

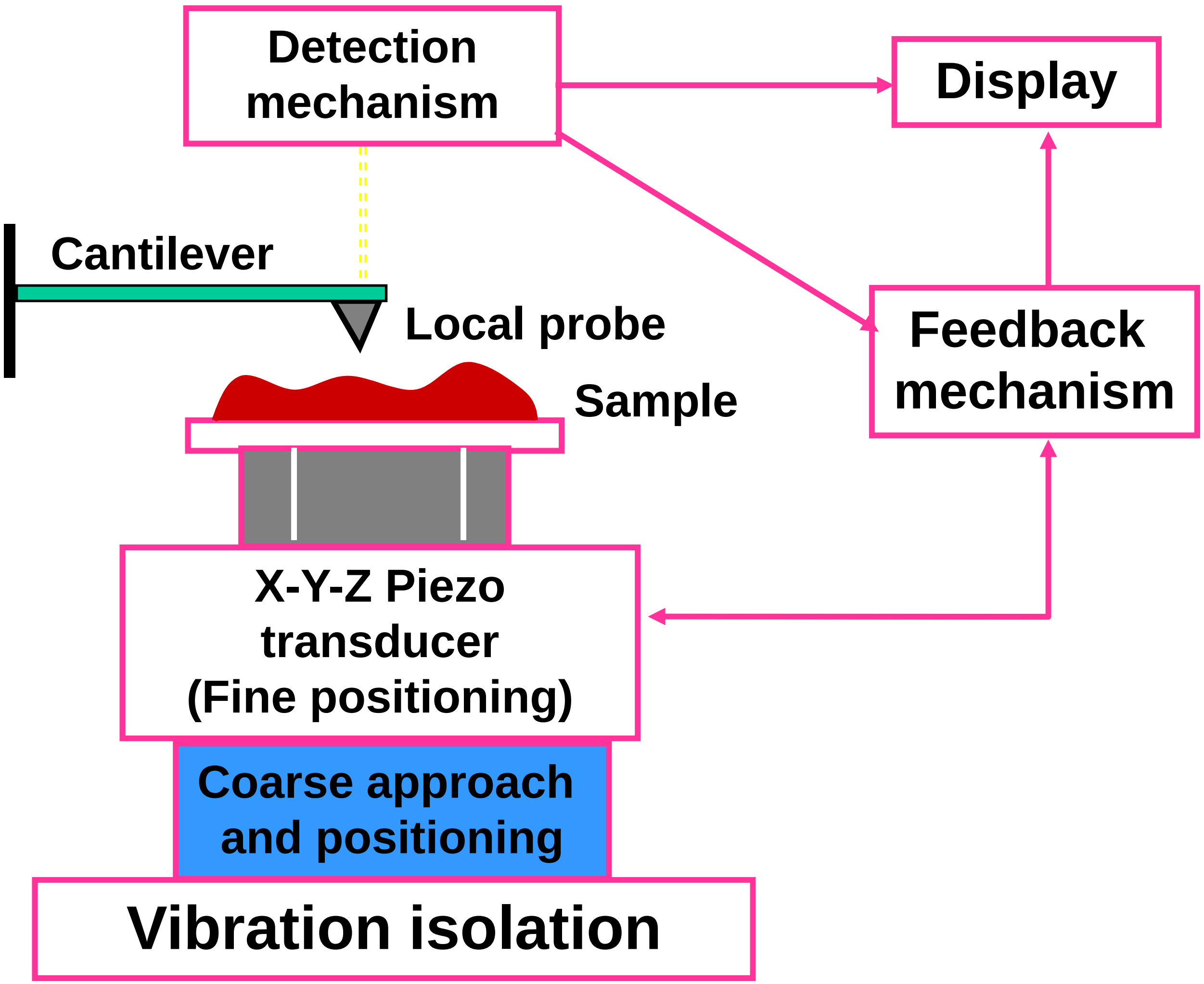
Deflection of Cantilever vs Piezo displacement



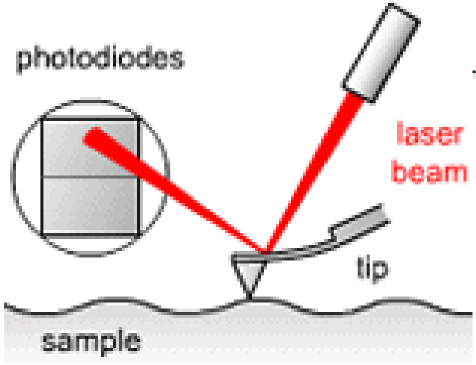
Reaction of the probe to the force

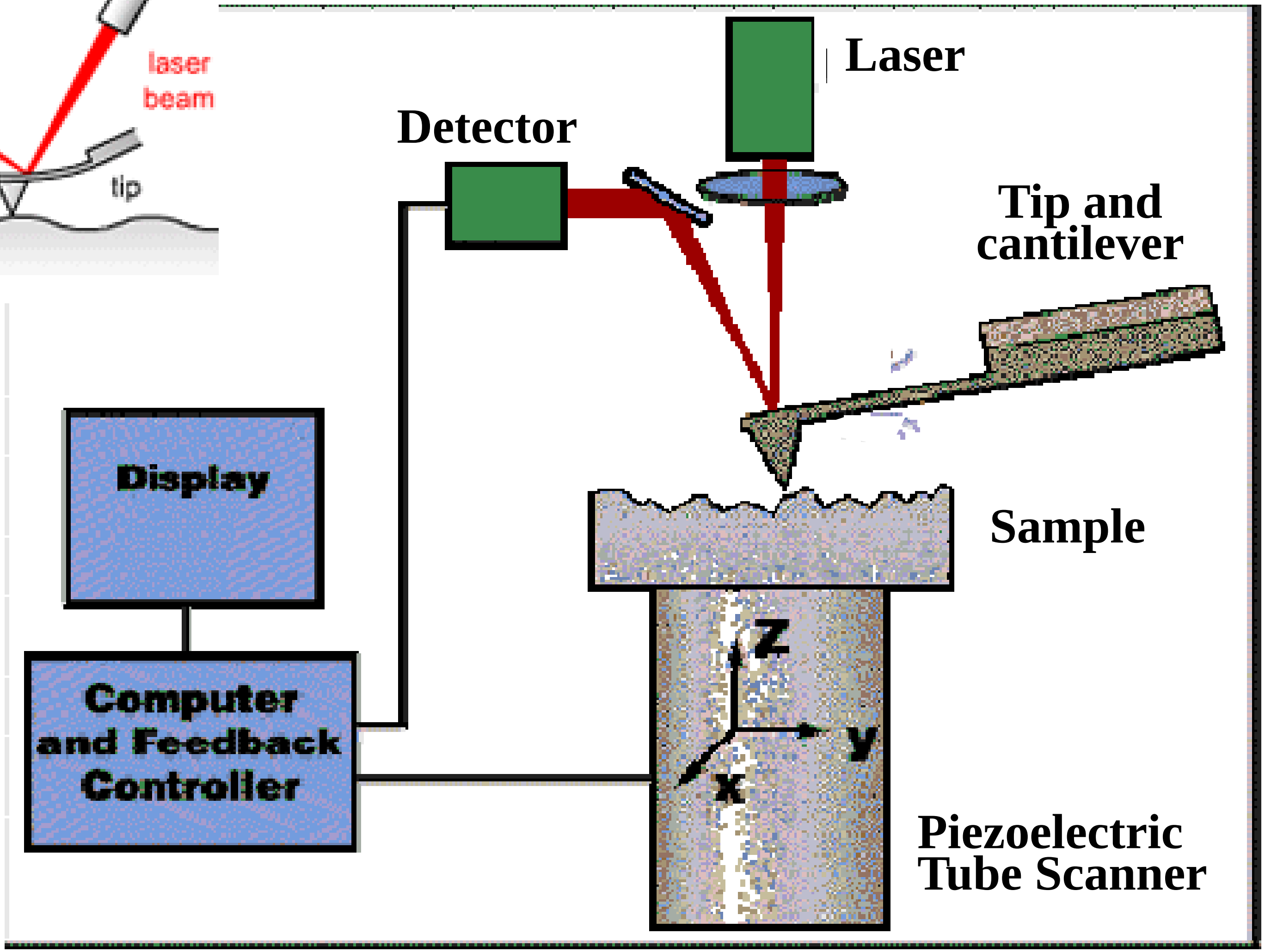


Structure of AFM

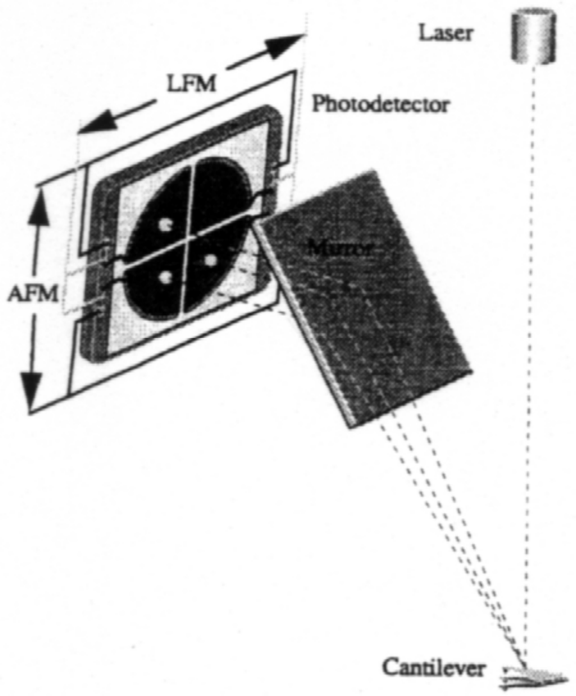


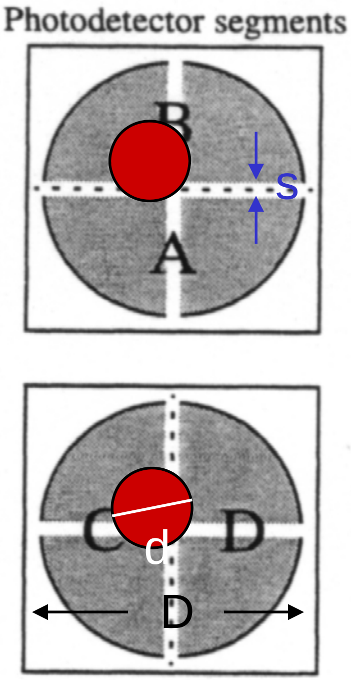
Core components of AFM

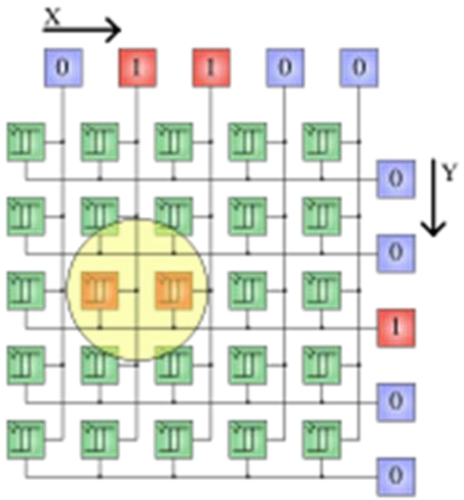




Position-sensitive Photo Diode (PSPD)

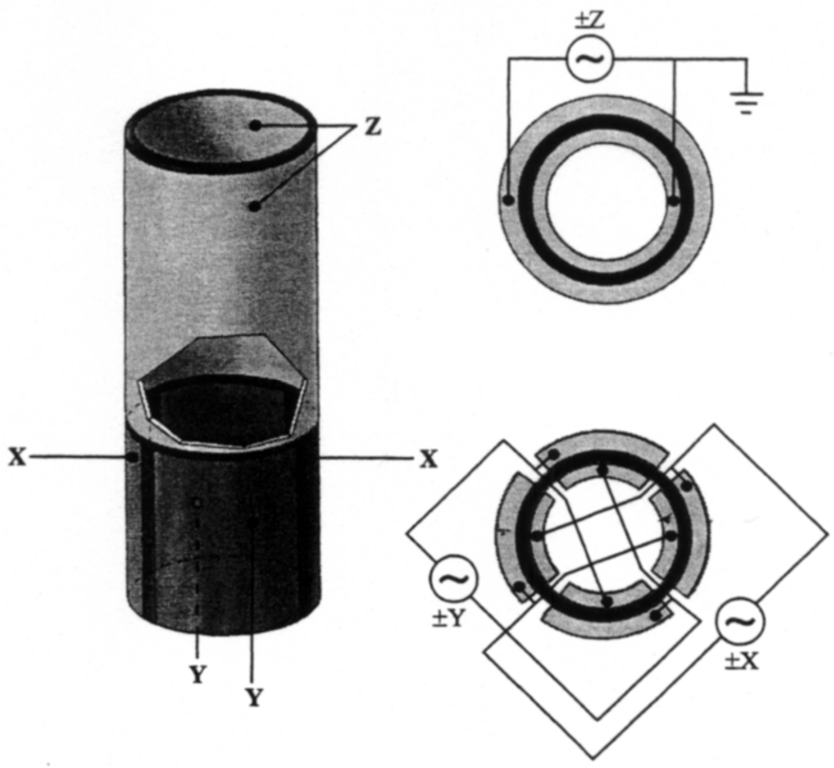


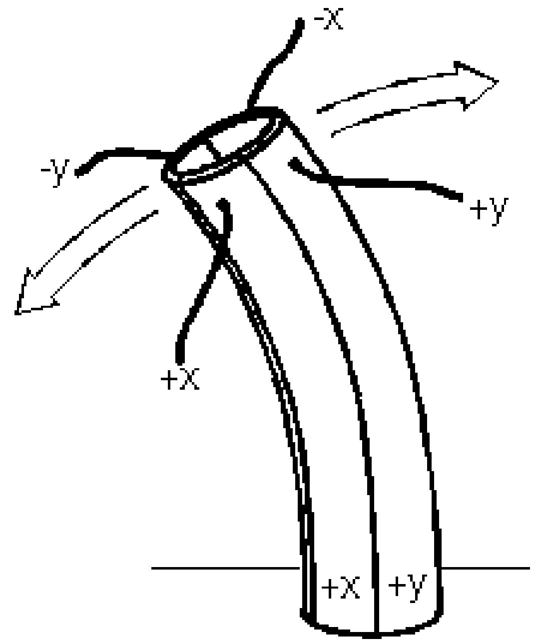




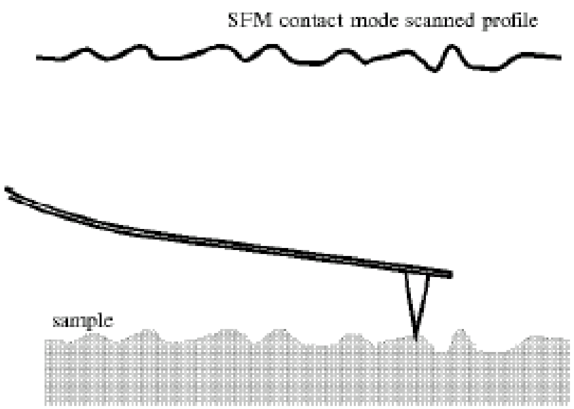
D ~ 10mm   d ~ 1mm   s ~ 0.01mm

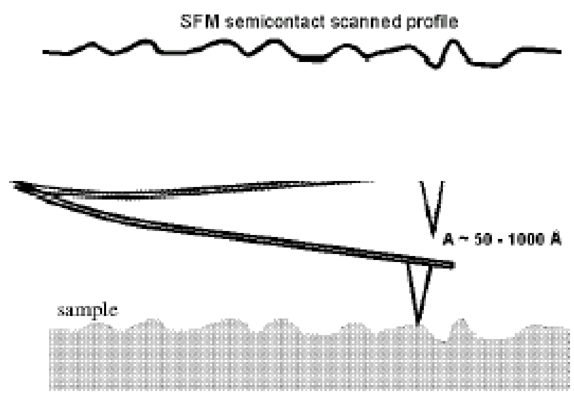
Piezo Scanner

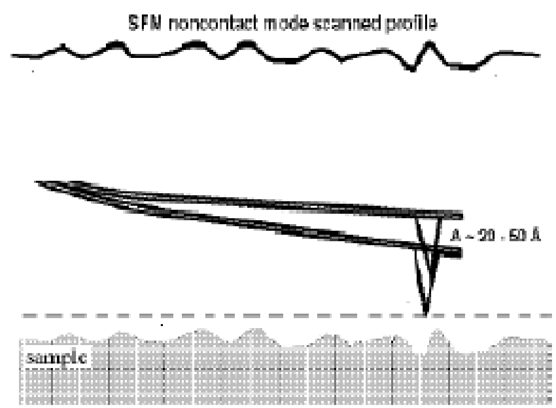




Three scanning modes of AFM







Contact Mode AFM

Semicontact Mode AFM

(Tapping mode)

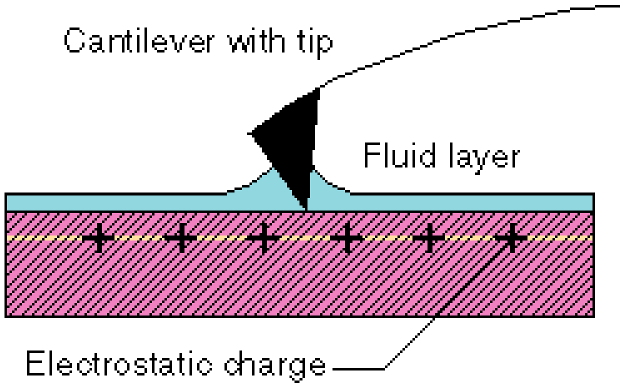
Non-contact Mode AFM

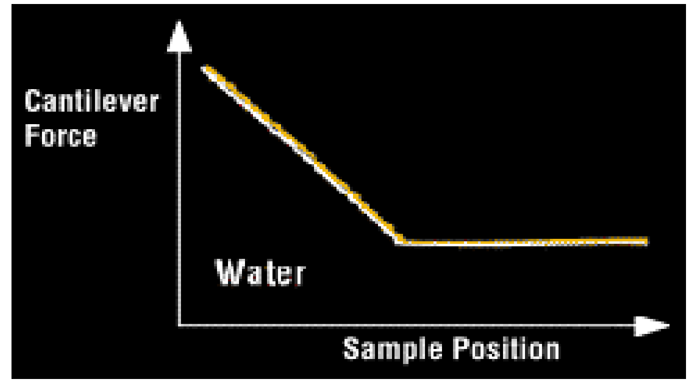
Two imaging methods in contact mode

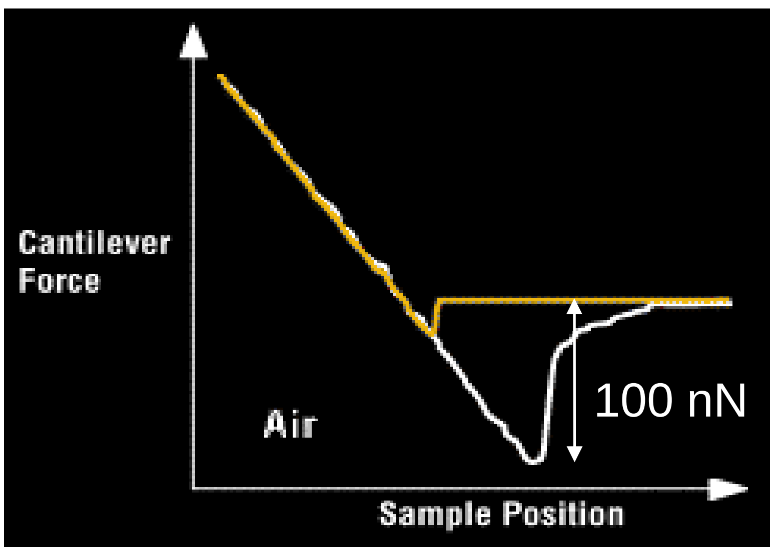
- Constant force method：By using a feedback loop the tip is vertically adjusted in such a way that the force always stays constant. The tip then follows a contour of a constant contact force during scanning. A kind of a topographic image of the surface is generated by recording the vertical position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

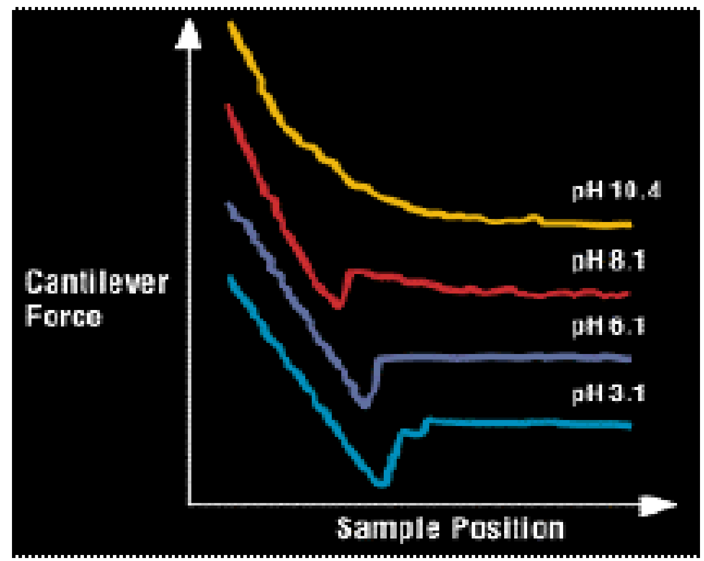
- Constant height method： In this mode the vertical position of the tip is not changed, equivalent to a slow or disabled feedback. The displacement of the tip is measured directly by the laser beam deflection. One of its advantages is that it can be used at high scanning frequencies.

Problems with the contact mode



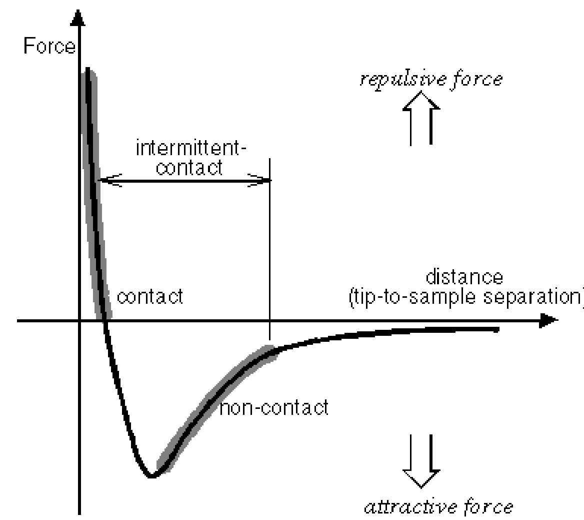


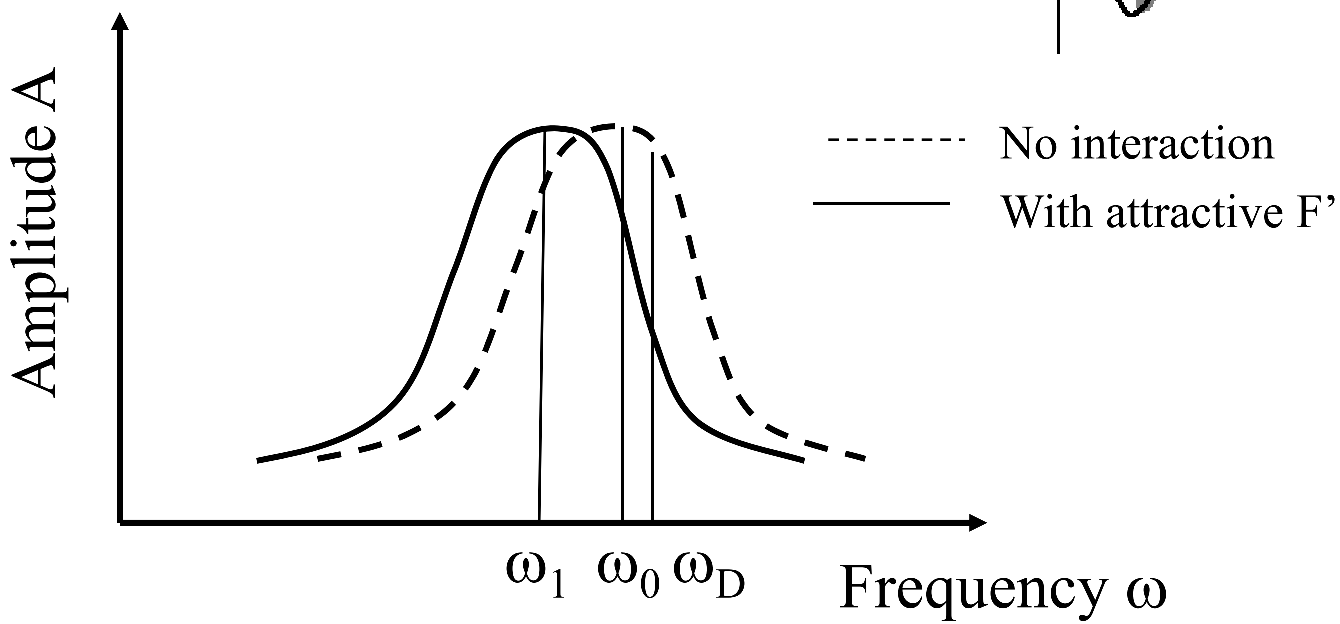




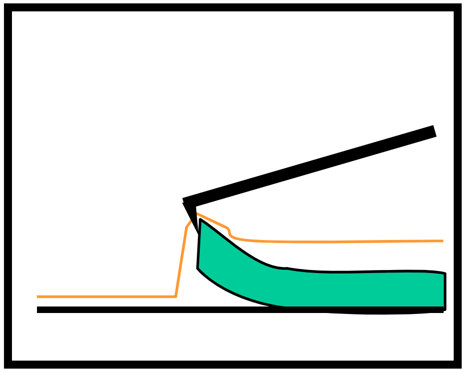
AC imaging mode

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

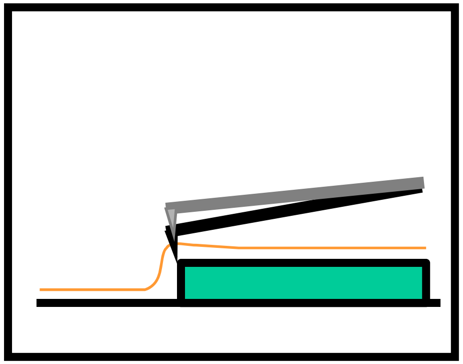




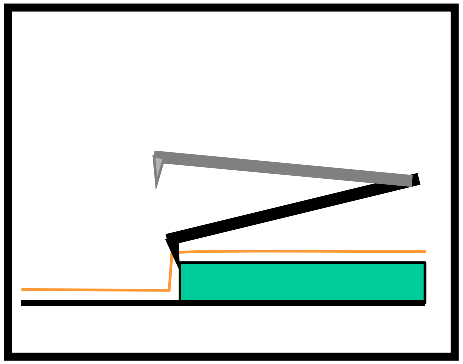
Comparison of three scanning modes



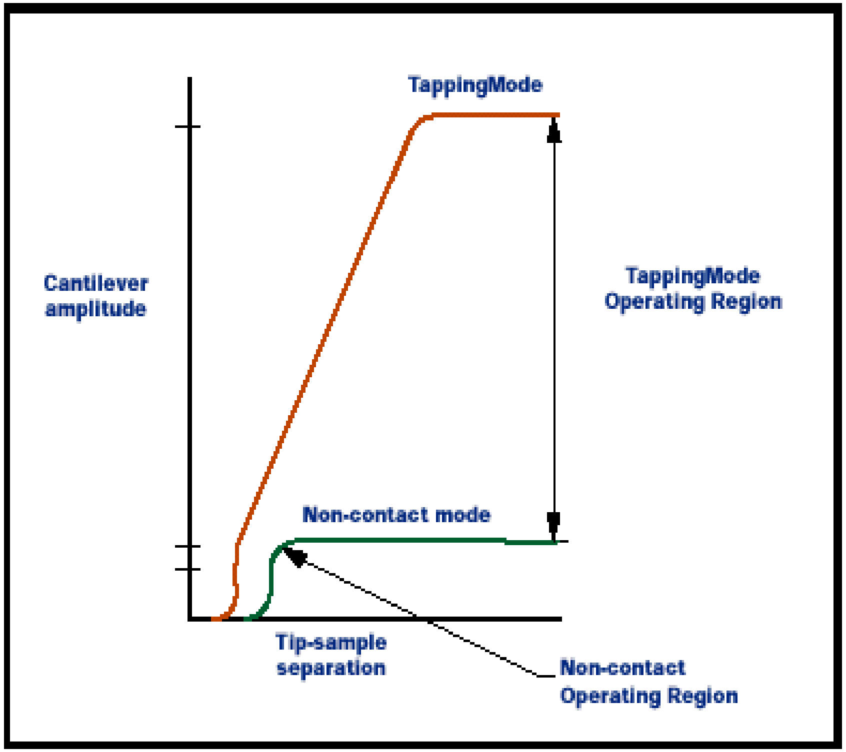
Contact



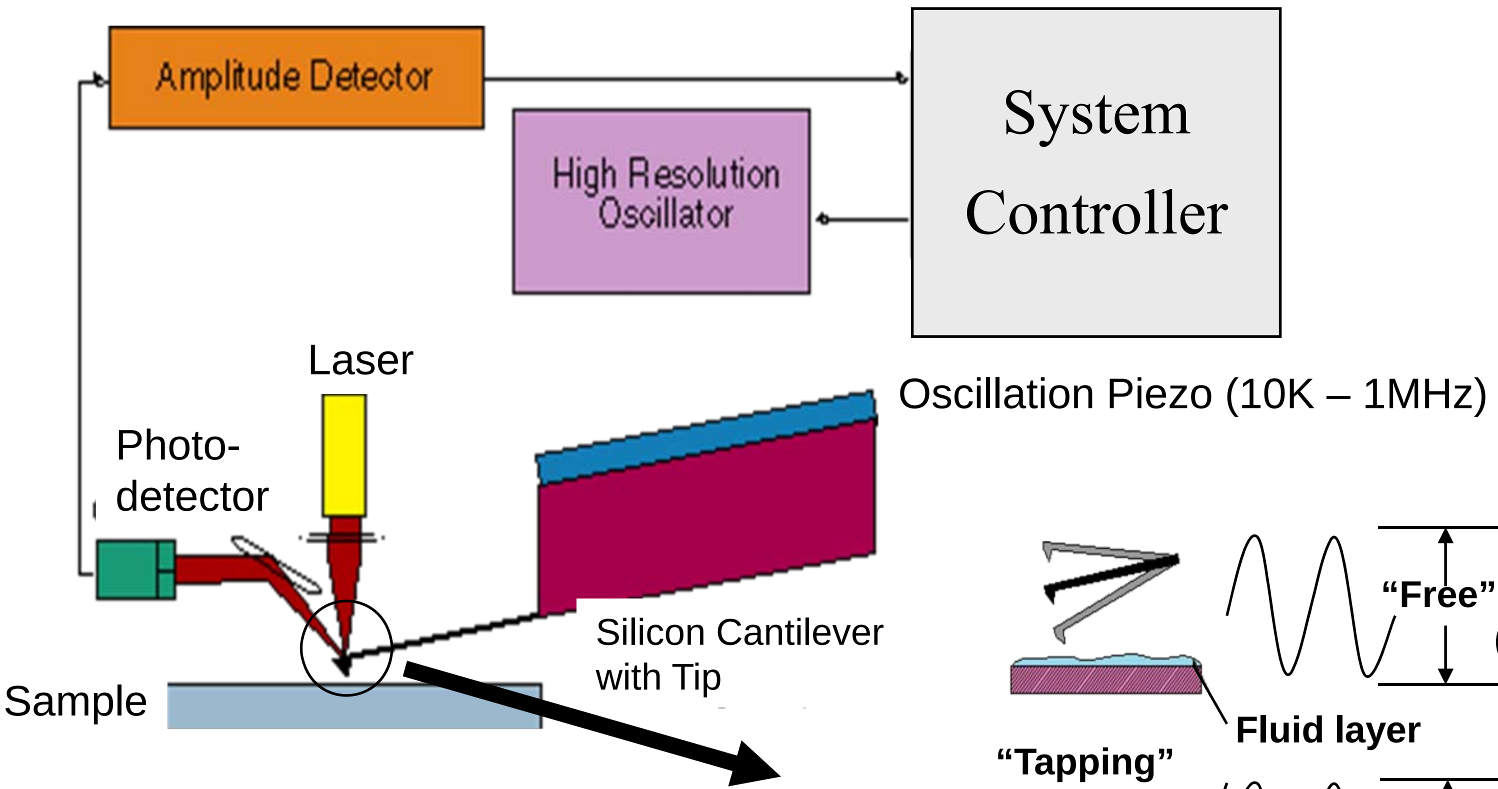
Non-contact

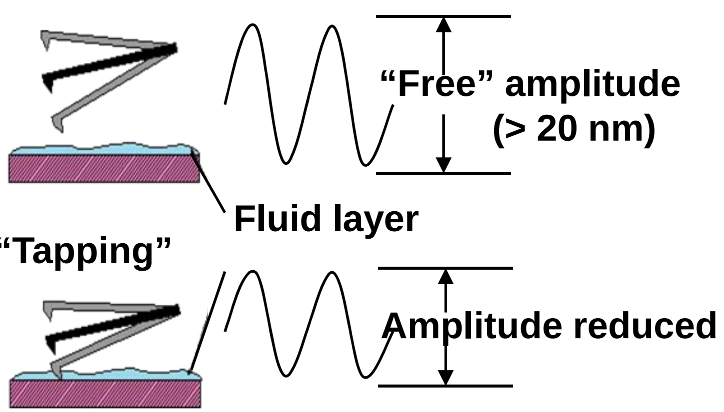


Intermittent-contact

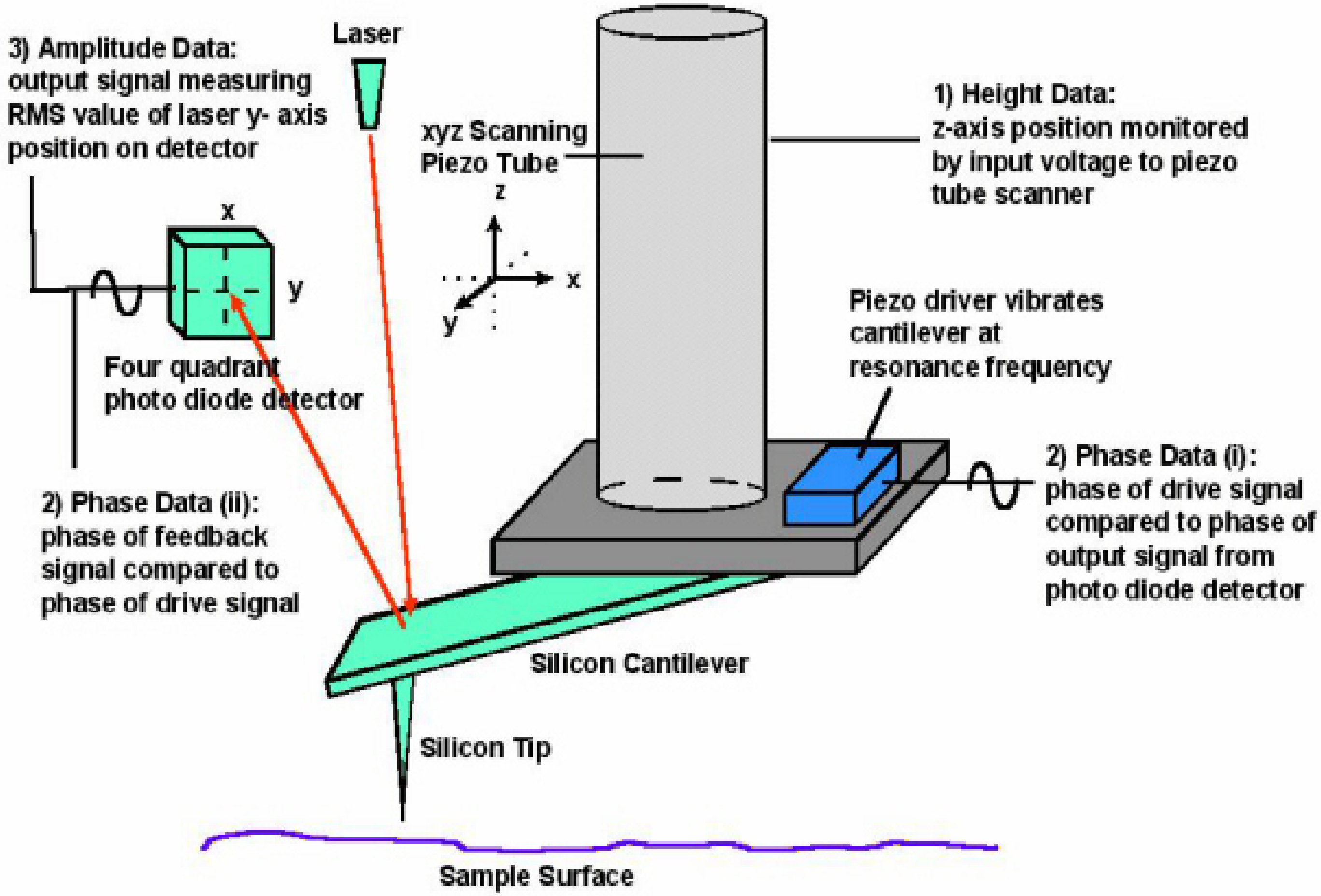


Tapping mode

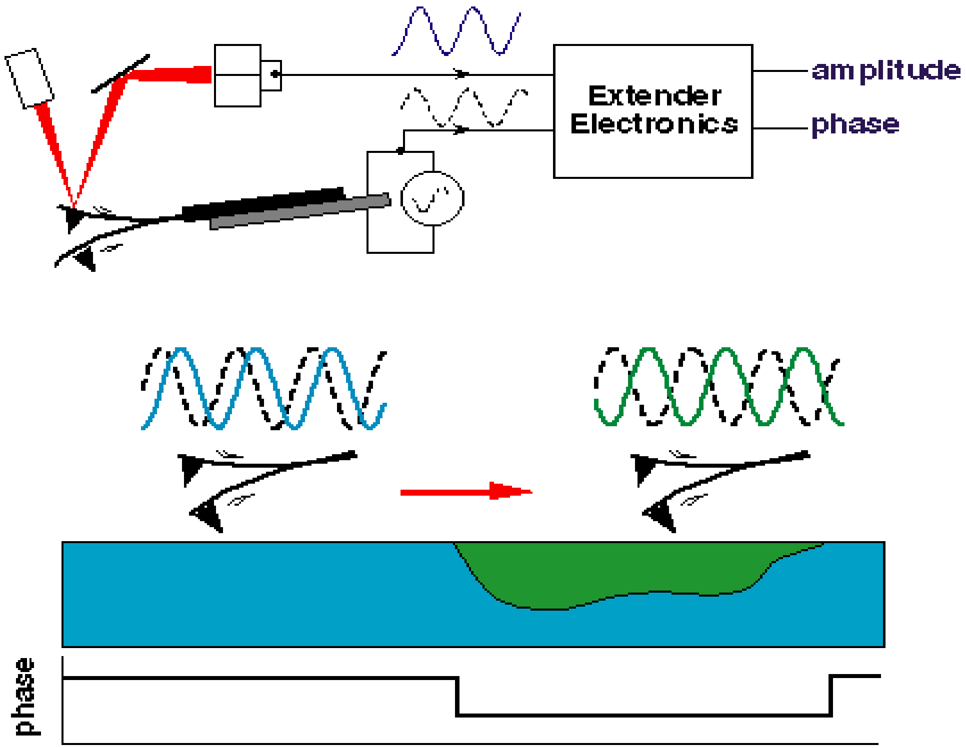


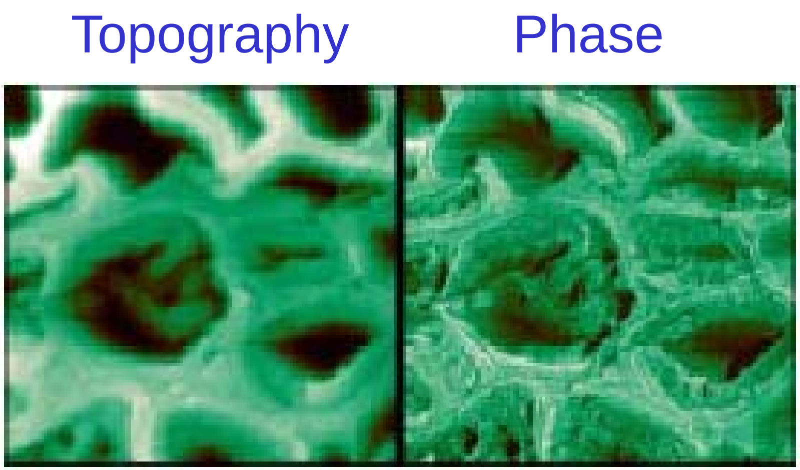


Three Types of Data Collected in Tapping Mode



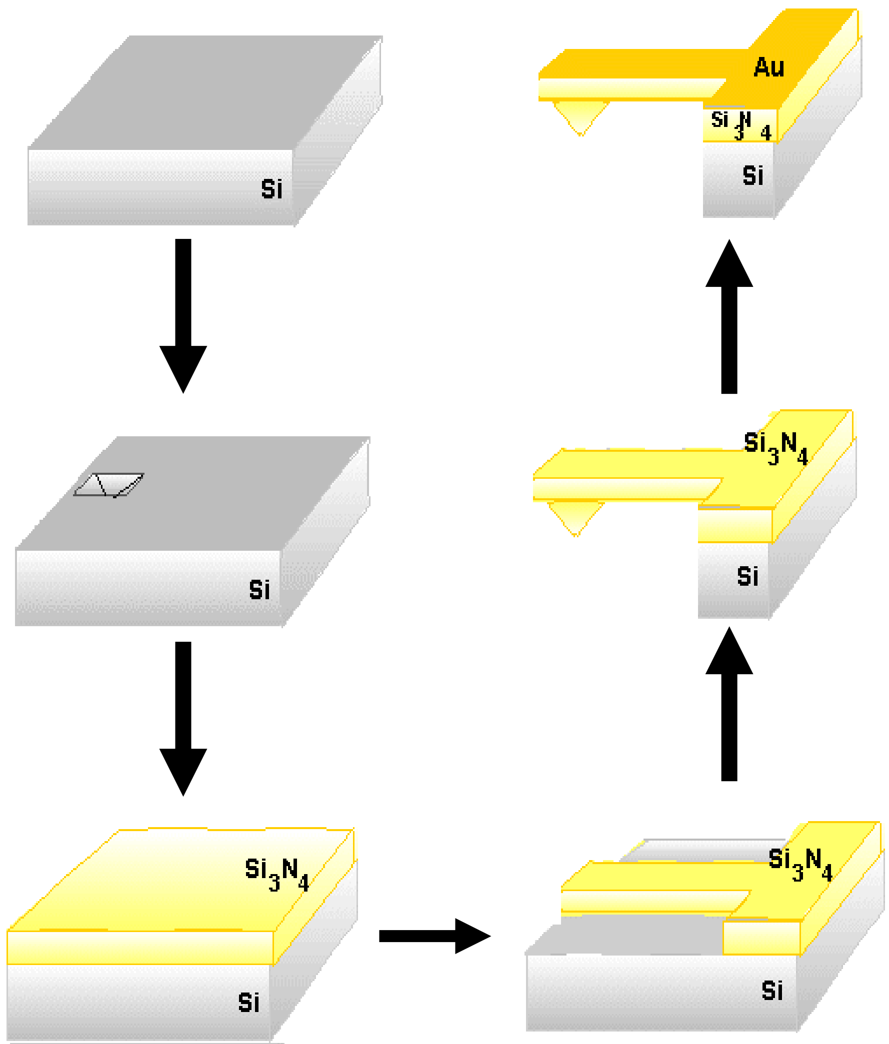
Images by tapping mode

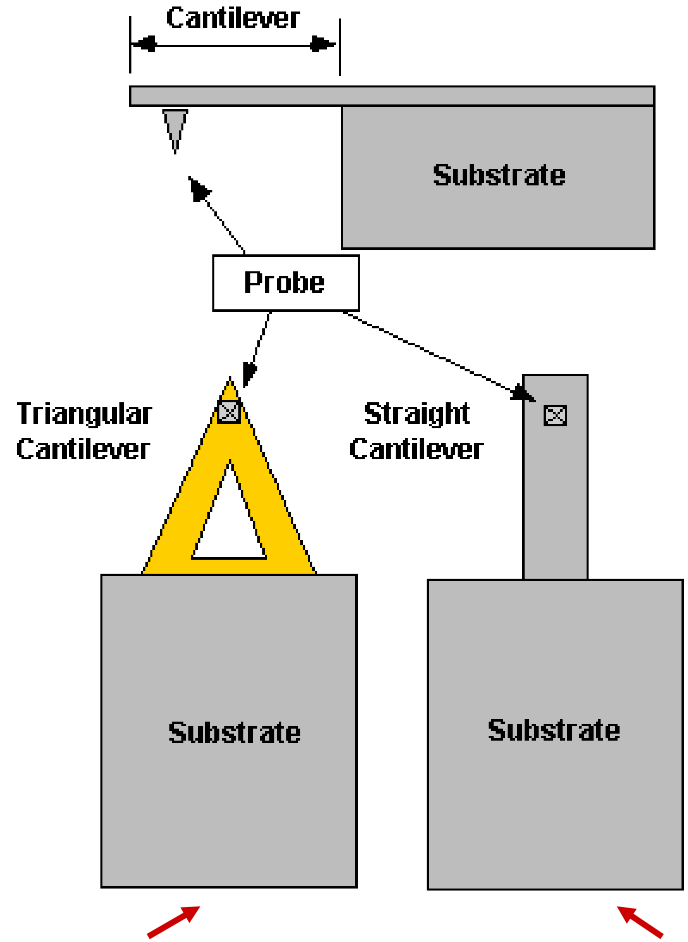




AFM image of a fresh
Alfalfa root section

Fabrication of AFM probes

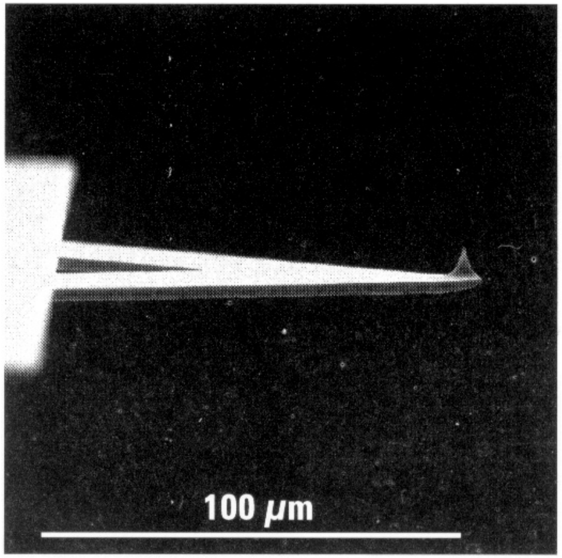




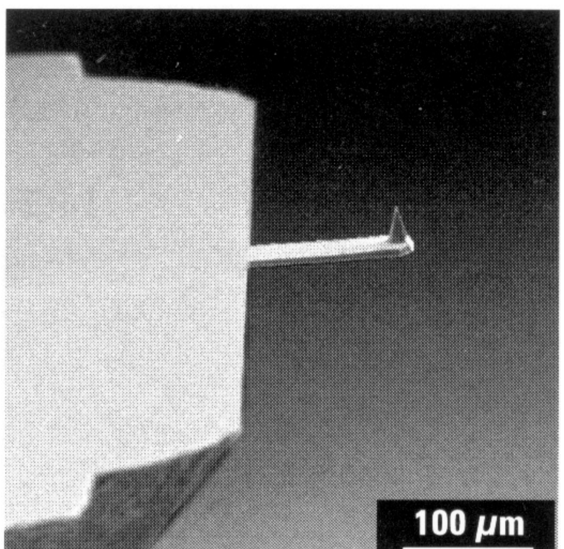
Typical Tip Dimension:
150µm x 30µm x 0.5µm
k ~ 0.1 N/m
Materials: Si_3N_4

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

V-shaped

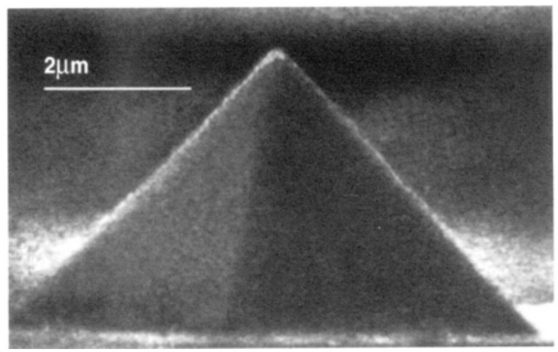


Rectangular-shaped

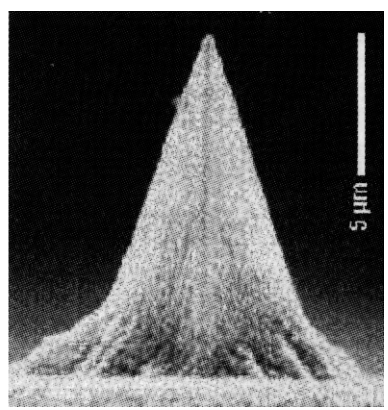


Materials: Si, SiO_2, Si_3N_4
Ideal Tips: hard, small radius of curvature, high aspect ratio

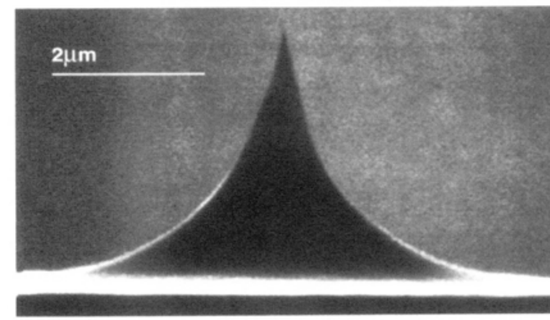
Pyramid Tip

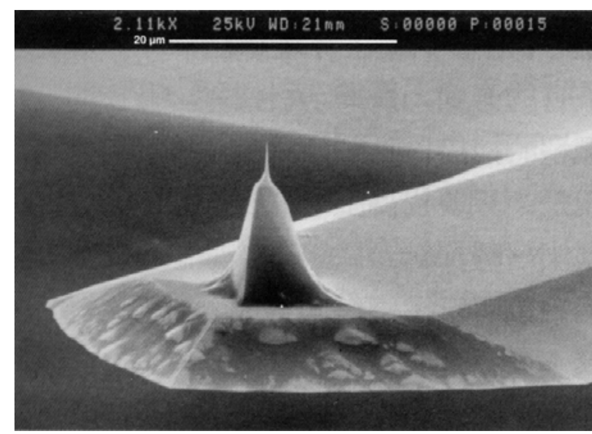


Diamond-coated Tip



Ultrasharp 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

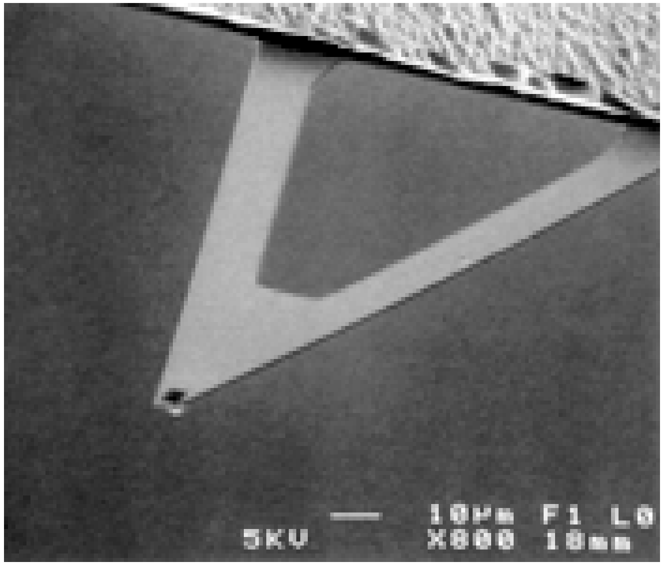
   Easy to bent and difficult to twist

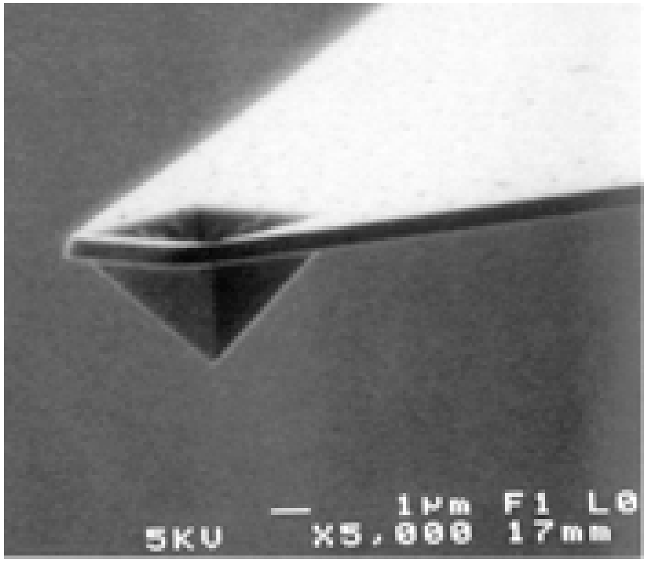
4) Sharp protrusion at the apex

   To better define the tip-sample interaction

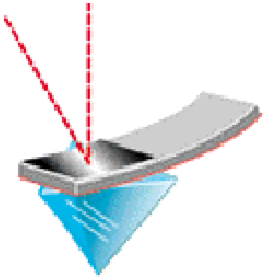
Tip of small shear force

(for Contact mode)



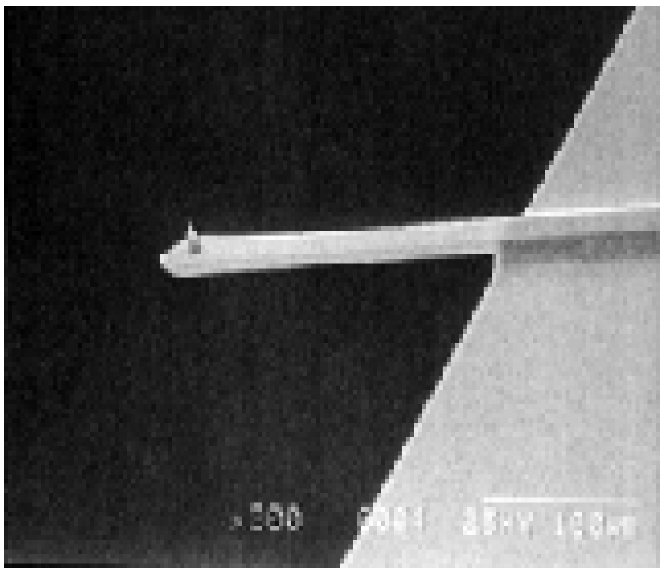


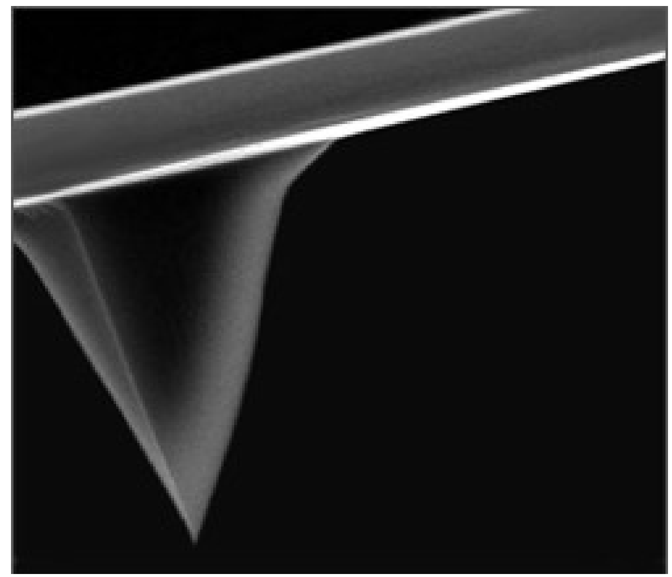
Typical Tip Dimension:
150μm x 30μm x 0.5μm
k ~ 0.1 N/m
Materials: Si_3N_4



Tip of high resonant frequency

(for Tapping mode)

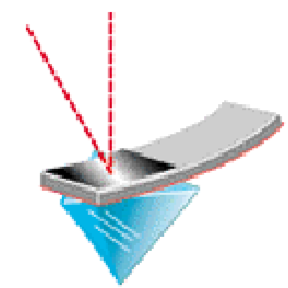




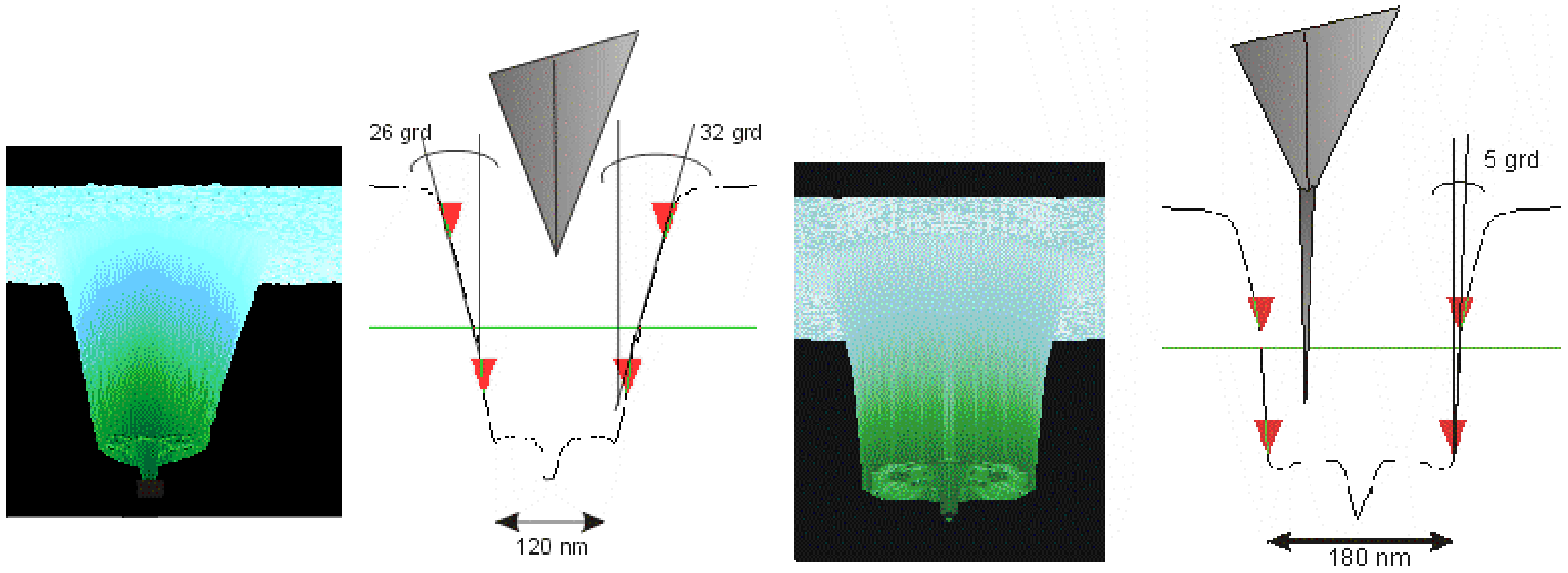
Typical Tip Dimension:
150μm x 30μm x 3μm

f_r ~ 100 kHz

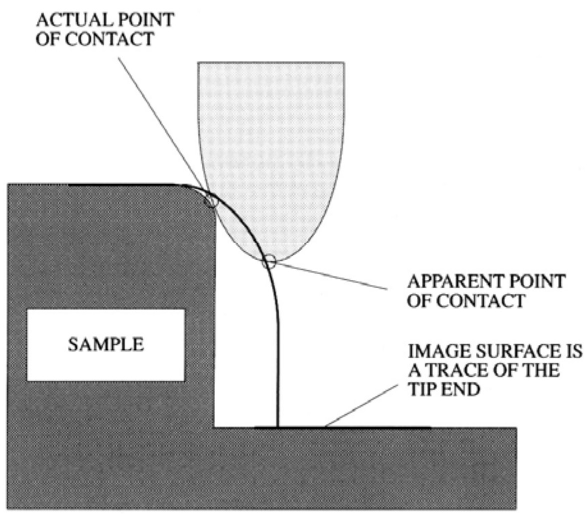
Materials: Si

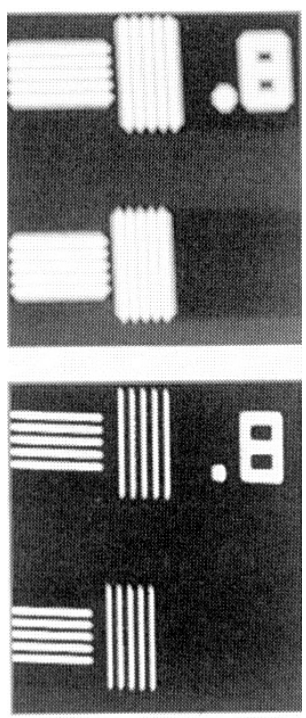


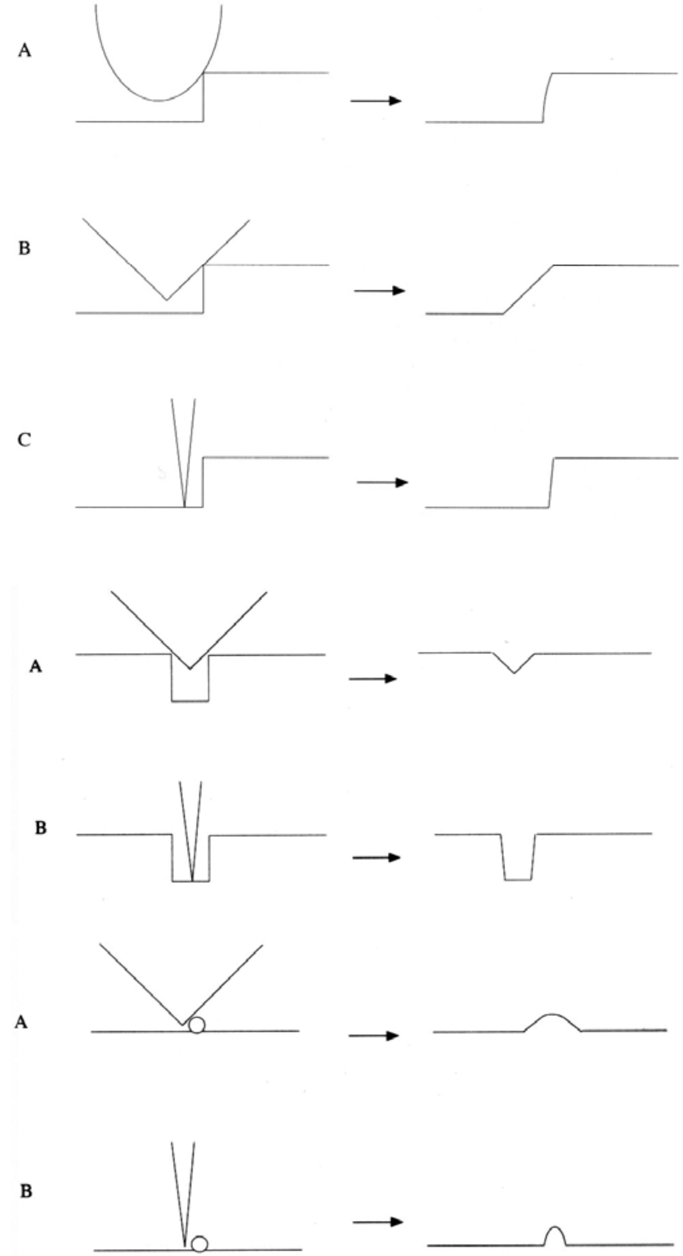
Ultra-sharp tip

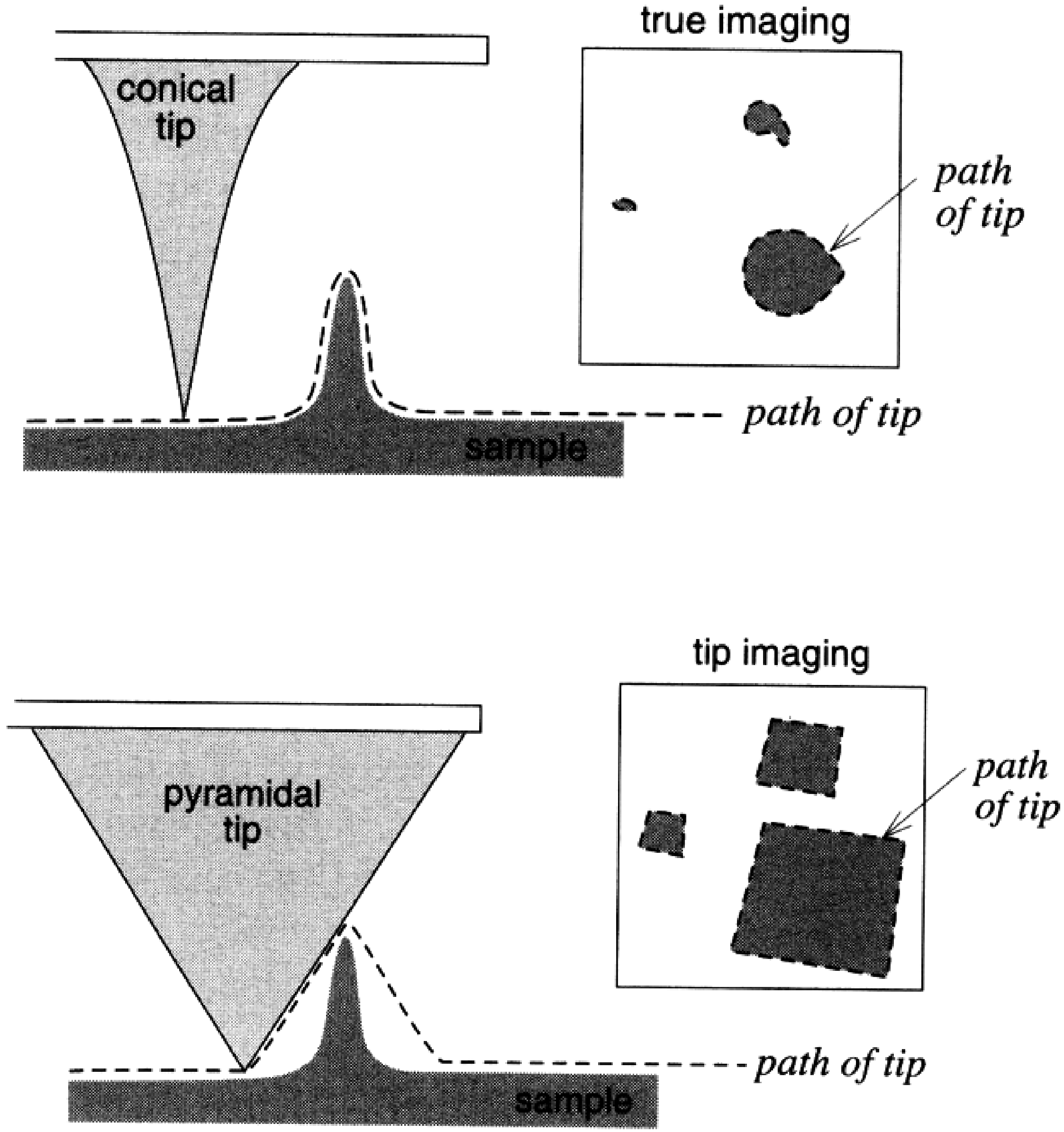


Effects of the Tip Shape



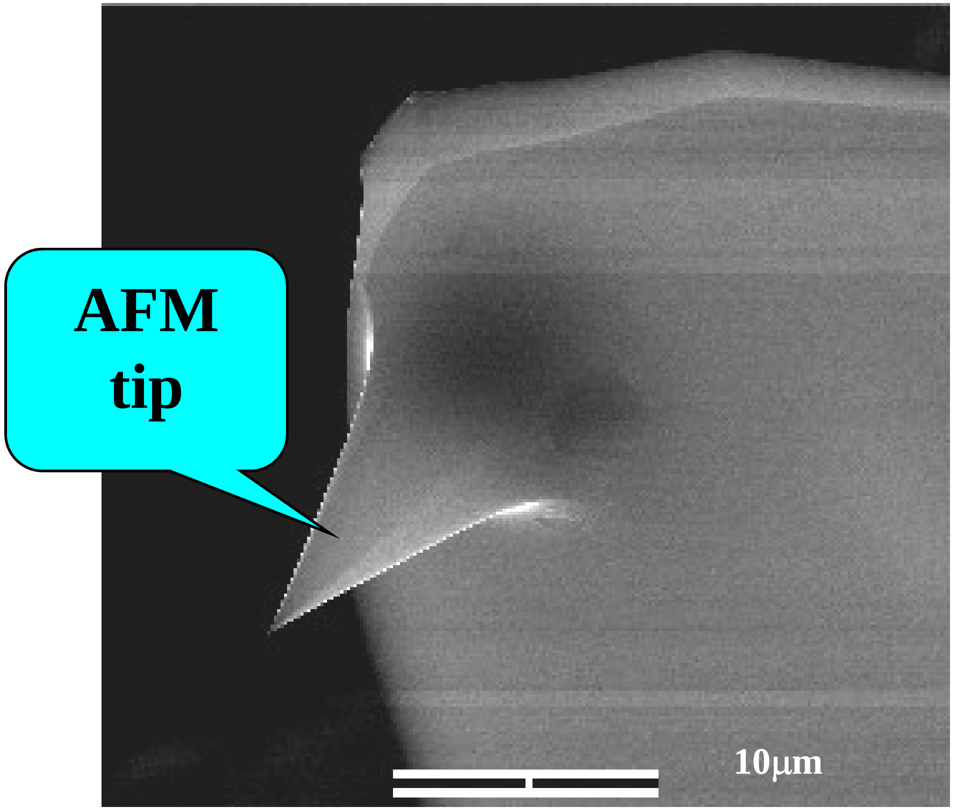






true imaging
conical tip
path of tip
path of tip
sample
tip imaging
pyramidal tip
path of tip
path of tip
sample

AFM Tip + Carbon Nanotube



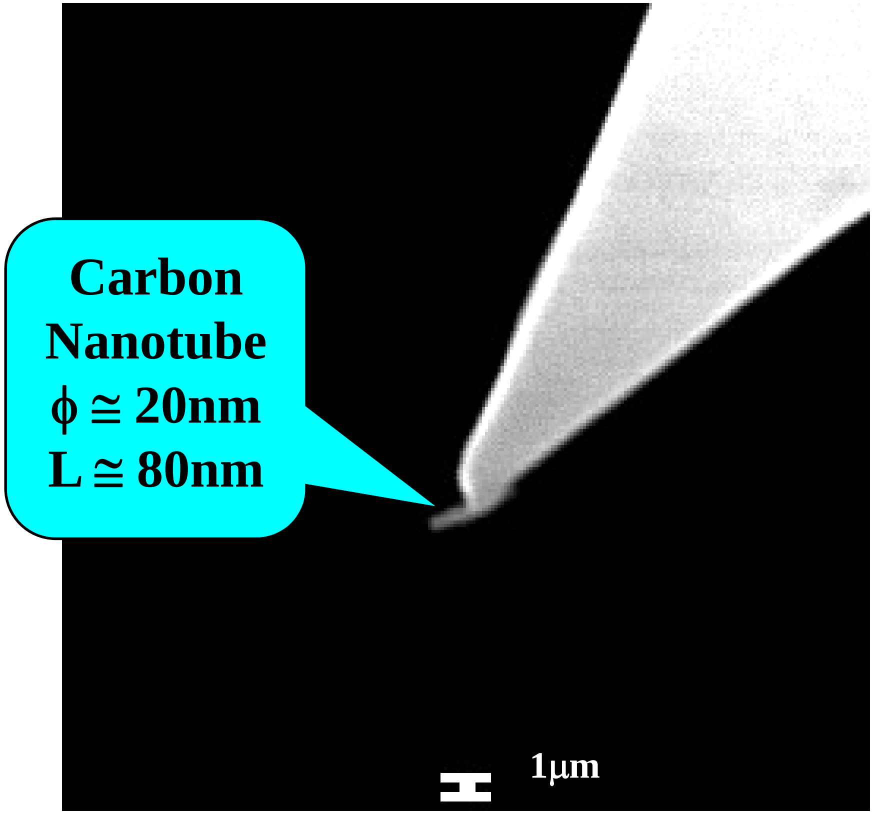
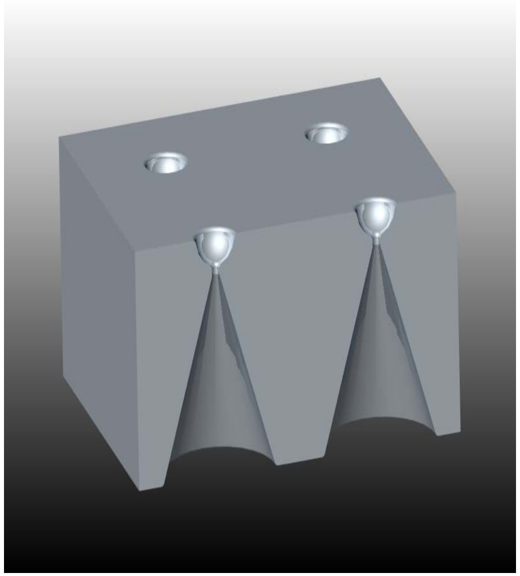
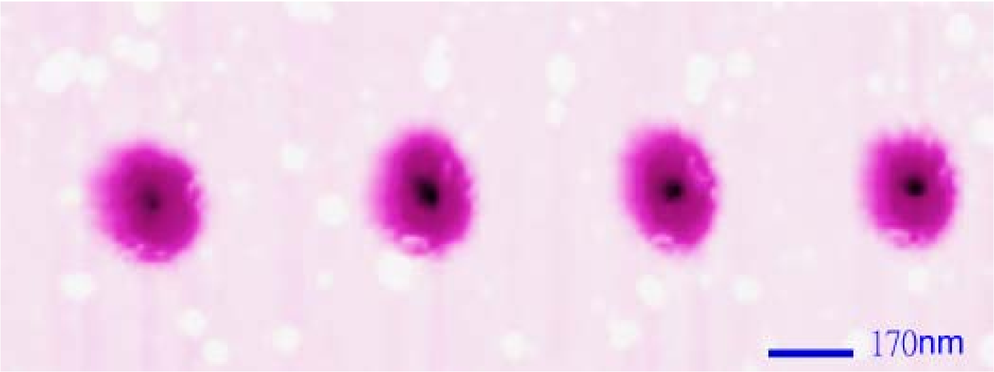


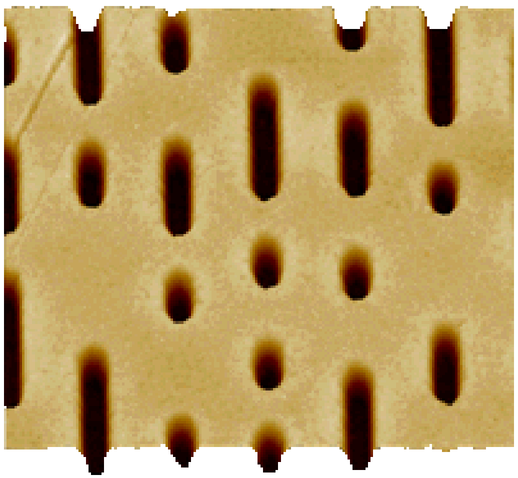
Image of high aspect ratio



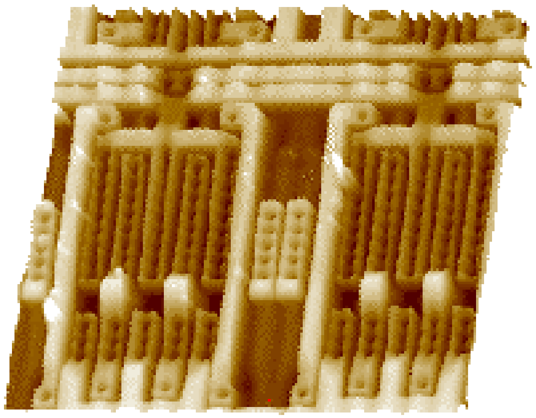


AFM images

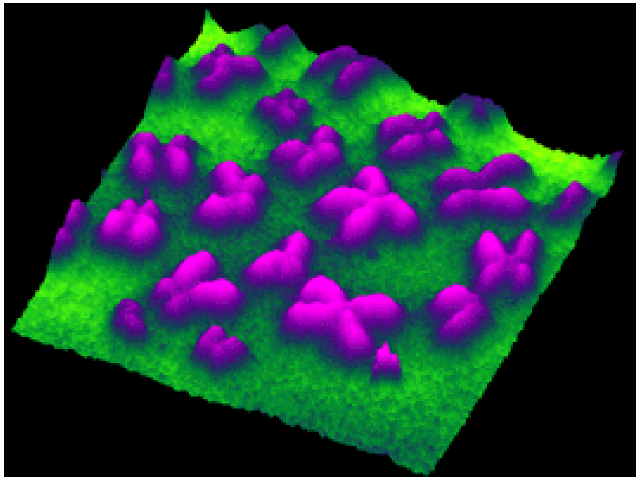
CD pits



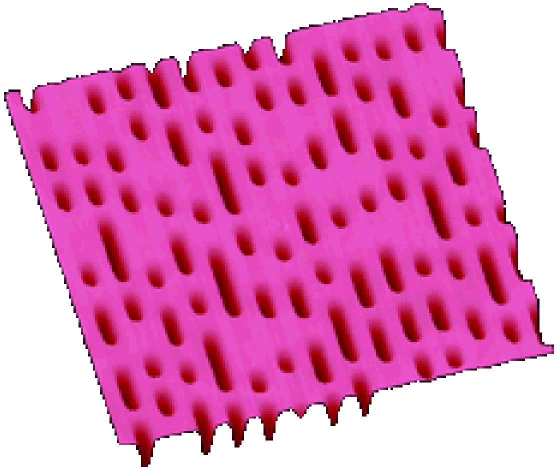
Integrated circuit



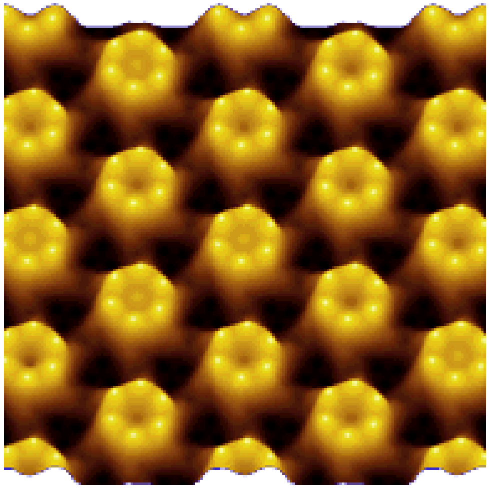
Chromosomes



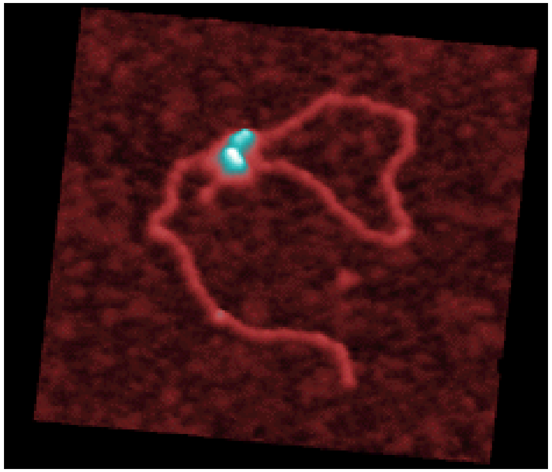
DVD pits



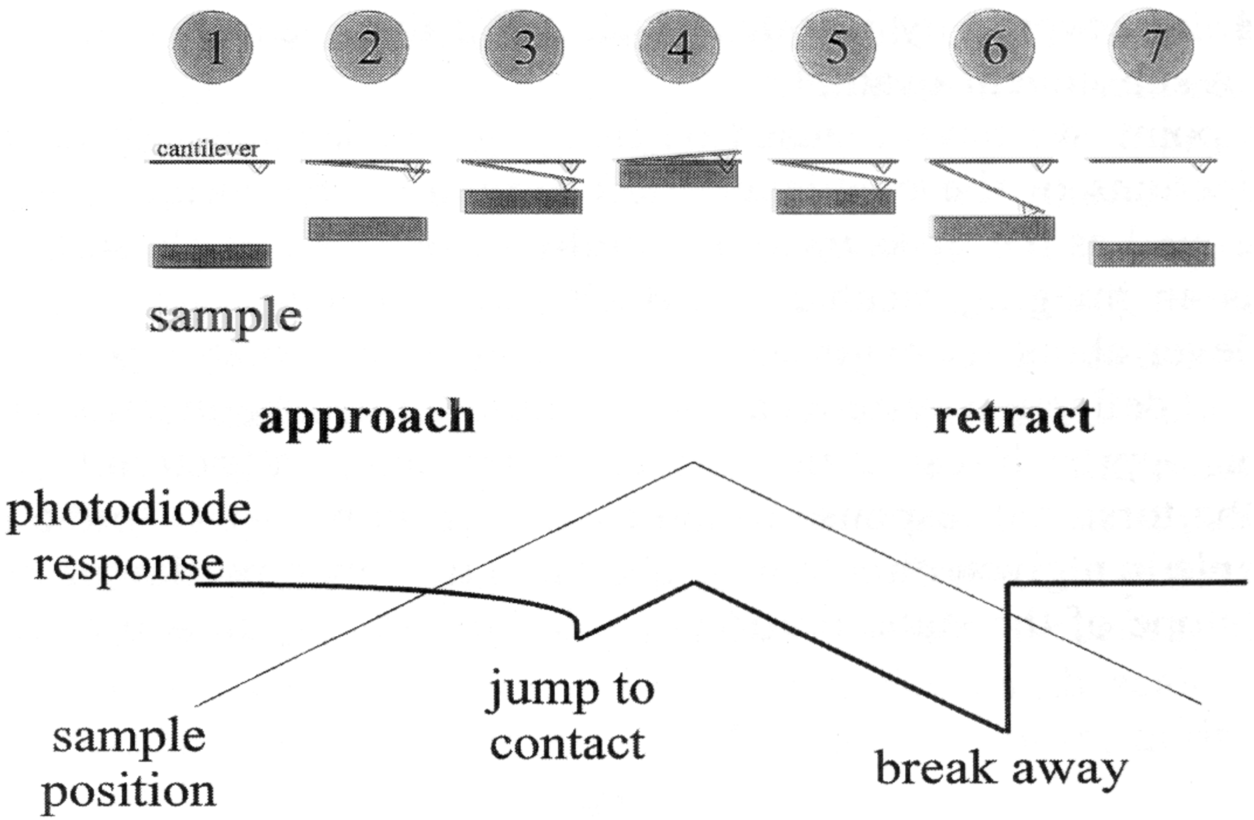
Bacteria

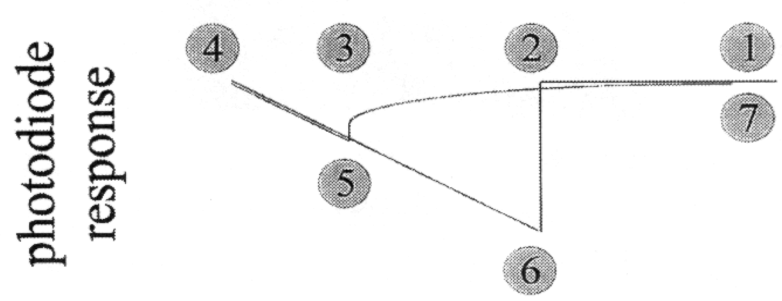


DNA

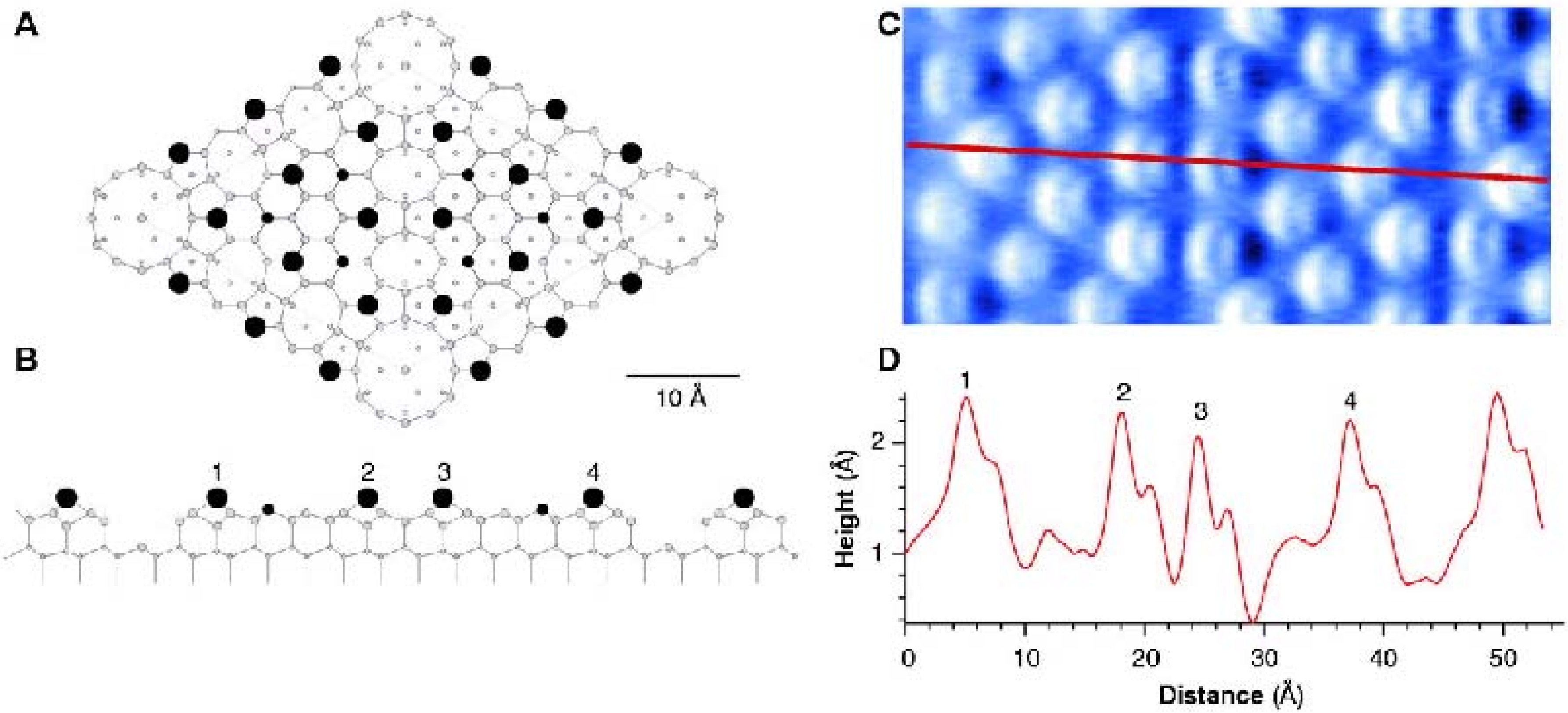


Force-Distance Curve

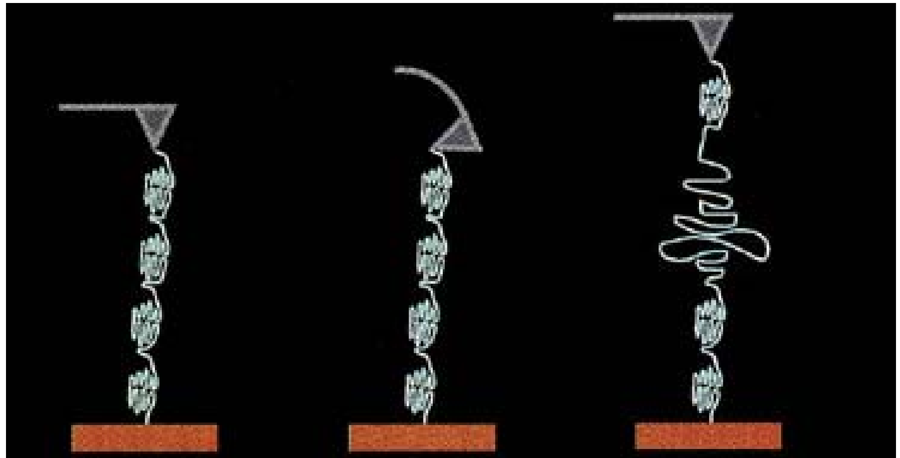




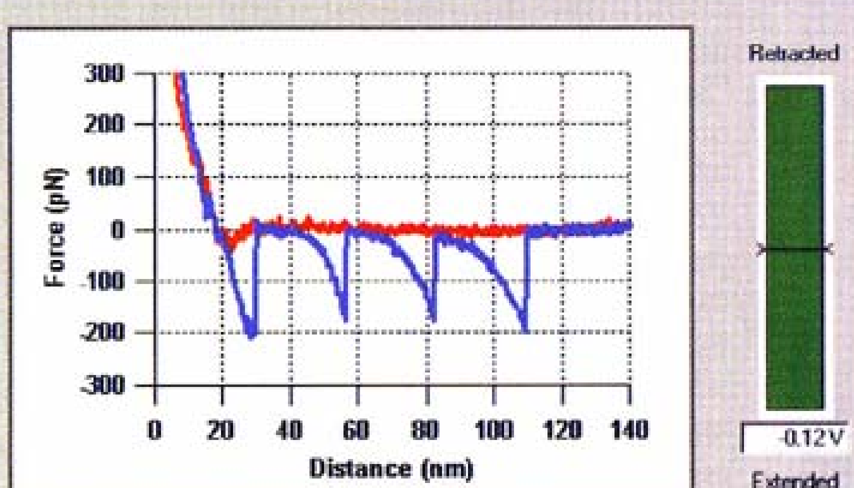
Atomic Image of Si(111)-(7×7) Taken with AFM



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

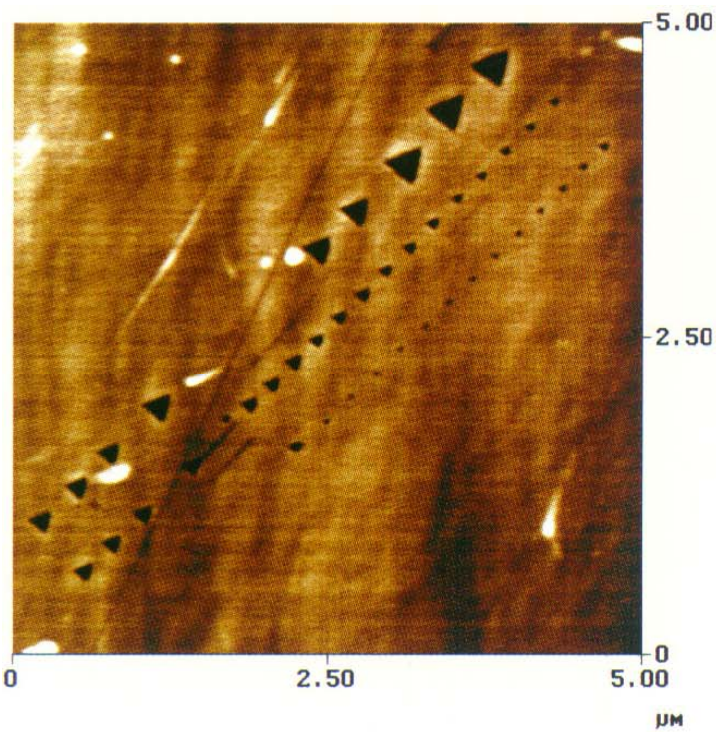


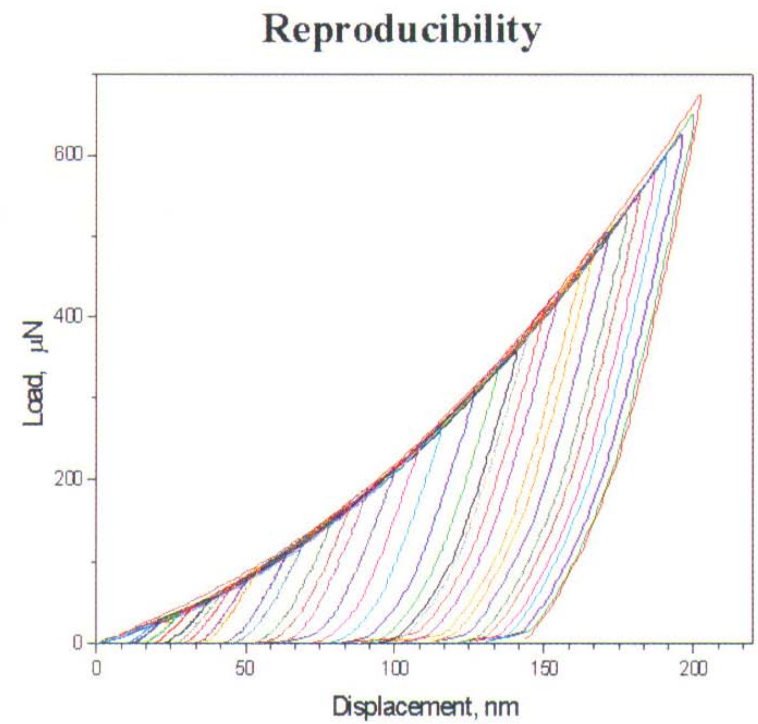
Force measurement of an unfolding complex molecule.



Advanced graphical user interface shows titin muscle molecule force curve.

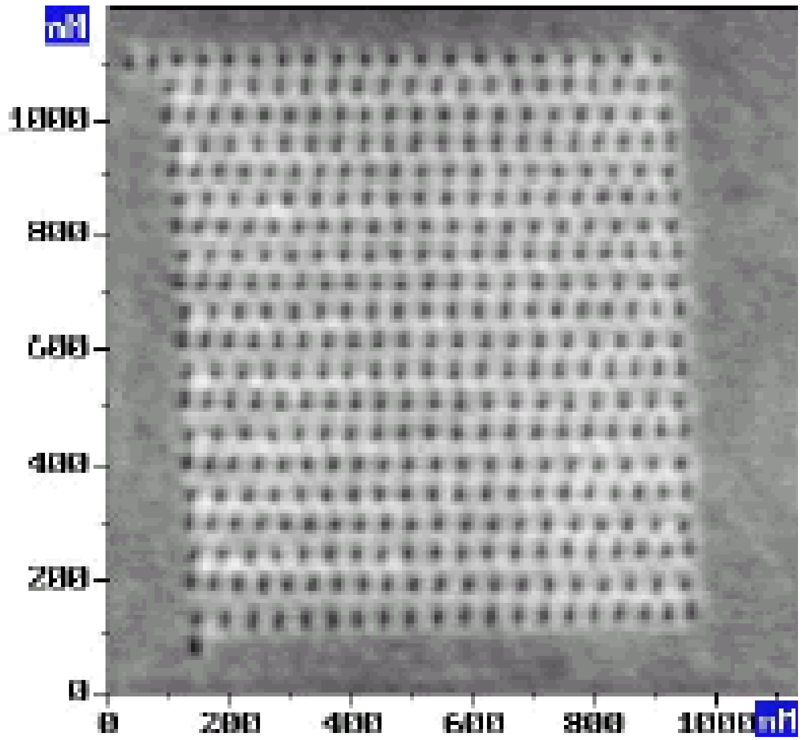
Measurement of Mechanical Properties



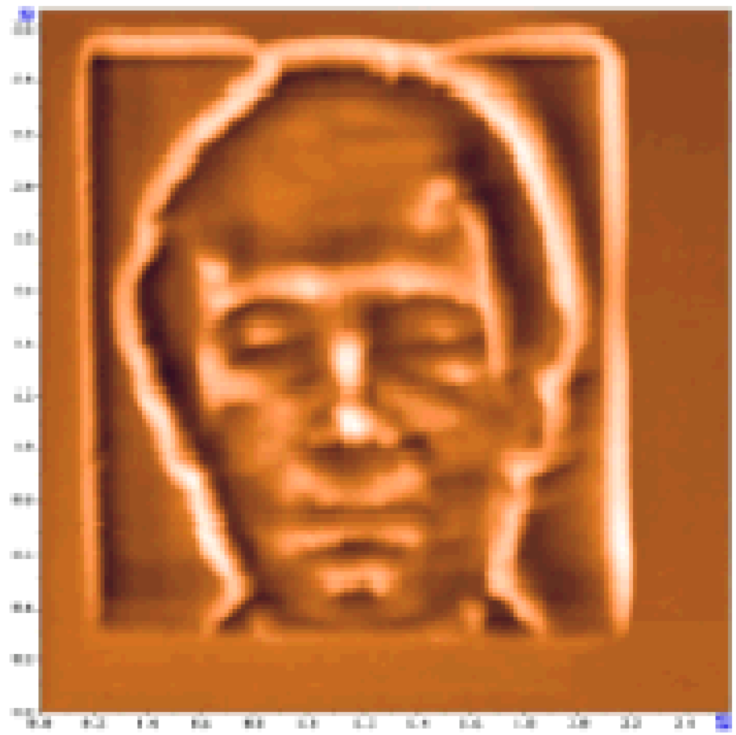


1. The load-displacement curves provide a "mechanical fingerprint" of material's response to deformation, from which parameters such as hardness and young's modulus of elasticity can be determined.
2. In measuring the mechanical properties of thin coated system, the size of contact impression should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

Nanolithography of Tapping-Mode AFM

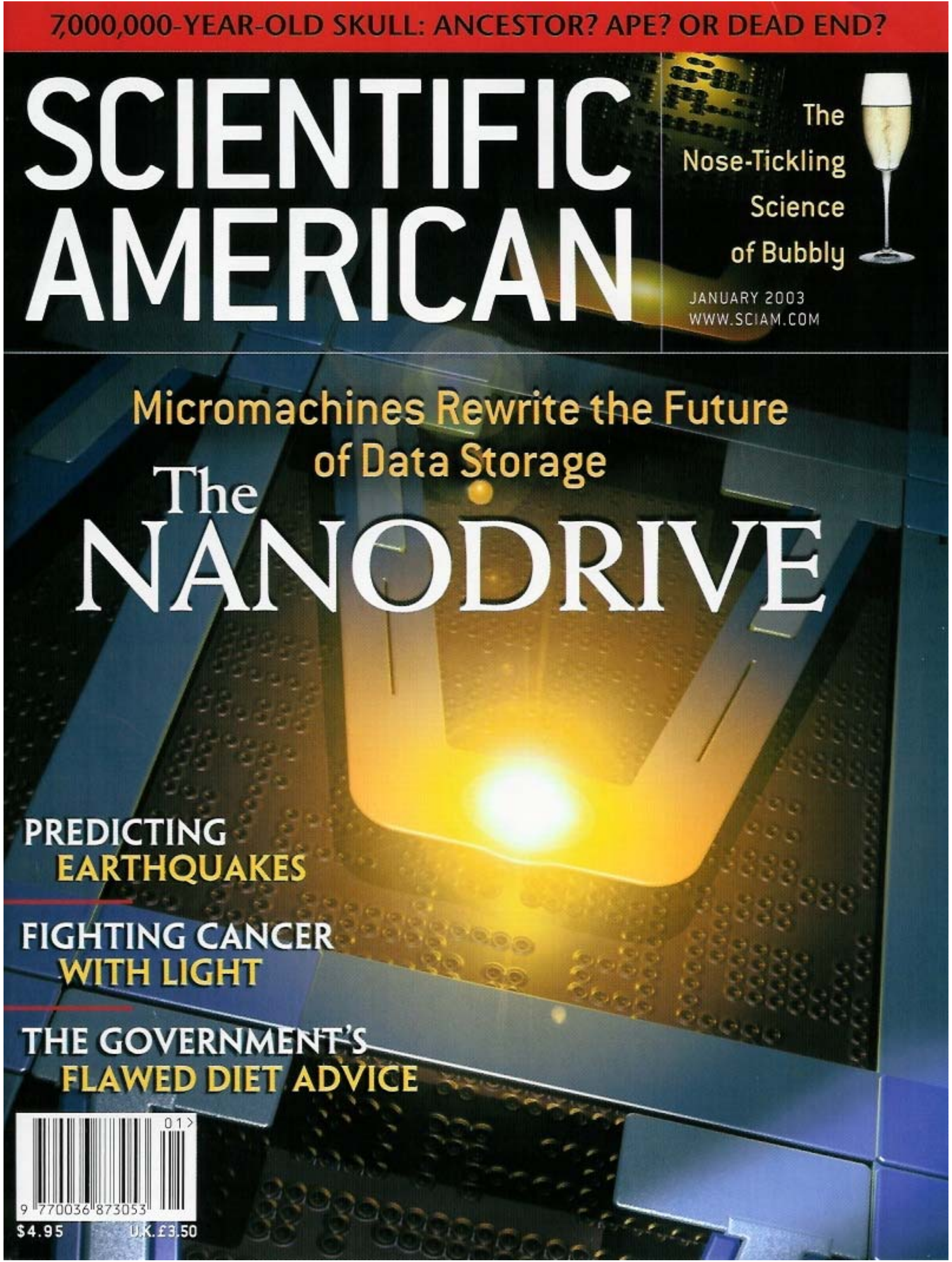


(1.2μm× 1.2μm)



(2.5μm× 2.5μm)

Image of polycarbonate film on silicon surface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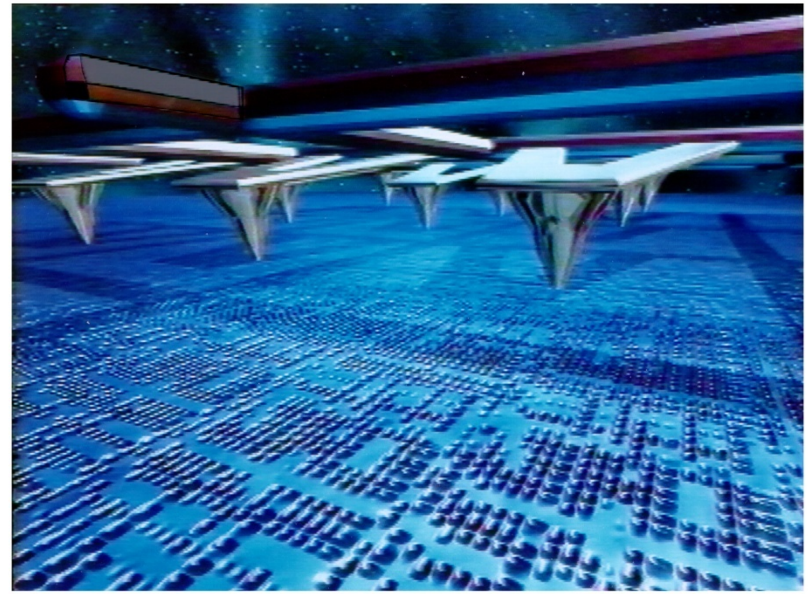
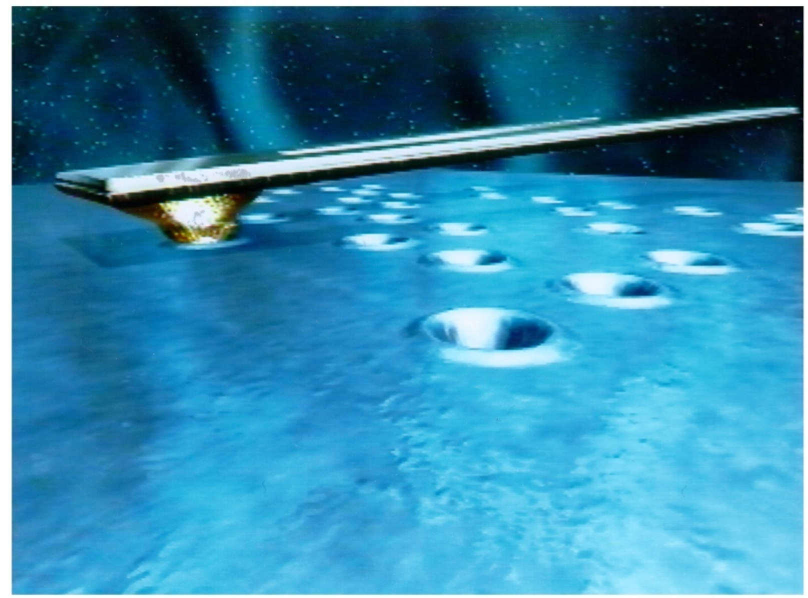
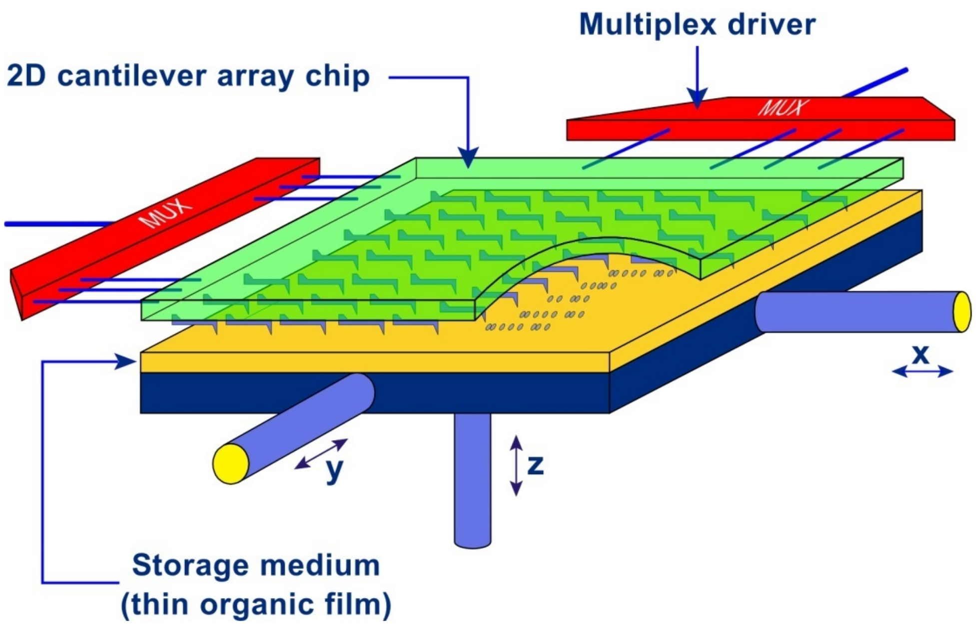


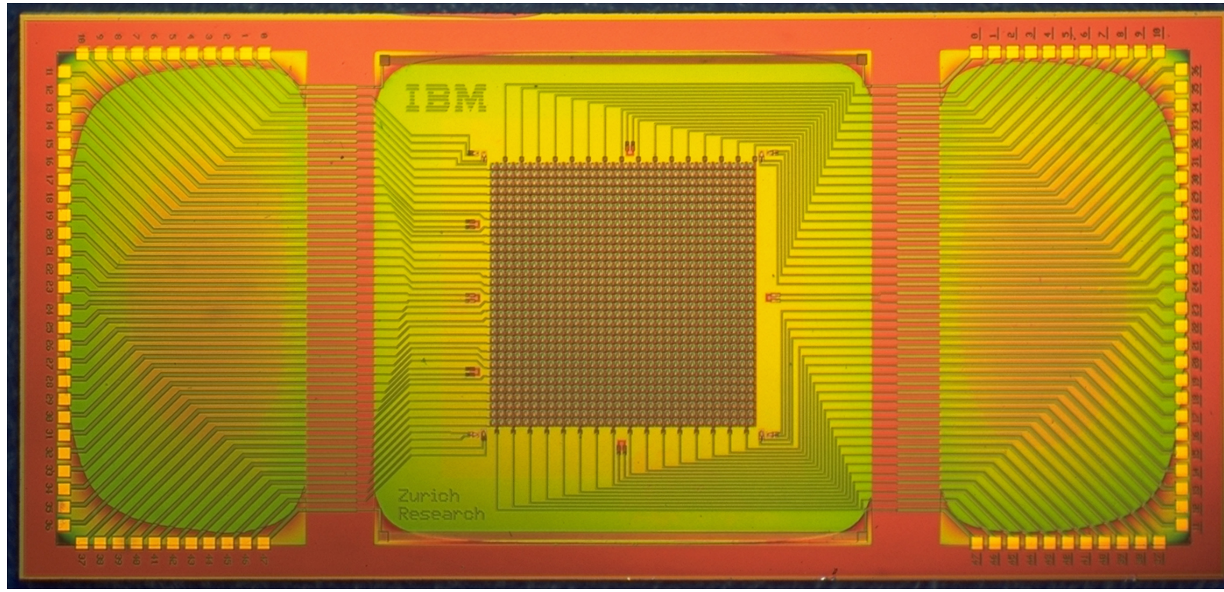


"MILLIPEDE"

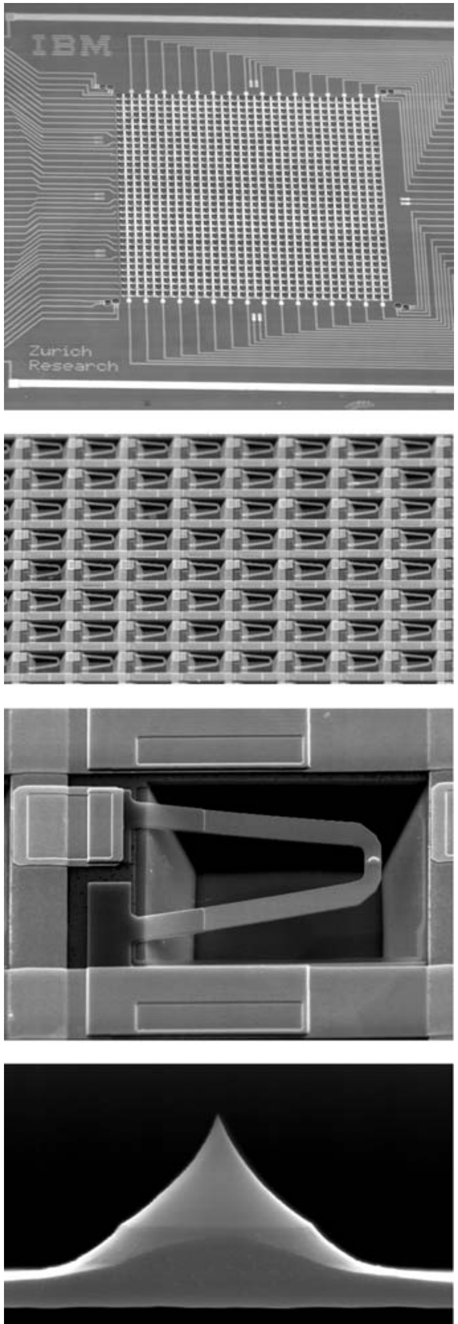
Highly parallel, very dense AFM data storage system



The Millipede concept: for operation of the device, the storage medium - a thin film of organic material (yellow) deposited on a silicon "table" - is brought into contact with the array of silicon tips (green) and moved in x- and y-direction for reading and writing. Multiplex drivers (red) allow addressing of each tip individually.



The Millipede chip: the image shows the electrical wiring for addressing the 1,024 tips etched out in a square of 3mm by 3mm (center). The chip's size is 7 mm by 14 mm.



Millipede cantilevers and tips: electron microscope views of the 3 mm by 3 mm cantilever array (top), of an array section of 64 cantilevers (upper center), an individual cantilever (lower center), and an individual tip (bottom) positioned at the free end of the cantilever which is 70 micrometers (thousands of a millimeter) long, 10 micrometers wide, and 0.5 micrometers thick. The tip is less than 2 micrometers high and the radius at its apex smaller than 20 nanometers (millionths of a millimeter).

AFM versus STM

1. 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 SEM

1. AFM provides extraordinary topographic contrast direct height measurements and SEM provides only 2D mapping of surface features.
2. For insulating samples, no metallic coating is necessary for AFM.

AFM versus TEM

1. Compared with Transmission Electron Microscopes, three dimensional AFM images are obtained without expensive sample preparation and yield far more complete information than the two dimensional profiles available from cross-sectioned samples.
2. No charging effect occurs in AFM.

AFM versus Optical Microscope

1. AFM has much better resolution than Optical Microscope.
2. AFM provides unambiguous measurement of step heights, independent of reflectivity differences between materials.