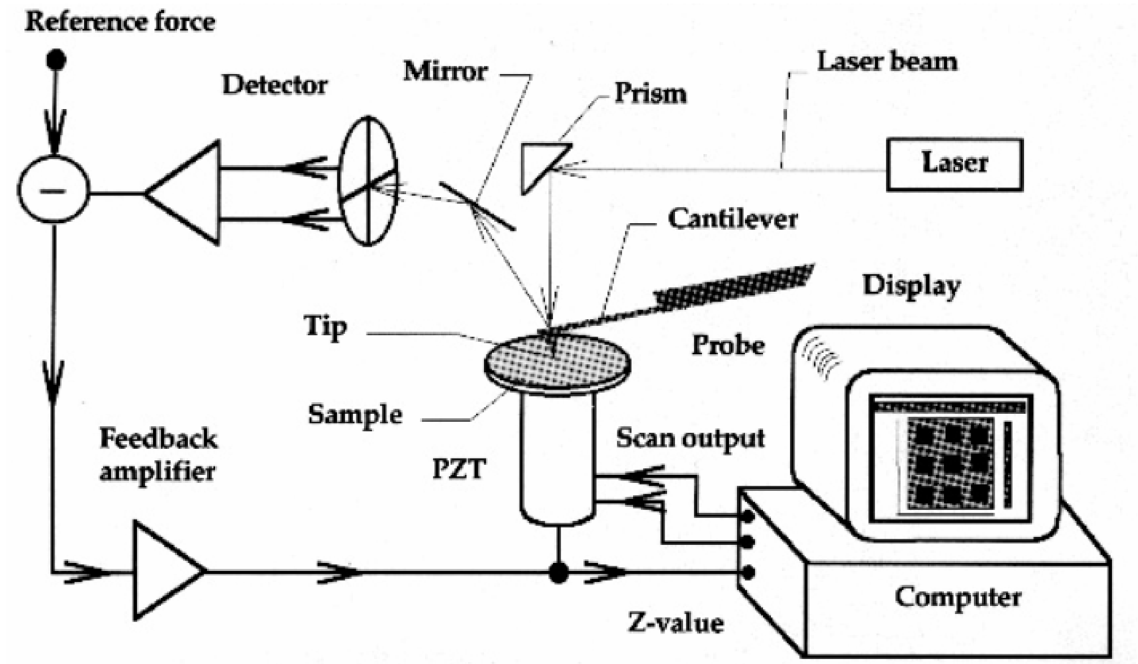
原子力顯微術 Atomic Force Microscopy (AFM)



$$F = k\Delta z$$

$$F = 10^{-9} – 10^{-6}\ N$$

$$k = 0.1 – 1\ N/m$$

參考文獻：

1. G. Binnig, C. F. Quate, and C. Gerber, Phys. Rev. Lett. **56**,930(1986).
2. 林鶴南,李龍正,劉克迅, 科儀新知 89,第 17 卷第三期第 29 頁(1995).
3. C. Bustamante and D. Keller, Physics Today, 32 December(1995).

R. Wiesendanger and H.J. Güntherodt, *Scanning Tunneling Microscopy II*, Springer-Verlag, (1992).

Surface Profilometer

1. Stylus profilometry was developed a long time ago to study the surface roughness of materials.
2. A topographic map is obtained similarly to an STM by raster scanning a sample relative to a stylus tip.
3. The stylus tip is in contact with the sample with a set force ~ 10^{-4} N.
4. The stylus tip radii are ~ 1μm. The large size of the tips has been the most serious limitation of the technique.

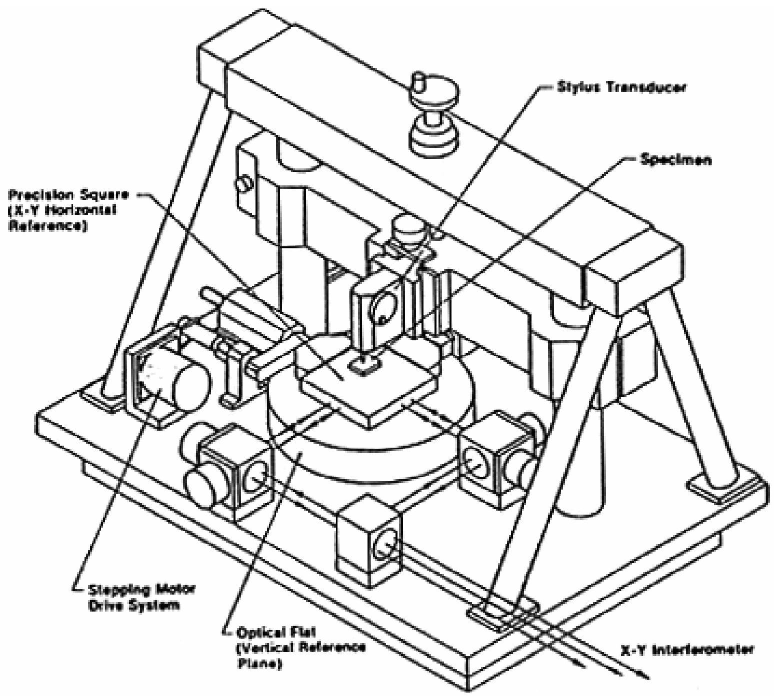


Fig. 2.2. Schematic drawing of a three-dimensional stylus profilometer. The system used for leveling the specimen surface with respect to the optical flat surface is not shown (Teague *et al.*, 1982).

The Birth of AFM

1. The AFM can be operated in the contact regime, similar to the stylus profilometer but with lower forces (10^{-6} -10^{-10} N), or in the non-contact regime.
2. The most critical component in this AFM is the cantilever-type spring. To achieve high sensitivity, the spring should be as soft as possible. On the other hand, a high resonant frequency is necessary in order to minimize sensitivity to mechanical vibrations. $\omega_o = (k/m)^{1/2}$, where k is the spring constant and m the effective mass loading the spring. The mass m and therefore the geometrical dimension of the force sensor should be kept as small as possible. ⇒ microfabricated cantilever.

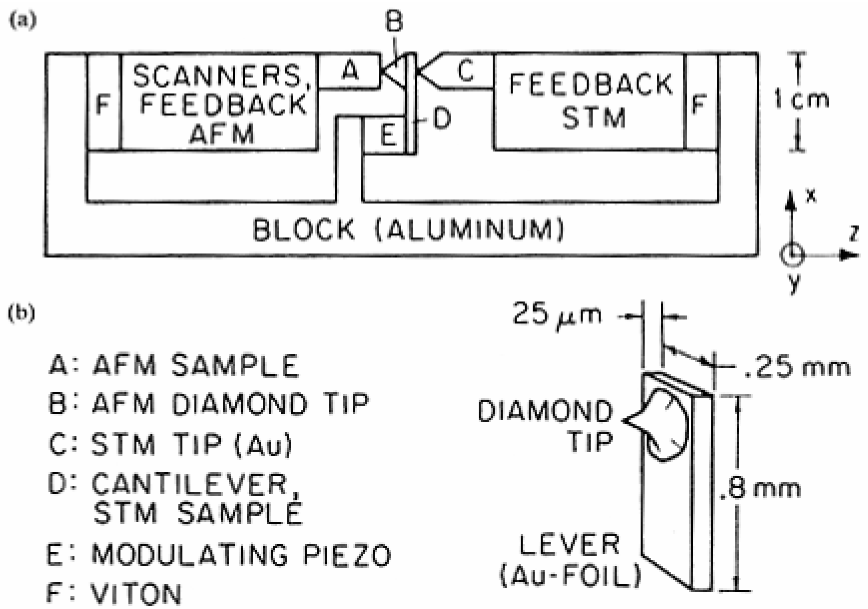
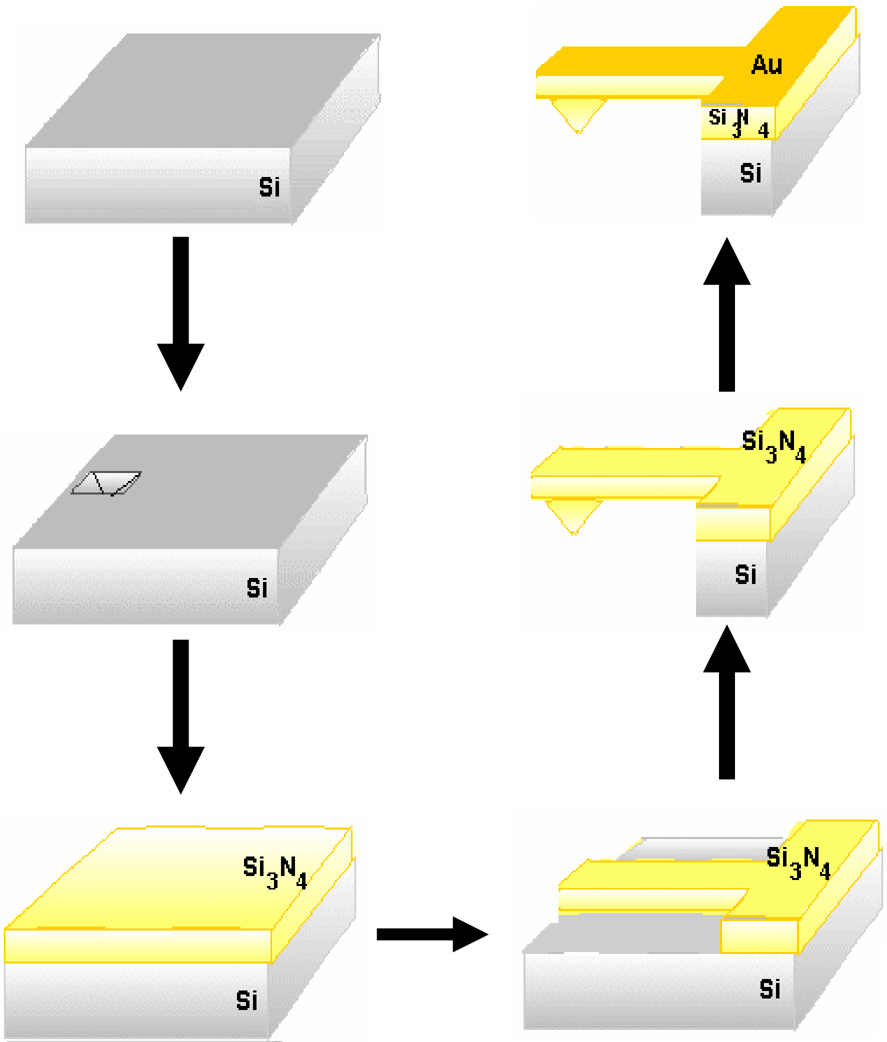
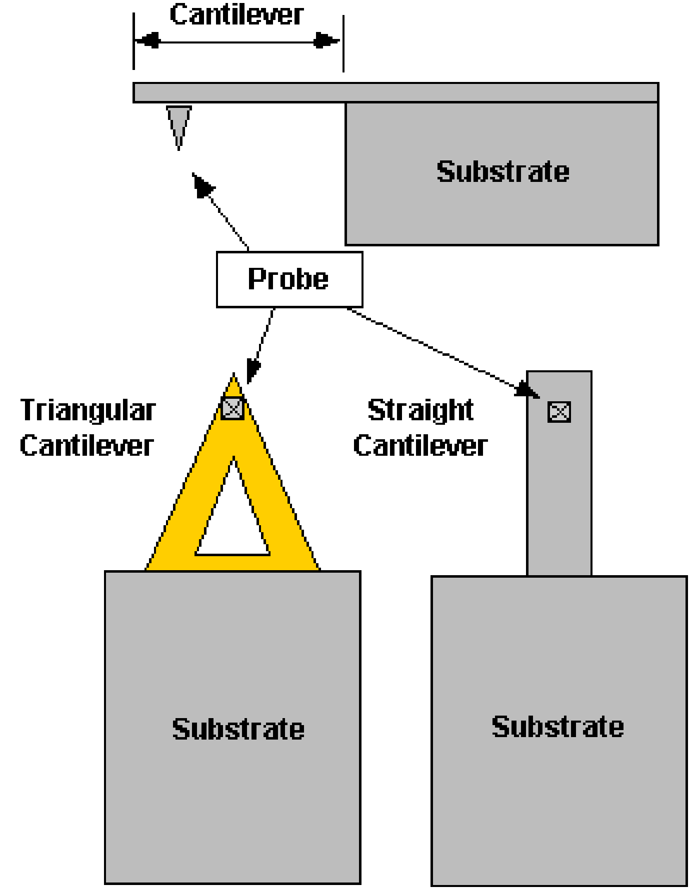


Fig. 2.3. Experimental set-up for the first AFM. The cantilever is not to scale in (*a*). Its dimensions are given in (*b*). The STM and AFM piezoelectric drives face each other, sandwiching the diamond tip that is glued to the cantilever

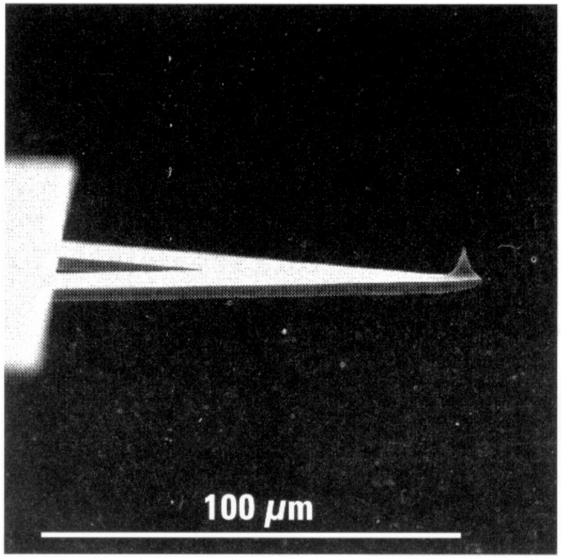




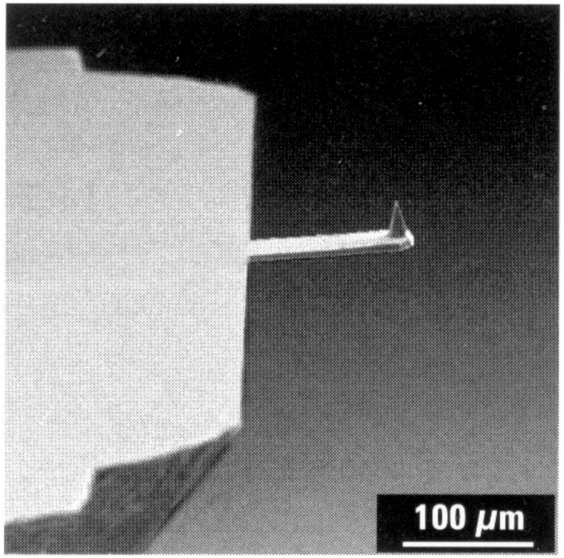
Typical Tip Dimension:
150µm x 30µm x 0.5µm
k ~ 0.1 N/m
Materials: Si_3N_4
V shaped to reduce lateral motion

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

V-shaped



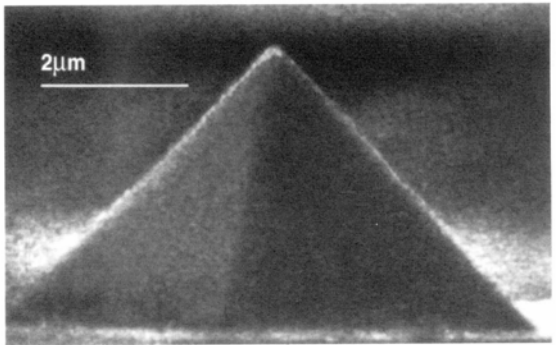
Rectangular-shaped



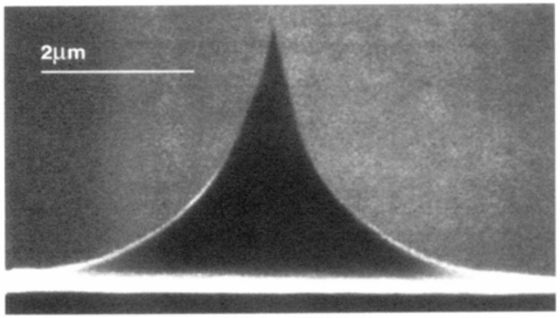
Materials: Si, SiO_2, Si_3N_4

Ideal Tips: hard, small radius of curvature, high aspect ratio

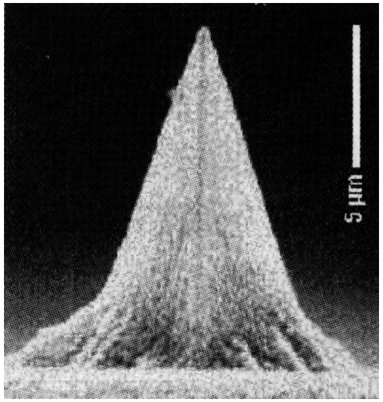
Pyramid Tip

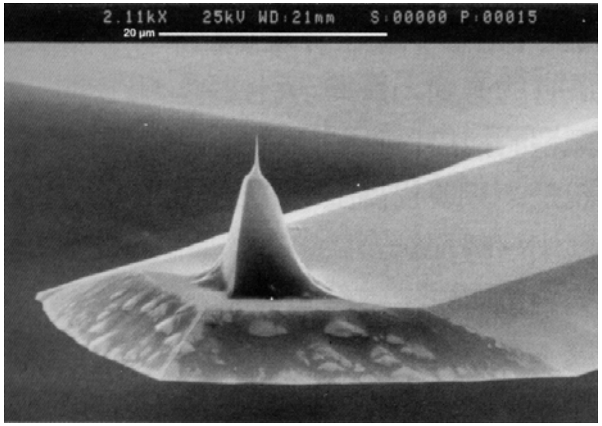


Ultrasharp Tip



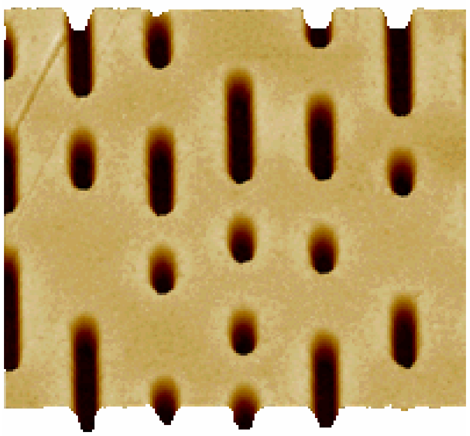
Diamond-coated Tip



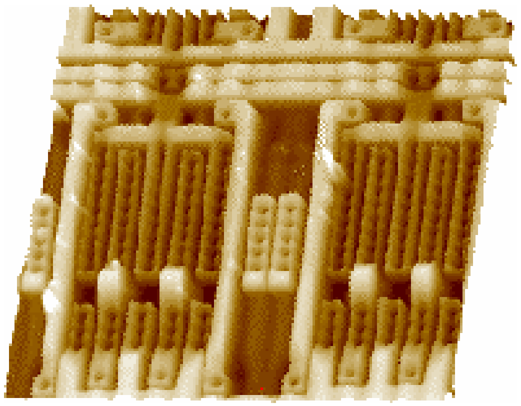


AFM images

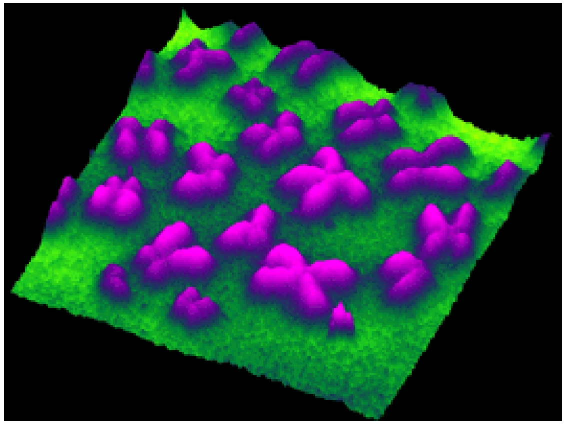
CD pits



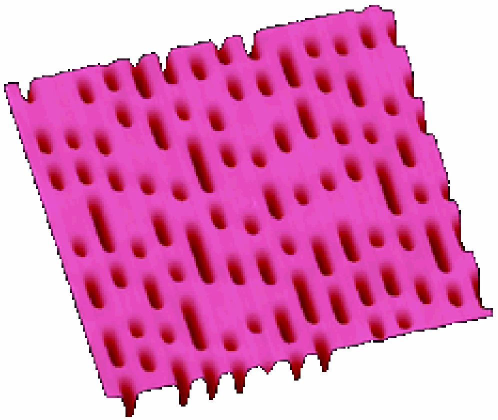
Integrated circuit



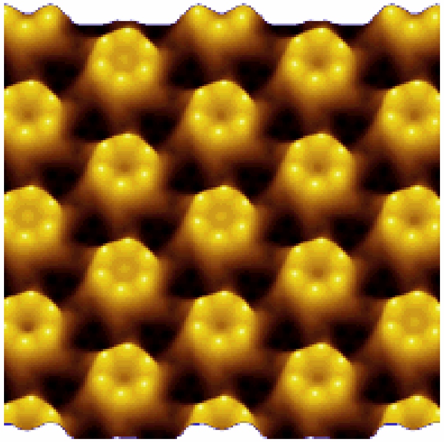
Chromosomes



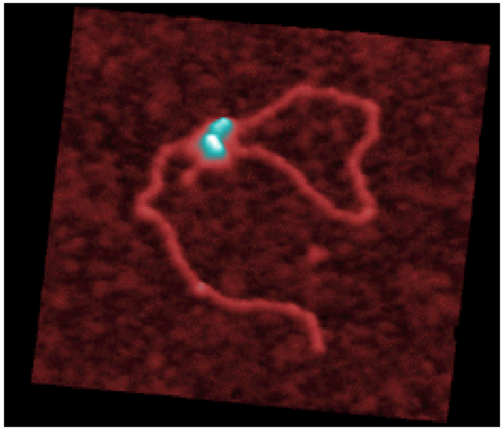
DVD pits



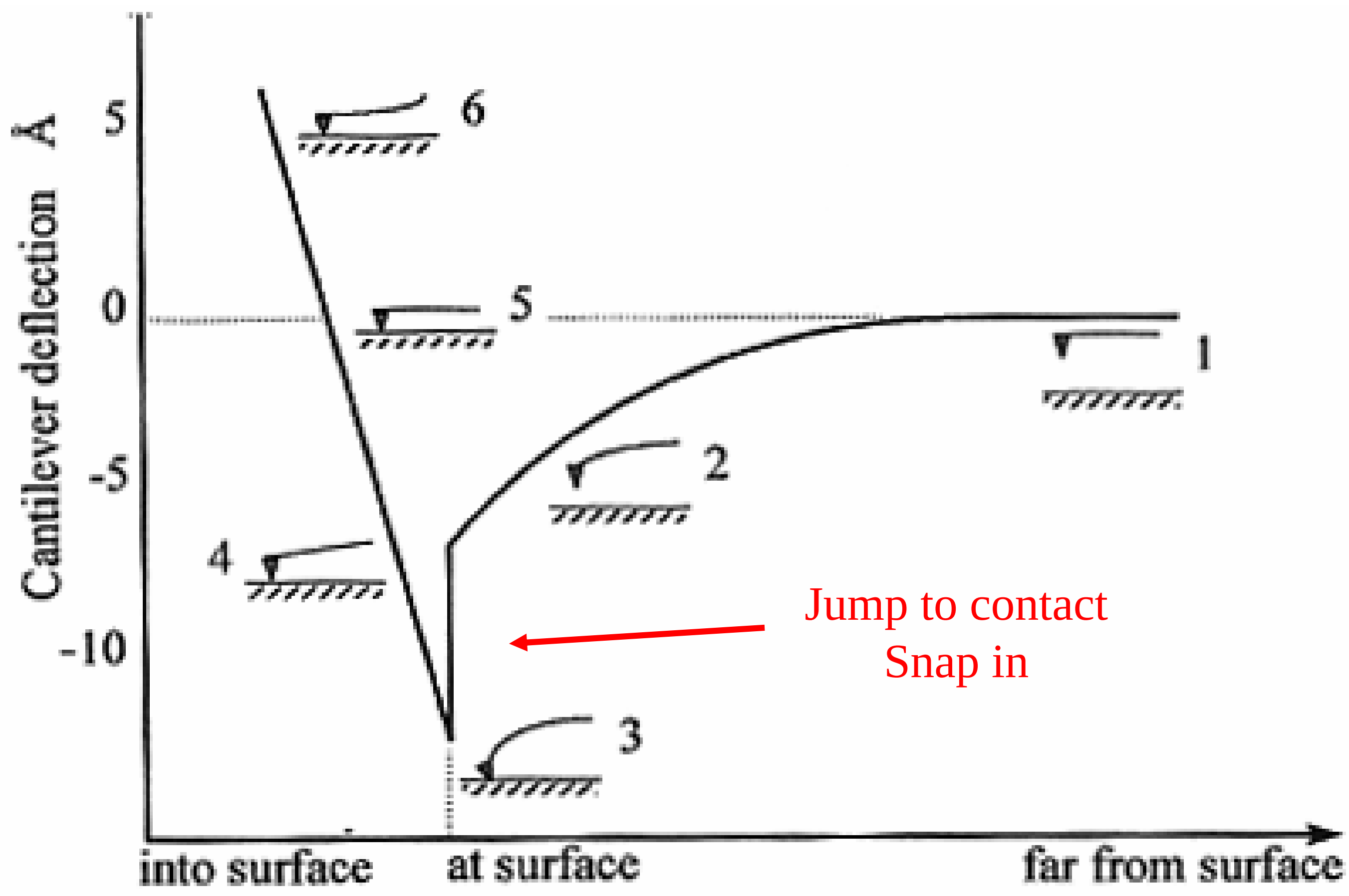
Bacteria



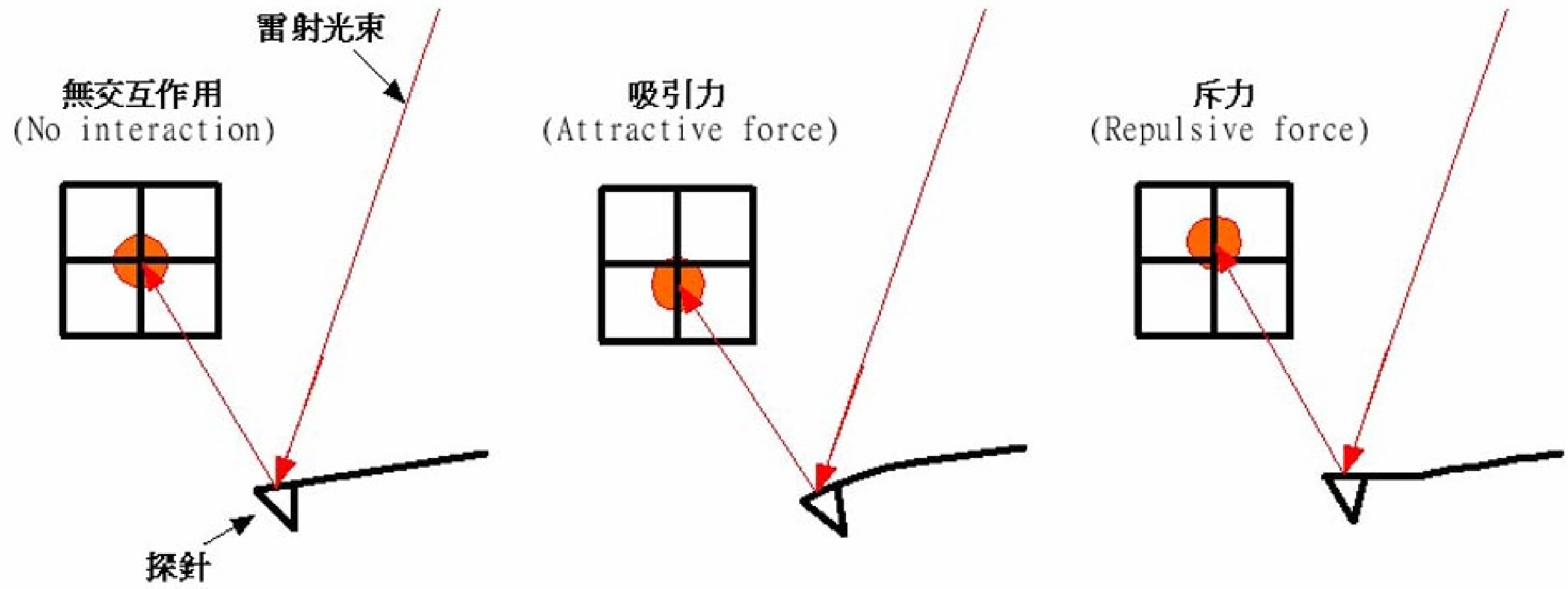
DNA



Ideal Force-Distance Curve



On a rigid sample in vacuum

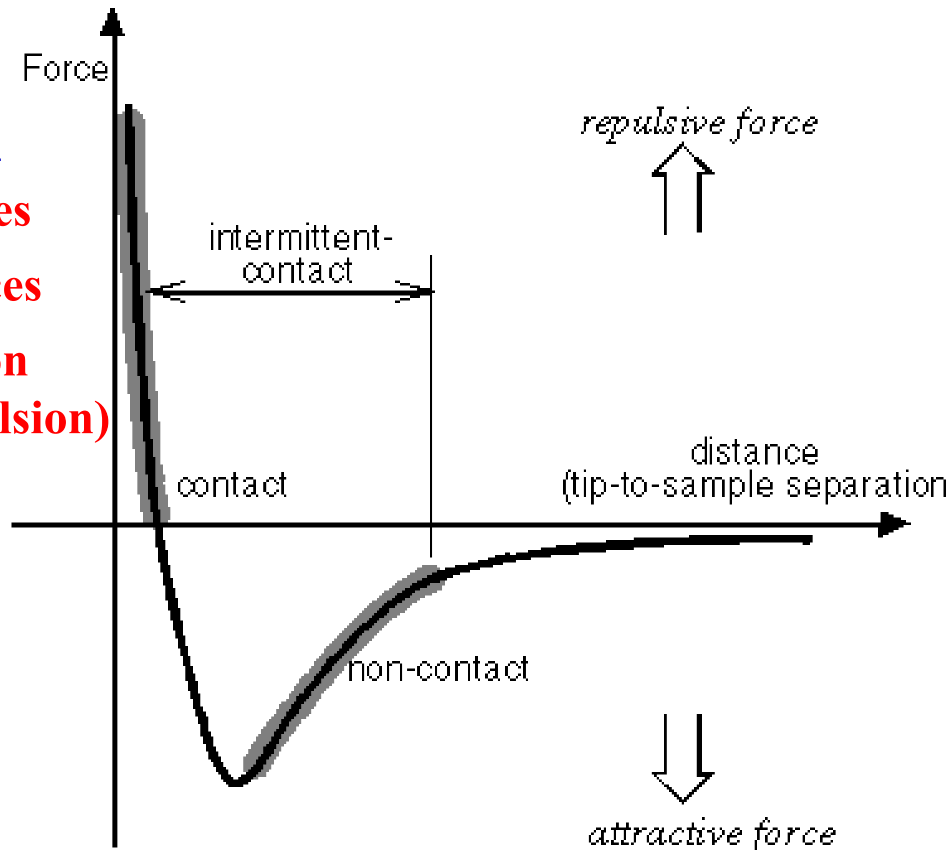


雷射光束
無交互作用
(No interaction)
吸引力
(Attractive force)
斥力
(Repulsive force)
探針

Forces between the Tip and the Sample

Short range forces:

1) Chemical forces
2) Repulsion forces
   (Pauli repulsion and ionic repulsion)



Long range forces:

1) Van der Waals (VDW) forces
2) Capillary forces
3) Magnetic forces
4) Electrostatic forces

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

1. The electromagnetic interaction is about forty orders of magnitude stronger than the gravitational interaction.
2. The attractive van der Waals interactions are caused by fluctuations in the electric dipole moment of atoms and their mutual polarization. They exist between all kinds of atoms or molecules and are effective for distance of a few Å to a few hundred Å. Force between atoms ≈ r^{-7}, between two planes ≈ r^{-3}, between a sphere and a plane ≈ r^{-2}.
3. Repulsive forces are very short ranged (≈ Å). $F \approx r^{-n}$ where $n > 8$.
4. Capillary forces: A layer of water condenses on the sample surface at normal relative humidity. The tip will be pulled down towards the sample by a strong liquid meniscus and "glued" to the sample. This is a major problem in AFM imaging.
5. Magnetic forces
6. Electrostatic (Coulombic) forces $F \approx r^{-2}$
7. Chemical forces: Ionic bonds, covalent bonds, metallic adhesive forces (metallic bonds). Attractive, very short ranged (falls off within a few Å).
8. The number of tip atoms that have an influence on the measurement depends on the nature of the interaction.
9. The environment must be taken into account (in gases, liquids, or vacuum). Dielectric constants and therefore VDW forces will be affected by the environment.
10. Scanning is a dynamic process, for instance, frictional forces.
11. The sample is not a rigid crystal. Elastic deformation or atomic relaxations?
12. Bonding between tip and sample might lead to a rearrangement of tip or sample atoms.

1. Most AFM studies are performed in the strongly repulsive regime. The repulsive force on the outermost tip atom is often underestimated because attractive long-range forces felt by tip atoms far from the outermost one can contribute significantly to the total force acting on the tip. In cases of tip radii of about 100 nm, the contribution of these long-range attractive forces might be as large as 10^{-8} N or even more. Thus while the total tip force might be attractive, the outermost tip atoms can still be in the strong repulsive force regime, eventually leading to a local surface deformation, particularly for soft elastic materials.

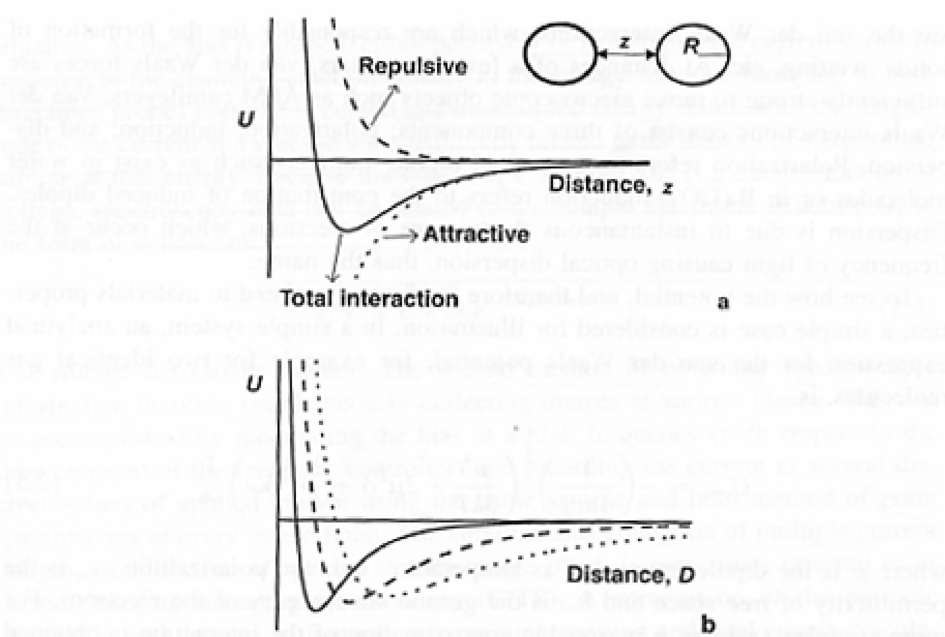
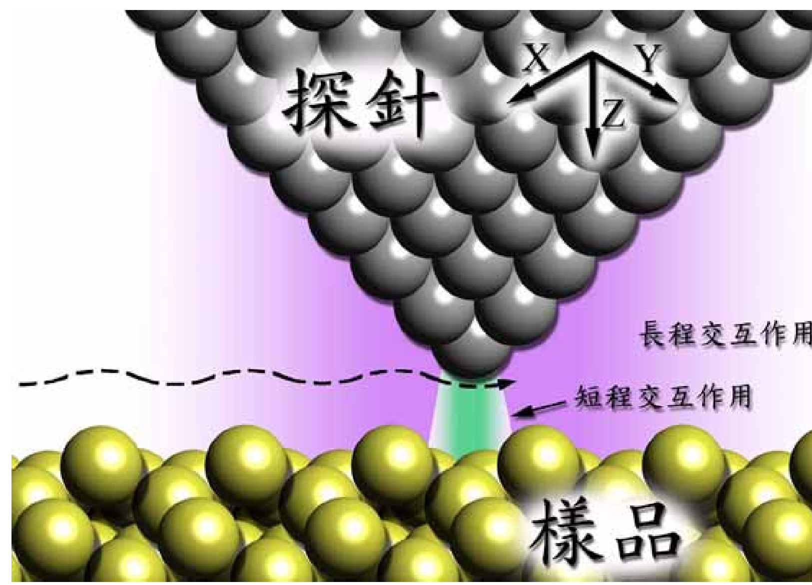
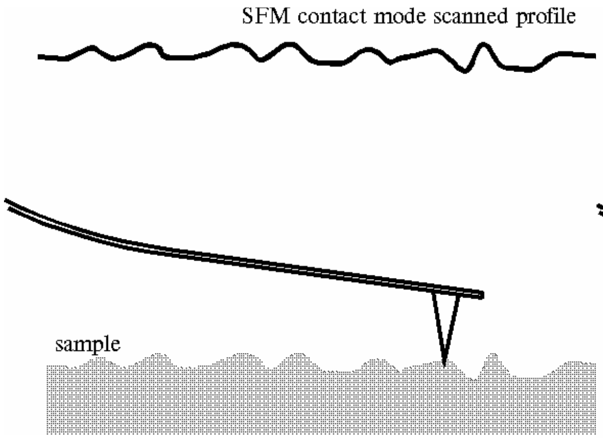


Figure 2.6. (a)The potential from an attractive van der Waals interaction (*dotted line*) and a hard wall repulsive interaction (*dashed line*) for two points showing the total interaction (*solid line*) as a sum of the two (b). The effect of geometry on the total potential is illustrated by comparing a point-point interactions (two molecules; *solid line*), a point-plane interaction (a molecule and a surface; *dashed line*) and a sphere-plane interaction (an AFM tip and a surface; *dotted line*). The power law decreases with larger components.



Three AFM Imaging Modes

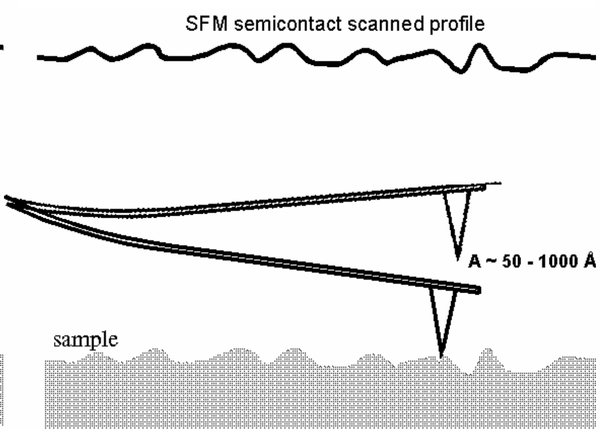
Contact Mode



接觸式

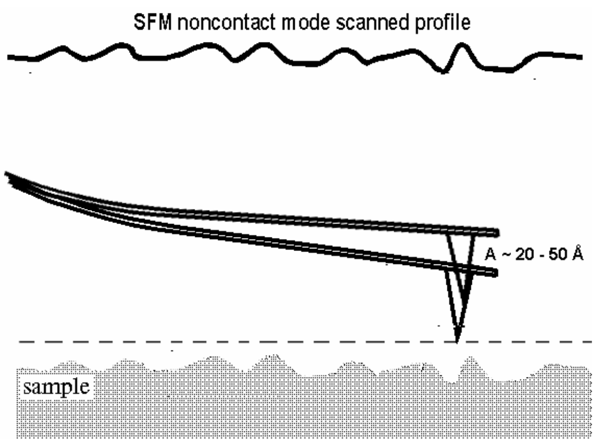
Tapping Mode

Semi-Contact Mode



暫接觸式

Non-Contact Mode



非接觸式

Contact Force Microscopy

1. In contact (dc) mode, cantilevers touches the surface while scanning in repulsive mode. Soft cantilevers are required for minimization of force. (k = 0.01-1.0 N/m)

2. AFM imaging operated at the contact mode can achieve a better resolution than non-contact and semi-contact modes.

3. It has been demonstrated that atomic-scale periodicities can be resolved by AFM operated in the contact mode with loading forces of 10^{-8} - 10^{-7} N. However, only the unit-cell periodicity is resolved, rather than the atomic or molecular structure within the unit cell.

A. Topography (constant force imaging)

The most common mode for AFM imaging. It measures topography with a constant force. The larger the cantilever is bent, the higher the imaging force the sample experiences. Contact mode exerts a significant shear or lateral force on the sample.

B. Force imaging (Constant height imaging)

Used for scanning relatively flat surfaces. (Z=const).

C. Force Curve Imaging

Force vs. distance curves are measured. This technique can also be used to analyse surface contaminants, viscosity, lubrication thickness, and local variations in the elastic properties of the surface.

Semi-Contact Mode (Tapping Mode)

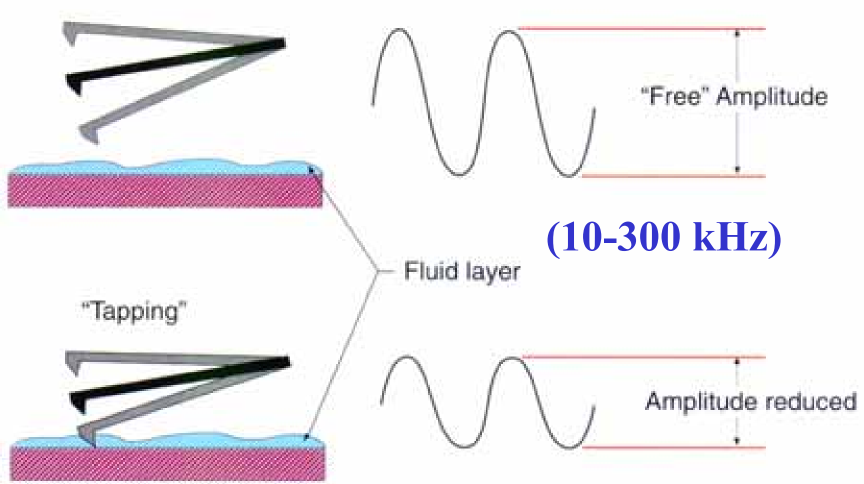
1. It measures topography by tapping the surface with an oscillating probe tip. The cantilever is oscillated near resonance so a high Q factor is important.

2. The purpose of this mode is to prevent the tip from being trapped by the capillary force. This technique can be used for non-destructive imaging of soft samples as well as of hard materials. Best achieved with a stiffer cantilever than for the contact mode. (k = 30-60 N/m)

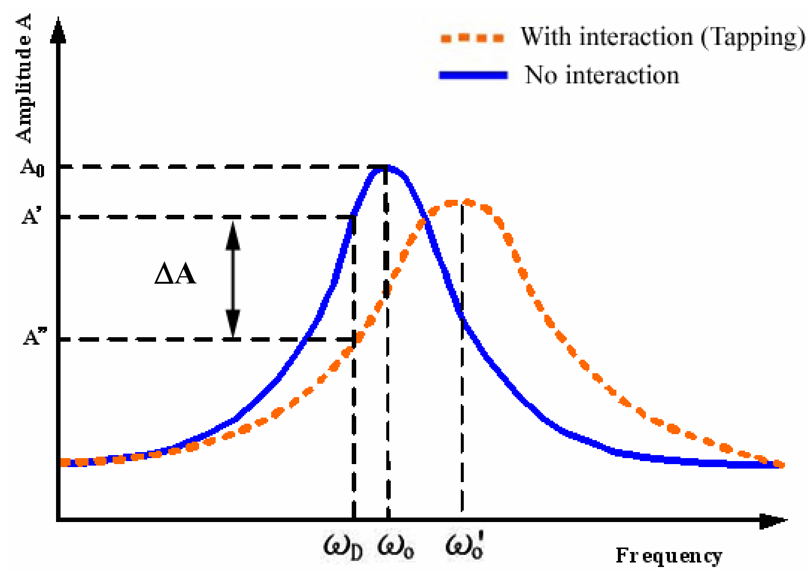
A. Topography (constant amplitude or constant force)

B. Phase imaging

One can obtain a contrast about variations of surface properties by mapping the phase of the cantilever oscillation during the semicontact mode scan. It is usually done simultaneously with topographic imaging.



(10-300 kHz)

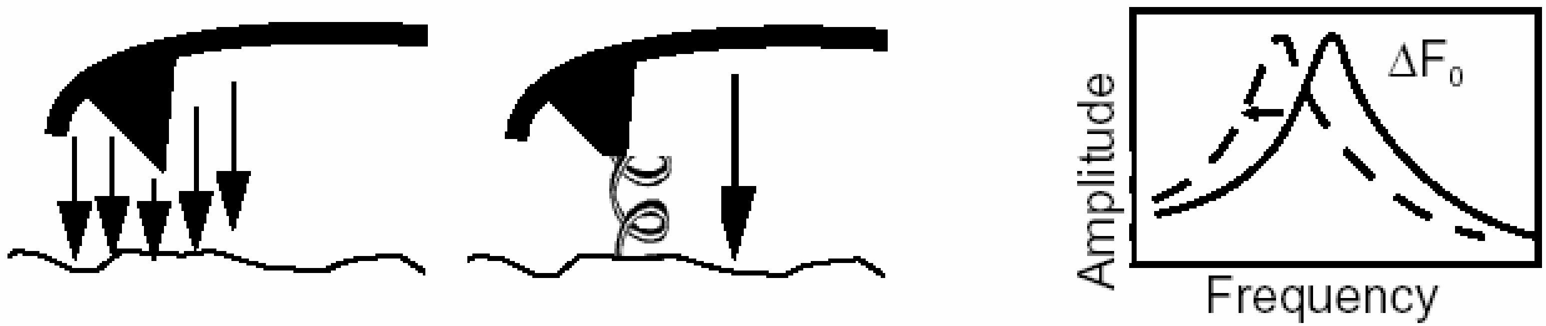


Resonance Frequency Shift

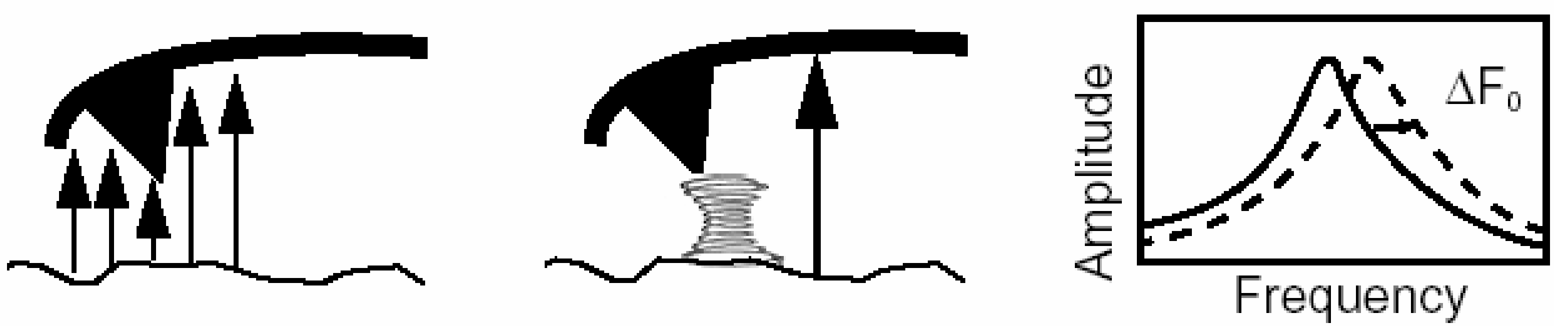
$$\underline{\Delta\omega} = \frac{\omega_0}{2k}\underline{\left(\frac{\partial f_{ts}}{\partial z}\right)}$$

Resonance frequency shift

Force gradient

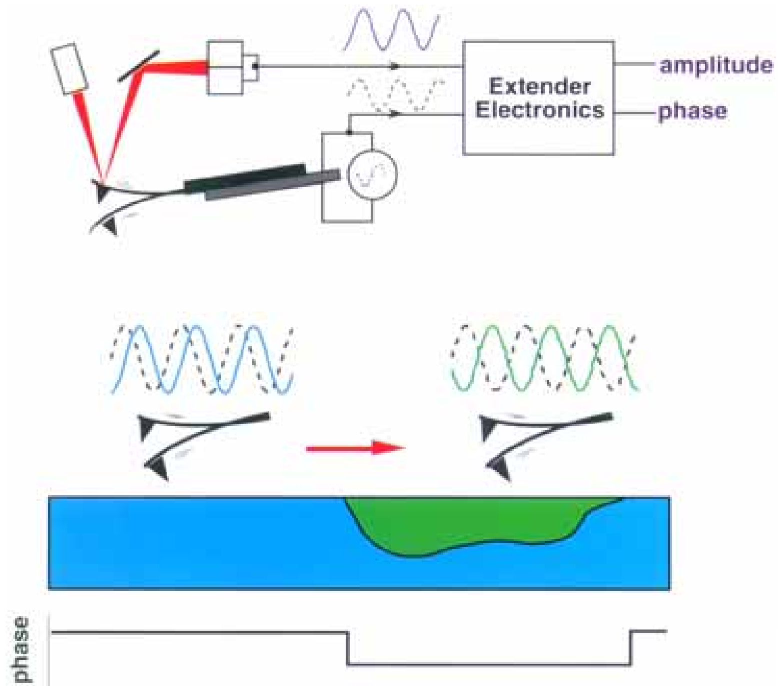


Attractive gradient equivalent to additional spring in tension attached to tip, reducing the cantilever resonance frequency.



Repulsive gradient equivalent to additional spring in compression attached to tip, increasing the cantilever resonance frequency.

Semi-Contact Mode (Tapping Mode)



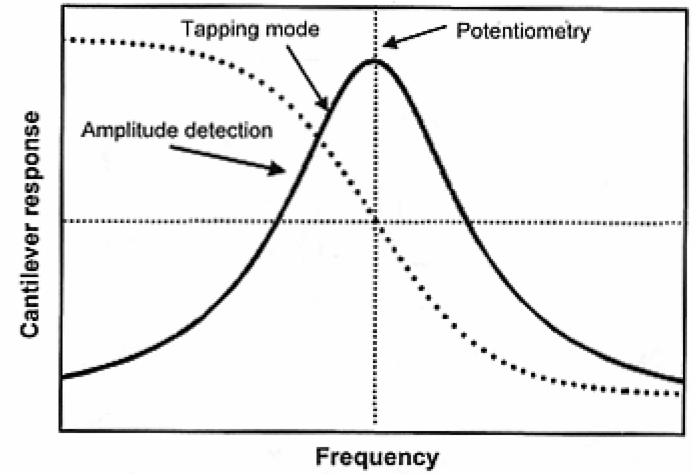
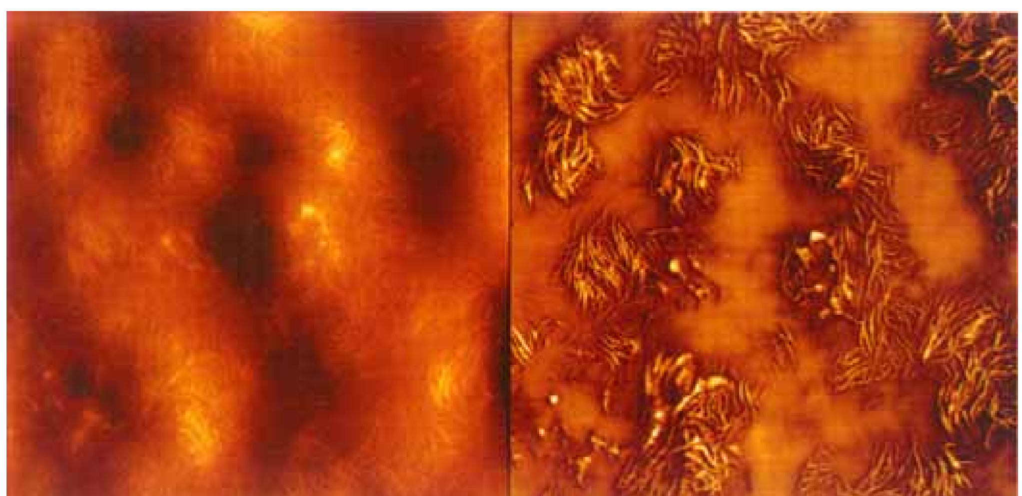


Figure 2.7. Frequency response of a typical AFM cantilever. The amplitude of the tip vibration as a function of driving frequency exhibits a peak that indicates the tip resonant frequency. The second line shows the phase of the cantilever oscillation.

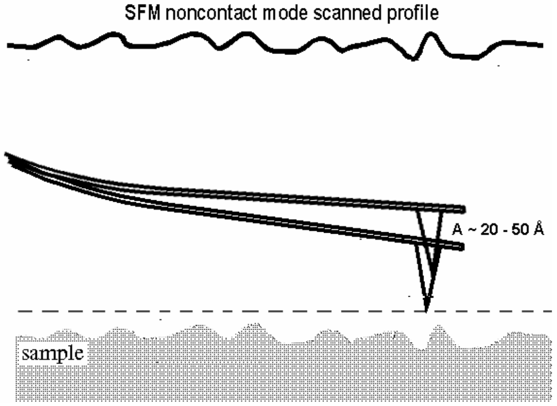
Height Image



Phase Image

Non-Contact Mode

1. The oscillation cantilever never actually touches the surface of the sample, but hovers a few nm above it, with an oscillation amplitude of only 5 nm.
2. This method provides measurement of van der Waals, electrostatic, magnetic forces near the surface. It allows investigation of very sensitive objects or those loosely coupled to a substrate surface without any destruction or displacement.
3. This mode is more complicated and less stable than the semicontact mode and the resolution is usually worse than in the semicontact mode. It is usually necessary to choose a fairly flexible cantilever with a low resonant frequency (k = 0.5-5 N/m). When imaging in air, the capillary force can easily trap such a tip, leaving it “glued” to the sample and halting its oscillation.
4. This mode can provide true atomic resolution in the UHV environment when combined with the frequency modulation technique.
5. It is also used in measurement of far-field forces (magnetic, electrostatic etc.) on a distance from a surface (Lift Mode or two-pass mode).



Cantilever Deflection Measurement Techniques

Requirements

1. A high sensitivity at the sub-Å unit level is needed.
2. The detection should have negligible influence on the cantilever deflection and should not cause imaging artifact.
3. The detection system should be easy to implement.

Major Techniques

A. Tunneling detection: the first method but unreliable to operate

a. Electron tunneling is extremely sensitive to the surface conditions.
b. Tunneling detection changes the effective spring constant of the cantilever.
c. The presence of thermal drifts can cause considerable problems.

B. Capacitance detection: Capacitance readout is based on measuring the capacitance between a conductor on the cantilever and another fixed conductor on the substrate that is separated from the cantilever by a small gap.

a. Changes in the gap due to cantilever deformation result in changes in the capacitance.
b. The detection sensitivity increases as the distance between two electrodes decreases.
c. The attractive electrostatic force between two electrodes also becomes large at small distance. Therefore, the force constant of the cantilever varies with capacitance.
d. Compact, UHV-compatible, and easy to configure, but is susceptible to temperature induced drift of the reference capacitor used in the measurement circuitry.

C. Laser beam deflection (optical lever): The simplest optical method. Most AFM designs used nowadays adopt this method.

a. The cantilever displacement is measured by detecting the deflection of the laser beam which is reflected off the rear side of the cantilever. The direction of the reflected laser beam is sensed by a position-sensitive detector (PSD). Sub-Å unit sensitivity is routinely achieved.

b. It requires a mirror-like surface at the rear side of the cantilever. The cantilever must be large enough to reflect light without introducing too much diffraction.

D. Optical interferometry: A fiber-optic technique that places a reference reflector with micrometers of the cantilever. The cantilever deflection measurement is based on the optical interference occurring in the micrometer-size cavity formed between the cleaved end of a single-mode optical fiber and the cantilever.

a. Superior signal to noise ratio, but harder to setup and susceptible to thermal drift.

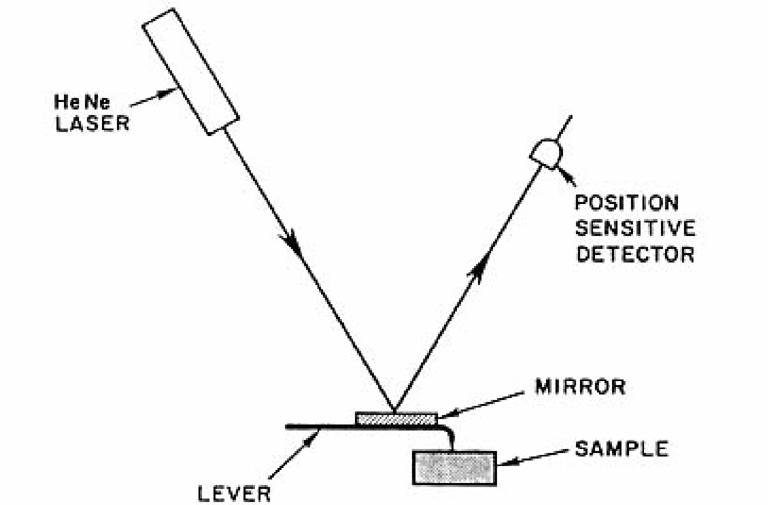
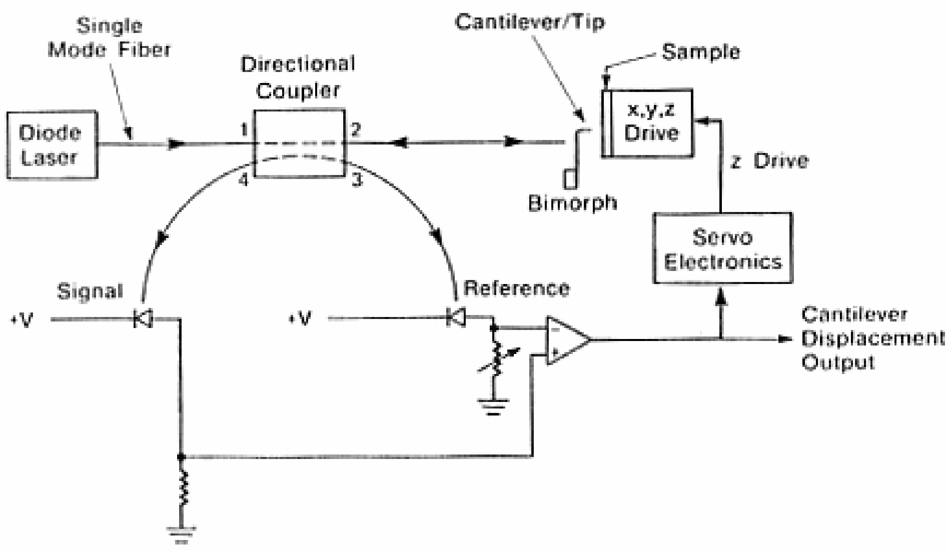
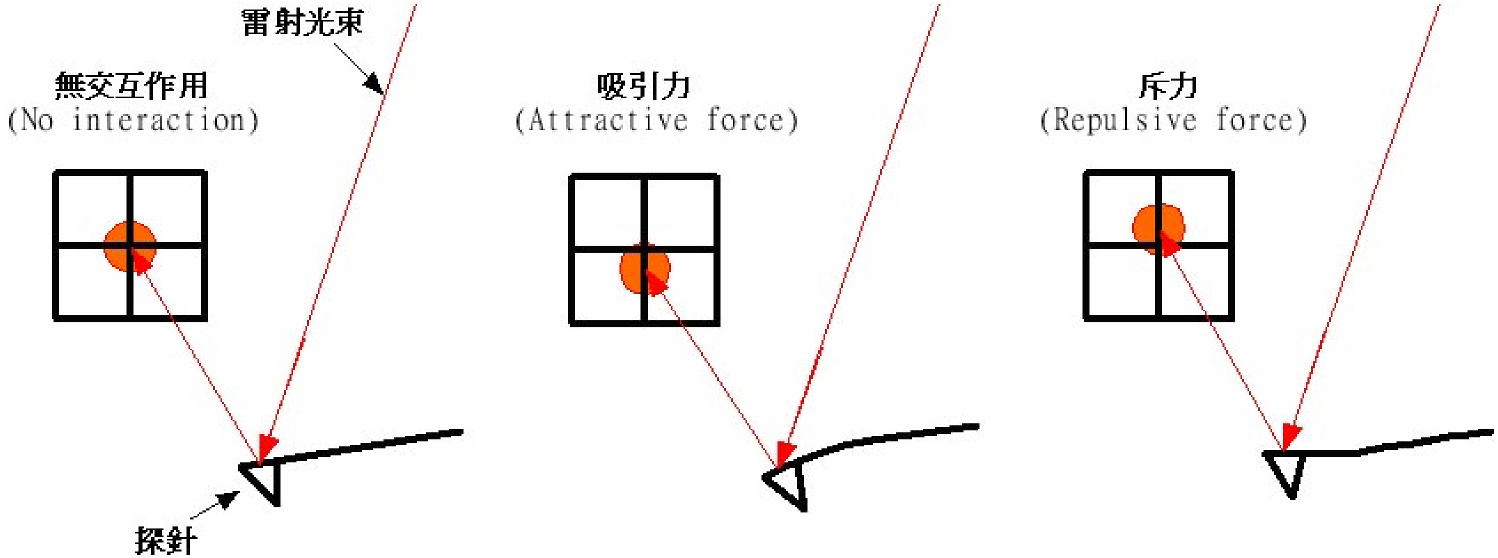
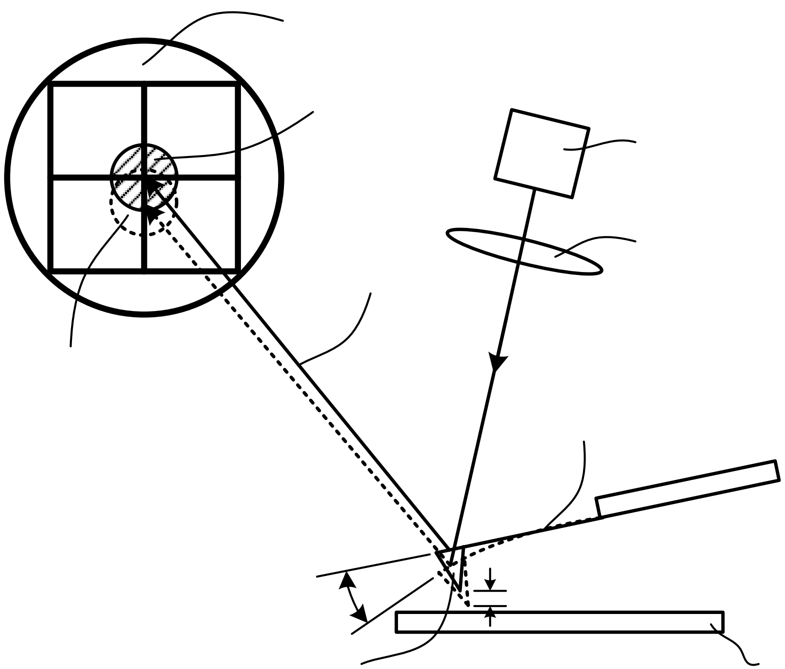


Fig. 2.7. Cantilever deflection detection scheme (Meyer and Amer, 1988).



Laser Beam Deflection





$$\delta_z = \frac{4}{Ew}\left(\frac{L}{t}\right)^3 F \quad \text{......(1)}$$

$$\theta = \frac{6}{Ewt}\left(\frac{L}{t}\right)^2 F \quad \text{......(2)}$$

$$\frac{\theta}{\delta_z} = \frac{3g}{2L} \quad \text{......(3)}$$

$$\delta_{PSD} = \tan 2\theta \cdot D = D \cdot \frac{3g\delta_z}{L} \quad \text{......(4)}$$

$$S_v = \frac{(S_A + S_B) - (S_C + S_D)}{(S_A + S_B + S_C + S_D)} \quad \text{......(5)}$$

F: interaction force;
L: length of the cantilever;
w,*t*: width and thickness of the cantilever, respectively;
g: geometric factor;
E:modulus of elasticity;
δ_{PSD} : displacement of laser beam on PSD.

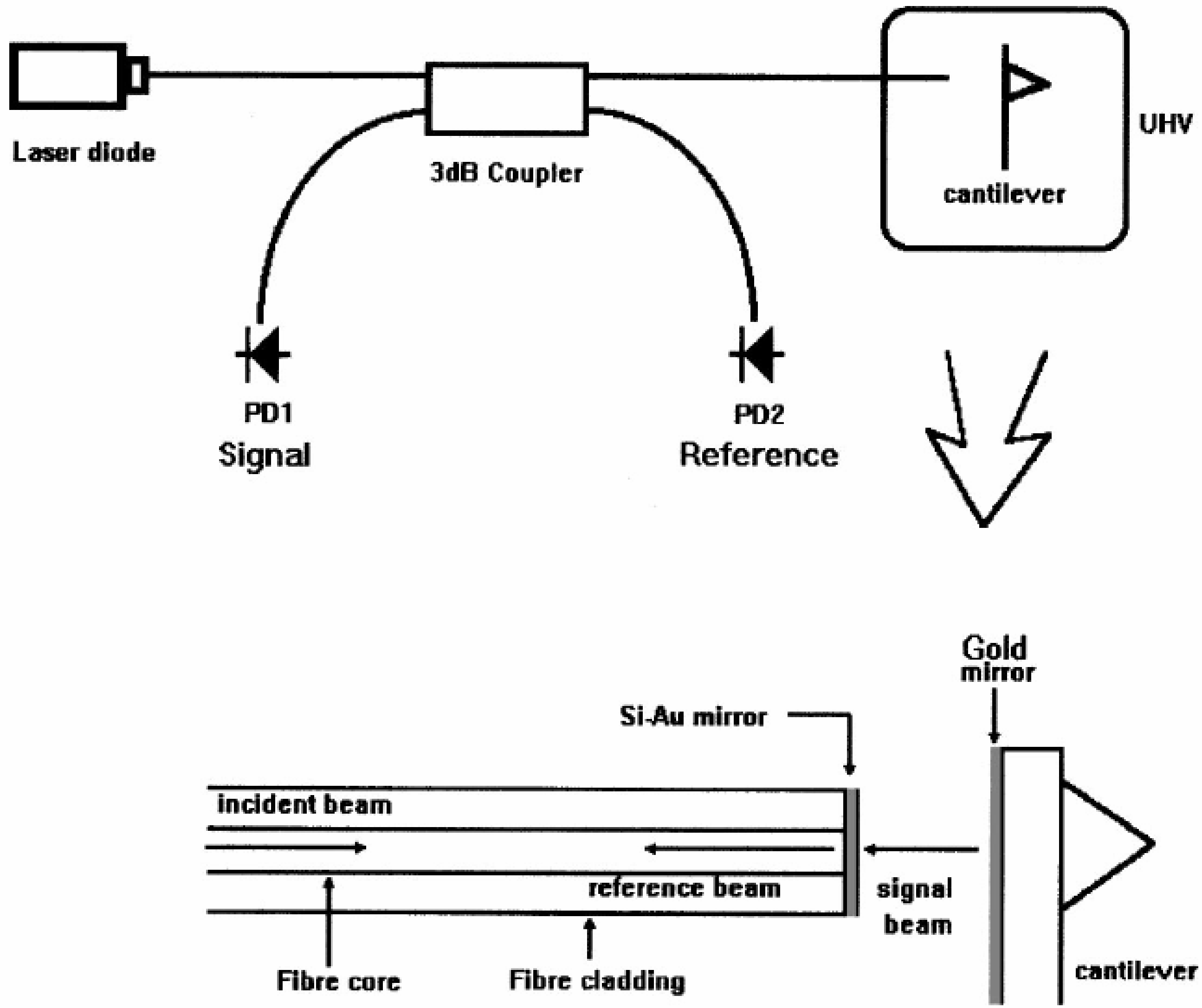


FIG. 4. All-fiber interferometer.

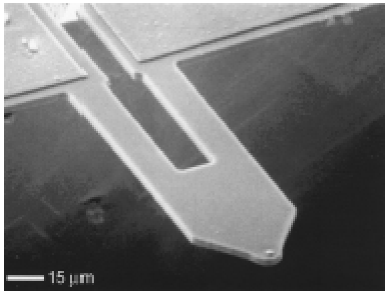
E. **Piezoresistance method**:

a. Piezoresistivity is the phenomenon of changes in the bulk resistivity with applied stress.

b. When a silicon cantilever with an appropriately shaped doped region is deformed, the change in the resistance of the doped region reflects the degree of the deformation.

c. Piezoresistive cantilevers are usually designed to have two identical ‘‘legs’’.

d. Disadvantage: It requires current to flow through the cantilever, which results in additional dissipation of heat and associated thermal drifts.



D. **Piezoelectric method**:

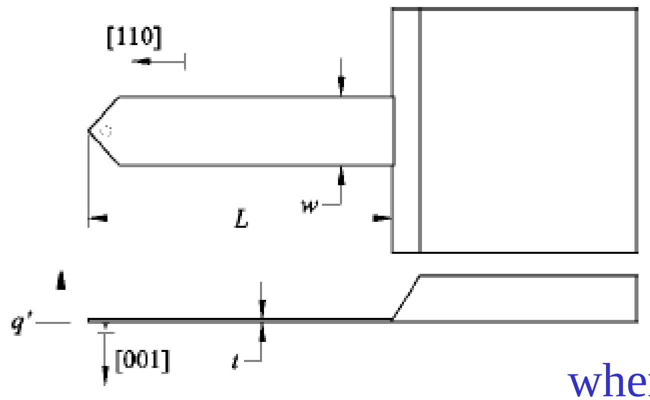
a. Due to a piezoelectric effect, transient charges are induced in the piezoelectric layer when a cantilever is deformed.

b. Piezoelectric readout technique requires deposition of piezoelectric material, such as ZnO, on the cantilever.

c. Disadvantages:

1. It requires electrical connections to the cantilever (as piezoresistance readout).
2. In order to obtain large output signals it requires the thickness of the piezoelectric film to be well above the values that correspond to optimal mechanical characteristics.
3. The piezoelectric readout is inefficient when slowly changing cantilever deflections need to be measured.

Microfabricated Cantilever



spring constant k $$k = \frac{Ywt^3}{4L^3},$$

where Y is Young's modulus.

The fundamental eigenfrequency f_0

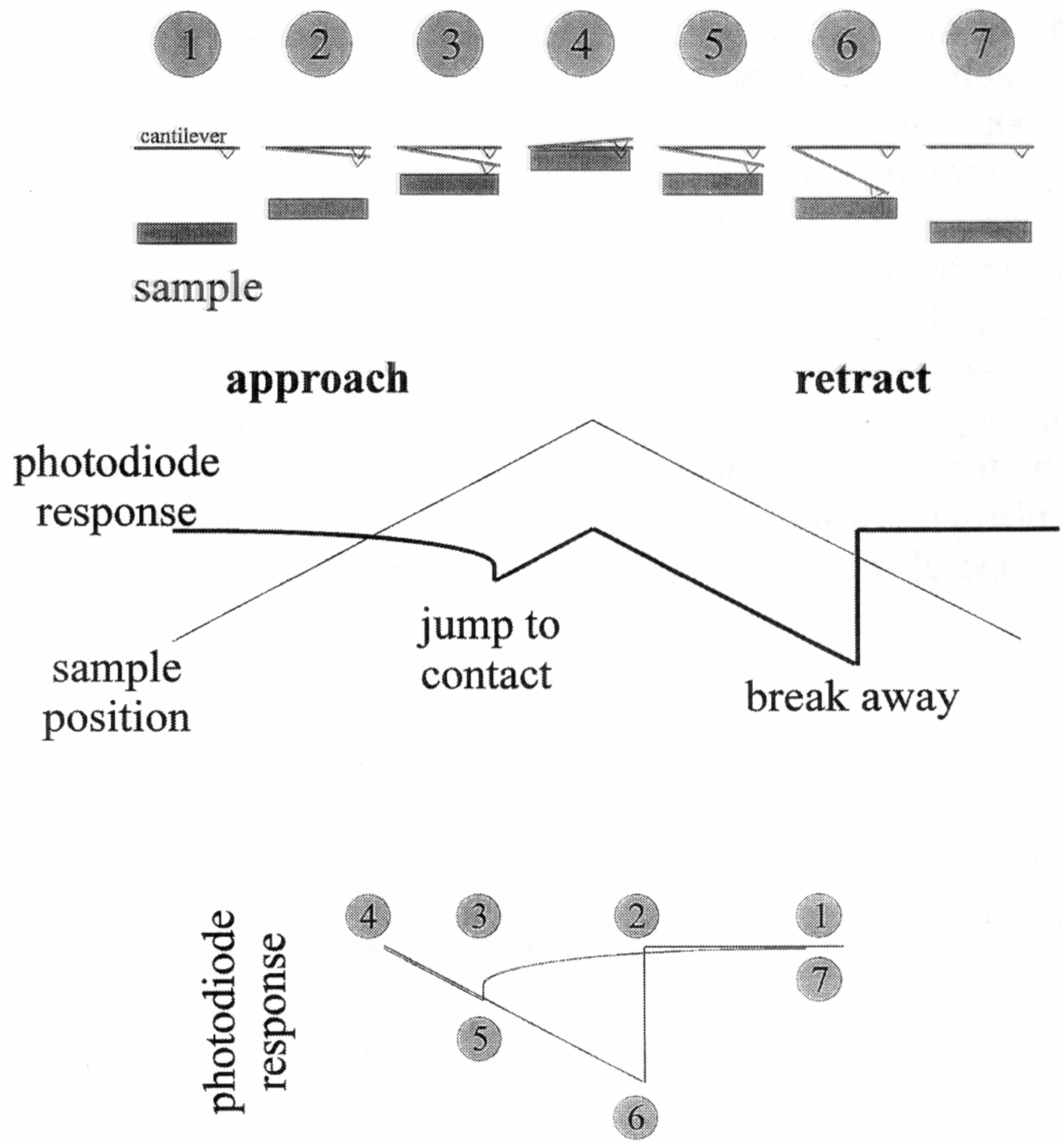
$$f_0 = 0.162 \frac{t}{L^2} \sqrt{\frac{Y}{\rho}},$$

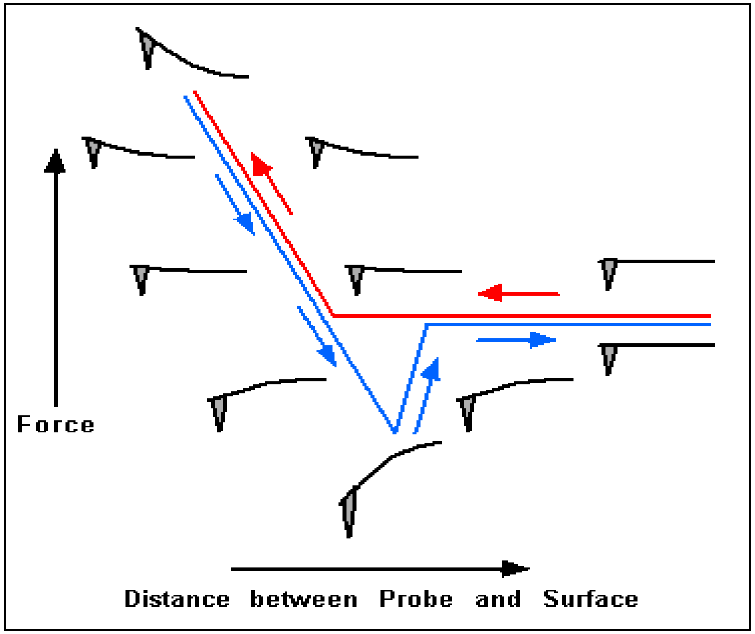
where ρ is the mass density of the cantilever material.

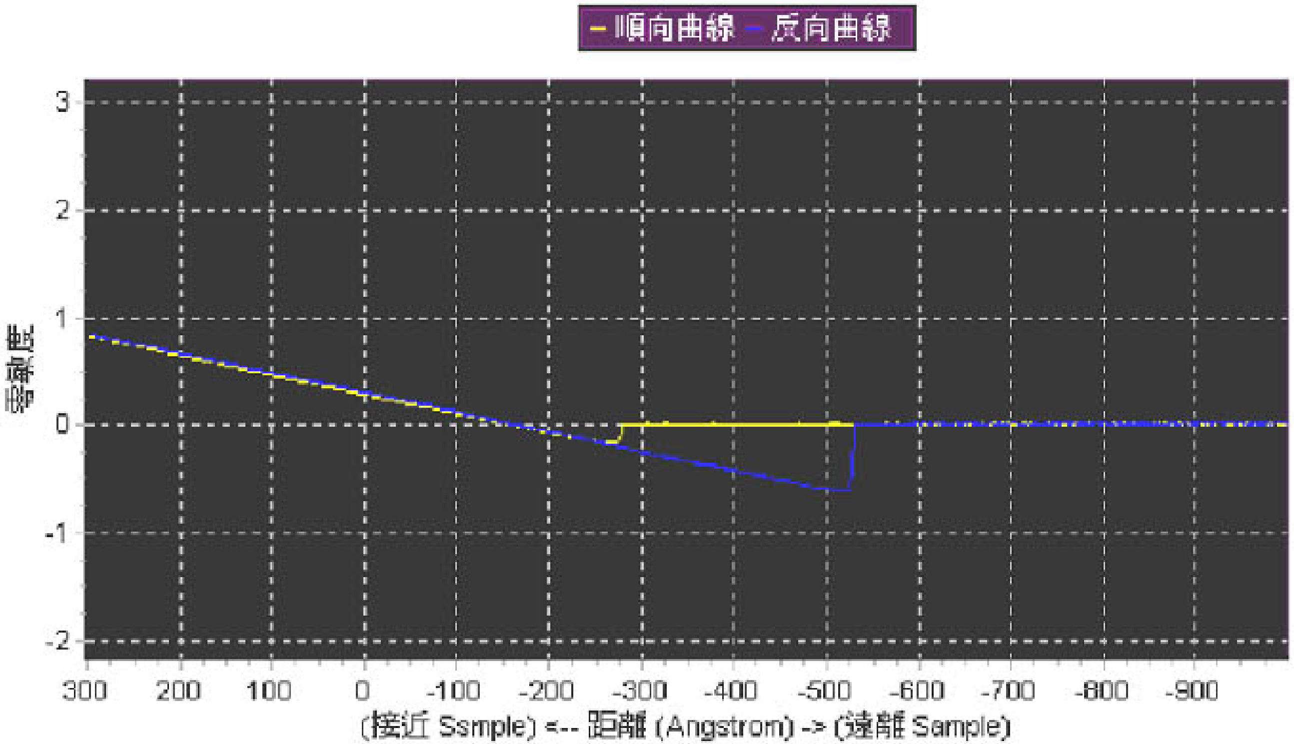
The properties of interest are the stiffness k, the eigenfrequency f_0 , the quality factor Q, the variation of the eigenfrequency with temperature $\partial f_0 / \partial T$, and of course the chemical and structural composition of the tip.

The Q factor depends on the damping mechanisms present in the cantilever. For micromachined cantilevers operated in air, Q is mainly limited by viscous drag and typically amounts to a few hundred, while in vacuum, internal and surface effects in the cantilever material are responsible for damping and Q reaches hundreds of thousands.

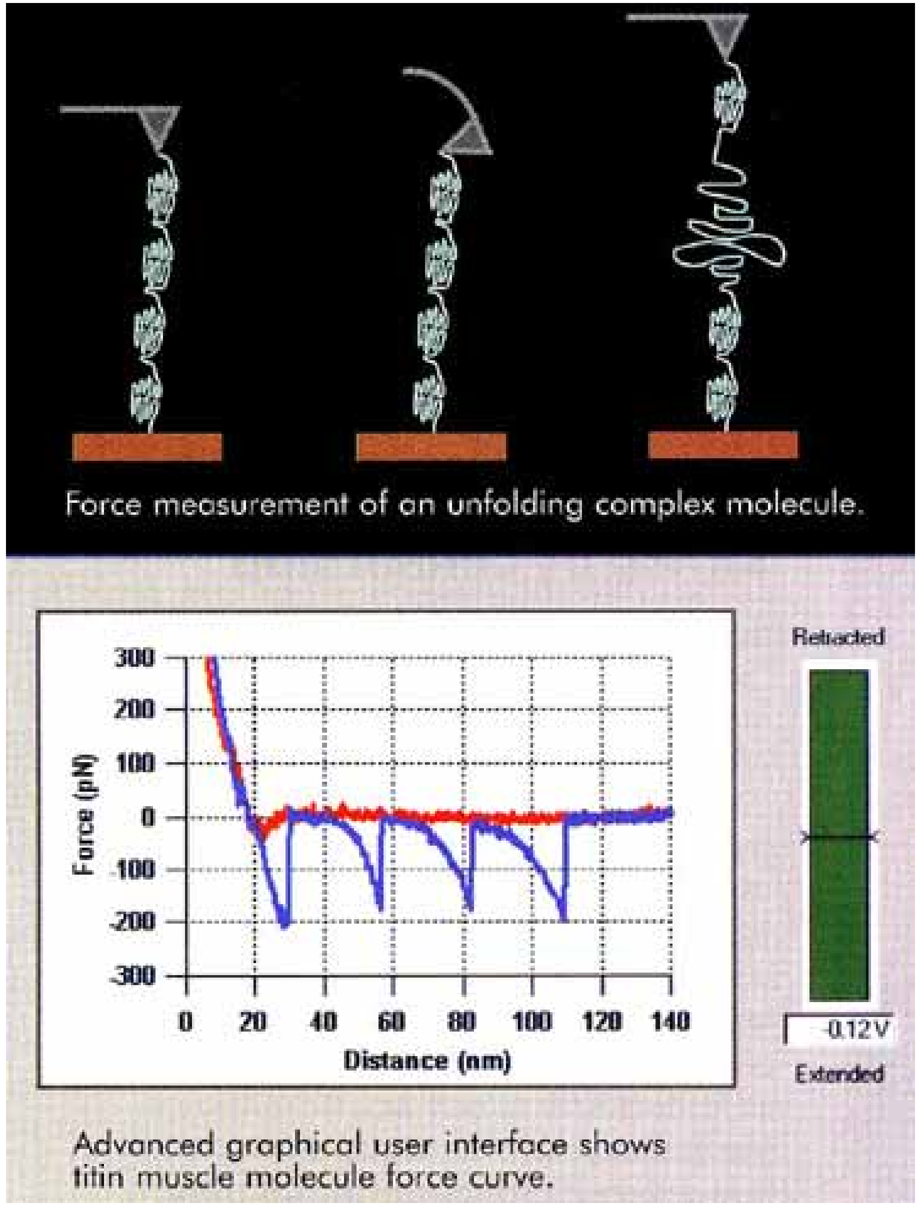
Force-Distance Curve contact-mode




Force
Distance between Probe and Surface


順向曲線 反向曲線
靈敏度
3
2
1
0
-1
-2
300
200
100
0
-100
-200
-300
-400
-500
-600
-700
-800
-900
(接近 Ssmple) <-- 距離 (Angstrom) -> (遠離 Sample)

Single Molecule Force Spectroscopy



Dynamic AFM

1. In the dynamic operation modes, the cantilever is deliberately vibrated. The cantilever is mounted on an actuator to allow the external excitation of an oscillation. There are two basic methods of dynamic operation: amplitude-modulation (AM) and frequency-modulation (FM). In AM-AFM, the actuator is driven by a fixed amplitude A_{drive} at a fixed frequency f_{drive} , where f_{drive} is close to but different from f_0 . When the tip approaches the sample, elastic and inelastic interactions cause a change in both the amplitude and the phase (relative to the driving signal) of the cantilever. These changes are used as the feedback signal. The change in amplitude in AM mode does not occur instantaneously with a change in the tip-sample interaction, but on a time scale of $\tau_{AM}=2Q/f_{o}$. With Q factors reaching 100 000 in vacuum, the AM mode is very slow. Albrecht et al. solved this problem by introducing the frequency-modulation (FM) mode, in which the change in the eigenfrequency occurs within a single oscillation cycle on a time scale of $\tau_{FM}=1/f_{o}$.
2. This technique can achieve high sensitivity (better than 10^{-5} N/m) and useful in vacuum, where Q values in excess of 10^{4} are easily achieved.

1. Albrecht et al., J. Appl. Phys. 69, 668 (1991).
2. Franz J. Giessibl, **Advances in atomic force microscopy**, REVIEWS OF MODERN PHYSICS, VOLUME 75, JULY 2003

Frequency-Modulation AFM

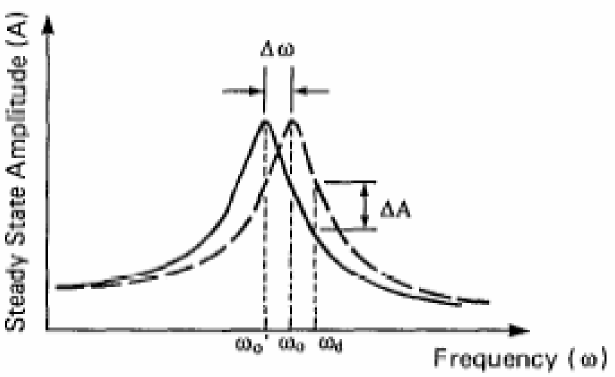
1. In the frequency-modulation (FM) method, the cantilever serves as the frequency-determining element of a constant amplitude oscillator. The frequency of the oscillator output is instantaneously modulated by variations in the force gradient acting on the cantilever . With FM detection, the S/N for a given bandwidth has the same dependence on Q as the conventional system.

Resonance Frequency Shift

$$\Delta\omega = \frac{\omega_0}{2k}\left(\frac{\partial f_{ts}}{\partial z}\right)$$

Resonance frequency shift

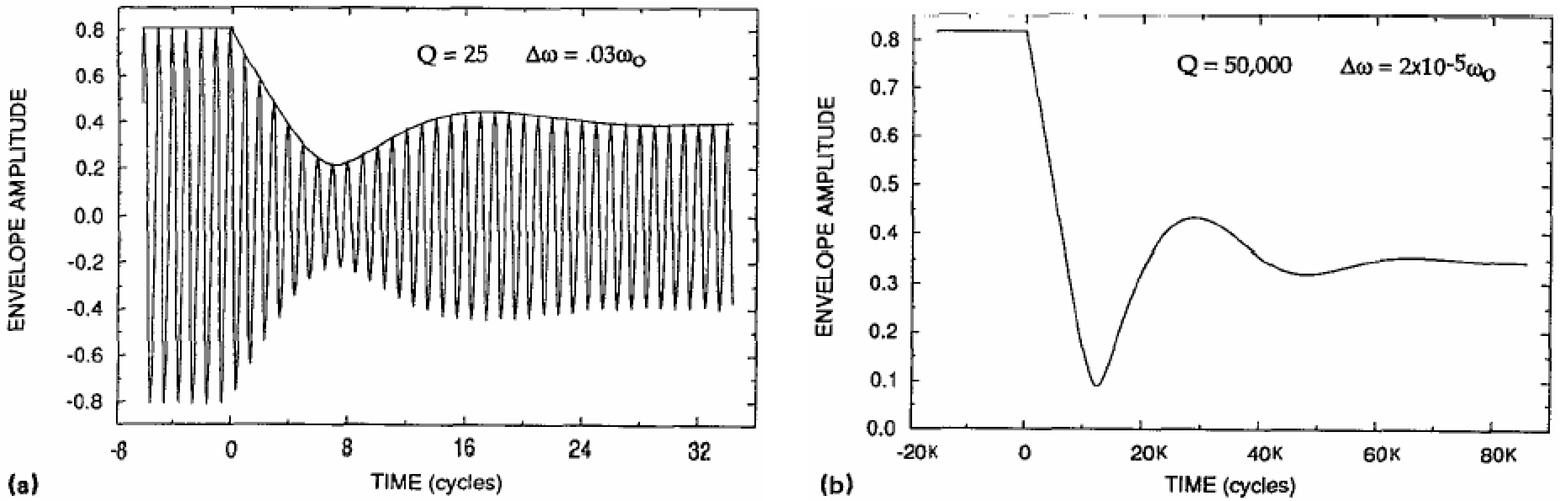
Force gradient



Minimum detectable force gradient

$$\delta F'_{\min} = \sqrt{2k_L k_B TB / \omega_0 Q \langle z^2_{\mathrm{osc}} \rangle},$$

Simulation of the amplitude response in slope detection for an instantaneous change in the resonant frequency at time t = 0. For t < 0, the cantilever is vibrating in a steady state.

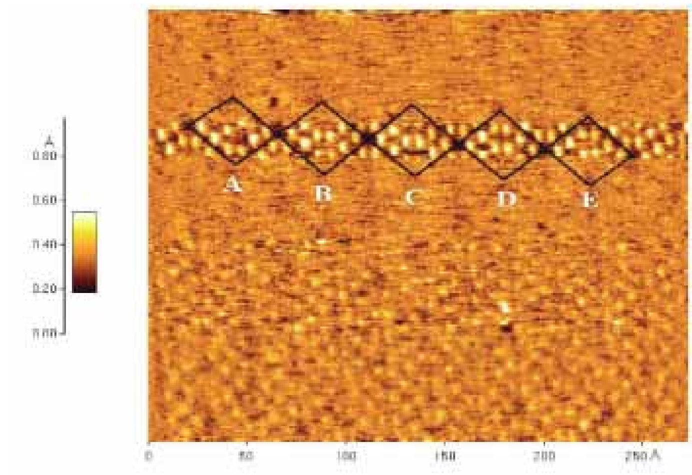


1. Low-Q values offer fast response, but low sensitivity, while high-Q values offer high sensitivity but slow response.
2. High-Q cantilevers have less thermal noise off resonance, which has the effect of reducing the noise level in both slope and FM detection.

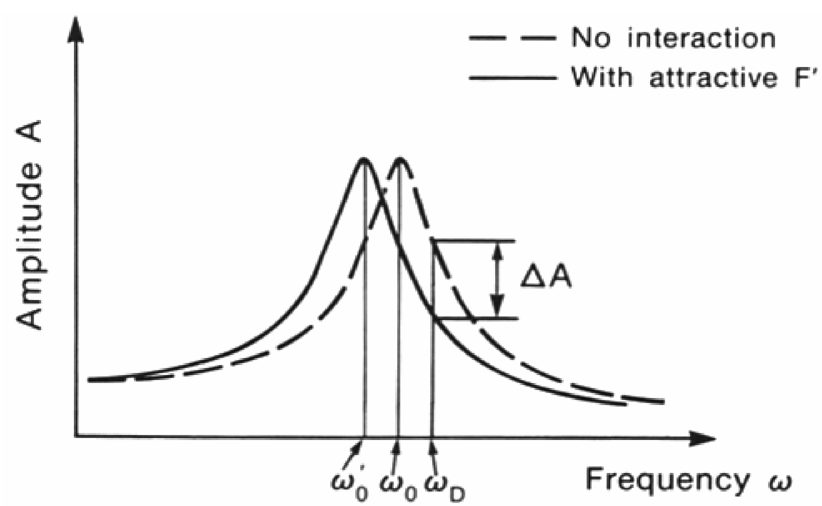
Albrecht et al., J. Appl. Phys. 69, 668 (1991).

Frequency-Modulation AFM

In 1995, Giesssibl succeeded in obtaining noncontact AFM (NC-AFM) images of the Si(111)7x7 surface with atomic resolution in UHV using a FM detection method.



Piezoresistive cantilevers
k = 17 N/m,
f_o = 114 kHz,
A = 34 nm,
Δf = -70 Hz,
Q = 28 000.

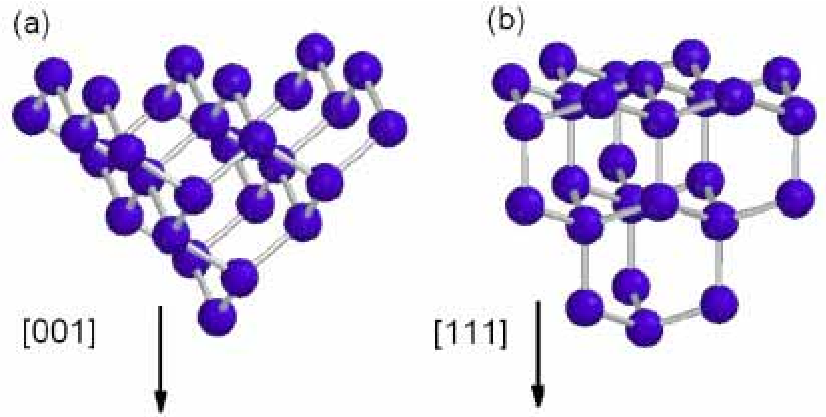


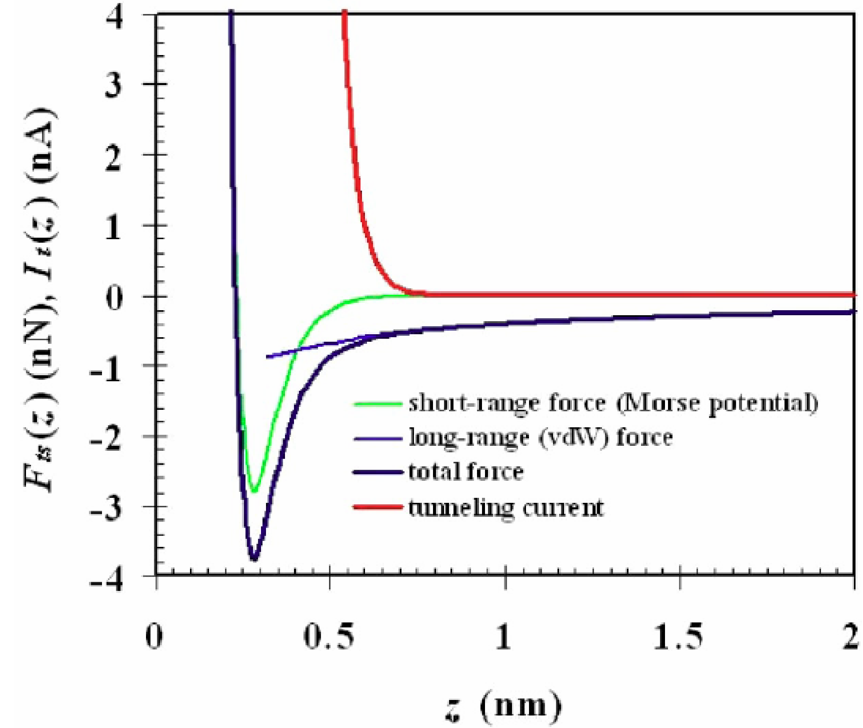
Principles of resonance detection in non-contact force microscopy. A change in force gradient F' causes a shift in the resonance curve. When the cantilever is driven at a fixed frequency ω_D, this results in a change in the oscillation amplitude ΔA. Alternatively, the shift in resonant frequency from ω_0 to ω_0' can be detected directly with an FM technique

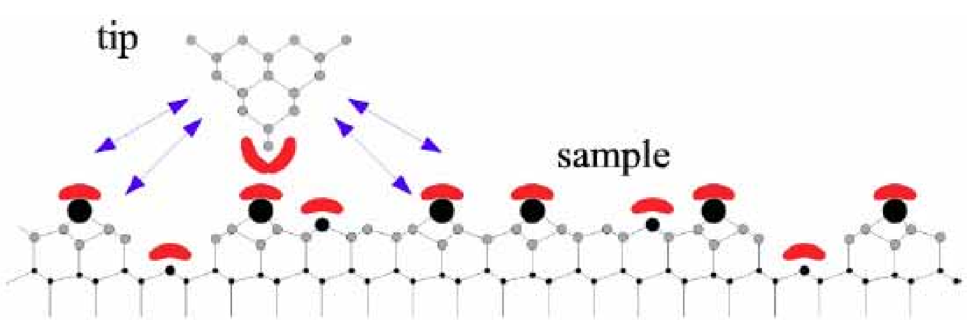
Challenge Faced by AFM with respect to STM

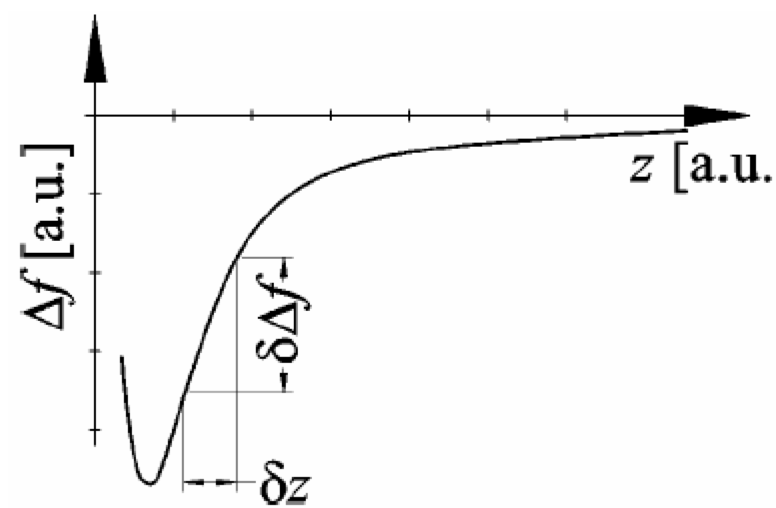
1. Implementing an AFM capable of atomic resolution is much more difficult than a STM.
2. The tunneling current is a monotonic function of the tip-sample distance and increases sharply with decreasing distance. As a consequence, even with a relatively blunt tip the chance is high that a single atom protrudes far enough out of the tip that it carries the main part of the tunneling current. In contrast, the tip-sample force has long- and short-range components and is not monotonic.
3. When a tip approaches a sample, a sudden jump-to-contact can occur when the stiffness of the cantilever is less than a certain value. This instability occurs in the quasistatic mode if $k < \max(\partial^2 V_{ts}/ \partial z^2)$. This can be avoided even for soft cantilevers by oscillating the cantilever at a large enough amplitude A: $kA > \max(-F_{ts})$.
4. In general, the force is attractive for large distances, and upon decreasing the distance between tip and sample, the force turns repulsive. Stable feedback is only possible on a branch of the force curve, where it is monotonic. Thus, it is much easier to establish a z distance feedback loop for an STM than for an AFM.
5. For imaging by AFM with atomic resolution, it is desirable to filter out the long-range force contributions and measure only the force components that vary at the atomic scale. While electrostatic, magnetic, and meniscus forces can be eliminated by equalizing the electrostatic potential between tip and sample, using nonmagnetic tips, and operating in vacuum, the van der Waals forces cannot be switched off. In *static* atomic force microscopy, long- and short-range forces add up to the imaging signal. In *dynamic* atomic force microscopy, attenuation of the long-range contributions is achieved by proper choice of the cantilever's oscillation amplitude A.

FM-AFM







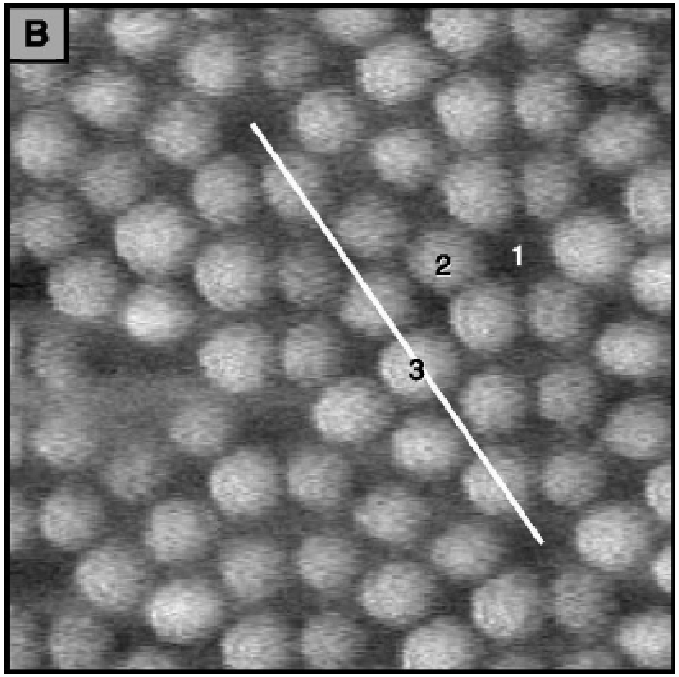


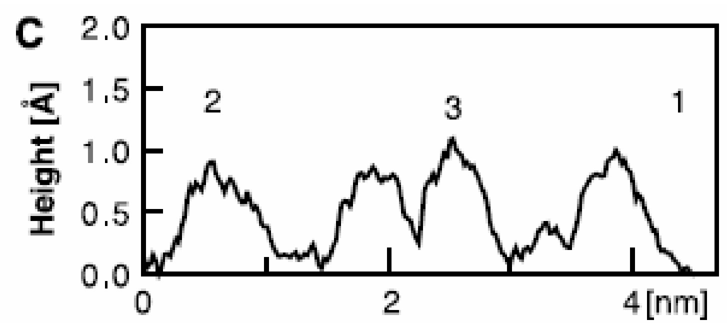
Franz J. Giessibl: Advances in atomic force microscopy

Rev. Mod. Phys., Vol. 75, No. 3, July 2003

UHV-AFM

7.2 K

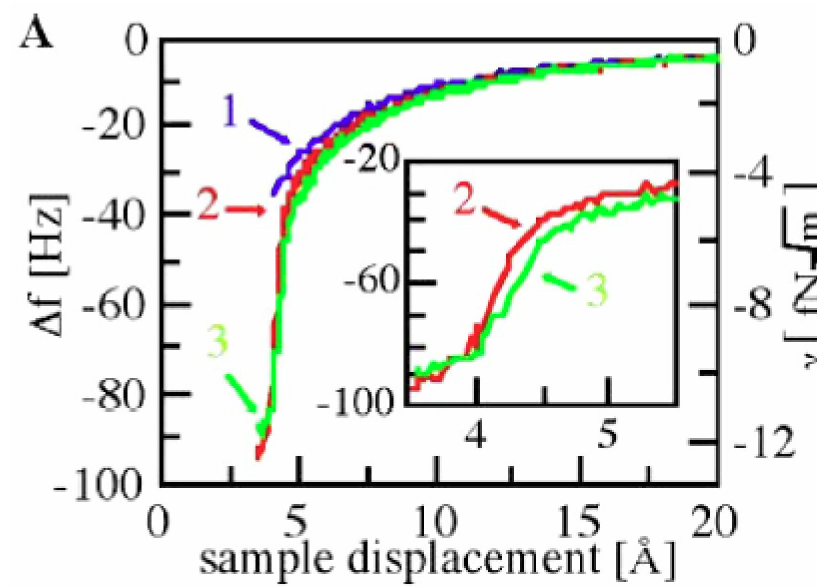


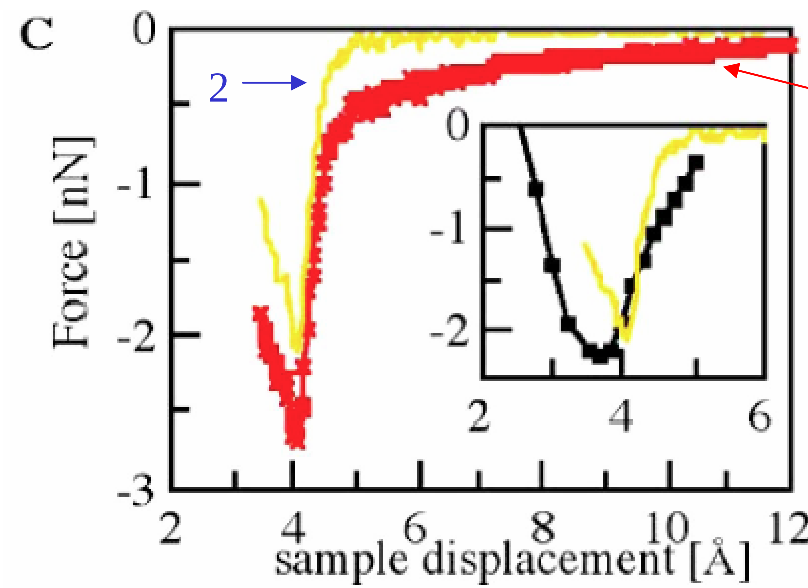


Constant-frequency-shift image (Δ *f*= -38 Hz)

Lantz et al., Science 291, 2580 (2001)

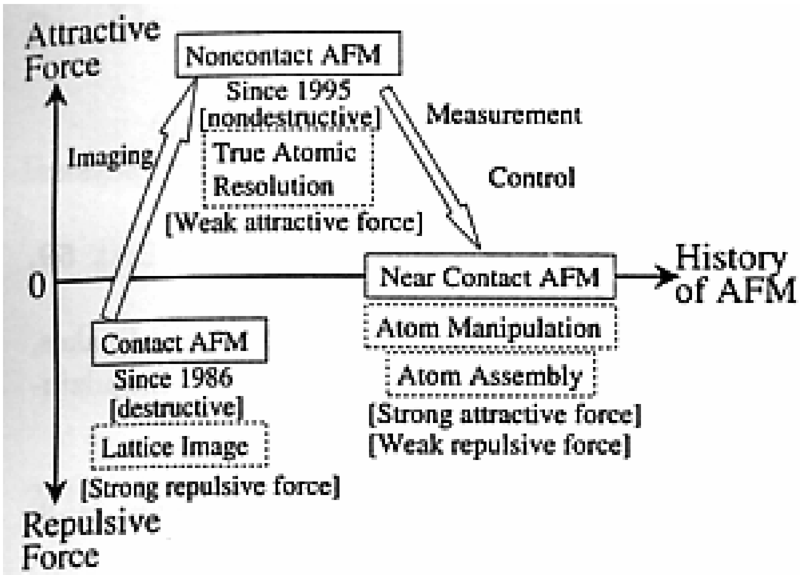
1 long-range force (on corner hole)

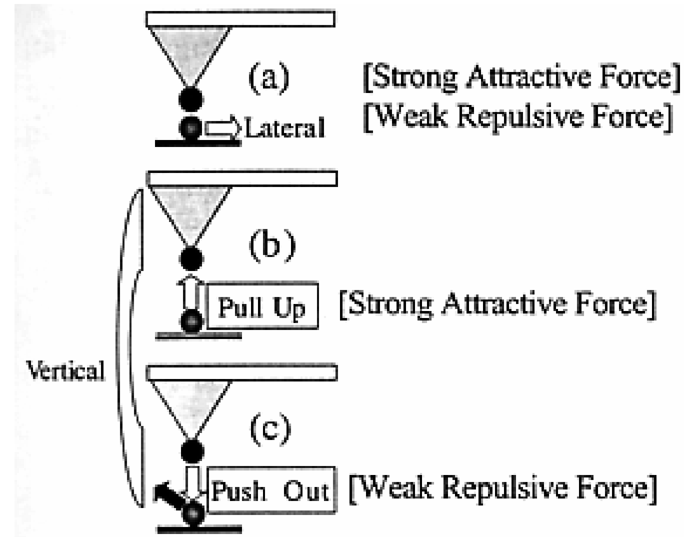




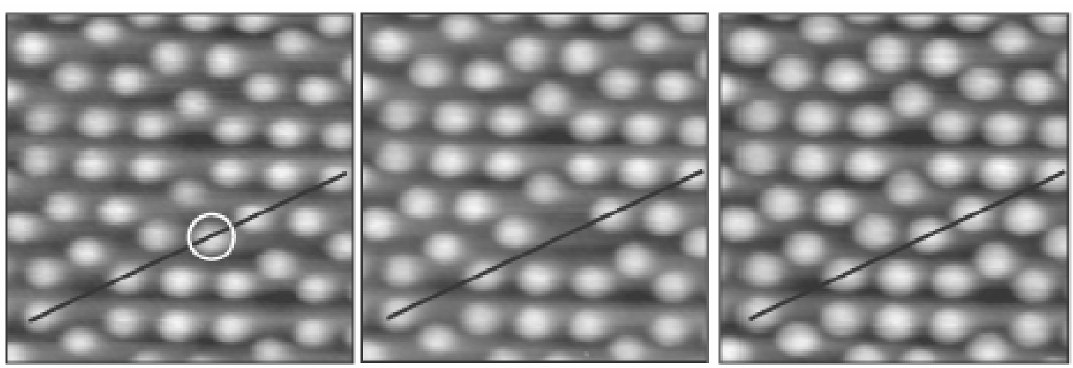
Total force

Atomic Manipulation with Noncontact-AFM



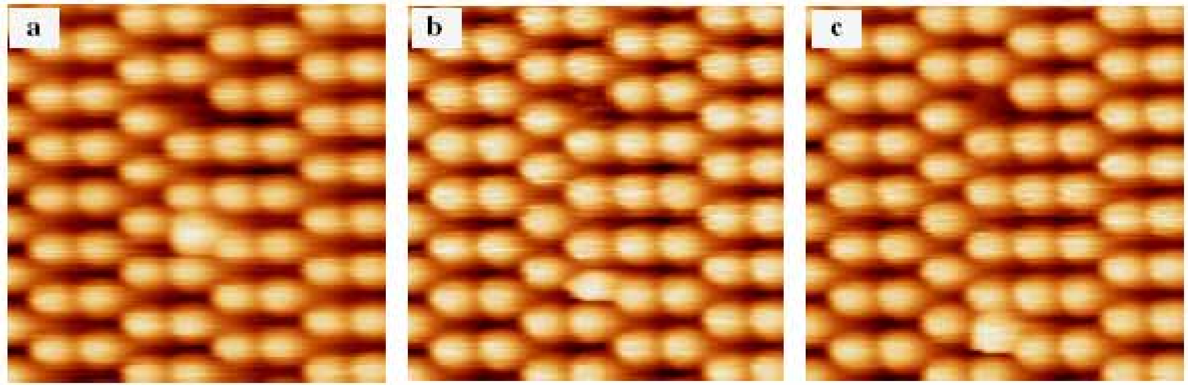


Morita et al. “Noncontact Atomic Force Microscopy, Springer 2002.



Phys. Rev. Lett. 90, 176102 (2003)

Migration of a Defect



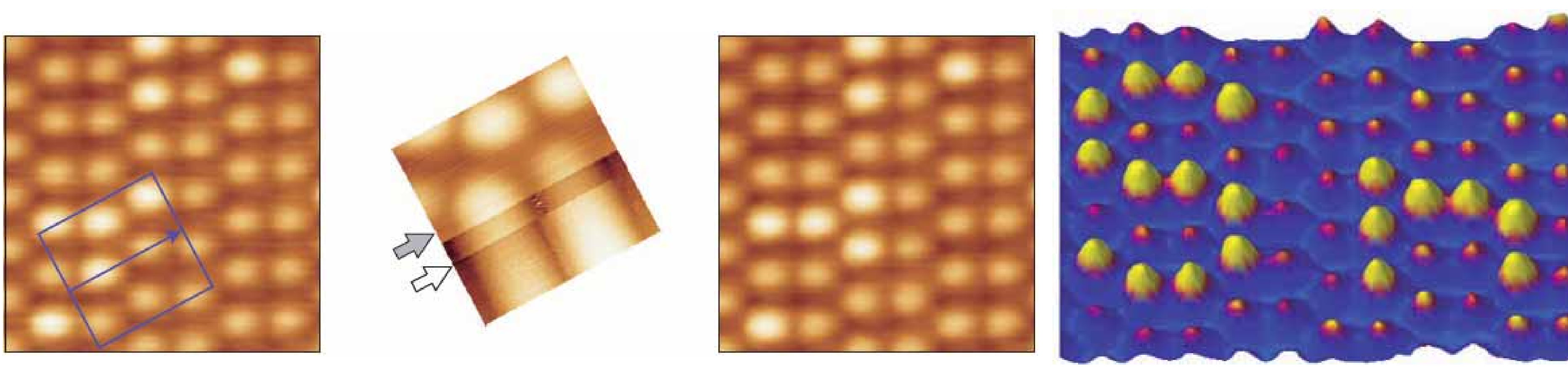
80 K

$\Delta f = -14.1$ Hz

$\Delta f = -14.7$ Hz

Nanotechnology 16, S112 (2005)

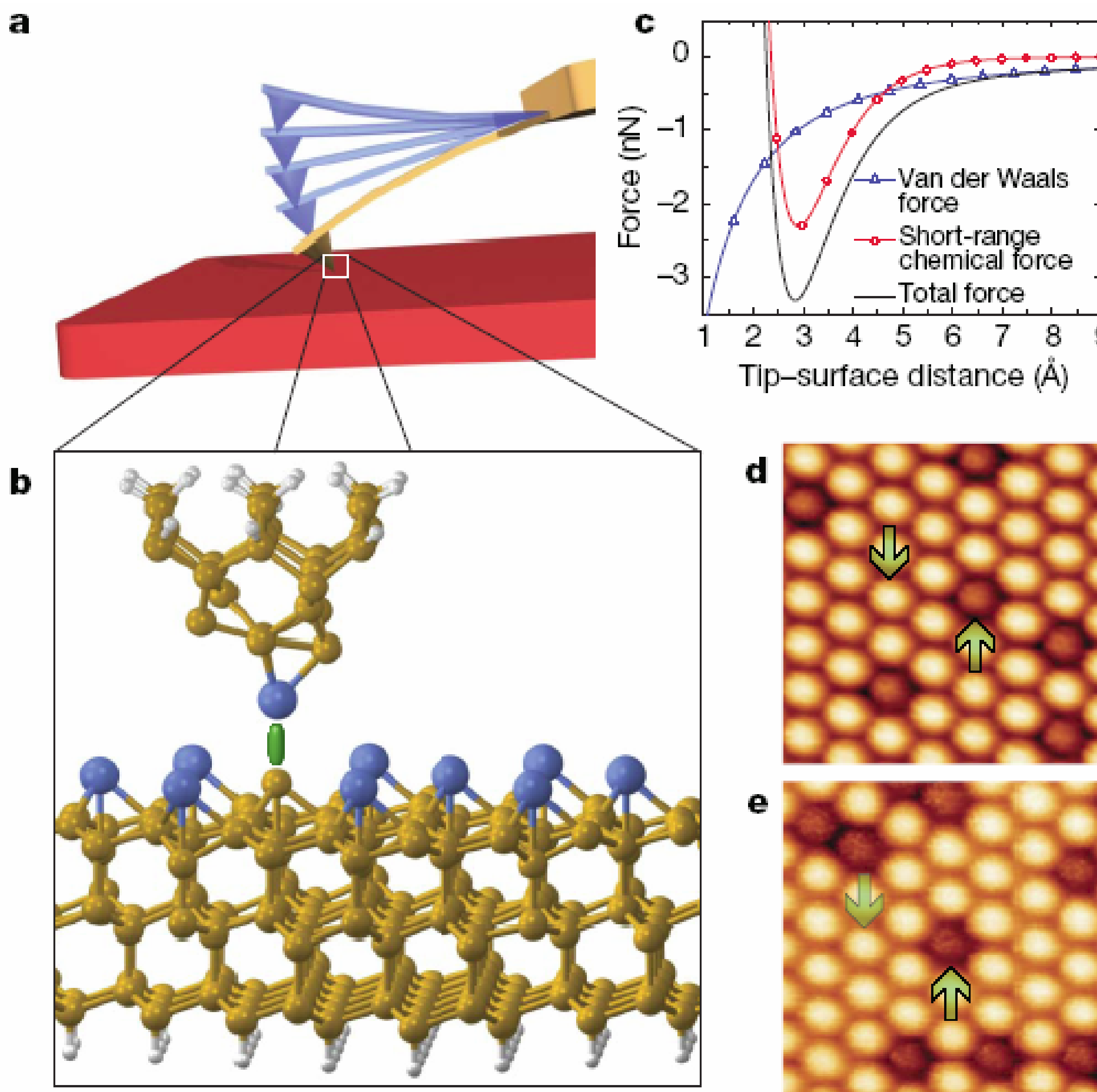
Manipulation of Sn Adatoms with NC-AFM



Nature Materials 4, 156 (2005)

Chemical Identification with Noncontact-AFM

NATURE | Vol 446 | 1 March 2007



True Atomic Resolution in Liquid by FM-AFM

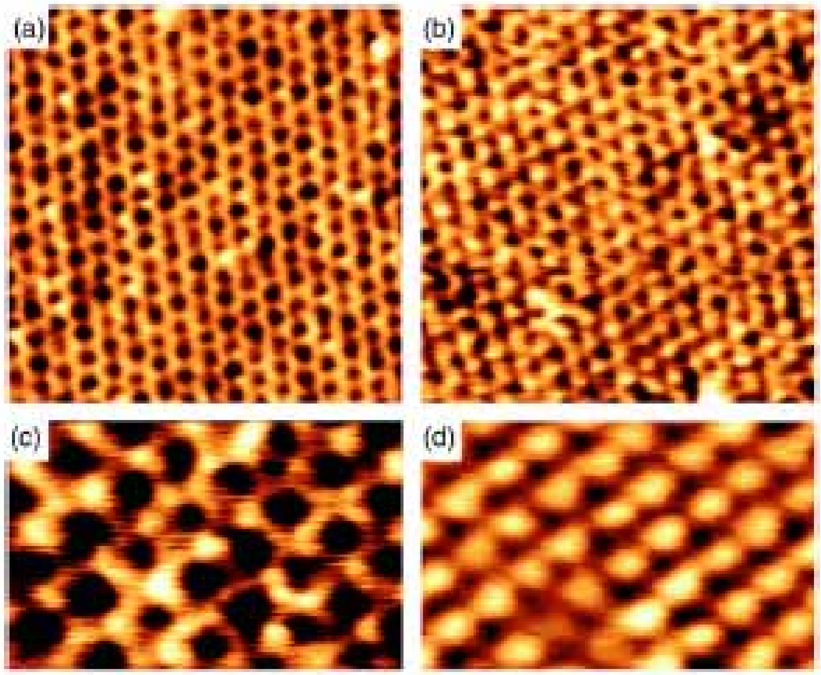


FIG. 3. (Color online) FM-AFM images of the cleaved (001) surface of muscovite mica taken in water. (a) 8 nm $\times$ 8 nm, $\Delta f = +54$ Hz, $A = 0.24$ nm, scanning speed: 671 nm/s; (b) 8 nm $\times$ 8 nm, $\Delta f = +240$ Hz, $A = 0.20$ nm, scanning speed: 1120 nm/s; (c) 4 nm $\times$ 2.5 nm, $\Delta f = +157$ Hz, $A = 0.16$ nm, scanning speed: 934 nm/s; (d) 4 nm $\times$ 2.5 nm, $\Delta f = +682$ Hz, $A = 0.20$ nm, scanning speed: 671 nm/s. The images were taken in constant height mode. The cantilever used was an n-Si cantilever (Nanosensors: NCH) with a spring constant of 42 N/m and a resonance frequency of 136 kHz in water. The Q factor measured in water was 30.

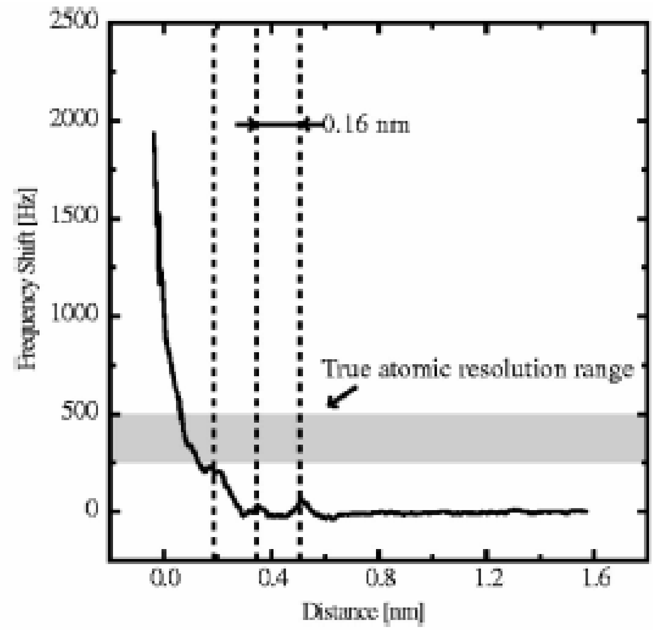


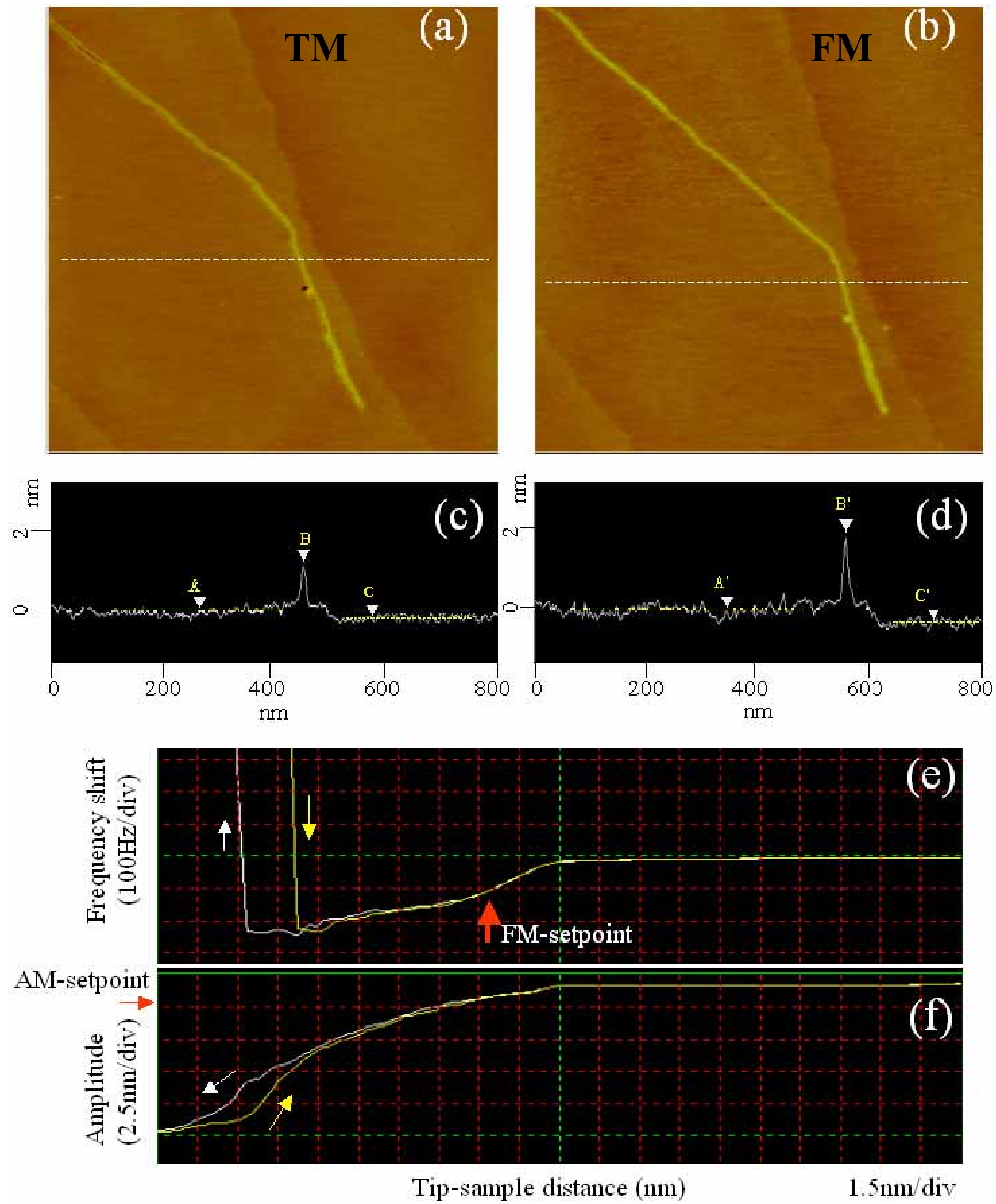
FIG. 4. Frequency shift–distance curve measured on a cleaved (001) surface of muscovite mica in water ($A = 0.33$ nm, $Q = 19$, $f_0 = 155$ kHz, $k = 42$ N/m). The curve was taken with a tip velocity of 0.7 nm/s and approximately 1000 data points. The tip-sample contact point is not identified.

APPLIED PHYSICS LETTERS **87**, 034101 2005

Comparison of Tapping-Mode AFM and FM-AFM

Duplex DNA on graphite

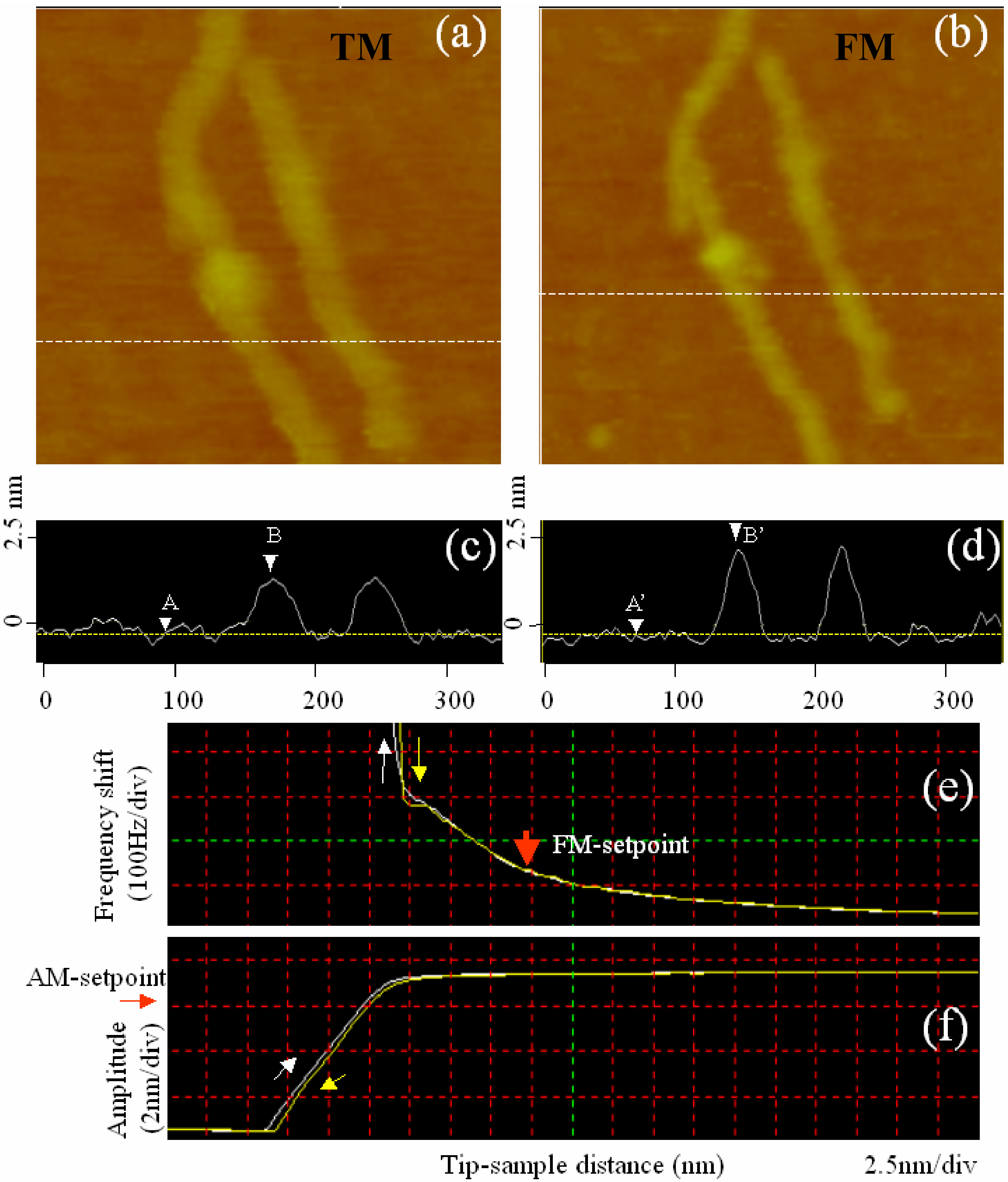
In Air



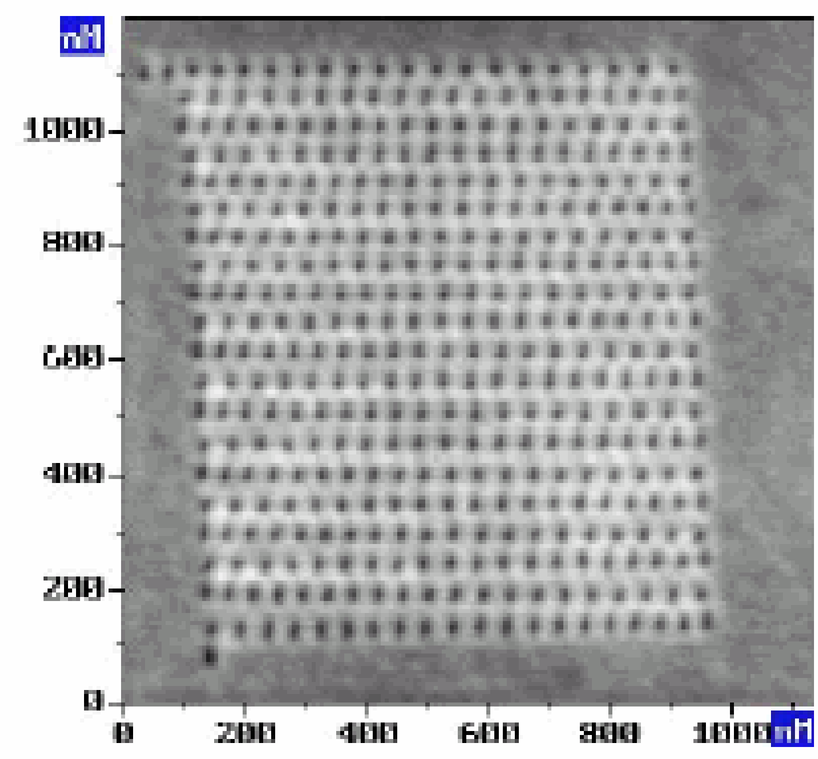
Comparison of Tapping-Mode AFM and FM-AFM

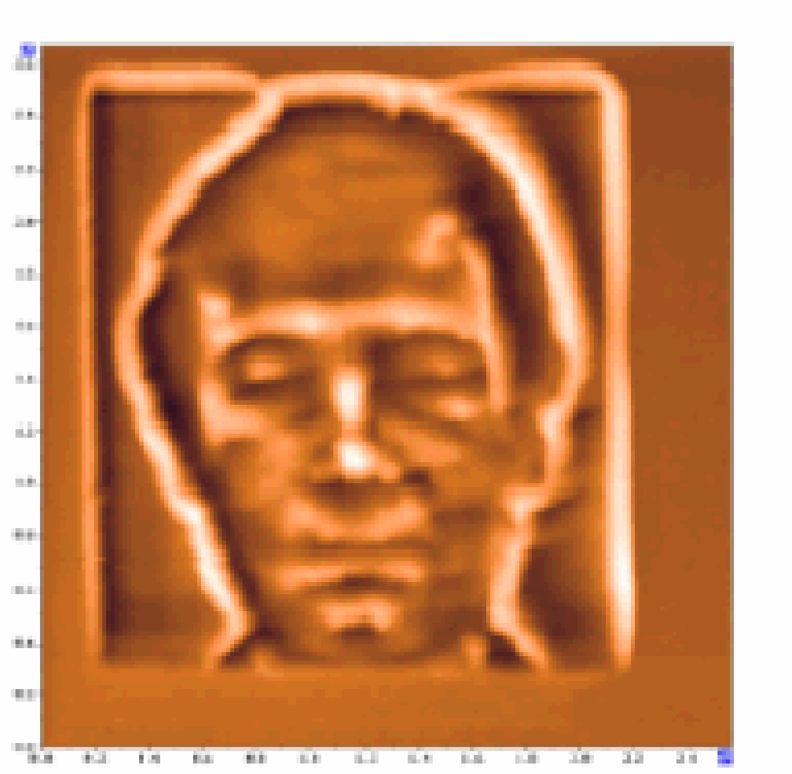
Duplex DNA on mica

In water



Nanolithography of Tapping-Mode AFM



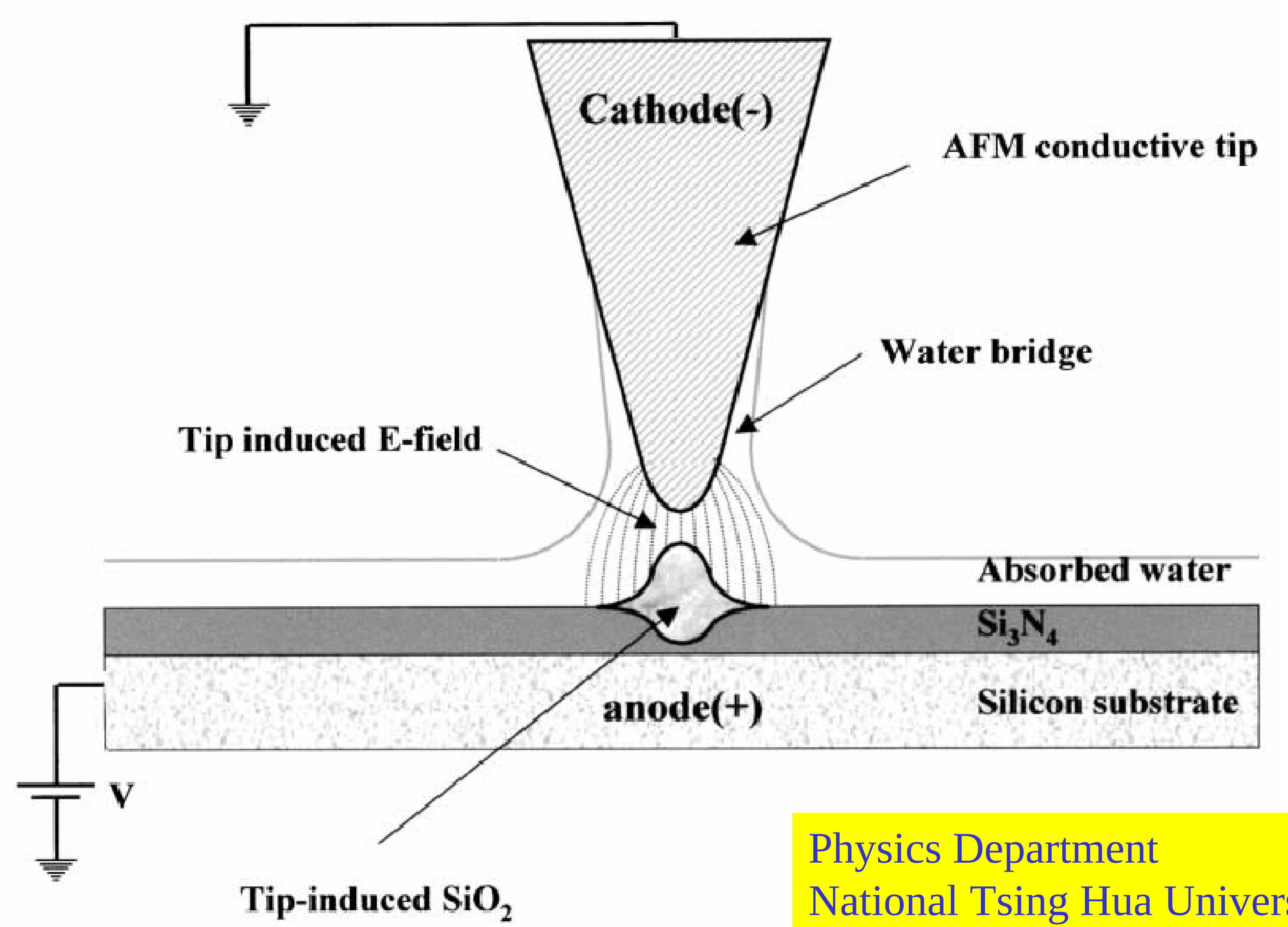


(1.2 μ m× 1.2 μ m)

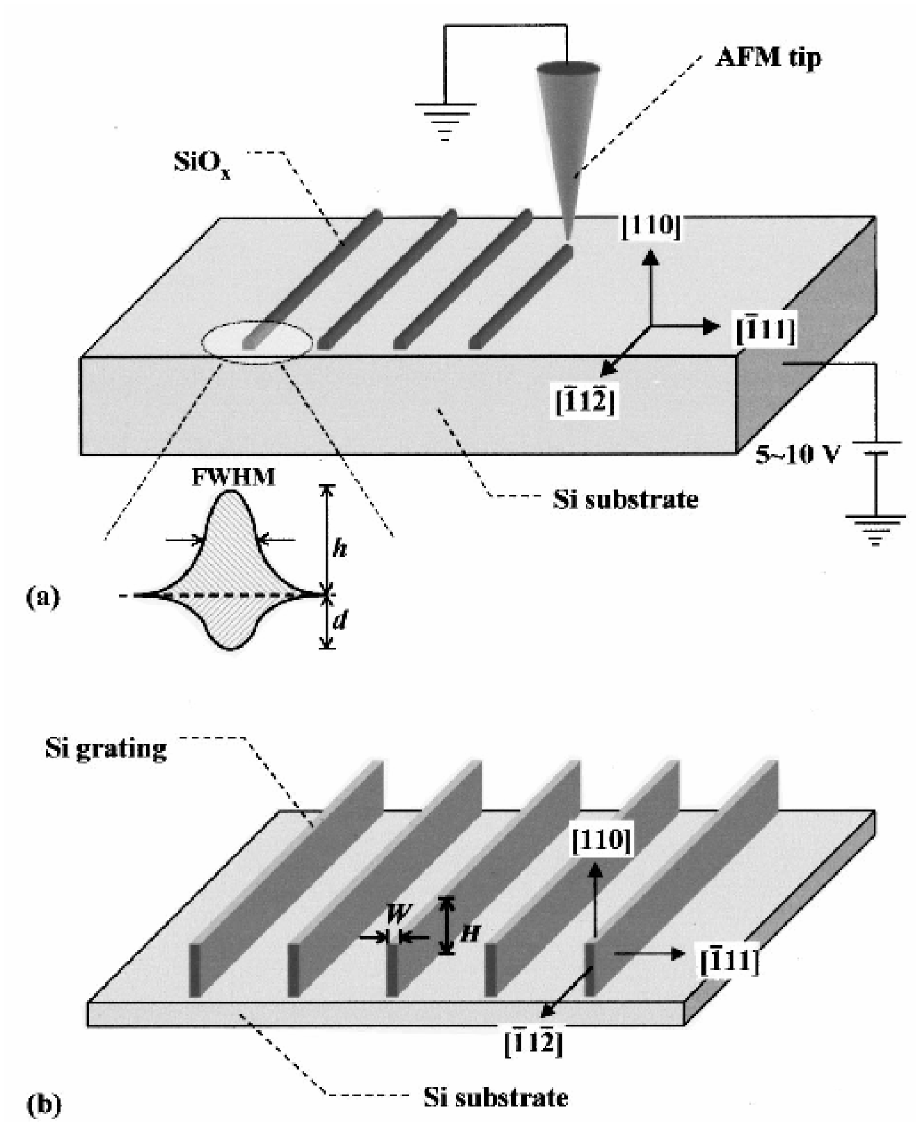
(2.5 μ m× 2.5 μ m)

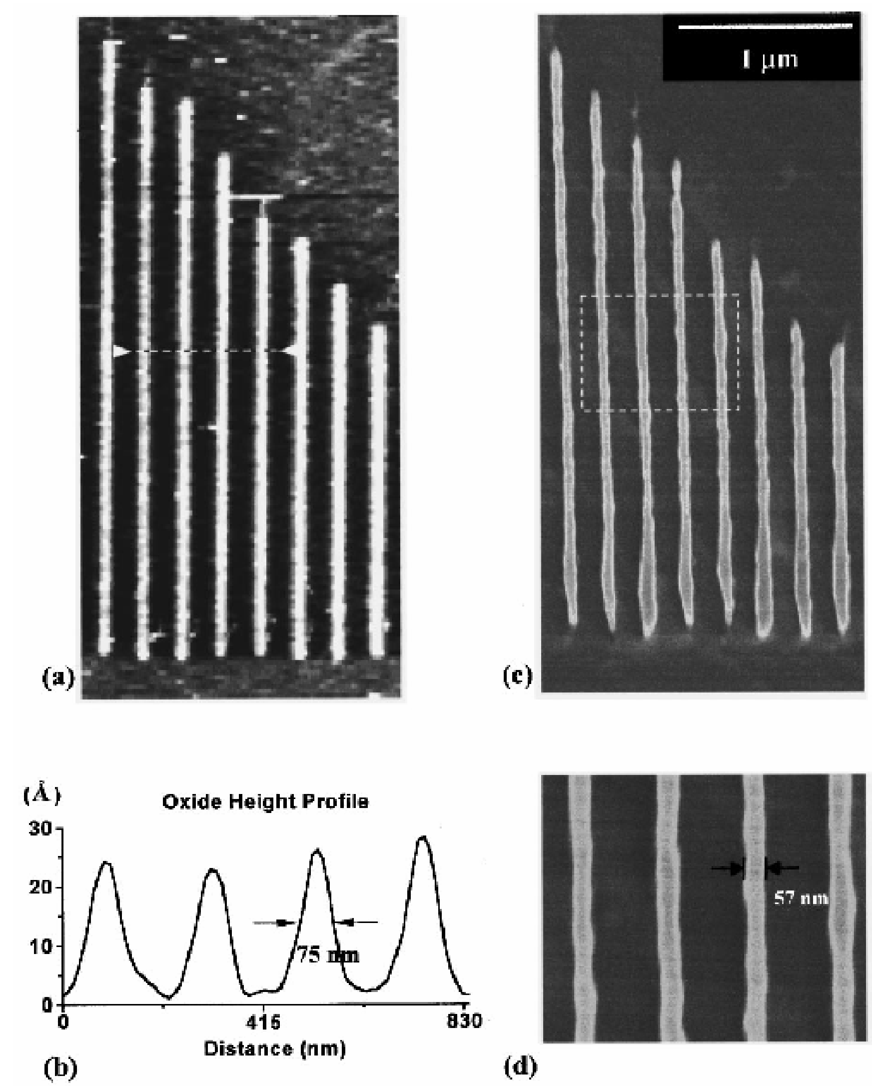
Image of polycarbonate film on silicon surface

Nano-Lithography with an AFM tip

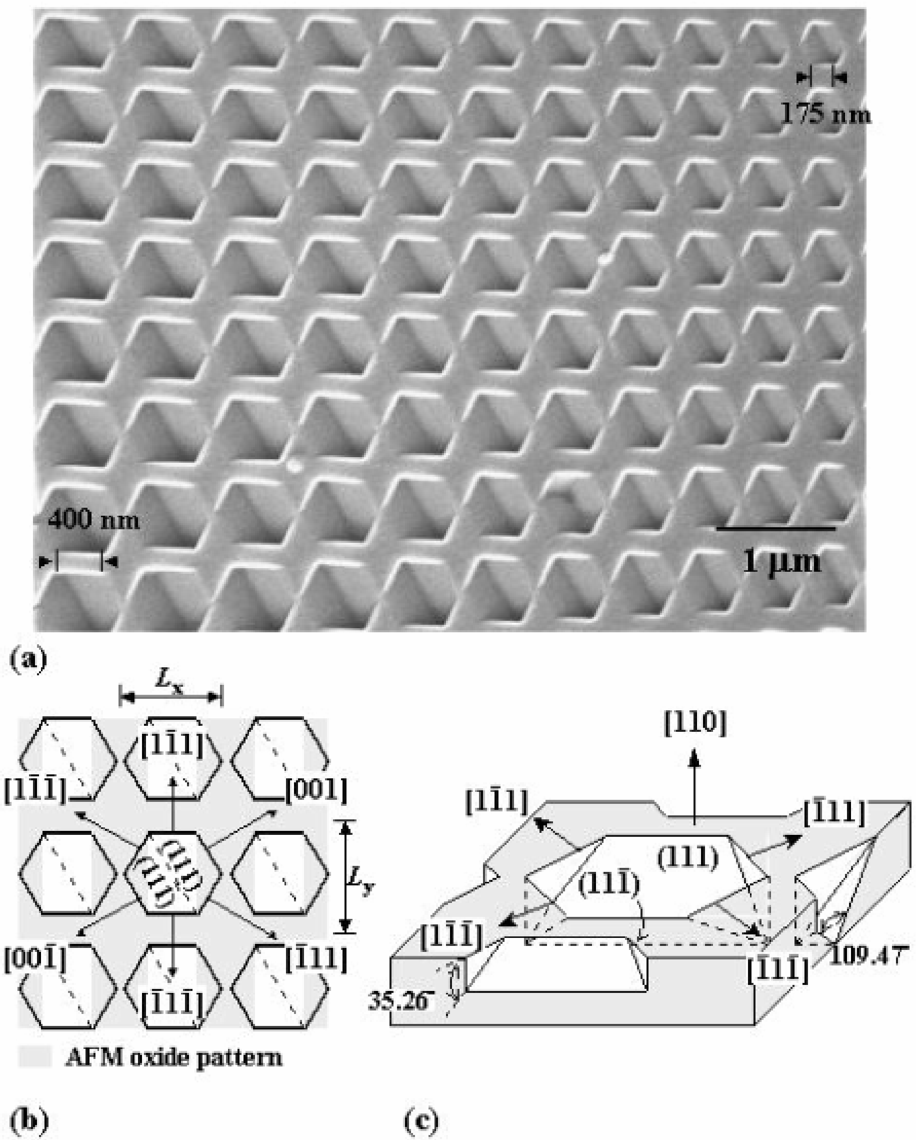


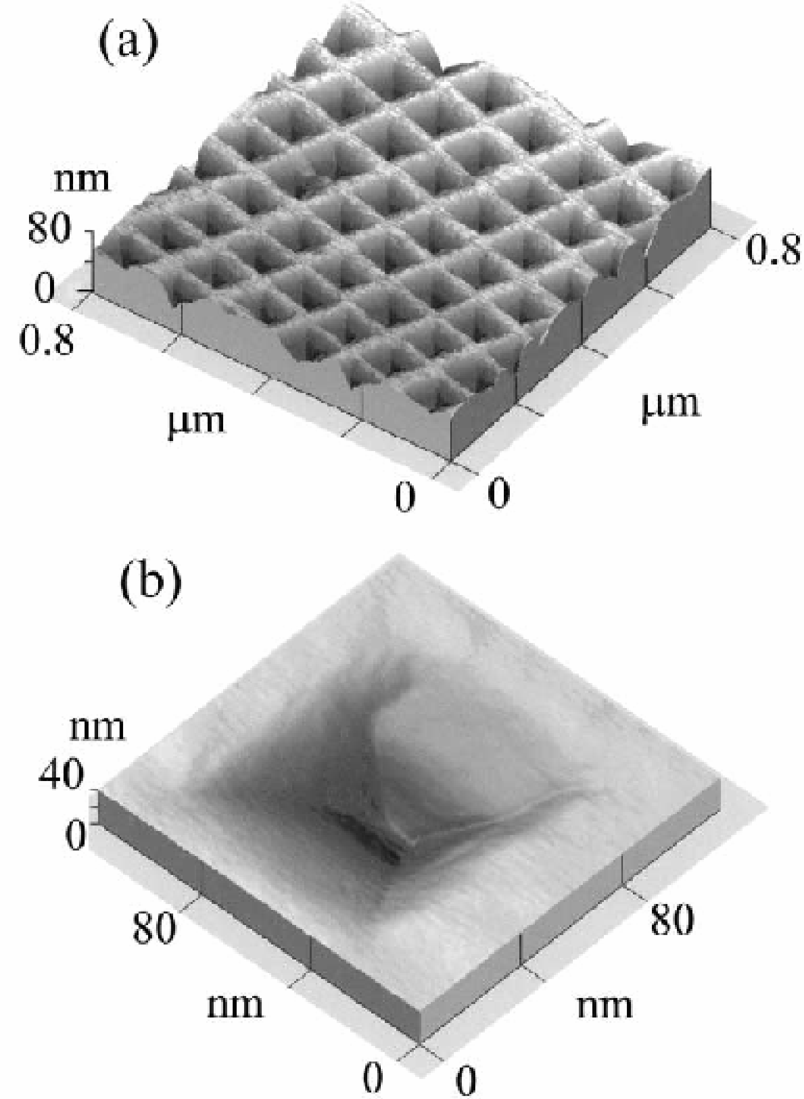
Physics Department
National Tsing Hua University



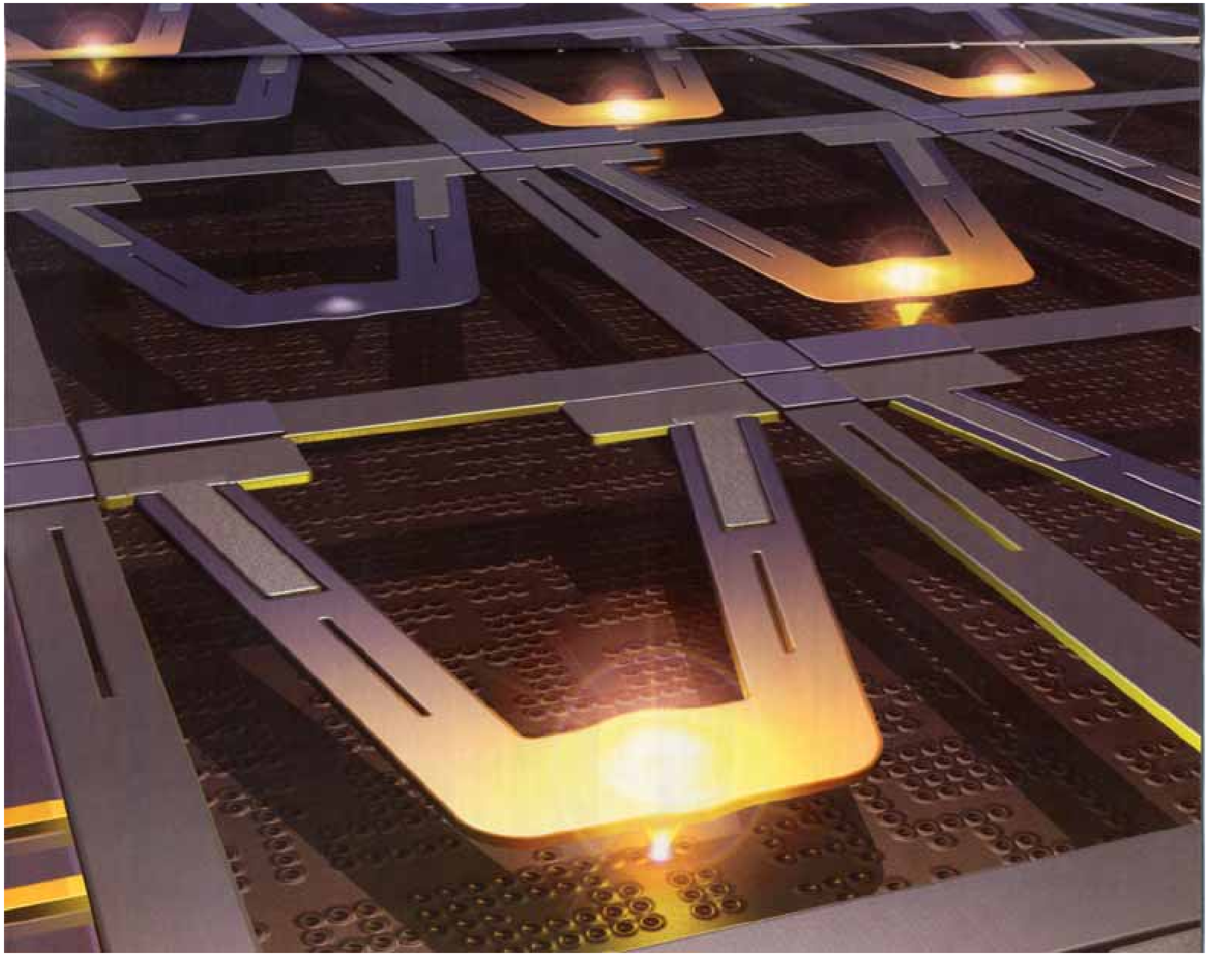


F.S.-S. Chien *et al*., APL 75, 2429 (1999)


175 nm
400 nm
1 µm
(a)
L_x
$[1\bar{1}1]$
$[1\bar{1}\bar{1}]$
[001]
L_y
$[00\bar{1}]$
$[\bar{1}11]$
$[\bar{1}1\bar{1}]$
AFM oxide pattern
(b)
[110]
$[1\bar{1}1]$
$[\bar{1}11]$
(111)
$(11\bar{1})$
$[1\bar{1}\bar{1}]$
$[\bar{1}1\bar{1}]$
35.26°
109.47°
(c)


(a)
nm
80
0
0.8
µm
0
0
µm
0.8
(b)
nm
40
0
80
nm
0
0
80
nm

IBM Nanodrive Project

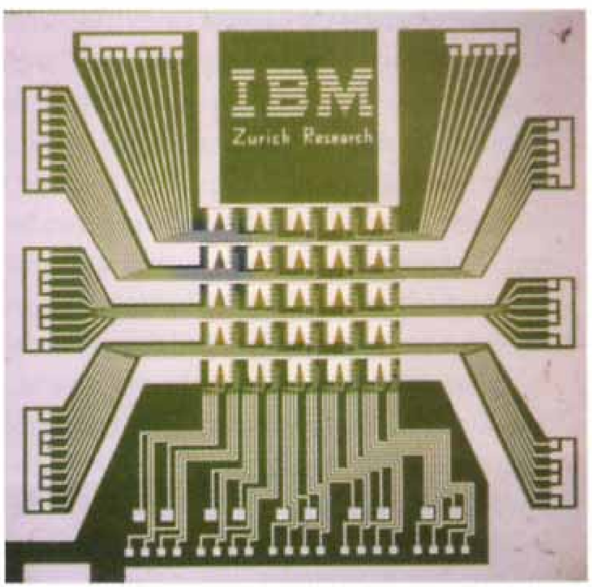


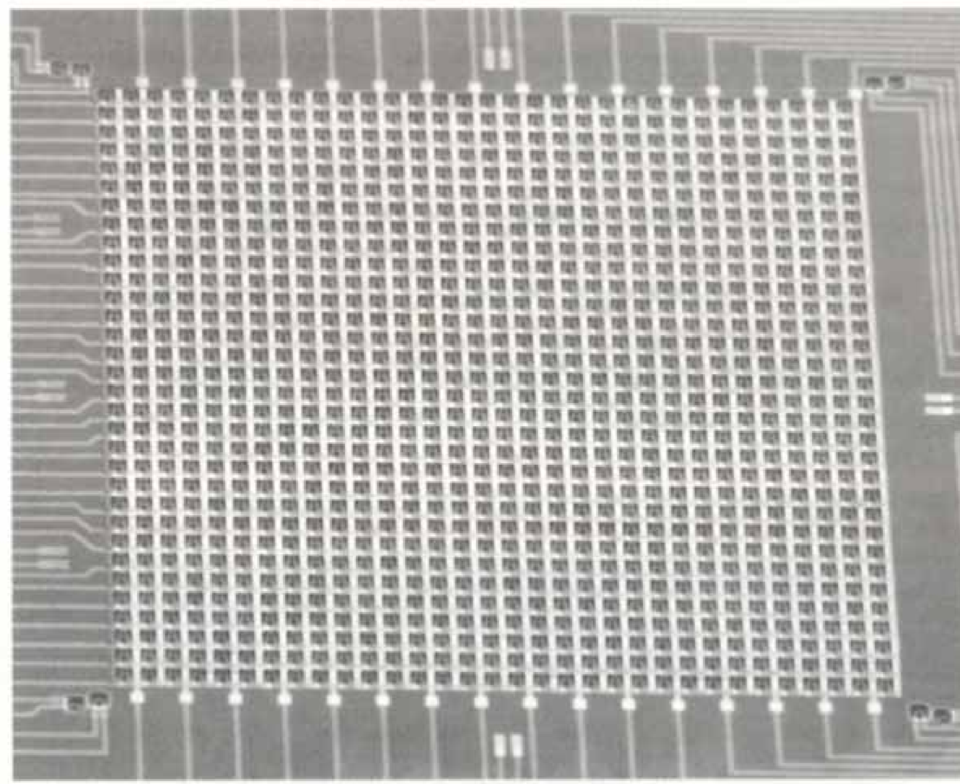
P. Vettiger & G. Binnig, Scientific American, pp 35-41, Jan. 2003

IBM Millipede Project

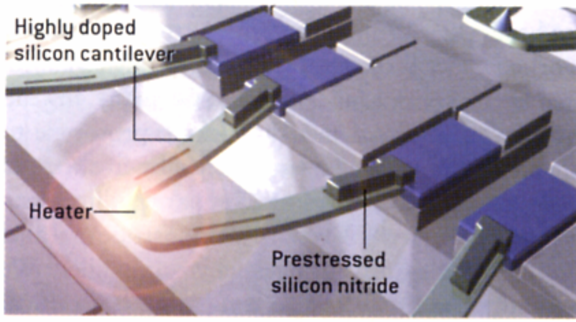
Millipede uses grids of tiny cantilevers to read, write, and erase data on a polymer media.

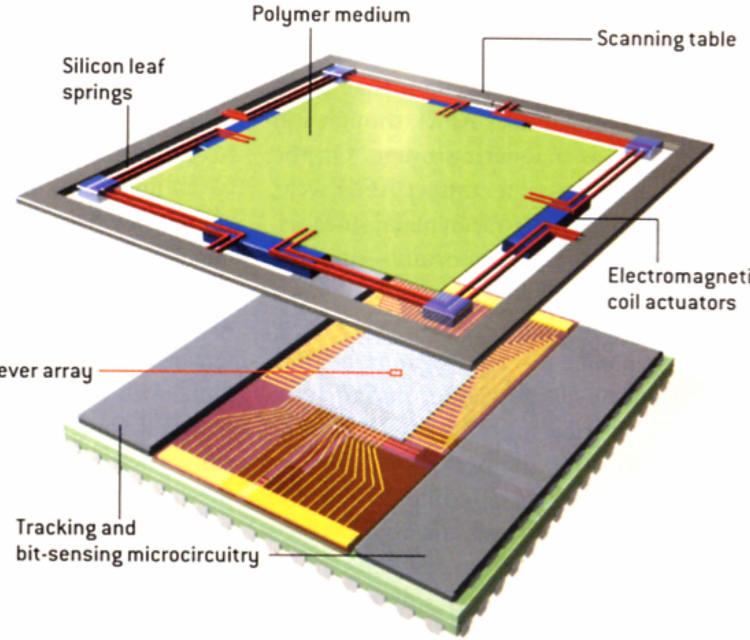
PROTOTYPE EVOLUTION: Whereas the first-generation Millipede chip contained an array of 25 cantilevers on a square that was five millimeters on a side (*below*), the succeeding prototype (*right*) incorporated 1,024 cantilevers in a smaller, three-millimeter square.

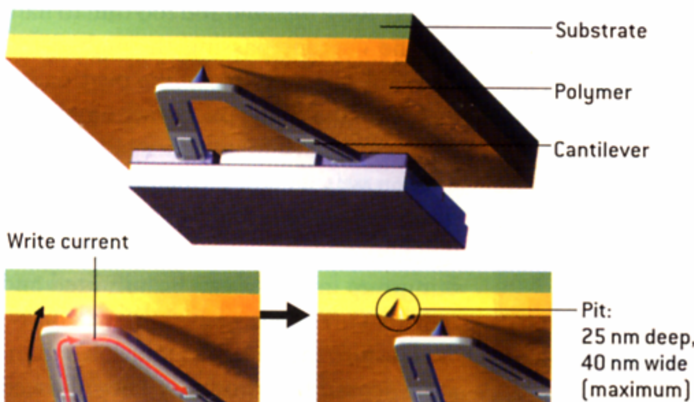




THE MILLIPEDE NANODRIVE prototype operates like a tiny phonograph, using the sharp tips of minuscule silicon cantilevers to read data inscribed in a polymer medium. An array of 4,096 levers, laid out in rows with their tips pointing upward, is linked to control microcircuitry that converts information encoded in the analog pits into streams of digital bits. The polymer is suspended on a scanning table by silicon leaf springs, which permits tiny magnets (*not shown*) and electromagnetic coils to pan the storage medium across a plane while it is held level over the tips. The tips contact the plastic because the levers flex upward by less than a micron.

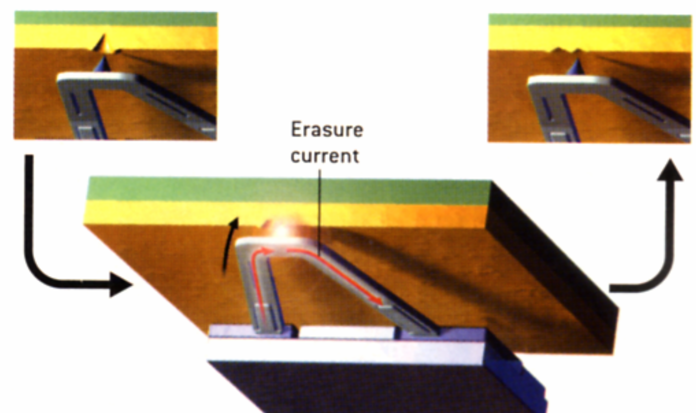






WRITING A BIT

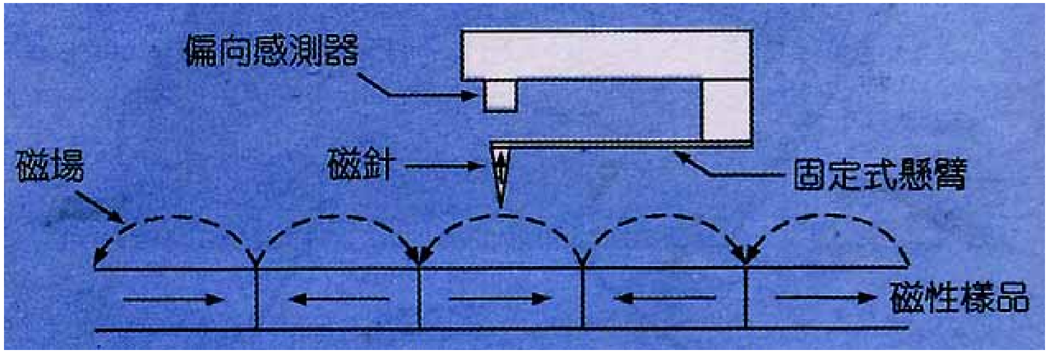
Using heat and mechanical force, tips create conical pits in linear tracks that represent series of digital 1's. To produce a pit, electric current travels through the lever, heating a doped region of silicon at the end to 400 degrees Celsius, which allows the prestressed lever structure to flex into the polymer. The absence of a pit is a 0.



ERASING A BIT

The latest Millipede prototype erases an existing bit by heating the tip to 400 degrees C and then forming another pit just adjacent to the previously inscribed pit, thus filling it in (*shown*). An alternative erasure method involves inserting the hot tip into a pit, which causes the plastic to spring back to its original flat shape.

Magnetic Force Microscopy (MFM)



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

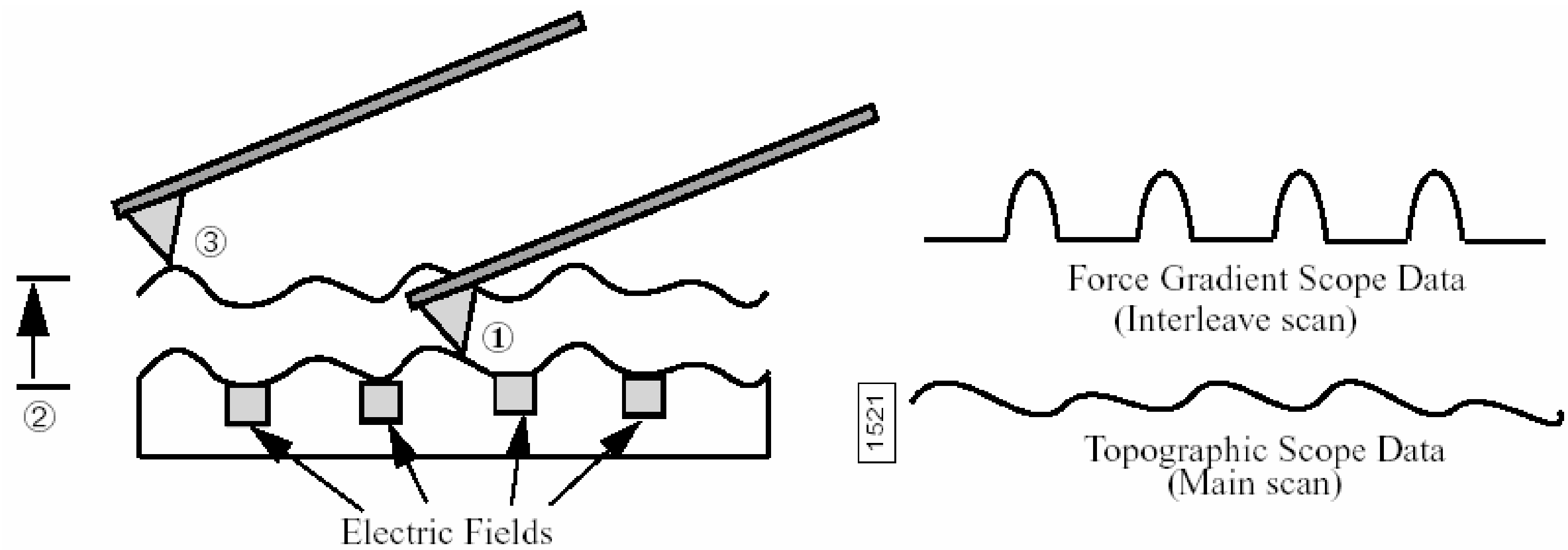
The tip is scanned several tens or hundreds of nanometers above the sample, avoiding contact. Magnetic field gradients exert a force on the tip's magnetic moment, and monitoring the tip/cantilever response gives a magnetic force image. To enhance sensitivity, most MFM instruments oscillate the cantilever near its resonant frequency with a piezoelectric element. Gradients in the magnetic forces on the tip shift the resonant frequency of the cantilever. Monitoring this shift, or related changes in oscillation amplitude or phase, produces a magnetic force image.

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.

Lift Mode (MFM & EFM)

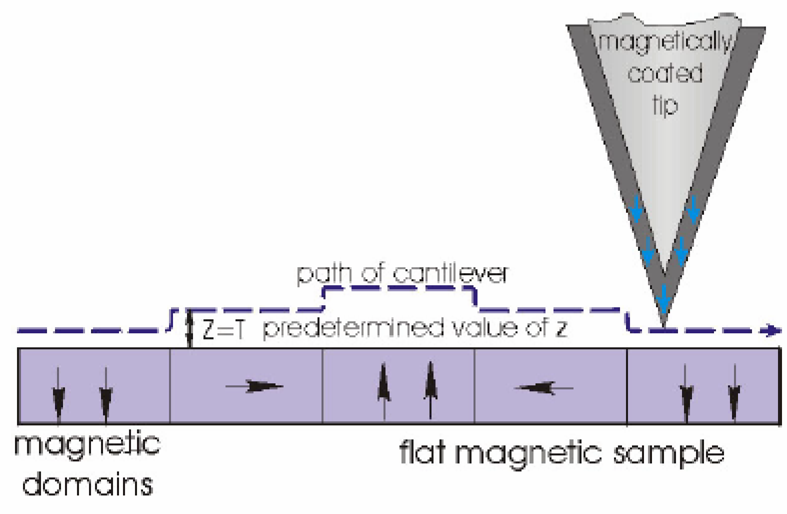


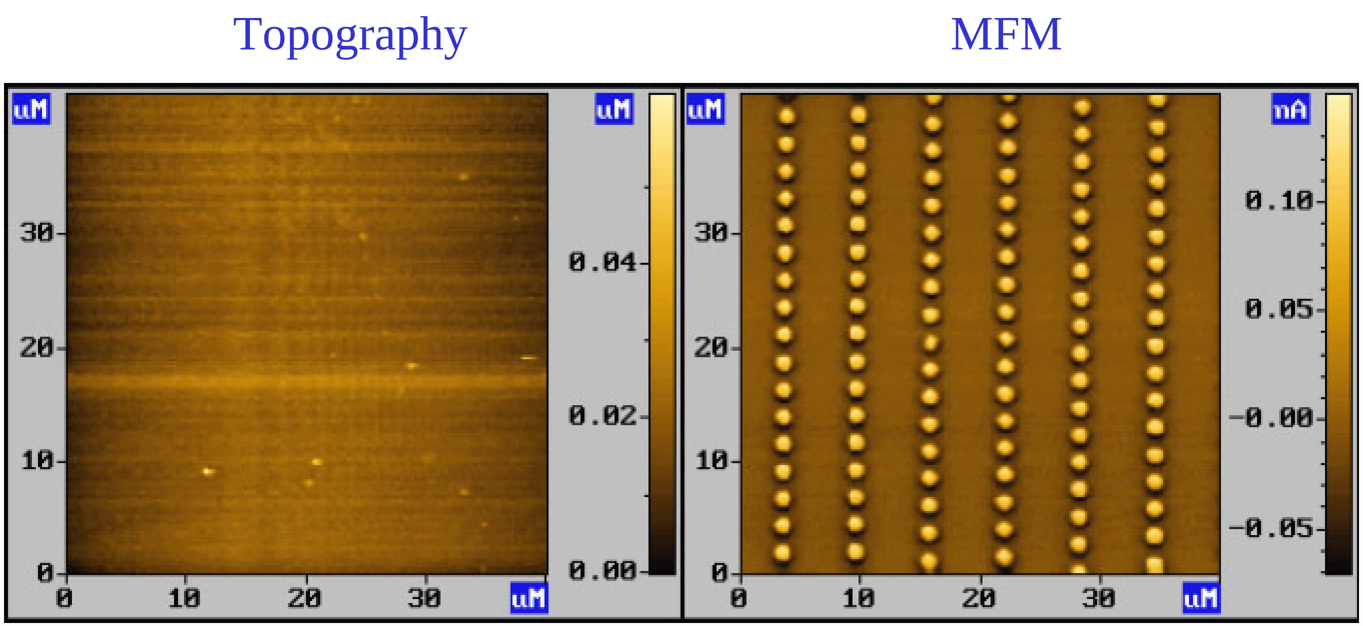
1. Cantilever measures surface topography on first (main) scan.

2. Cantilever ascends to lift scan height.

3. Cantilever follows stored surface topography at the lift height above sample while responding to electric influences on second scan (measured by amplitude, phase or frequency detection).

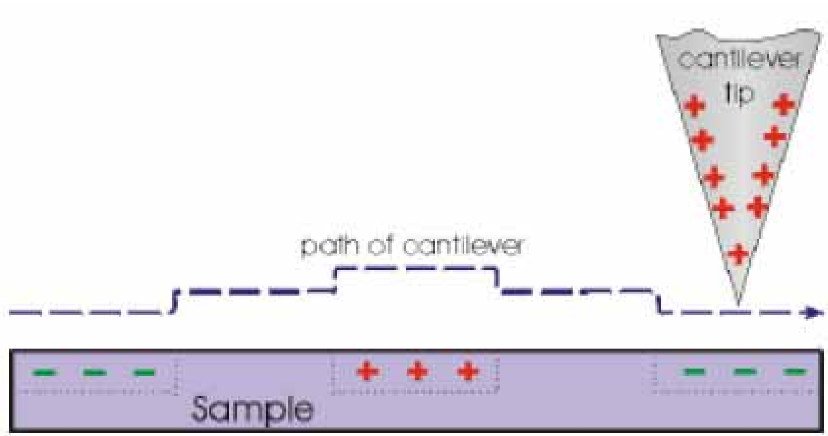
Magnetic Force Microscopy (MFM)



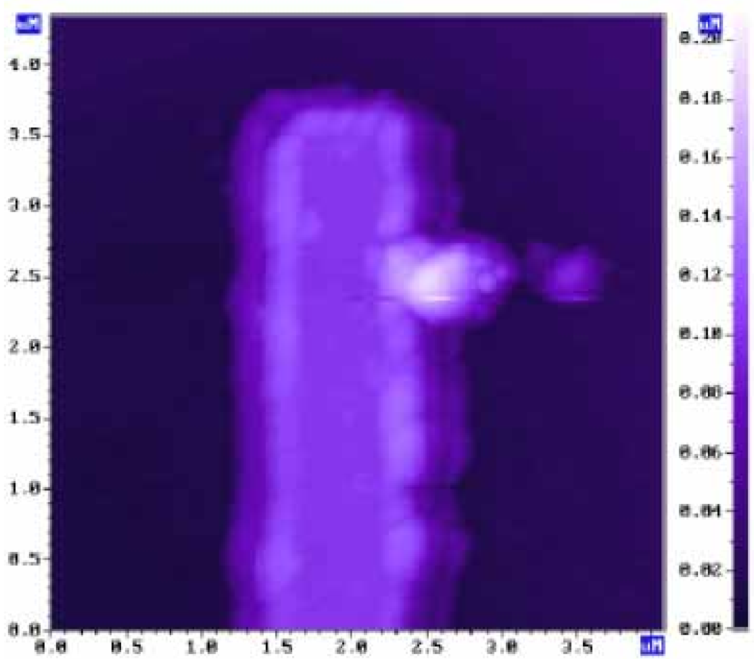


Magneto-optical disk

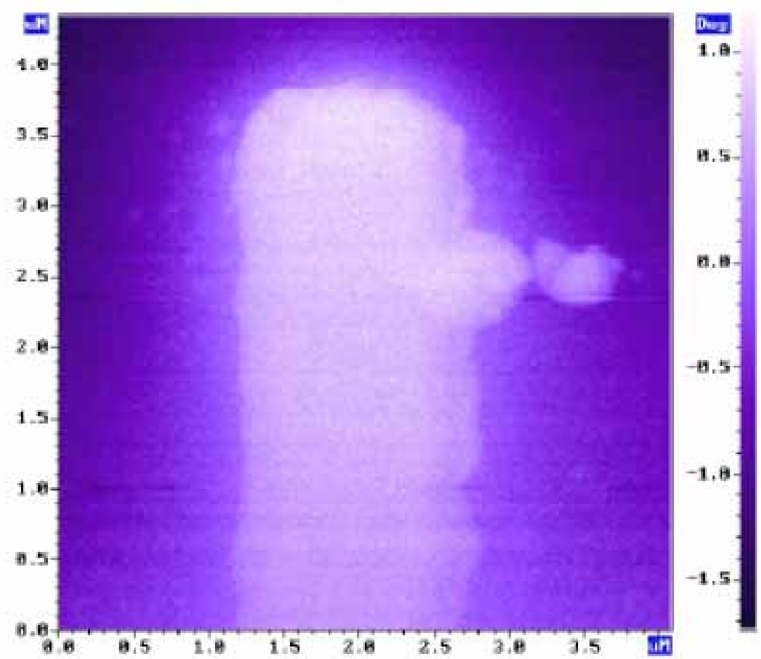
Electrostatic Force Microscopy (EFM)



Topography

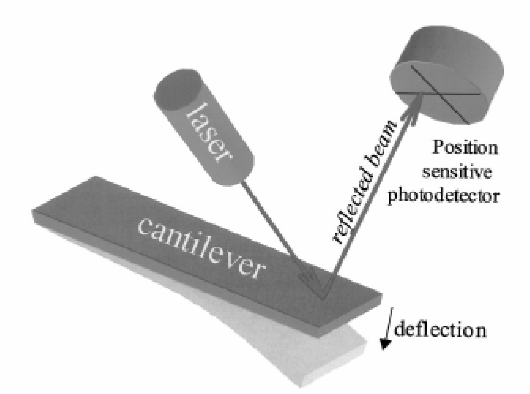


EFM

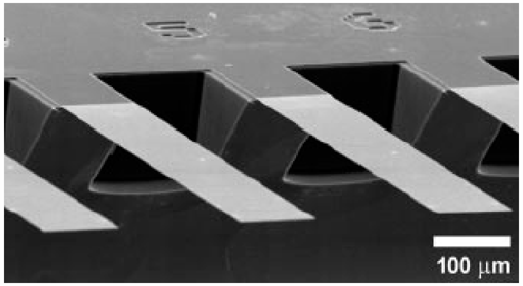


Metallic electrode under the voltage

Cantilever-Based Chemical and Biological Sensors



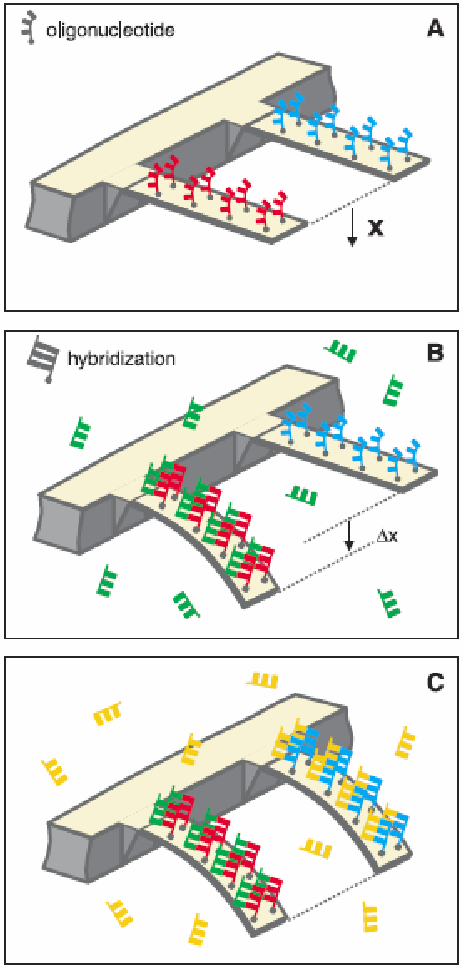
silicon cantilever array



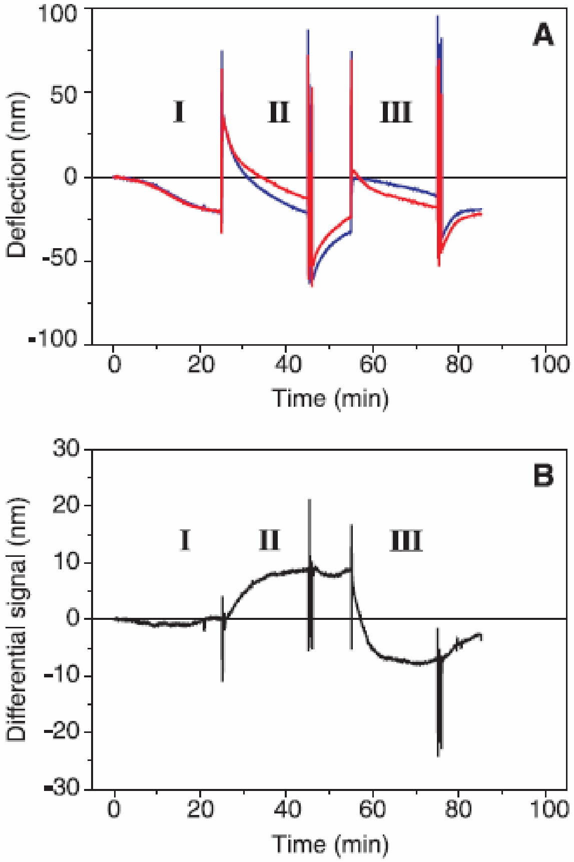
Molecular recognition

DNA hybridization

Receptor-ligand binding



surface stress changes

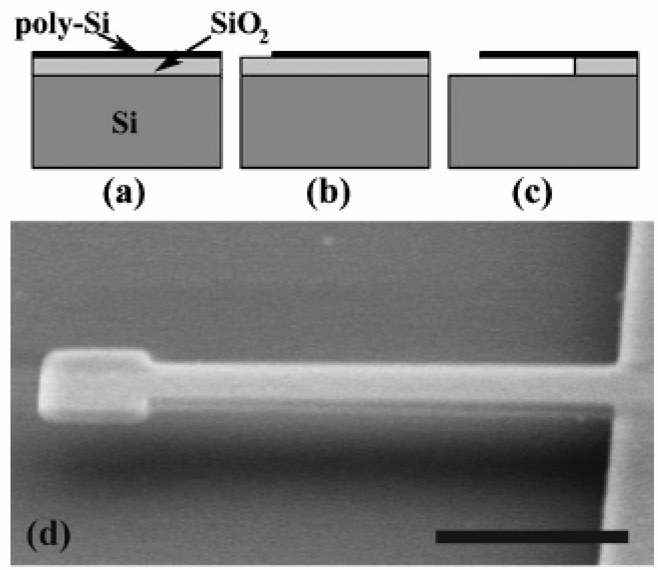


Science **288**, 316 (2000)

Virus detection using nanoelectromechanical devices

Mass sensitivities on the order of 10^{-19} g/Hz
Detect the mass of single-virus particles

Appl. Phys. Lett. 85, 2604 (2004)



l=6 μm, *w*=0.5 μ m, *t*=150 nm with a 1 μm x 1 μm paddle. Scale bar corresponds to 2 mm.