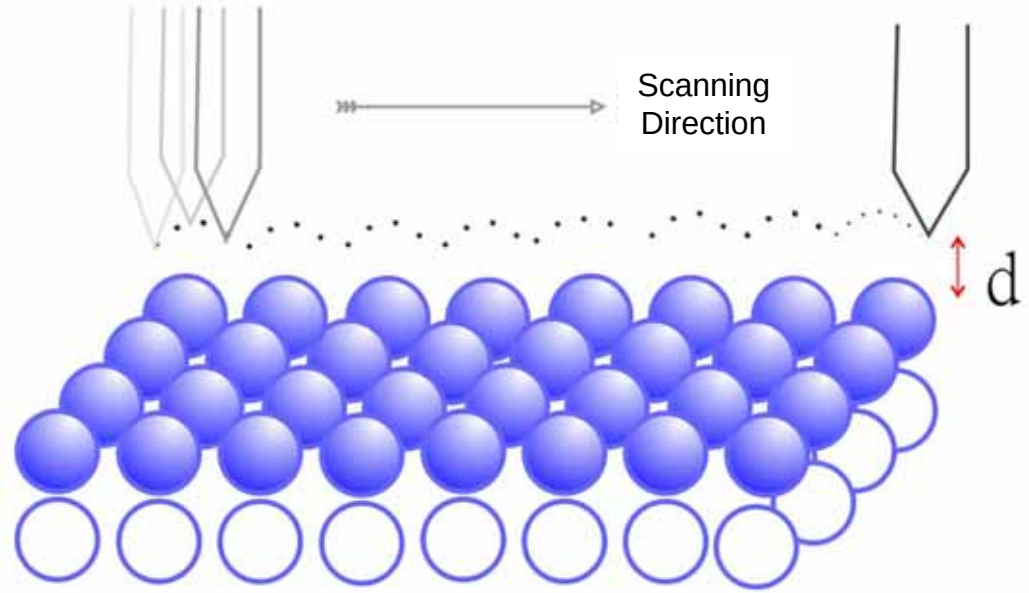
Scanning Tunneling Microscopy

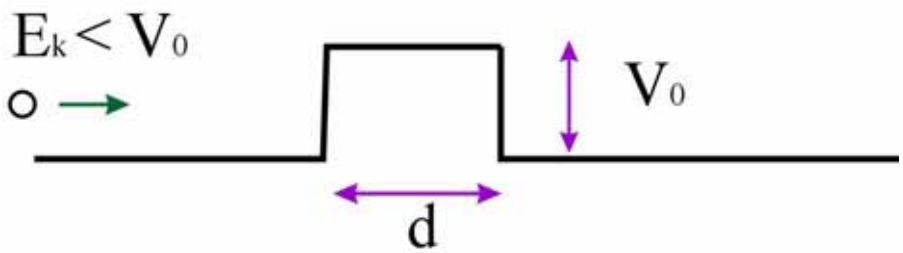


References:

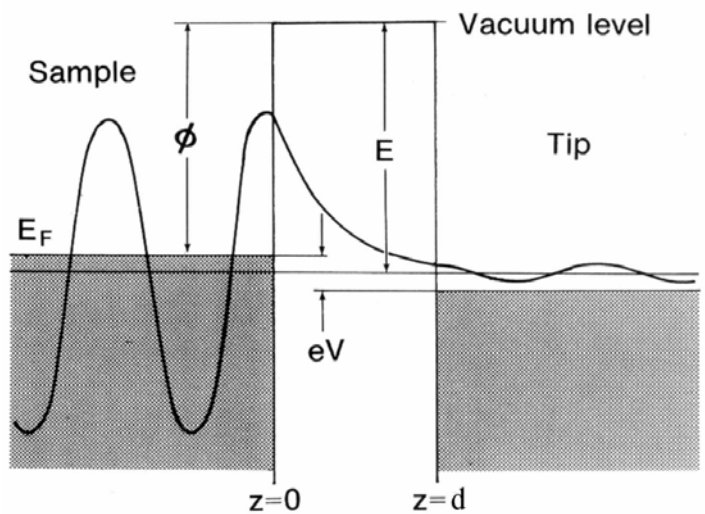
1. G. Binnig, H. Rohrer, C. Gerber and Weibel, Phys. Rev. Lett. **49**, 57(1982); and ibid **50**,120(1983).
2. J. Chen, *Introduction to Scanning Tunneling Microscopy*, New York, Oxford Univ. Press(1993).

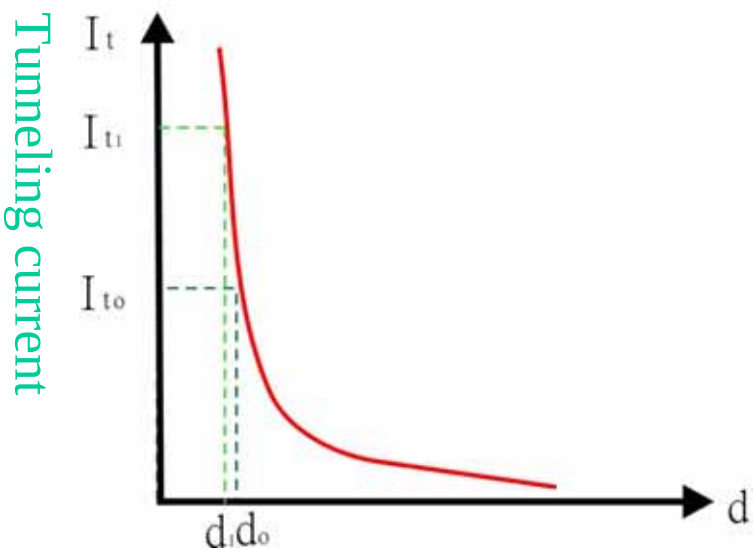
Tunneling

Classical



Quantum Mechanics





Tunneling current I_t

$I_t \propto (V/d)\exp(-A\phi^{1/2}d)$

$A = 1.025\ (eV)^{-1/2}Å^{-1}$

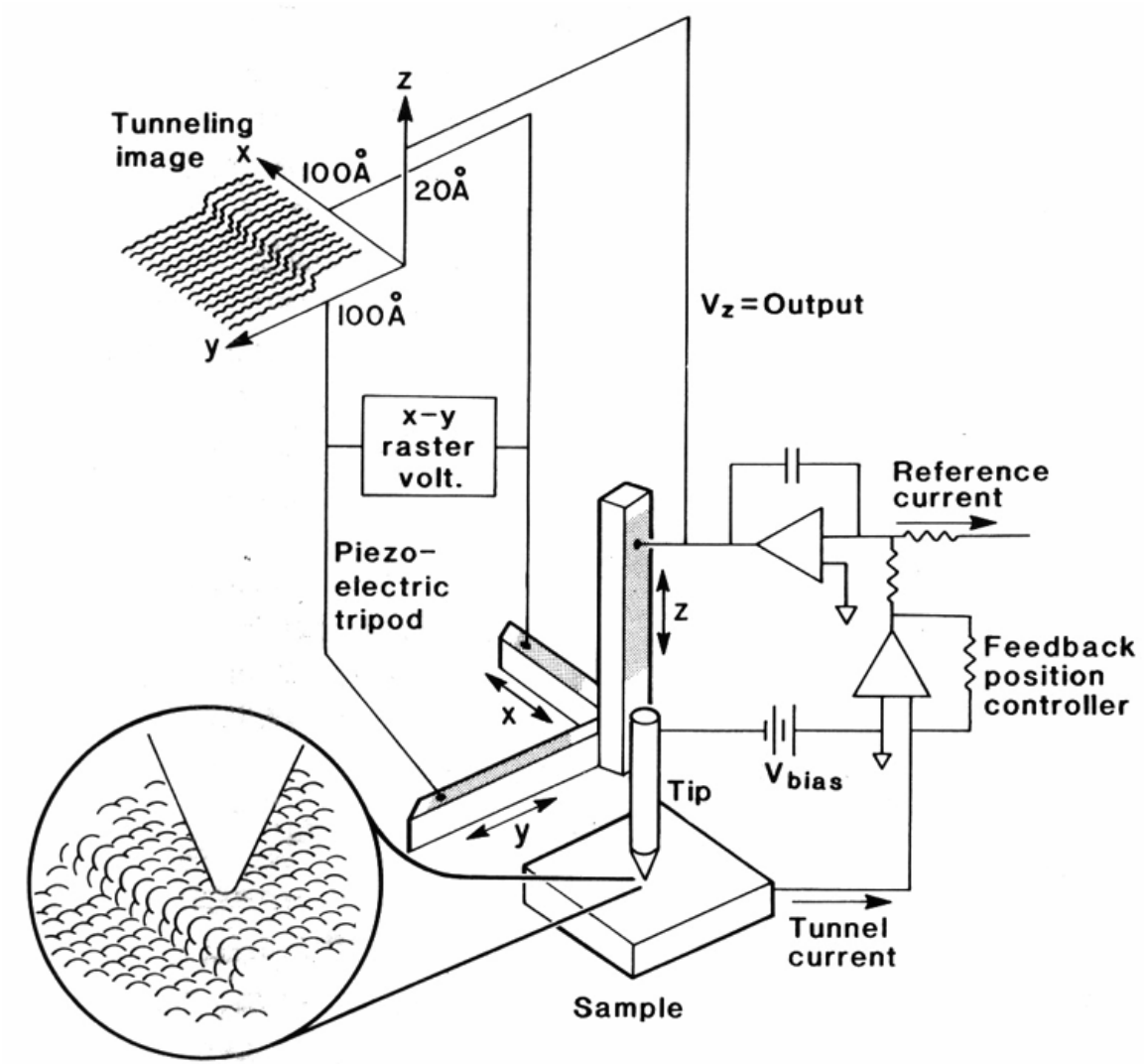
I_t = 10 pA~10nA

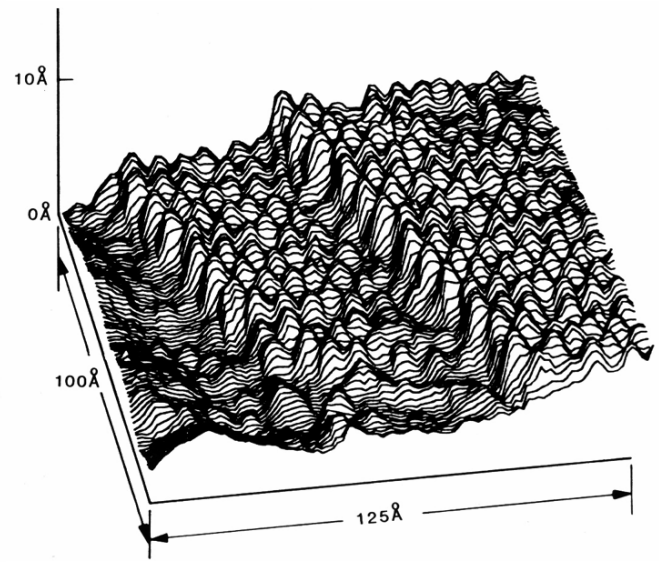
V = 1mV ~ 3V

d decreases by 1 Å,

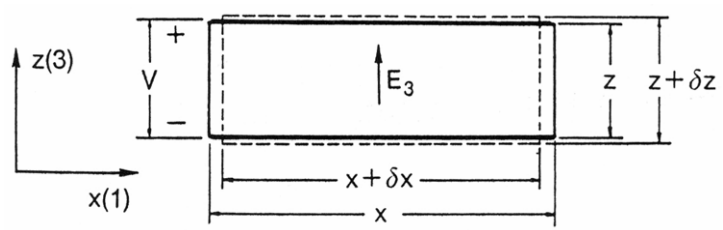
I_t will be reduced by 10 times.

Schematics of STM



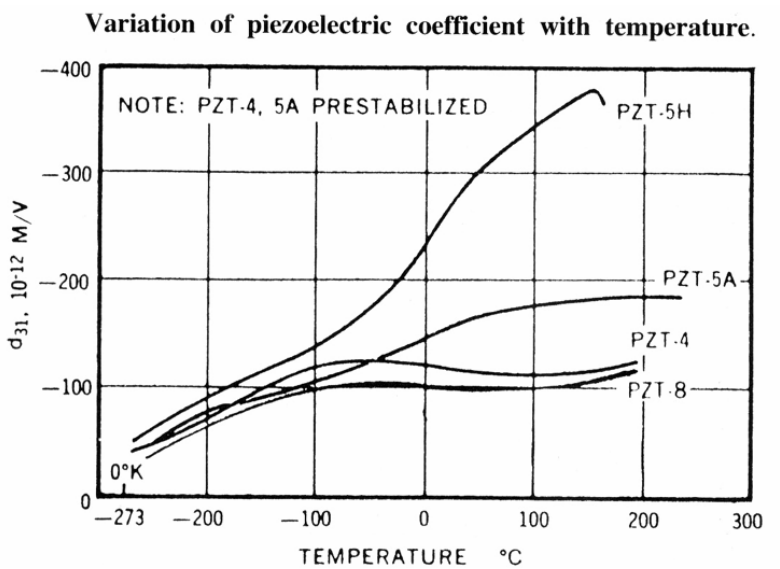


Piezoelectric Scanner

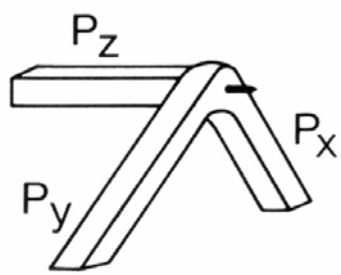


$d_{31} = S_1/E_3$, $S_1 = \delta x/x$, $E_3 = V/z$

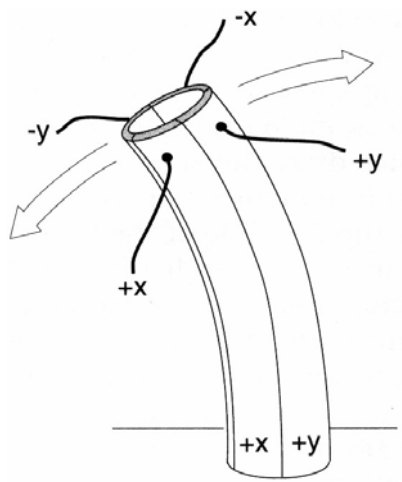
$d_{33} = S_3/E_3$, $S_3 = \delta z/z$



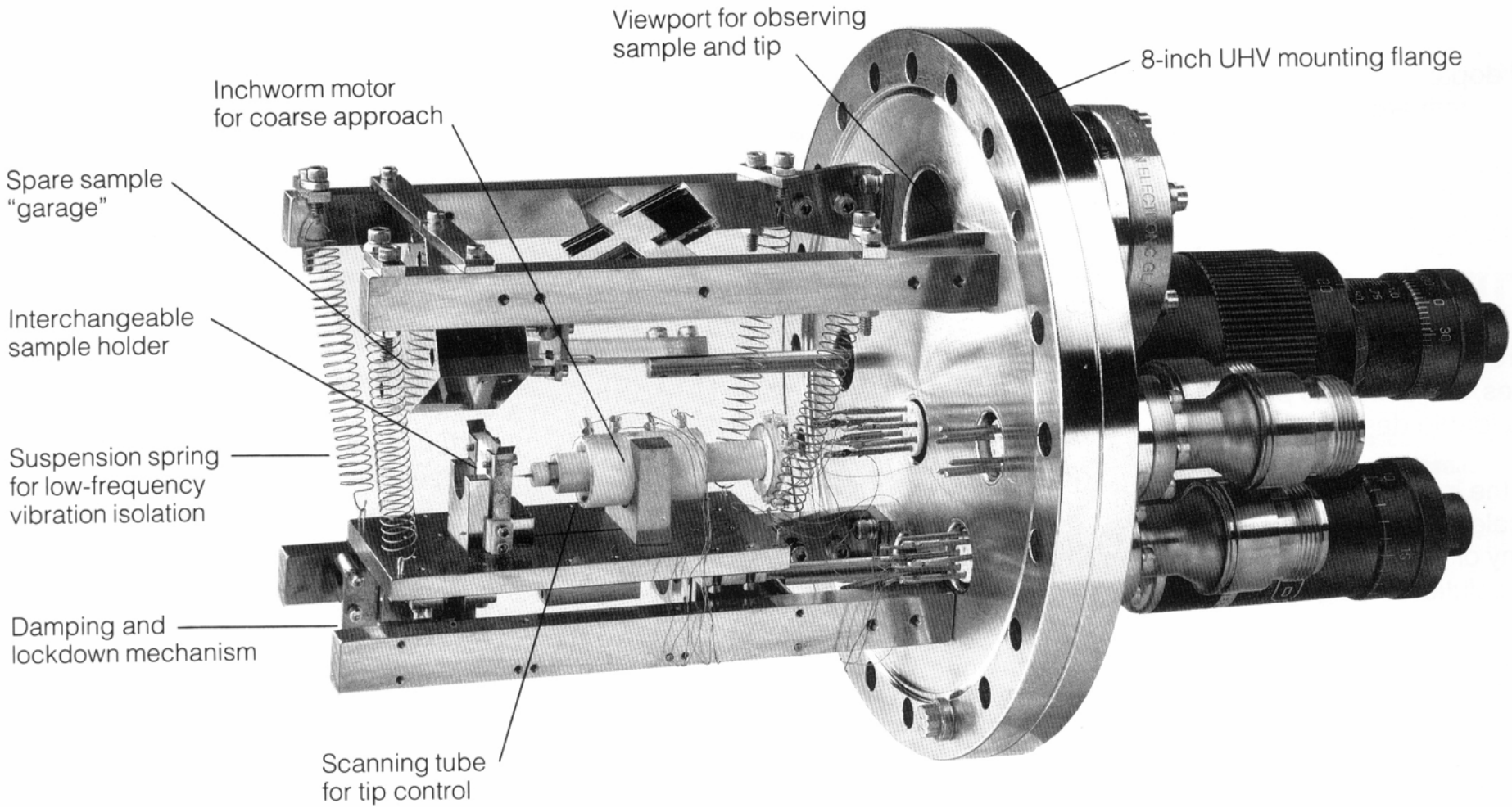
Tripod scanner



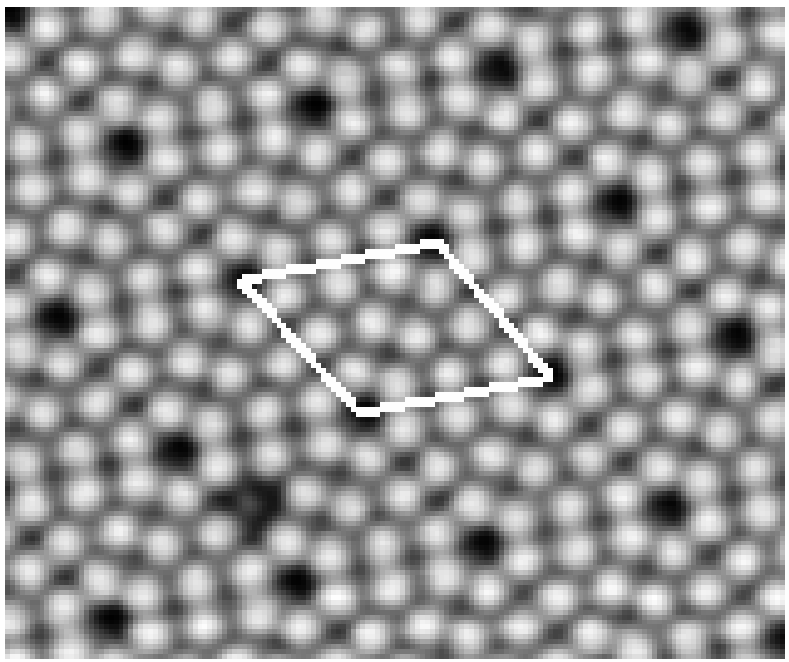
Tube scanner



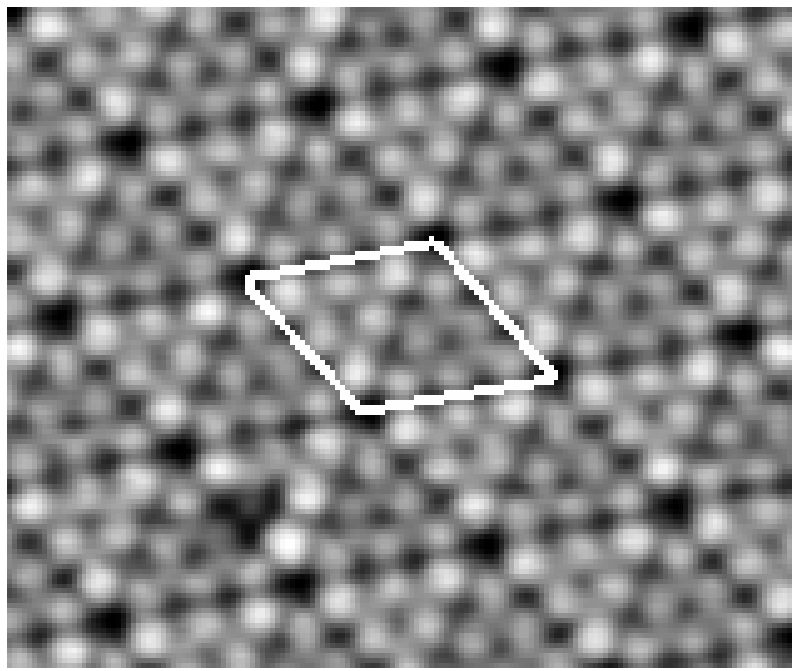
Ultra-High Vacuum Scanning Tunneling Microscope



STM Images of Si(111)-(7×7)



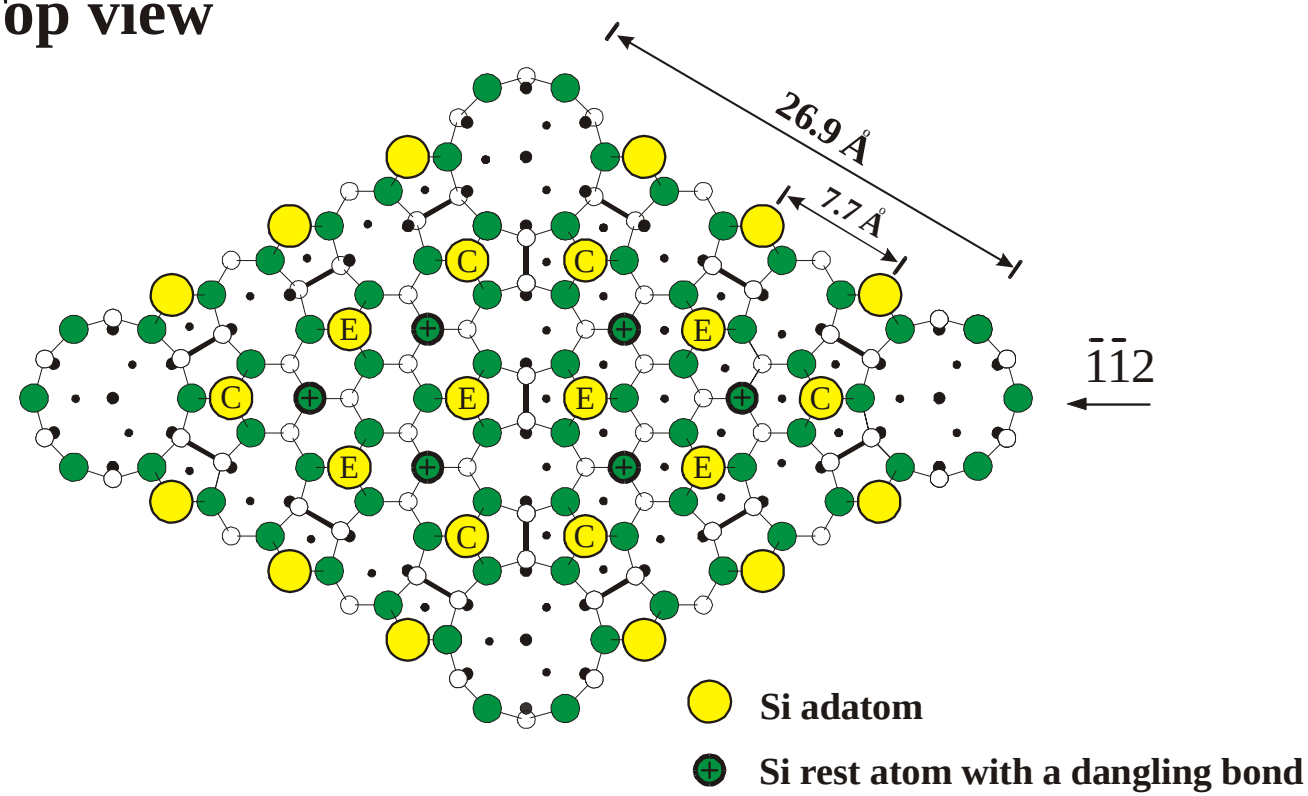
Empty-state image



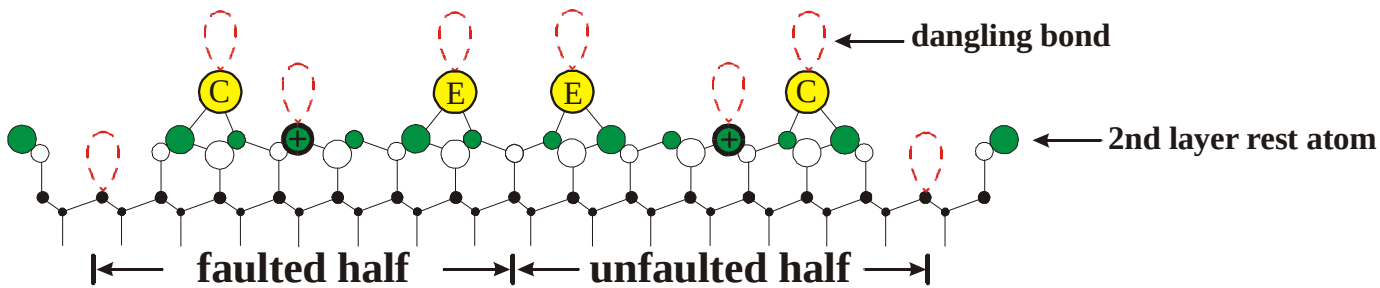
Filled-state image

Atomic Model of Si(111)-(7×7)

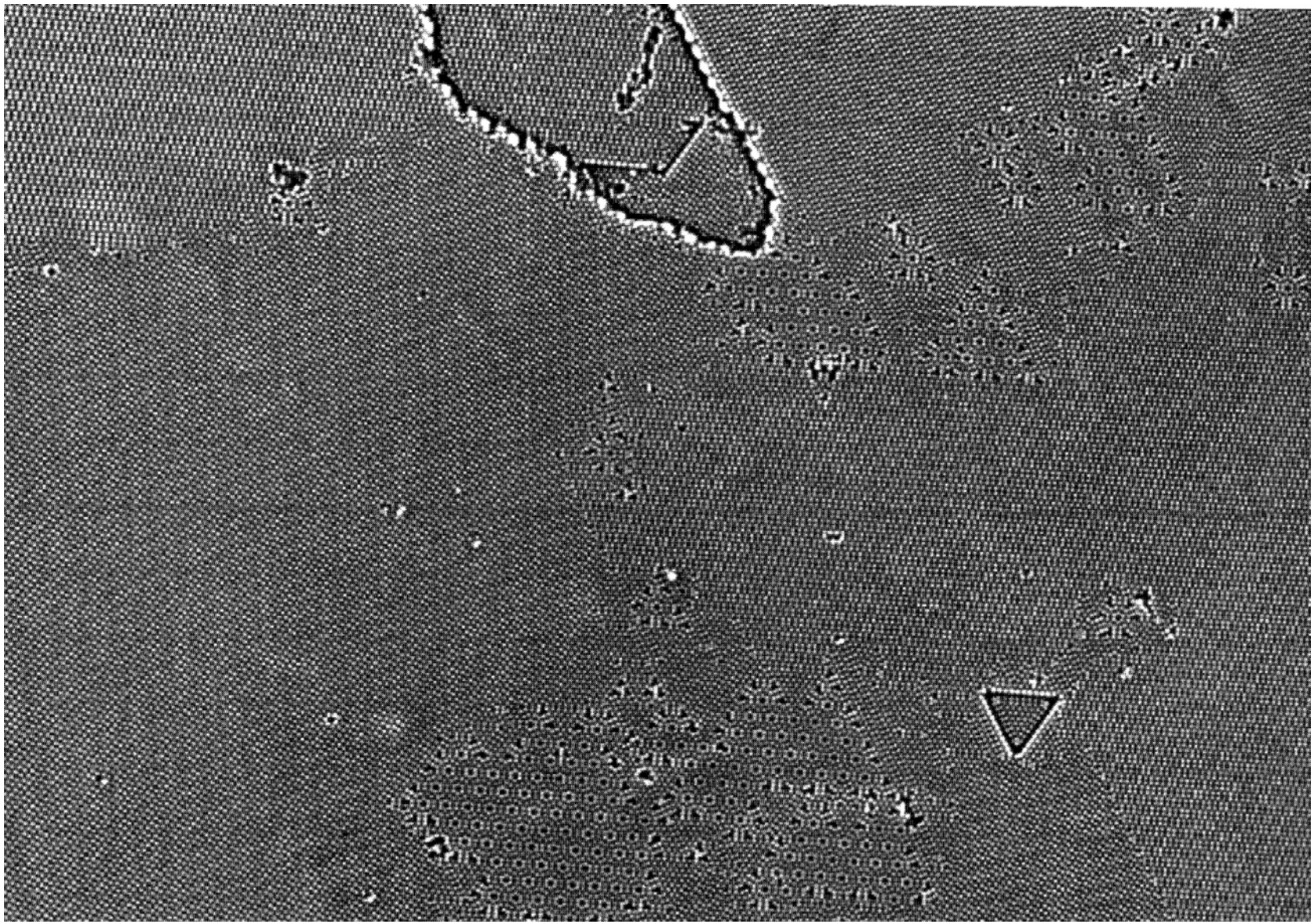
Top view



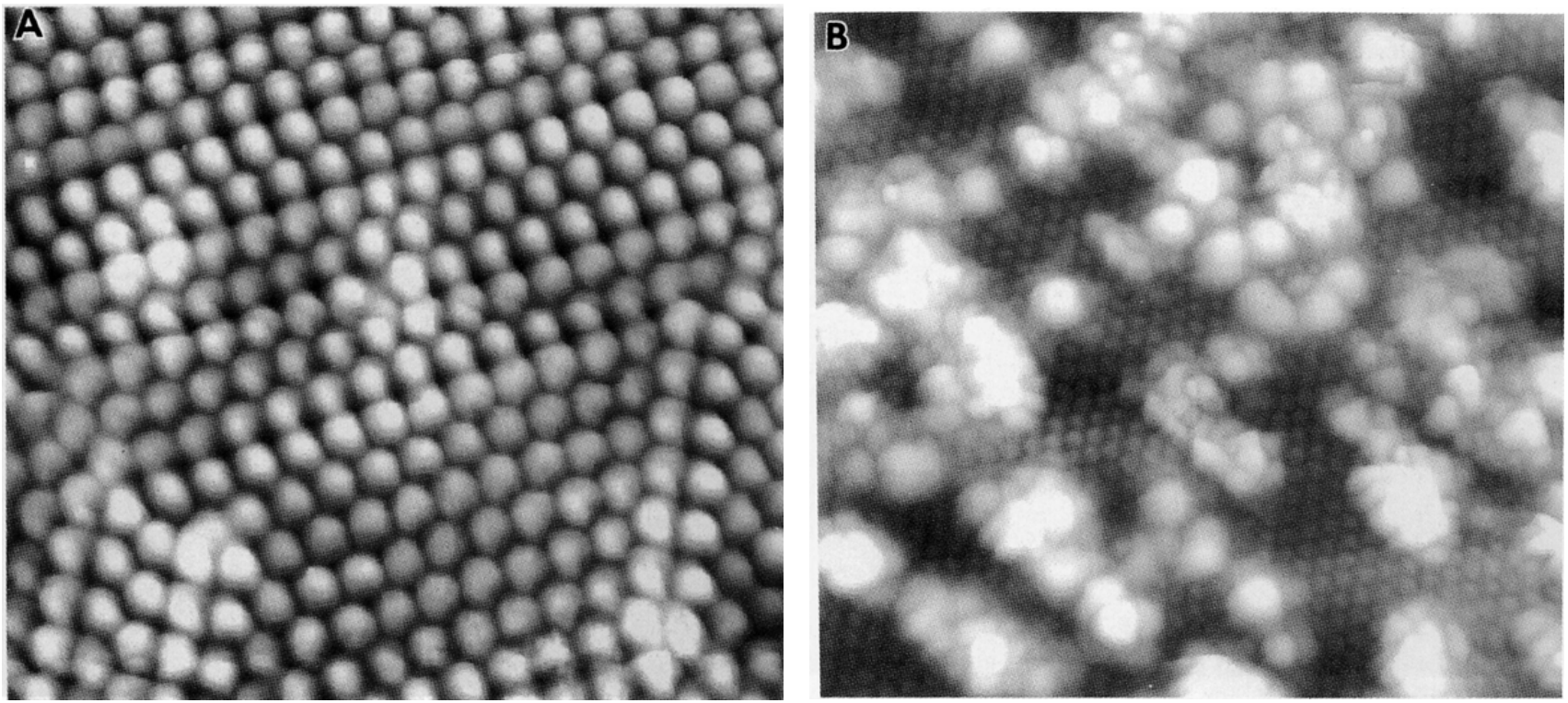
Side view



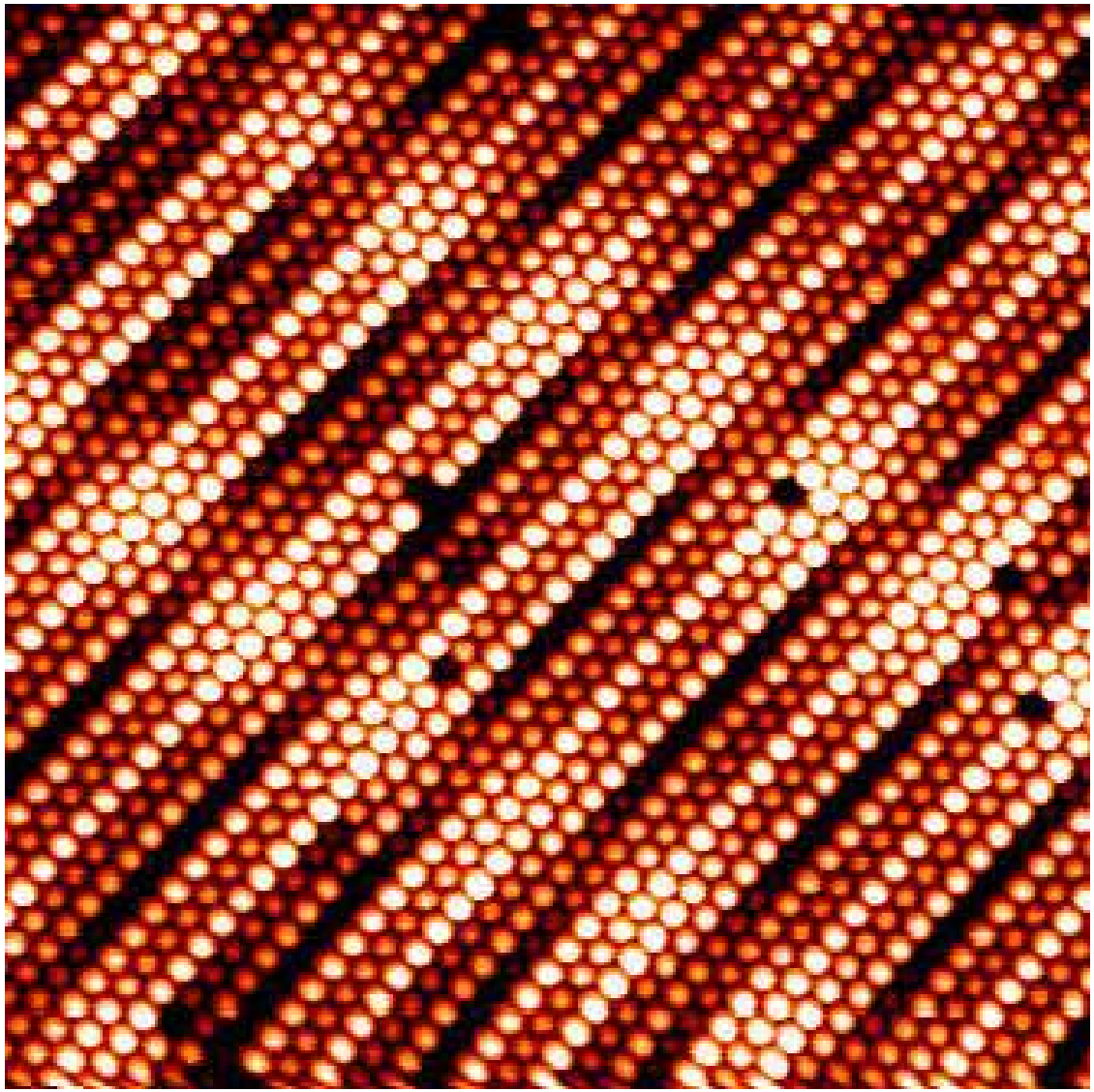
Atomic Structure of the Ge(111) Surface



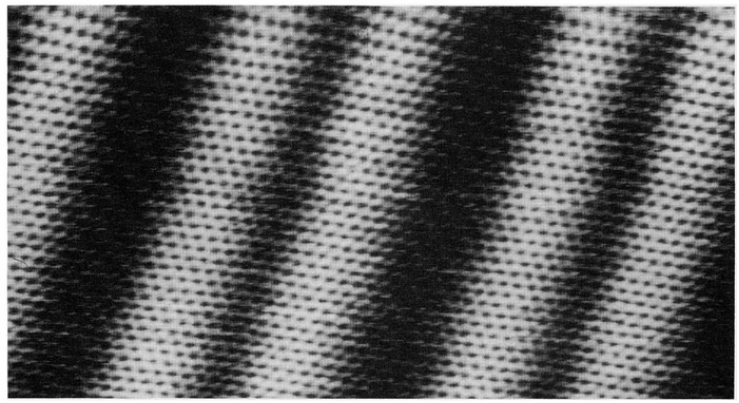
Ge(111)



Atomic Structure of the Pt(001) Surface



Surface Science **306**, 10 (1994).



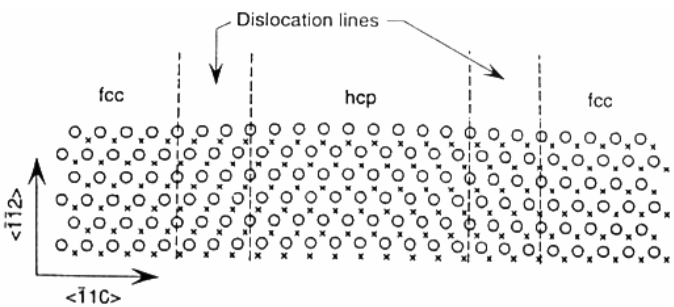
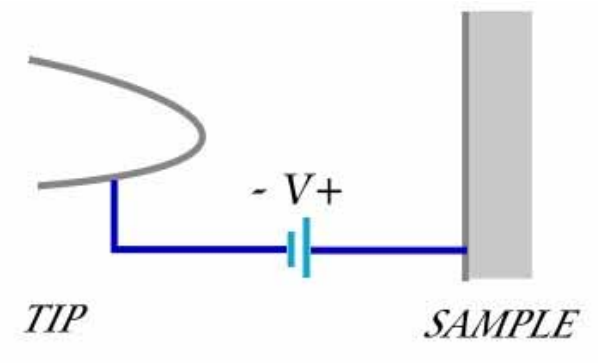


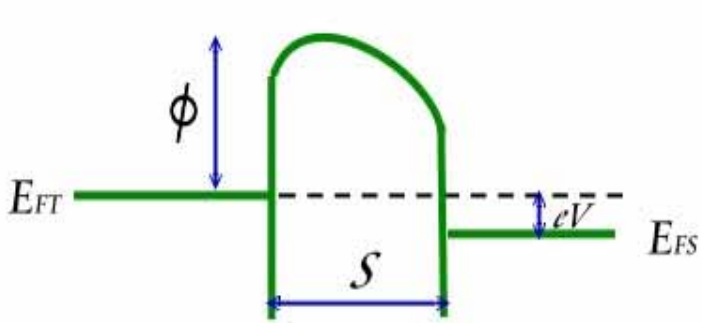
Fig. 1. In-plane structure of the Au(111) surface with a $22 \times \sqrt{3}$ reconstruction. The circles and crosses correspond to atoms in the first and second surface layers, respectively. Surface atoms in both sides of the figure lie on fcc sites, whereas atoms in the center of the figure lie on hcp sites. The domain walls (dislocation lines) involve atoms in bridge sites.

Large-scale image of the Au(111)-22×$\sqrt{3}$ reconstruction. The Au(111) surface reconstructs at room temperature to form a 22×$\sqrt{3}$ structure, which has a two-fold symmetry. On a large scale, three equivalent orientations for this reconstruction coexist on the surface. Furthermore, on an intermediate scale, a herring-bone pattern is formed.

Science 258, 1763 (1992).

Theory of STM



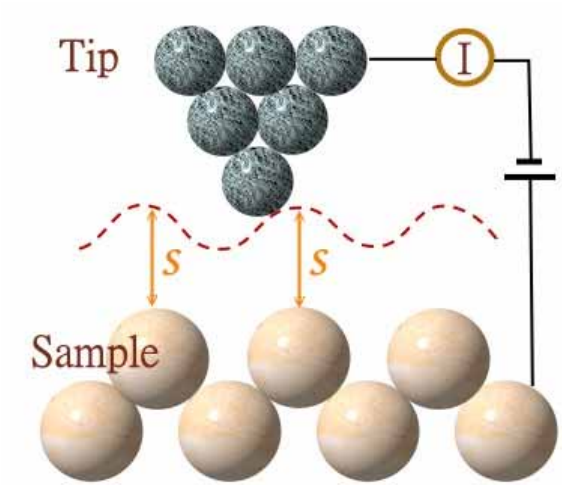


From one-dimensional tunneling problem

tunneling current (eV<< ϕ)

$$I \propto \frac{V}{S}\exp\left(-A\phi^{\frac{1}{2}}S\right)$$

$$A = 1.025(eV)^{-\frac{1}{2}}\ \overset{0}{A}^{-1}$$



Constant Current Mode

Tunneling current

$$I_{T\to S} = \frac{2\pi e}{\hbar}\sum_{\mu\nu} f\left(E_\mu\right)\left[1 - f\left(E_\nu + eV\right)\right]\left|M_{\mu\nu}\right|^2 \delta\left(E_\mu - E_\nu - eV\right)$$

where $f(E)$ is Fermi function

E_μ is the energy of state μ ,where μ and ν run over all the states of the tip and surface , respectively.

$M_{\mu\nu}$ is tunneling matrix element

$$M_{\mu\nu} \equiv \frac{\hbar^2}{2m}\int d\vec{s}\left(\psi_\mu * \nabla\psi_\nu - \psi_\nu \nabla\psi_\mu *\right)$$

where ψ_μ is the wave function, and the integral is over any plane in the barrier region.

$$I = I_{T\to S} - I_{S\to T}$$

$$= A'\int_{-\infty}^{\infty} \rho_T\left(E\right)\rho_S\left(E+eV\right)\left|M\left(E\right)\right|^2\left[f\left(E\right) - f\left(E+eV\right)\right]dE$$

where ρ_S and ρ_T are the densities of states in the sample and the tip, respectively.

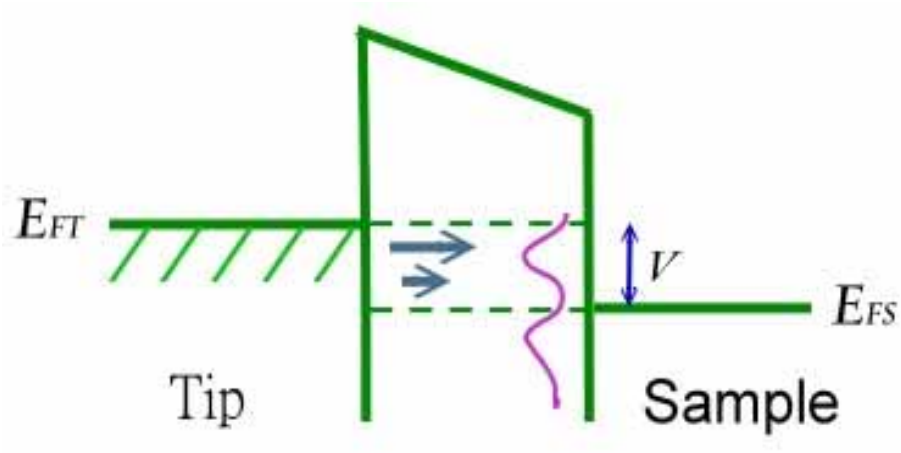
Tunneling current

$$I \equiv A' \int_{-\infty}^{\infty} \rho_T(E)\rho_S(E+eV)\left|M(E)\right|^2 \left[f(E) - f(E+eV)\right]dE$$

Transmission probability of the electron

$$M(E) = \exp\left[-A\phi^{\frac{1}{2}}S\right]$$

Usually, we assume ρ_T is featureless (ie. $\rho_T \approx const.$), and the sample electronics states dominate the tunnel spectra.



However, the tips might have effect on the tunnel spectra, if

1. we have atomically sharp tips ,or
2. the tip has picked up a foreign atom.

Case Ⅰ -----metals

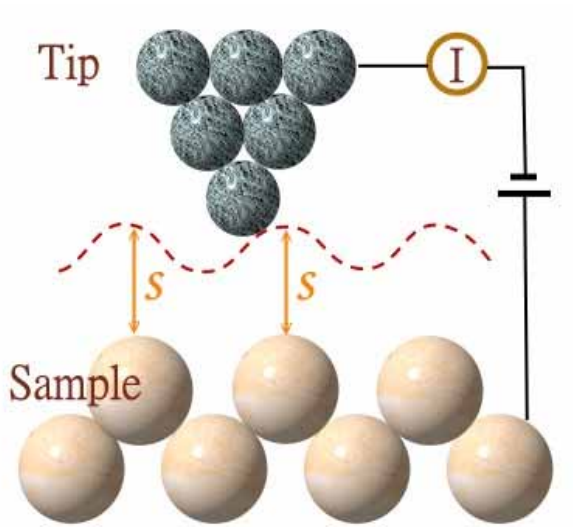
In the low-voltage limit

$$I \propto V\rho_S(\tilde{r}_t;E_F)\rho_t(E_F)$$

where $\rho_S(\tilde{r}_t;E_F)$ is the surface density of states of the sample at the center of the tip($\tilde{r}_t$),

$$\rho_S(\tilde{r};E) \equiv \sum_\nu |\psi_\nu(\tilde{r})|^2 \delta(E_\nu - E)$$

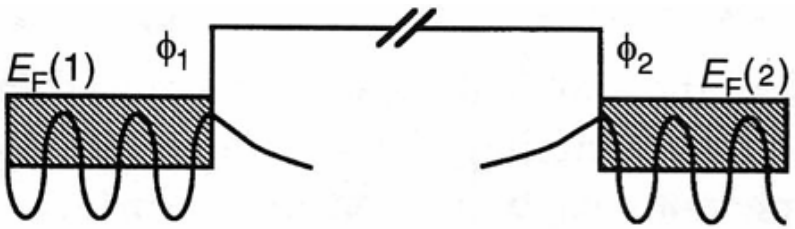
$\rho_t(E_F)$ is the density of states of the tip at the Fermi level and is often regarded as a constant.



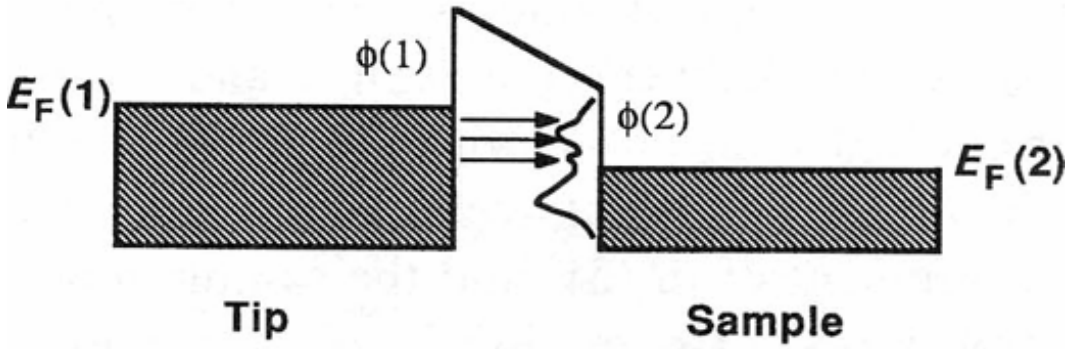
Constant Current Mode

Electronic Structures at Surfaces

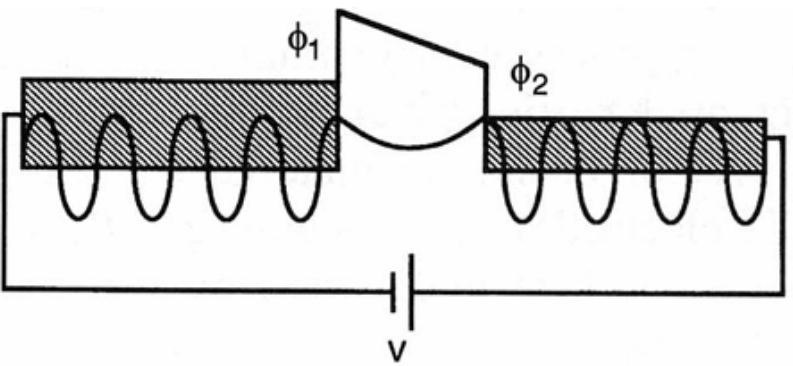
Not Tunneling



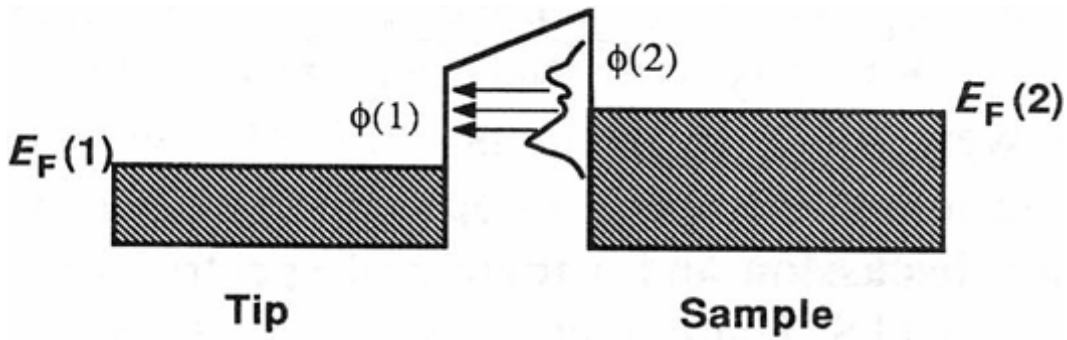
Empty-State Imaging



Tunneling

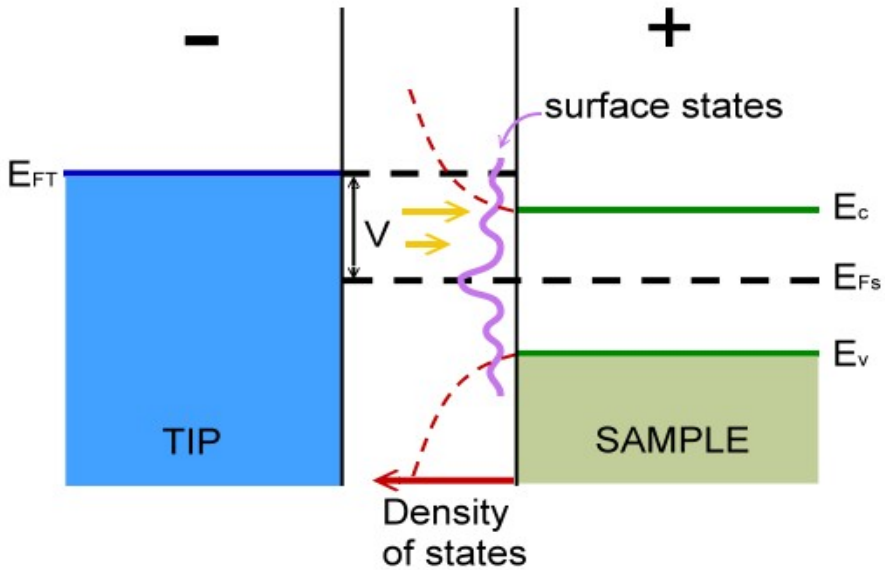


Filled-State Imaging

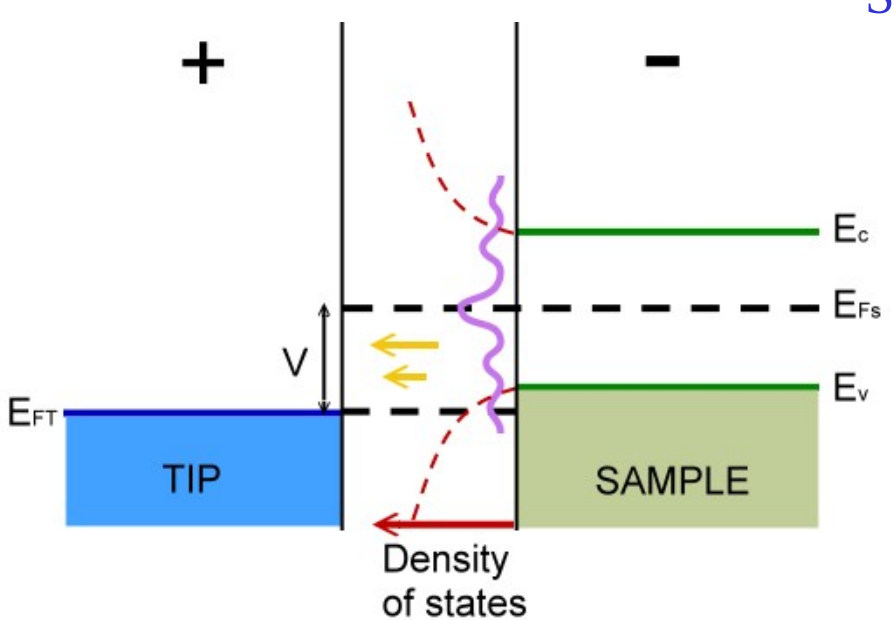


Example -----Semiconductor

1.Tip-negative



2.Tip -positive



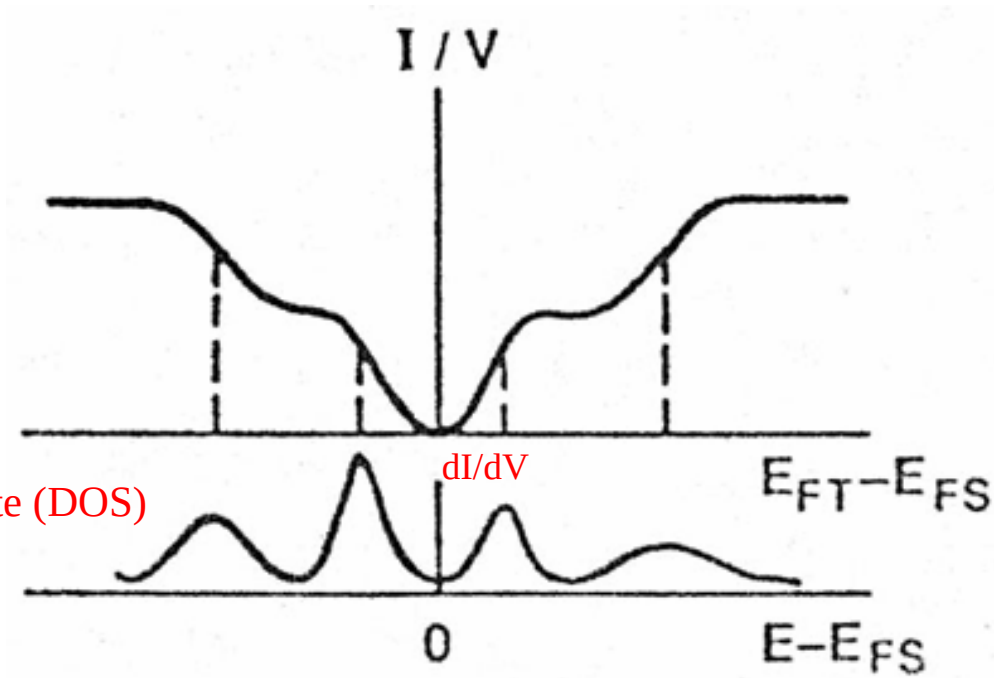
Science **234**, 304 (1986).

Scanning Tunneling Spectroscopy

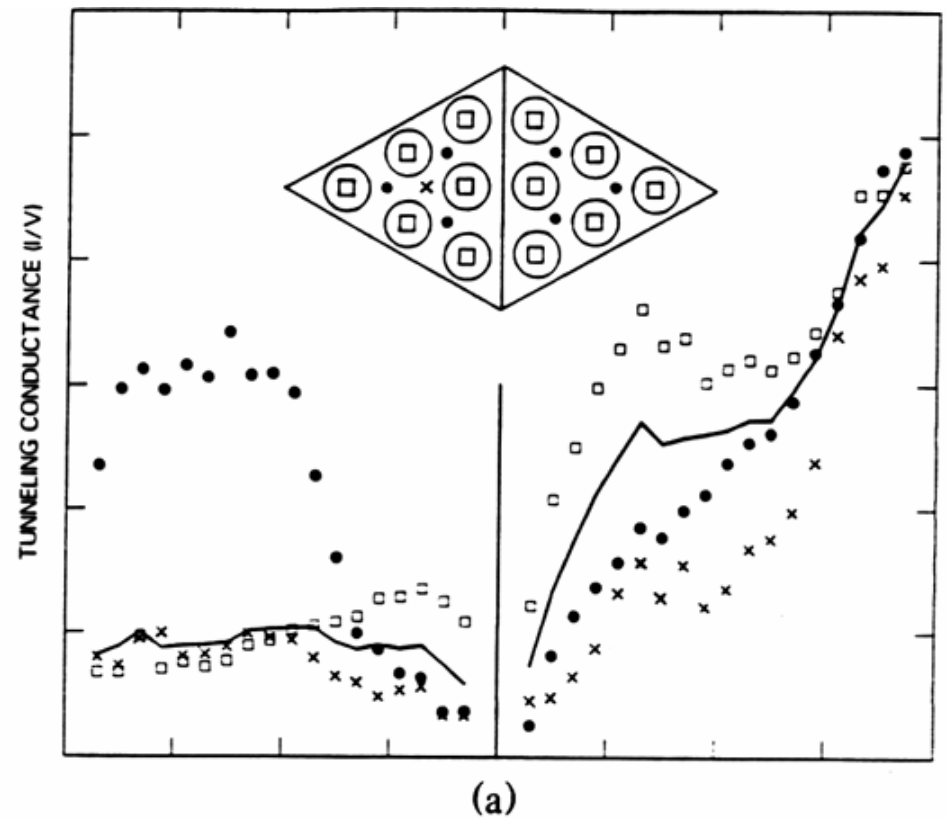
STM provides atomic-scale topographic information, and atomic-scale electronic information. However, the mixture of geometric and electronic structure information often complicates interpretation of observed feature.

Several spectroscopic modes:

1. **Voltage-dependent STM imaging.**
2. **Tunneling I-V curves, current-imaging-tunneling spectroscopy (CITS).**
3. **Scanning tunneling spectroscopy (STS): dI/dV and topograph.**



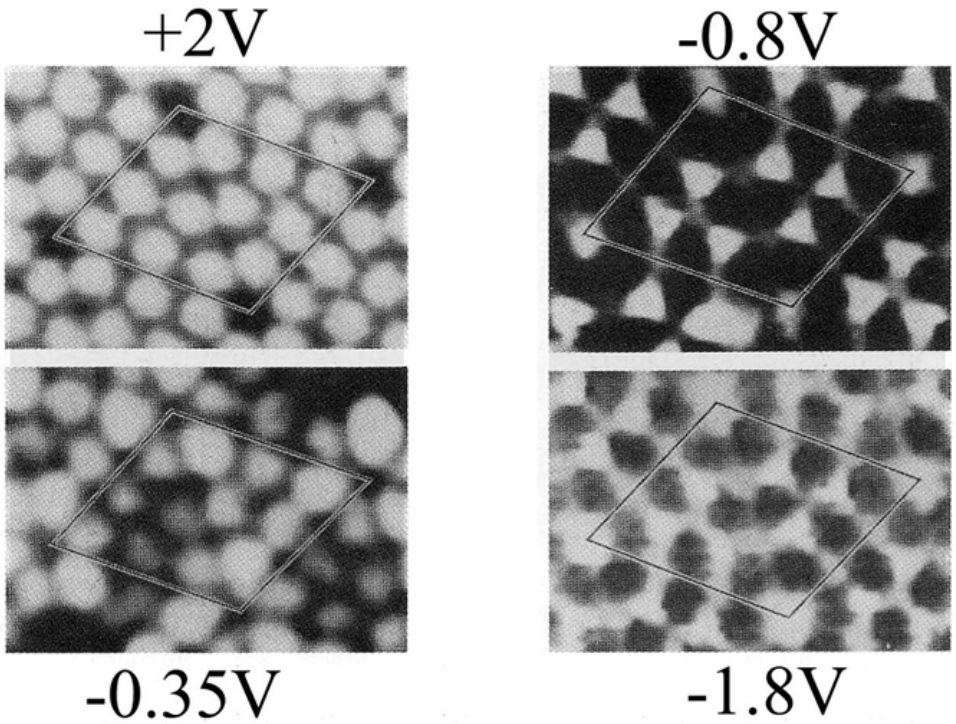
STS of Si(111)-(7x7)

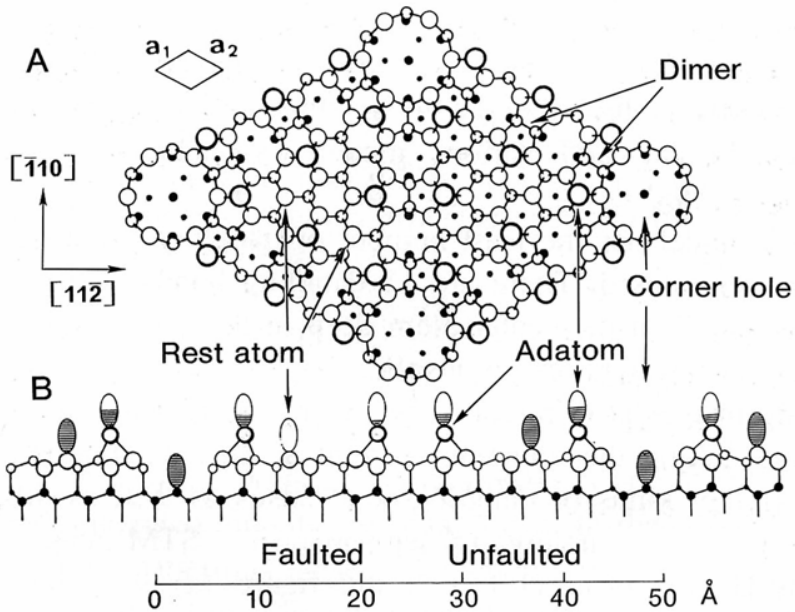


Science **234**, 304 (1986).

STS of Si(111)-(7x7)

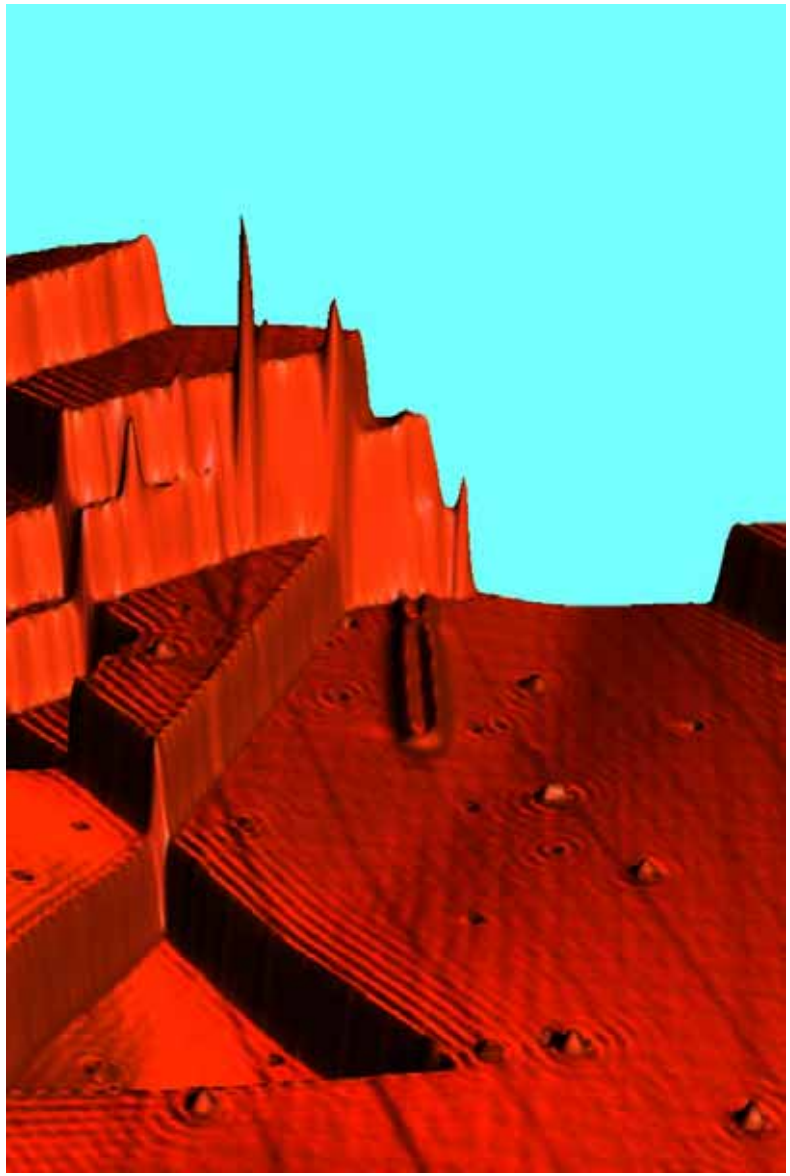
topograph





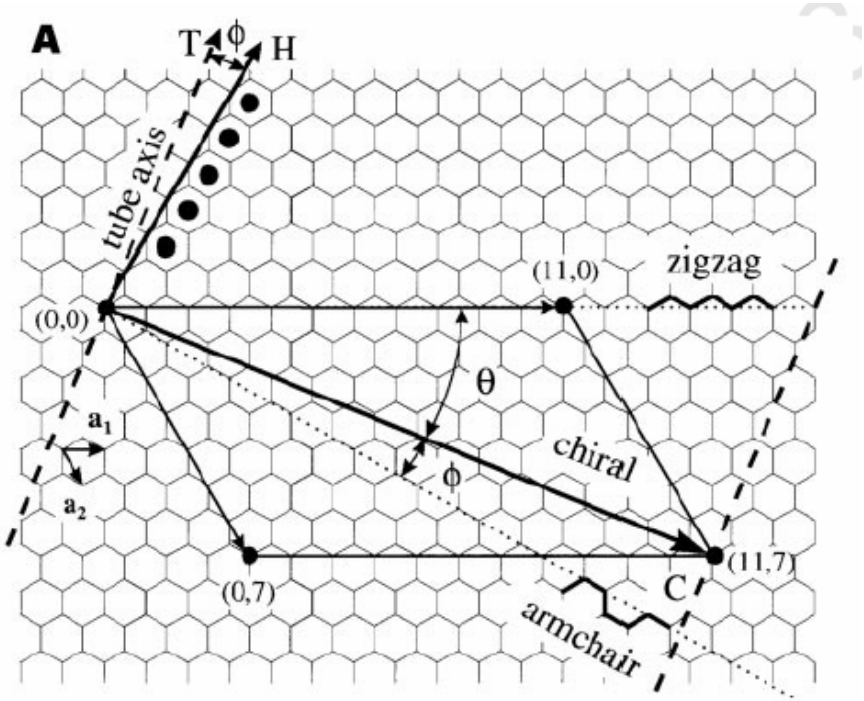
1. Science **234**, 304-309 (1986).
2. Phys. Rev. Lett. **56**, 1972-1975 (1986).

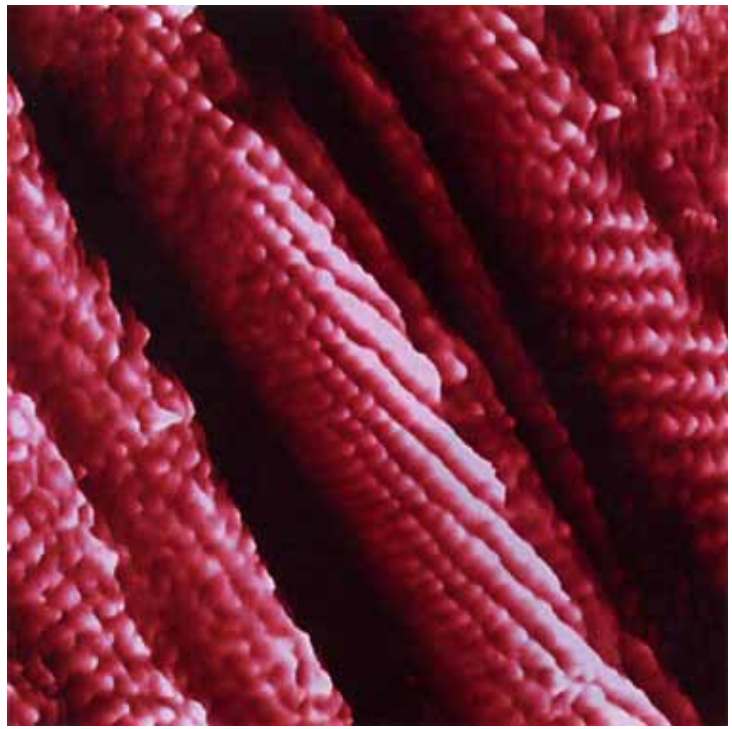
Surface States at Cu(111)

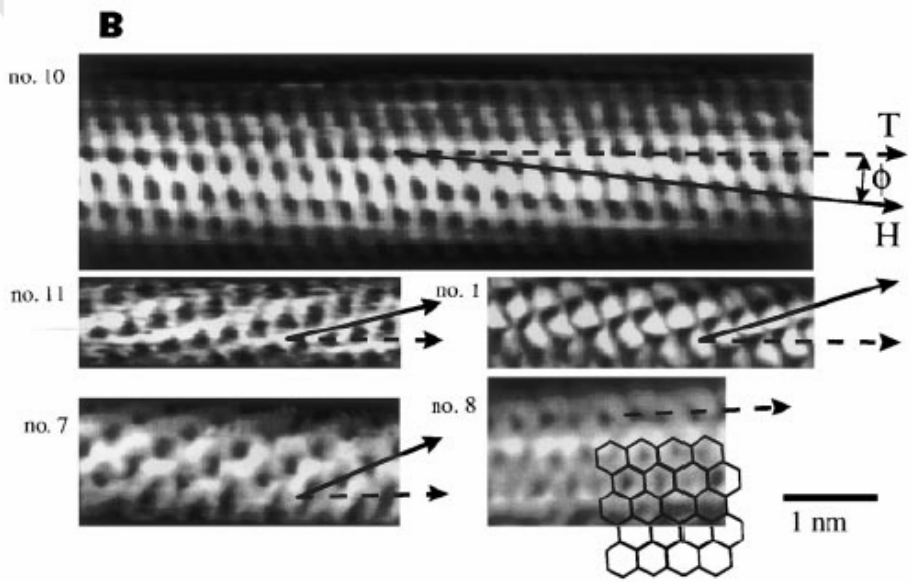


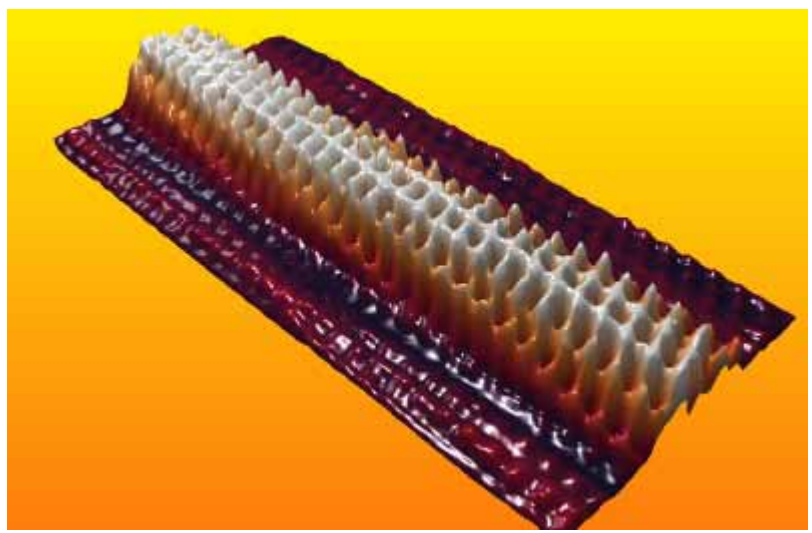
Nature **363**, 524 (1993).

Single-Wall Carbon Nanotubes



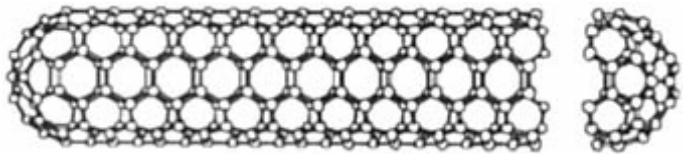






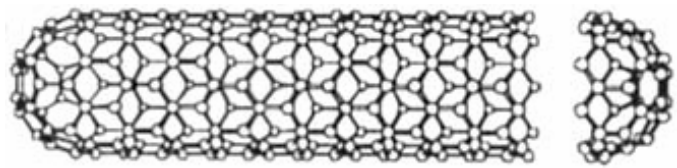
Electronic Structure of Single-Wall Nanotubes

1. Armchair nanotubes (n,n) → metallic

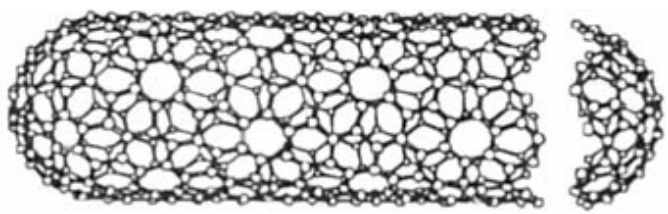


2. Zigzag nanotubes (n,0) → metallic, when n=3q

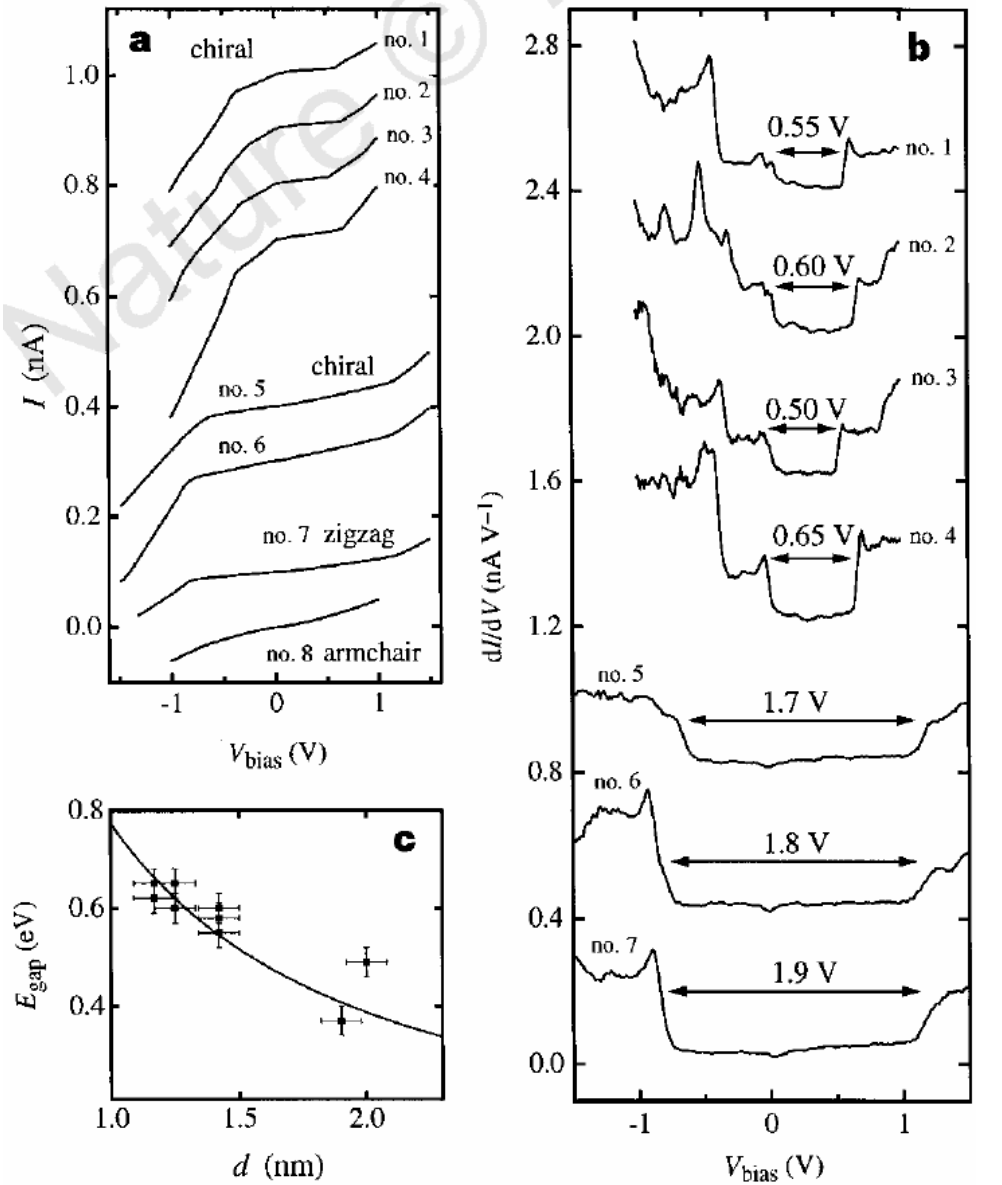
   → semiconducting, otherwise

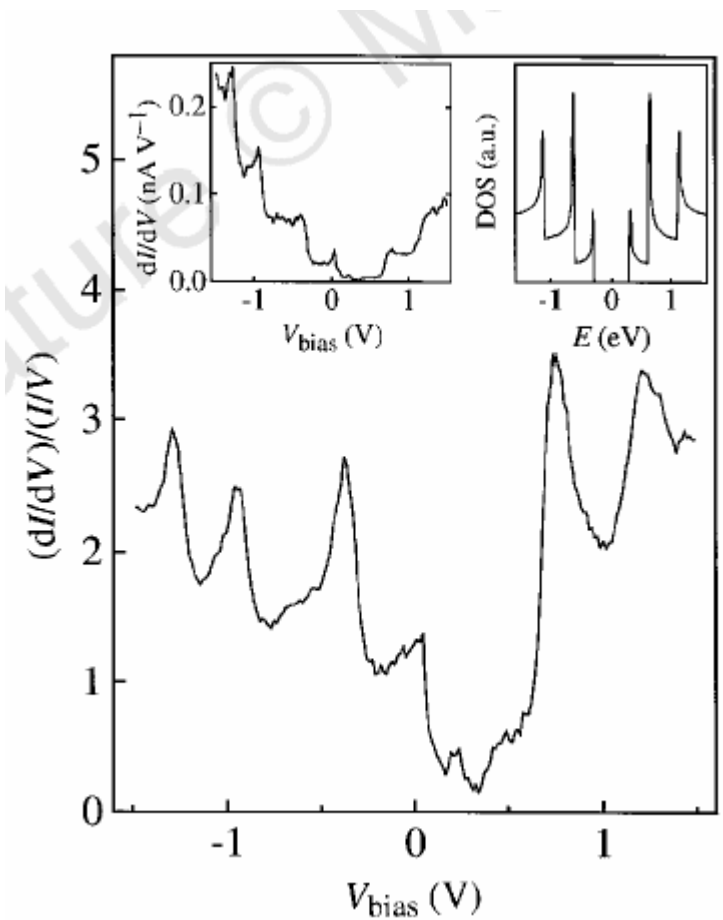


3. Chiral nanotubes (n,m) → metallic, when m=n+3q



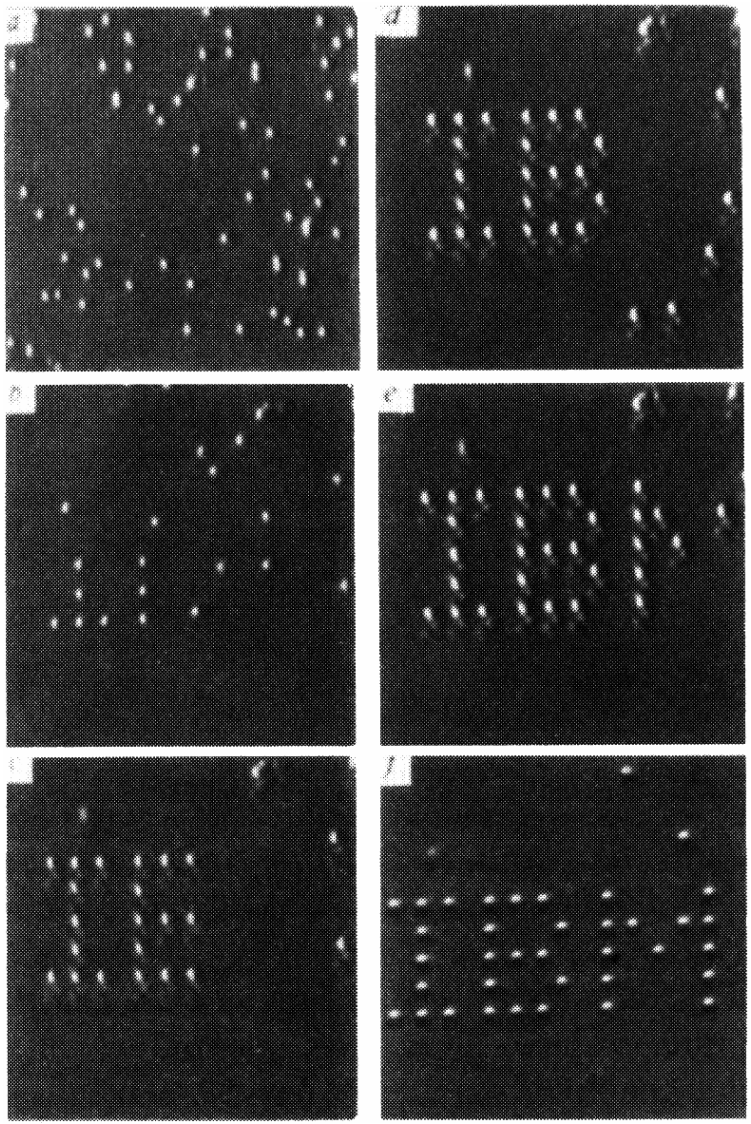
Electronic Structure of Single-wall Nanotubes



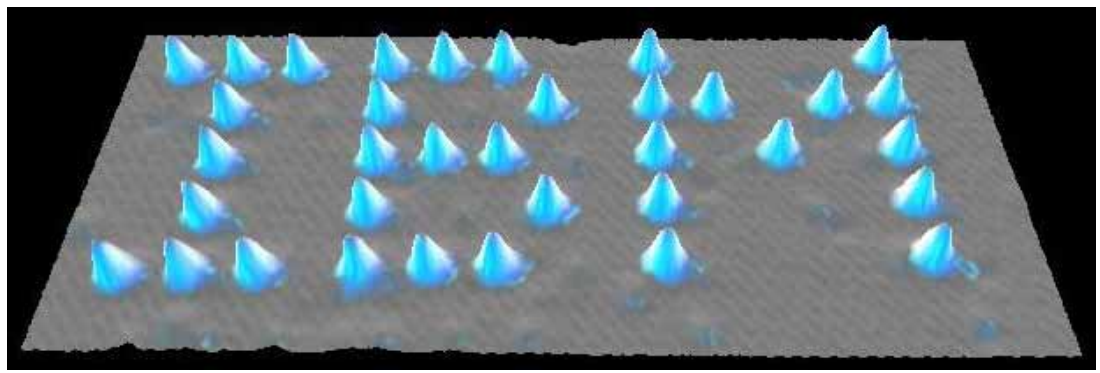


Nature **391**, 59 (1998).

Atomic Manipulation with STM

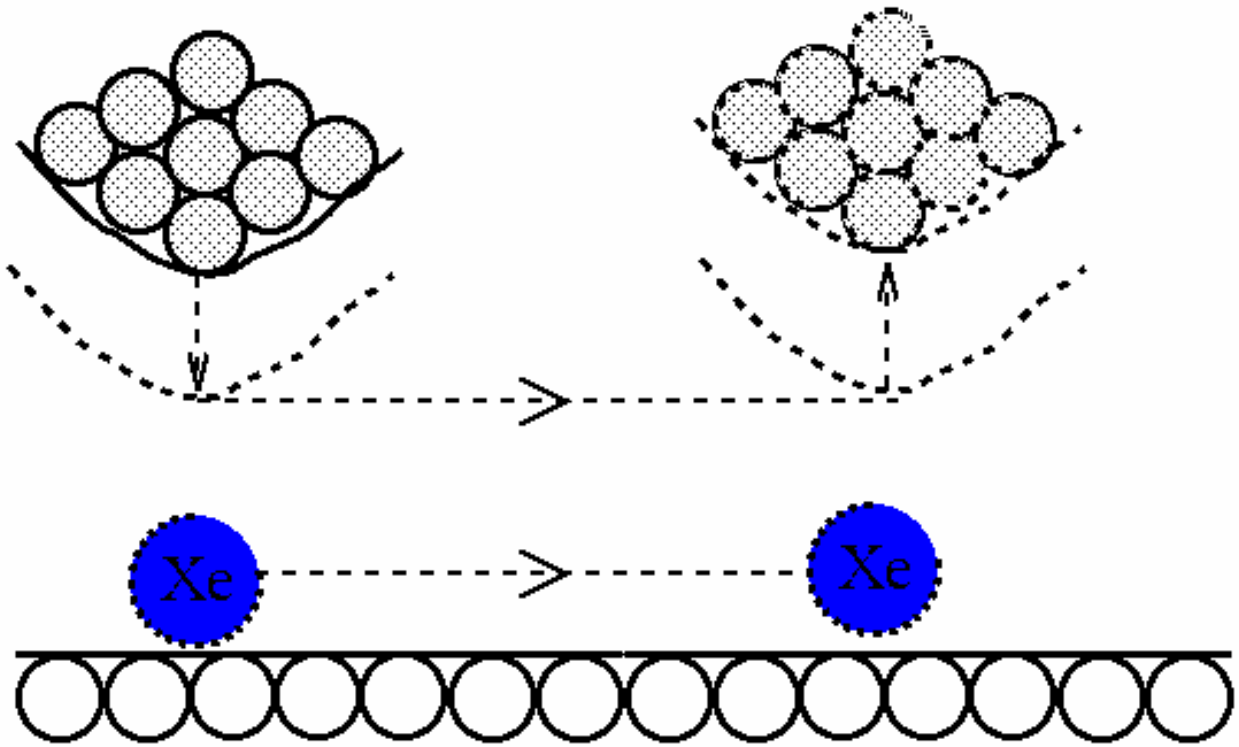


Nature **344**, 524 (1990)



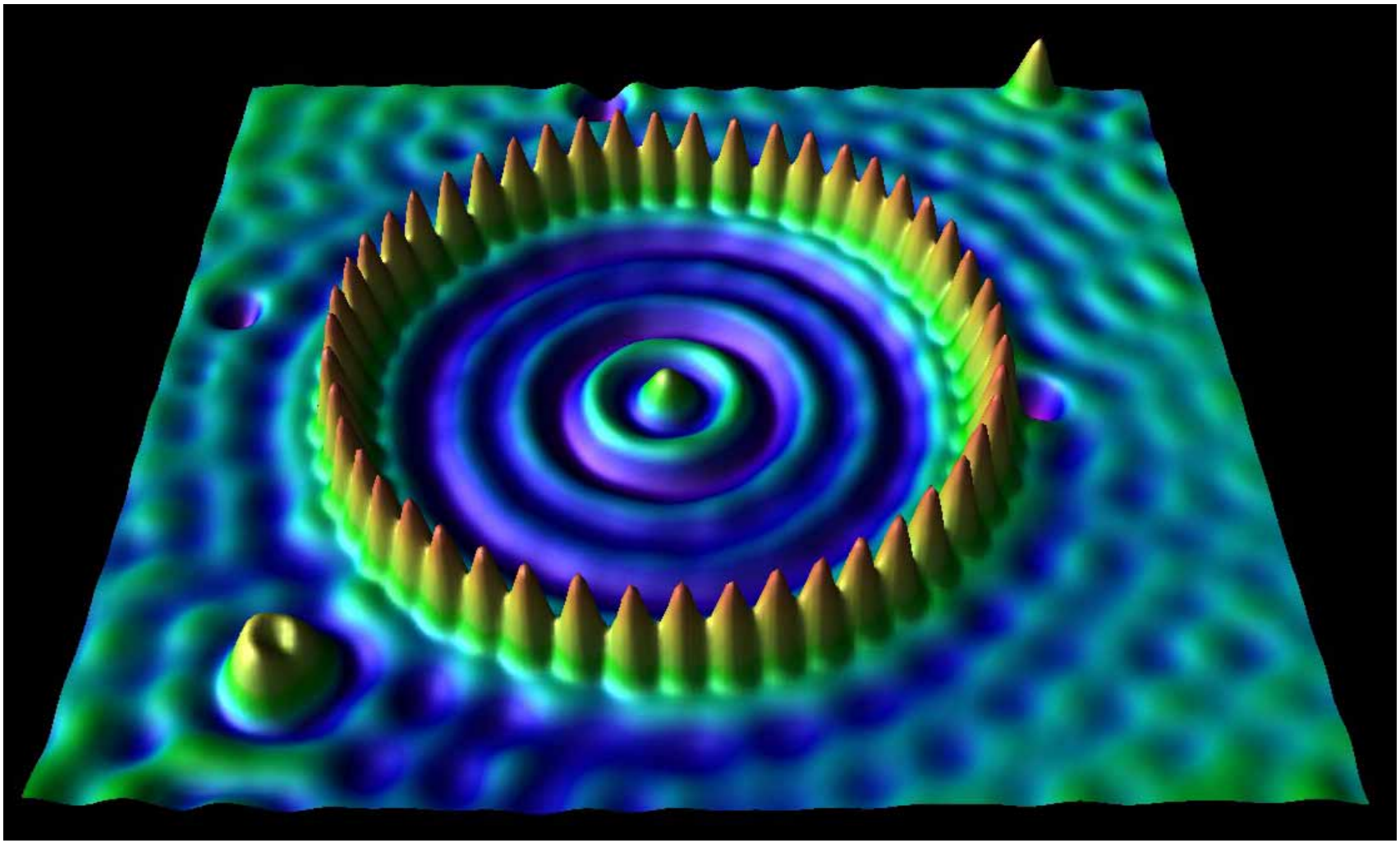
Positioning Atoms with an STM

D.M. Eigler & E.K. Schweizer Nature **344** 524 (1990)

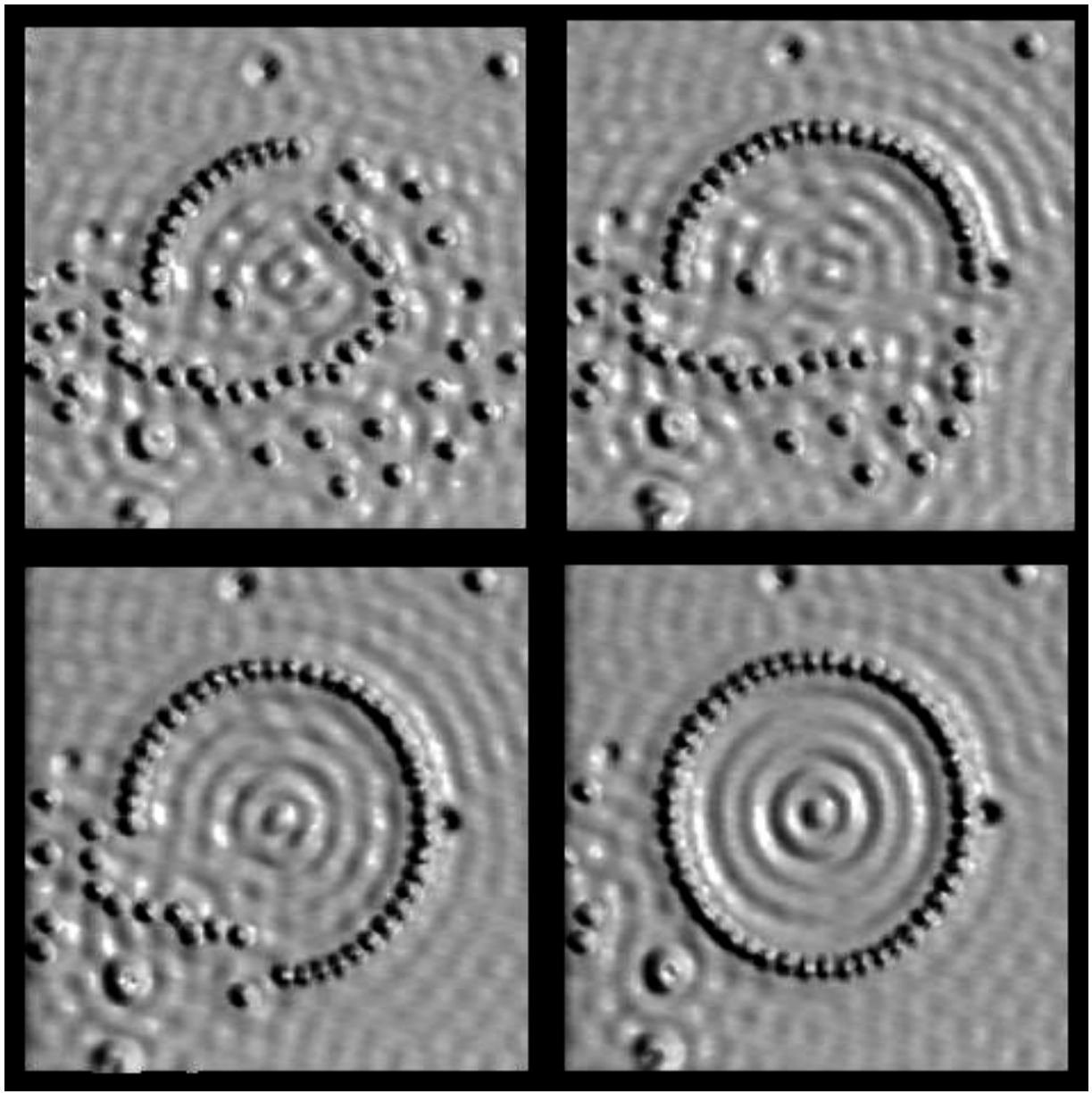


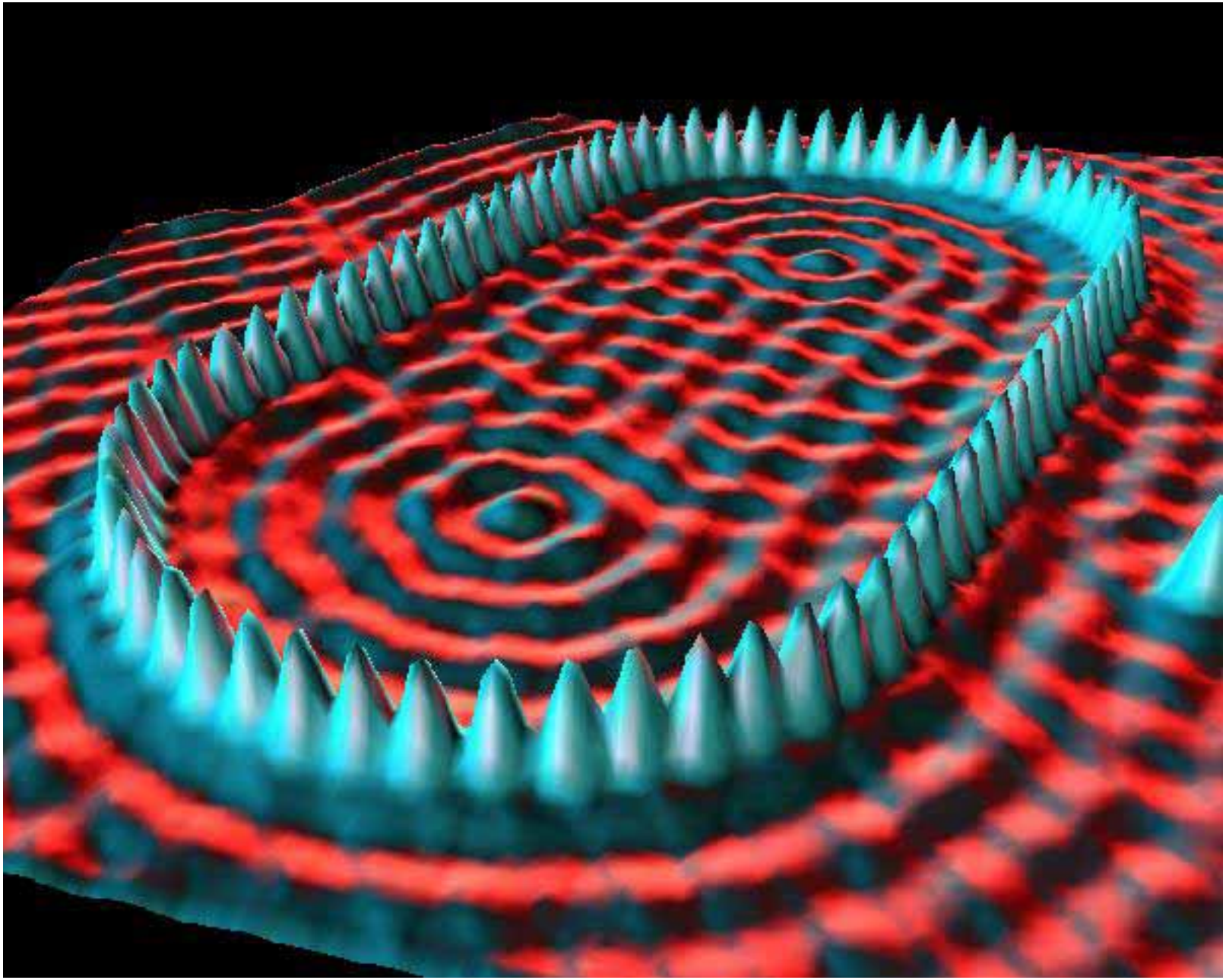
The STM tip is brought down near the atom, until the attraction is enough to hold it as the atom is dragged across the surface to a new position.

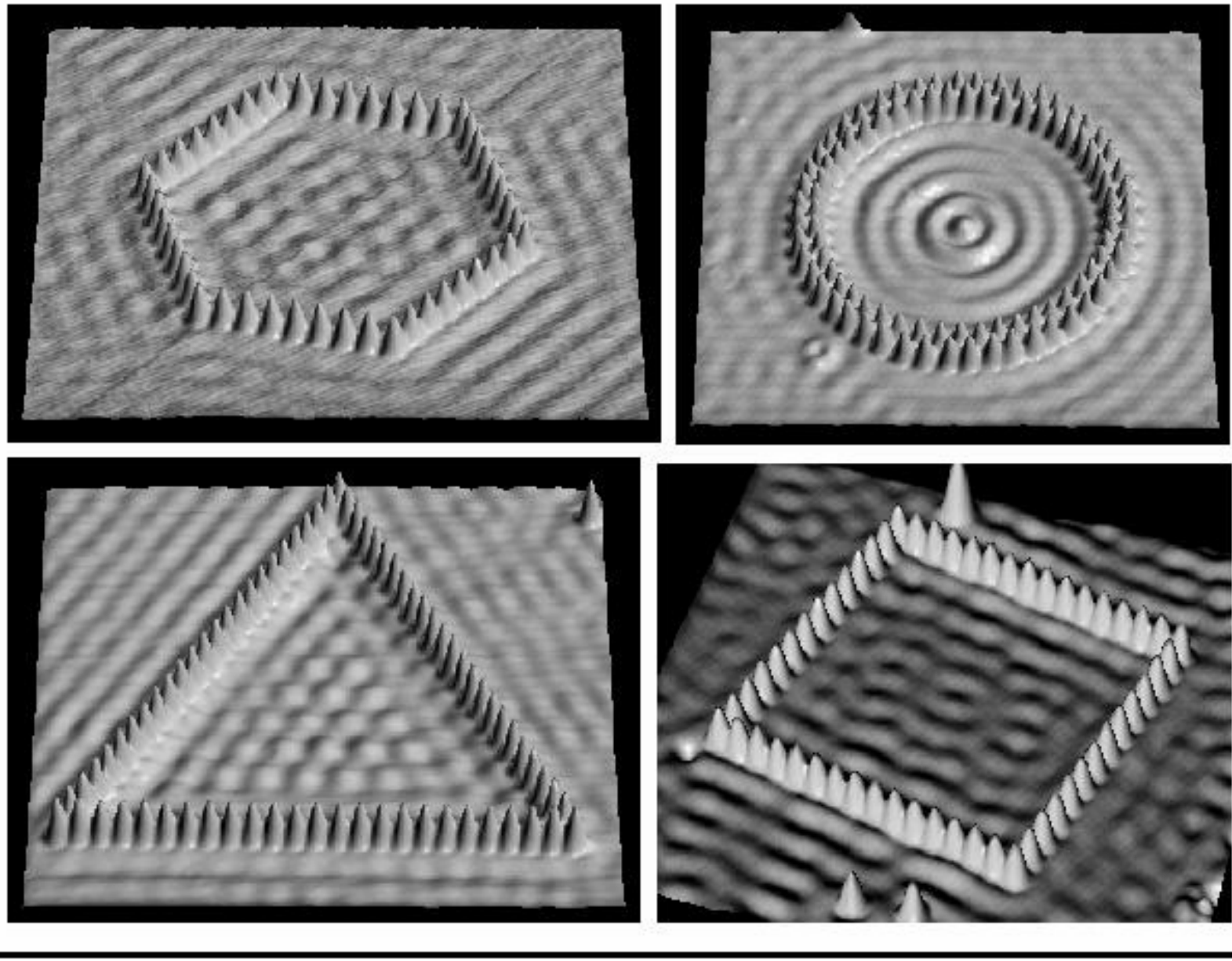
Quantum Corral



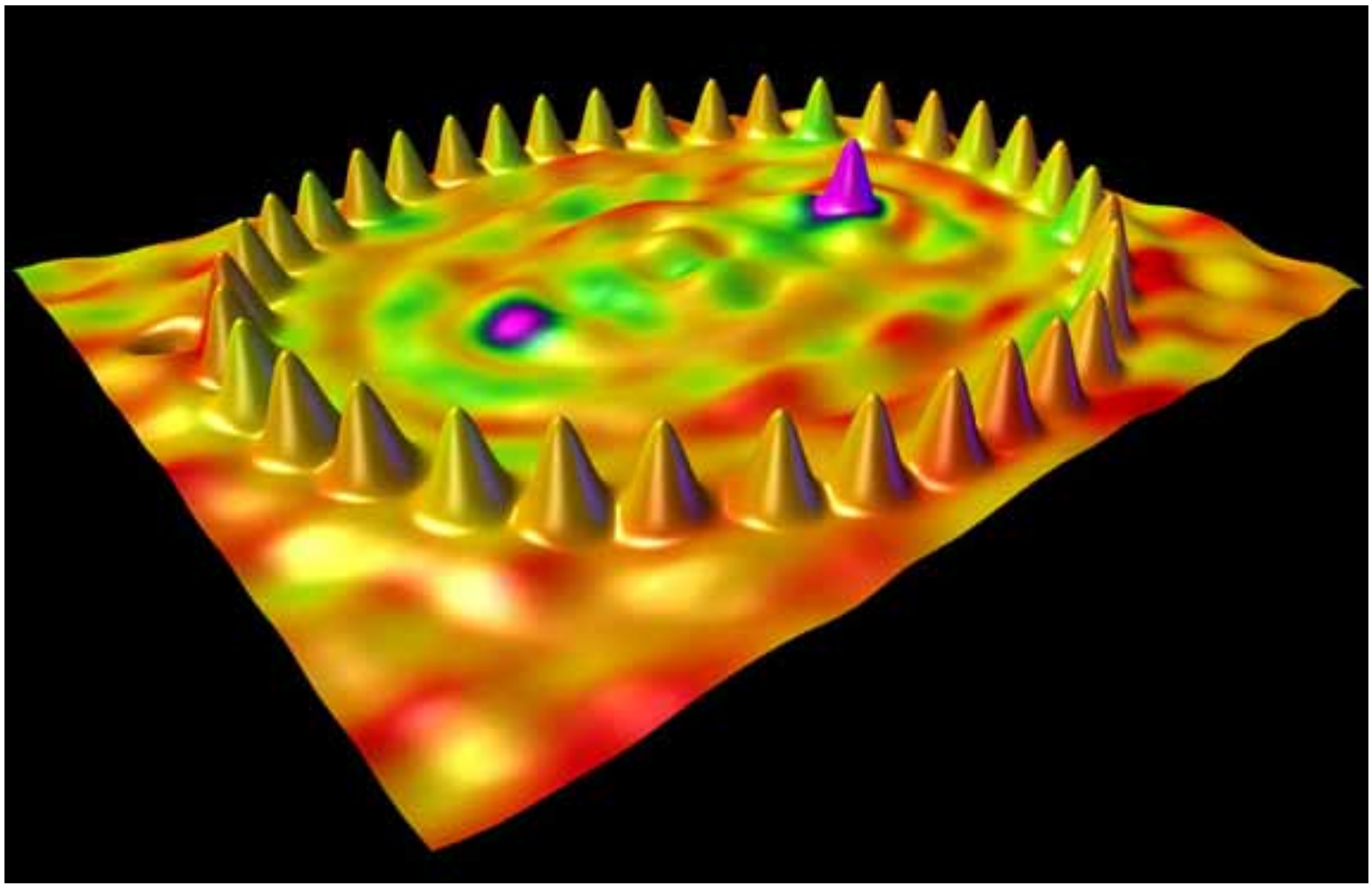
M.F. Crommie *et al., Science* 262, 218 (1993).







Quantum Mirage



H. C. Manoharan *et al., Nature* 403, 512 (2000).

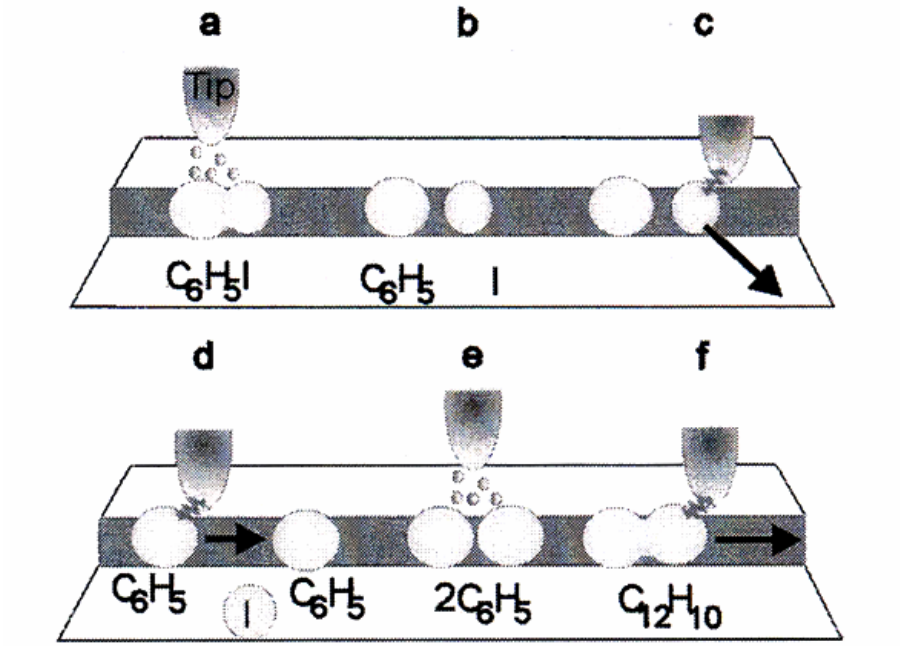
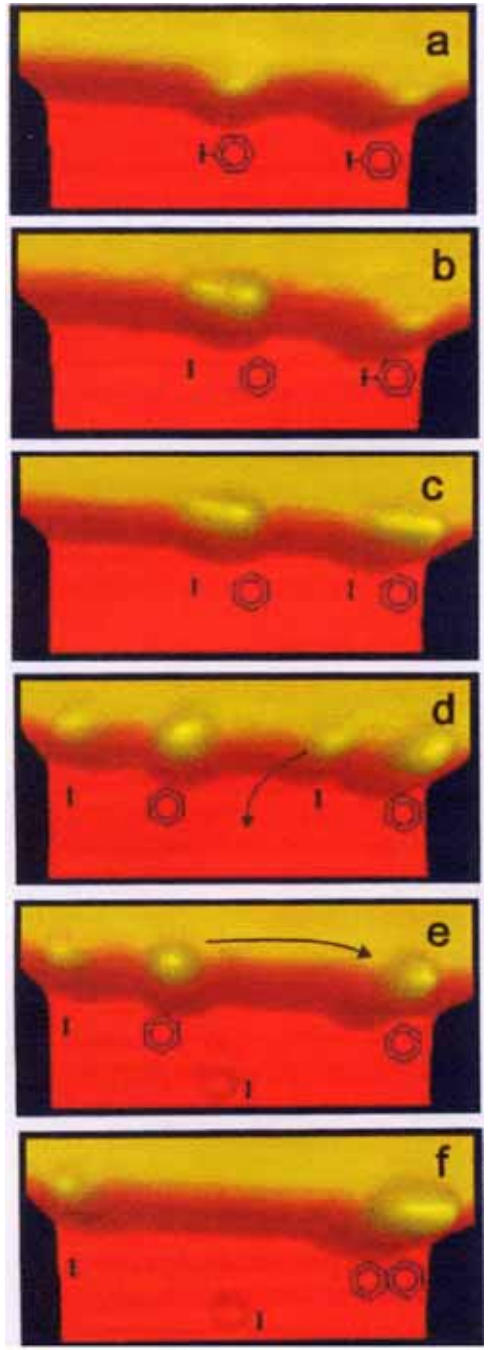
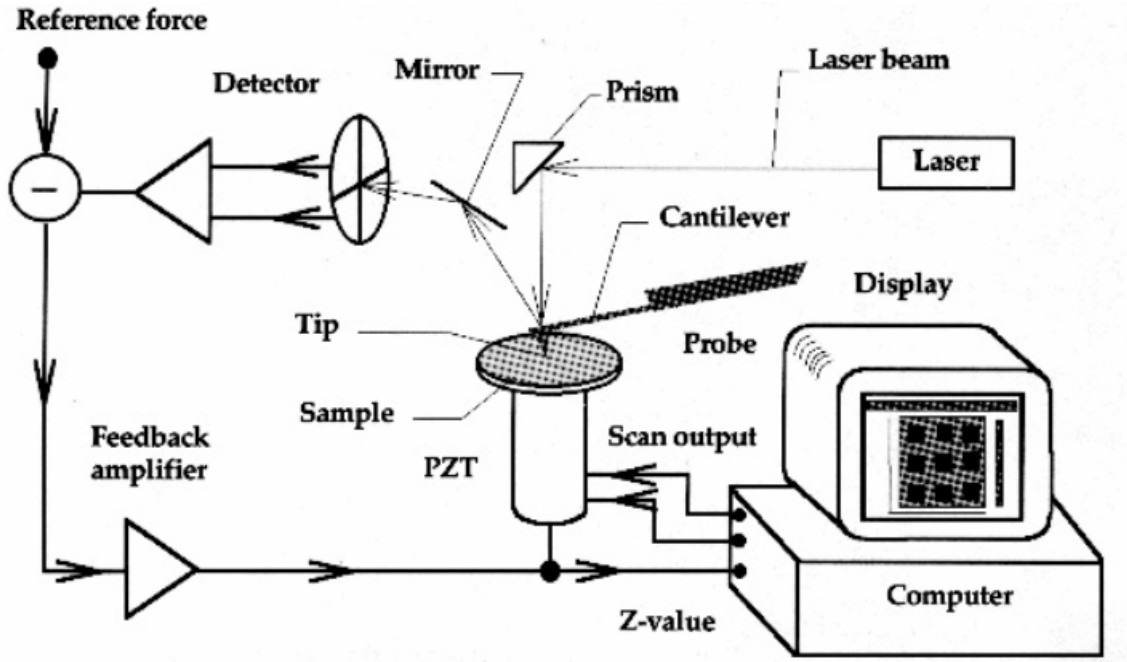


FIG. 1. Schematic illustration of the STM tip-induced synthesis steps of a biphenyl molecule. (a),(b) Electron-induced selective abstraction of iodine from iodobenzene. (c) Removal of the iodine atom to a terrace site by lateral manipulation. (d) Bringing together two phenyls by lateral manipulation. (e) Electron-induced chemical association of the phenyl couple to biphenyl. (f) Pulling the synthesized molecule by its front end with the STM tip to confirm the association.



Phys. Rev. Lett. 85, 2777 (2000)

Atomic Force Microscopy (AFM)



$$F = k\Delta z$$

$$F = 10^{-9} - 10^{-6}\ N$$

$$k = 0.1 - 1\ N/m$$

References:

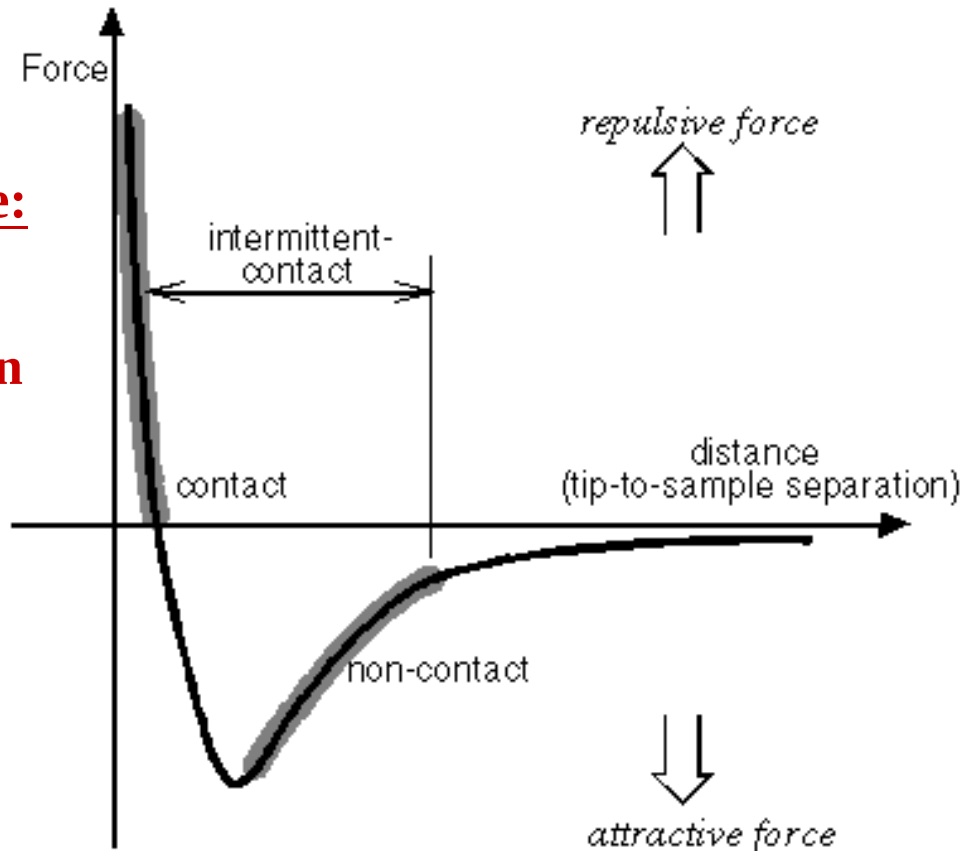
- G. Binnig, C. F. Quate, and C. Gerber, Phys. Rev. Lett. 56, 930 (1986).
- C. Bustamante and D. Keller, Physics Today, 32, December (1995).
- R. Wiesendanger and H.J. Güntherodt, *Scanning Tunneling Microscopy II* , Springer-Verlag, (1992).

Interaction between the probe and sample

Short-range:

1) Bonding

2) Repulsion



Long-range:

1) Van der Waal

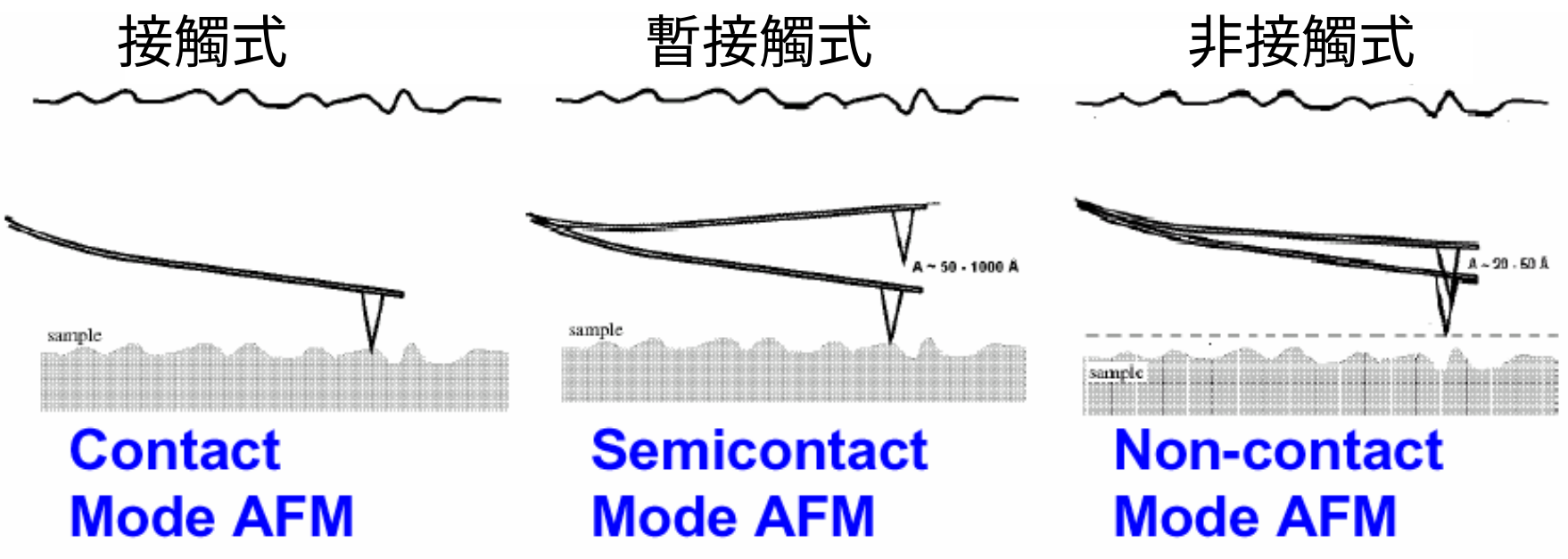
2) Capillary

3) Magnetic

4) Electrostatic

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

Three scanning modes of AFM

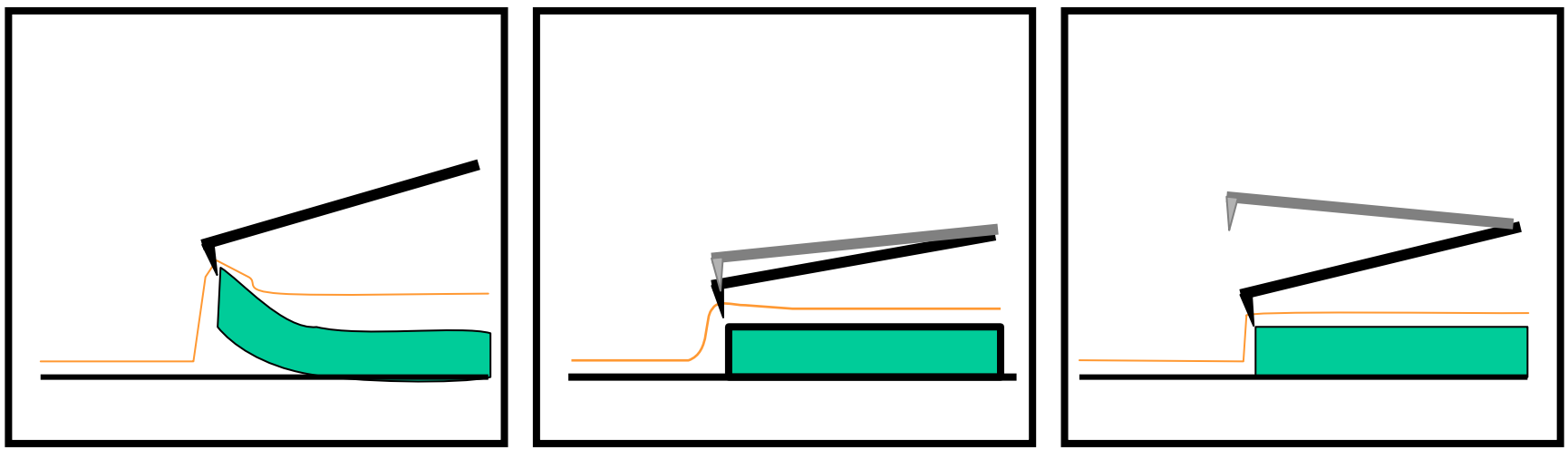


三種 AFM 掃描模式之比較

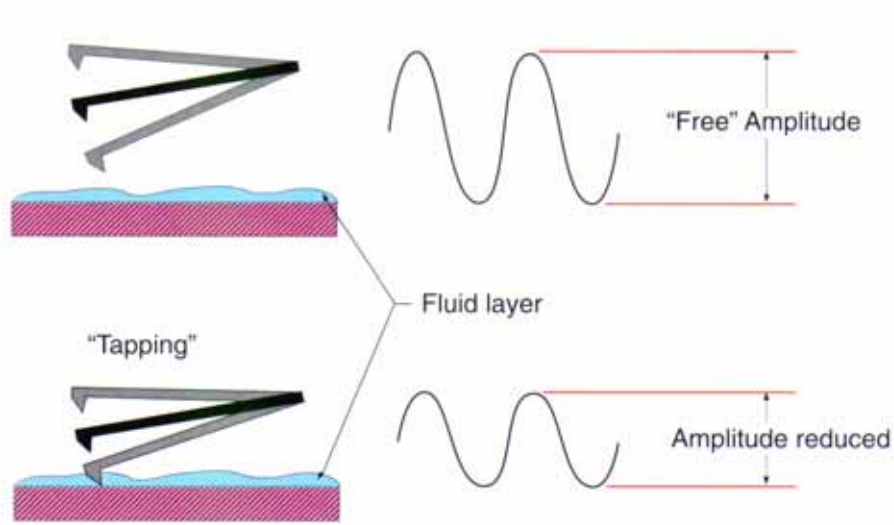
Contact

Non-contact

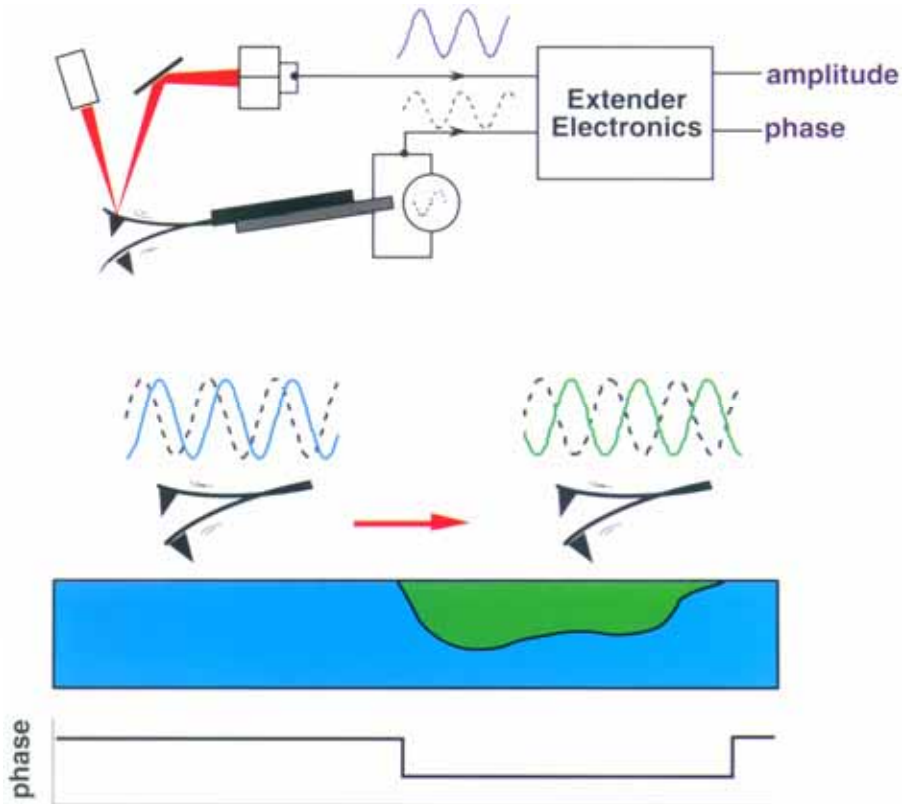
Semi-contact

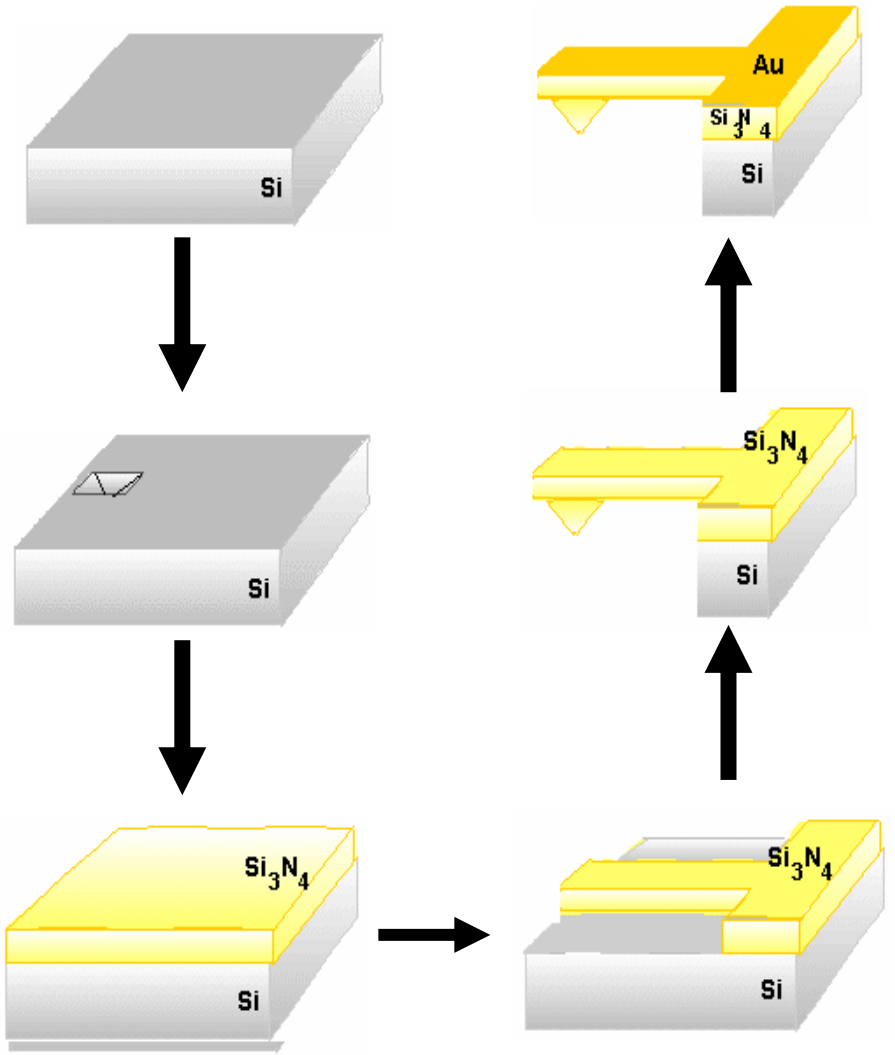


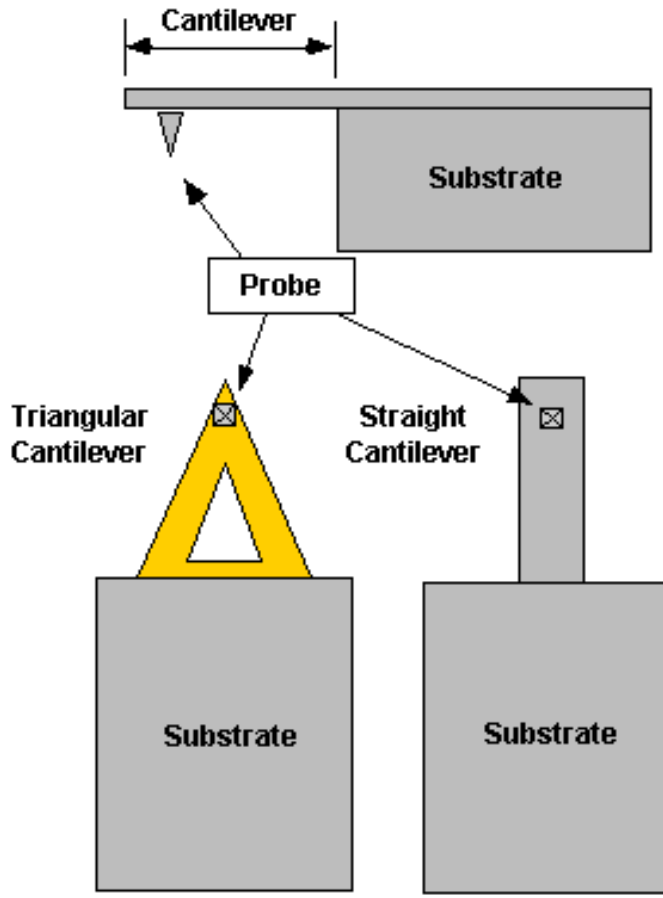
Tapping Mode (10-300 kHz)



Phase image



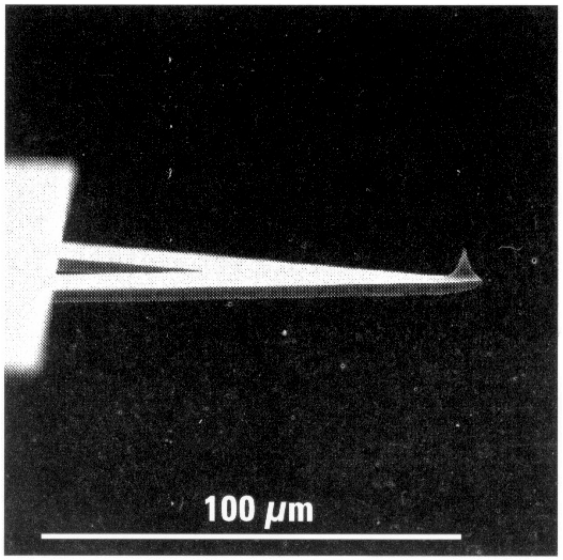




Typical Tip Dimension:
150μm x 30μm x 0.5μm
k ~ 0.1 N/m
Materials: Si_3N_4

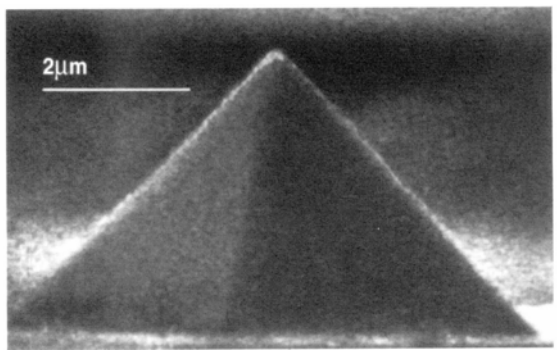
Typical Tip Dimension:
150μm x 30μm x 3μm
f_r ~ 100 kHz
Materials: Si

V-shaped

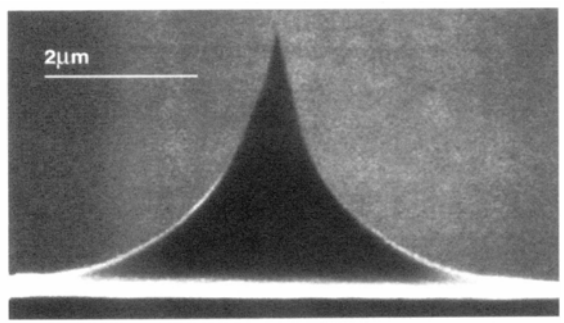


Materials: Si, SiO_2, Si_3N_4
Ideal Tips: hard, small radius of curvature, high aspect ratio

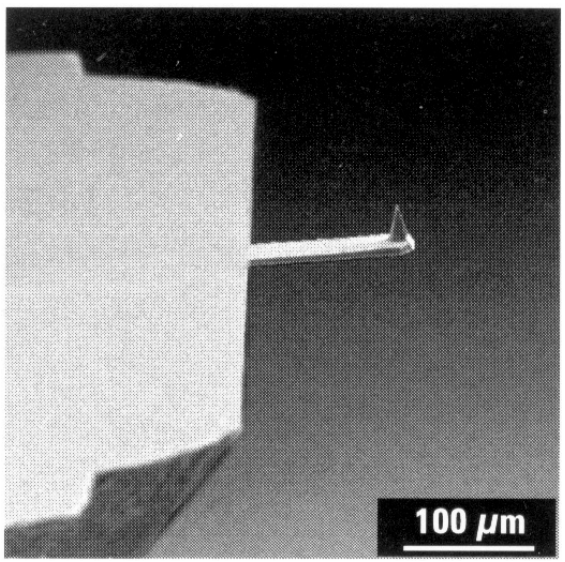
Pyramid Tip



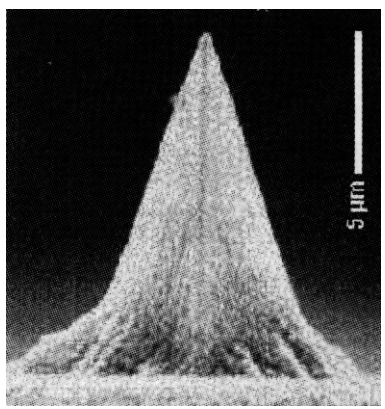
Ultrasharp Tip

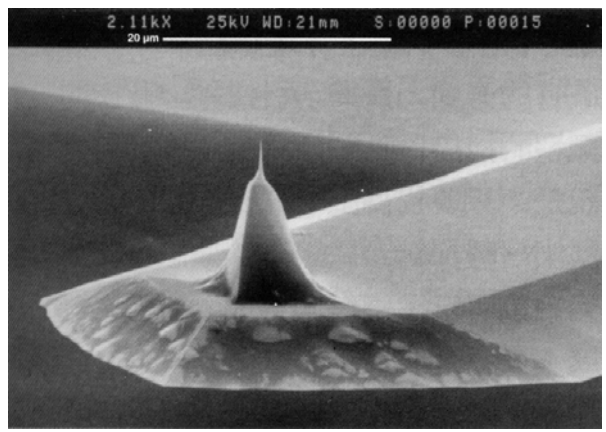


Rectangular-shaped

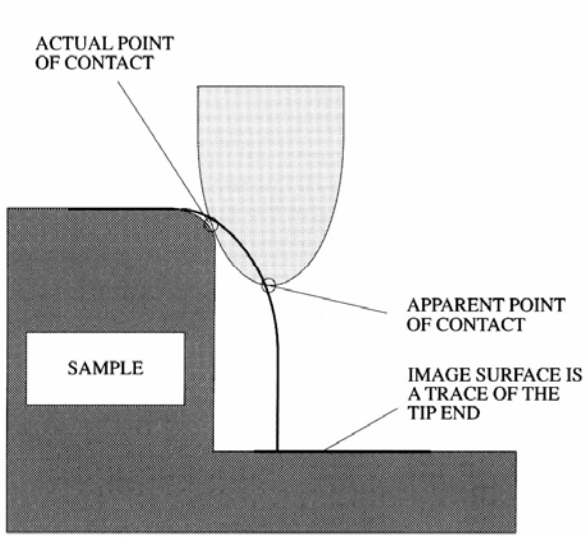


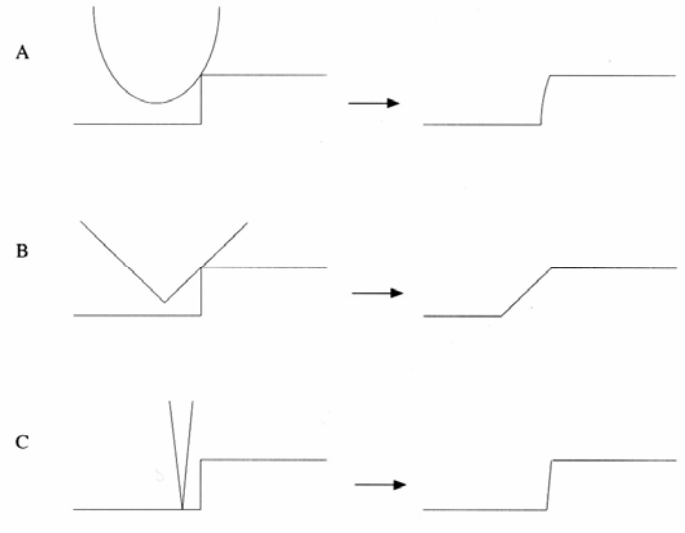
Diamond-coated Tip

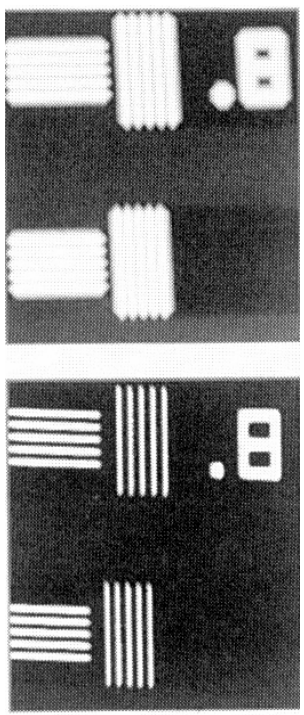


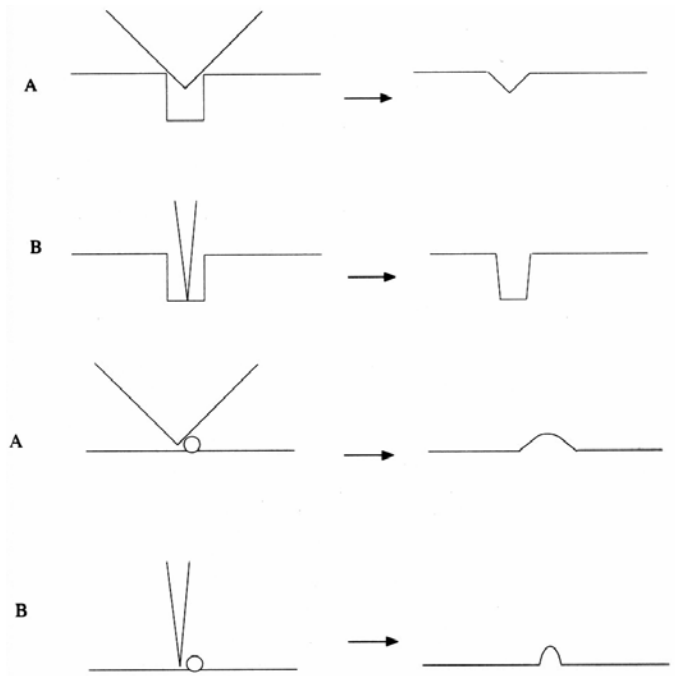


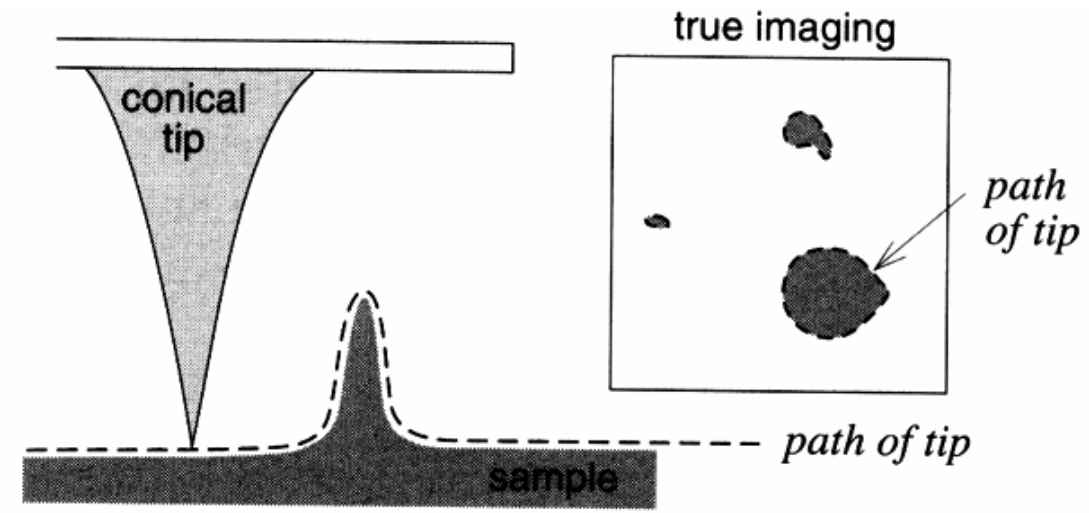
Effects of the Tip Shape

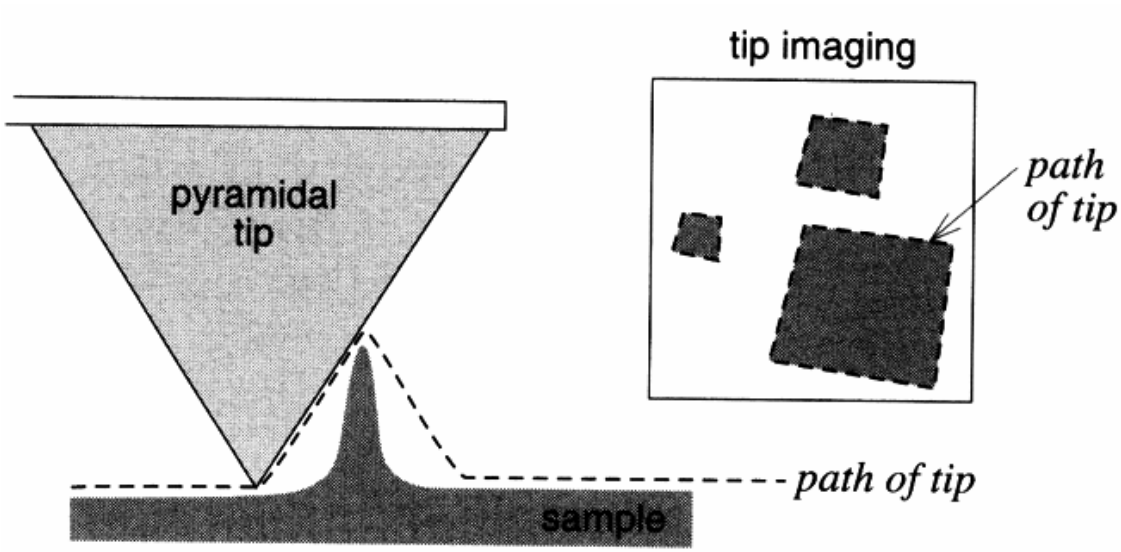




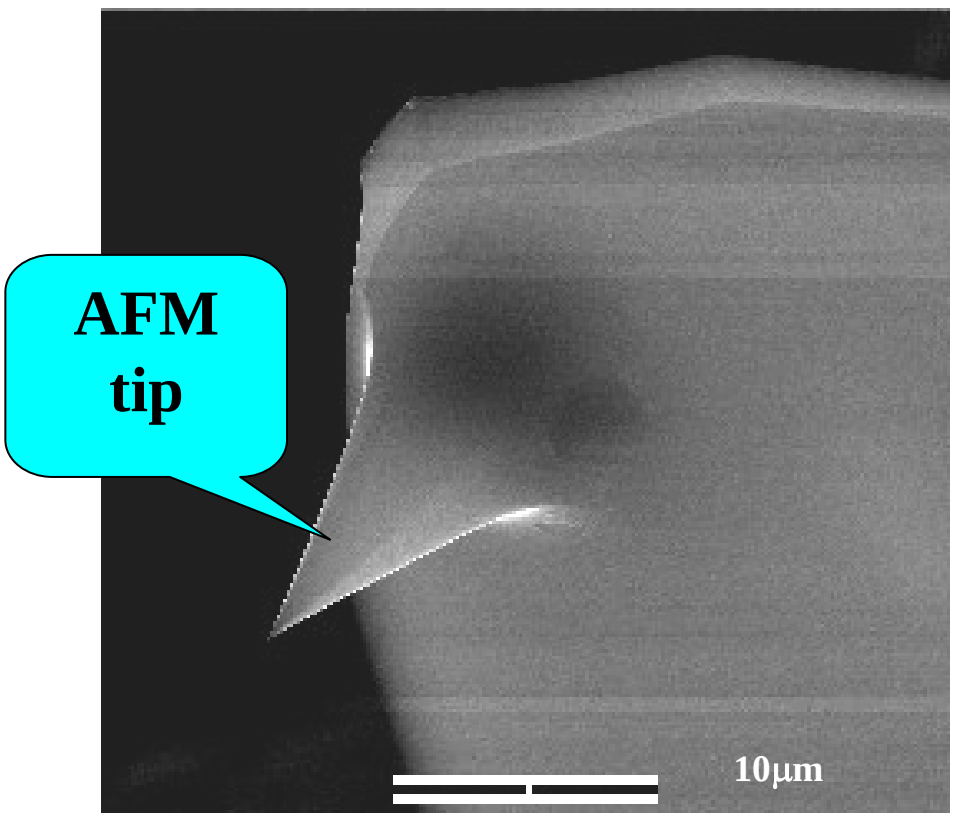


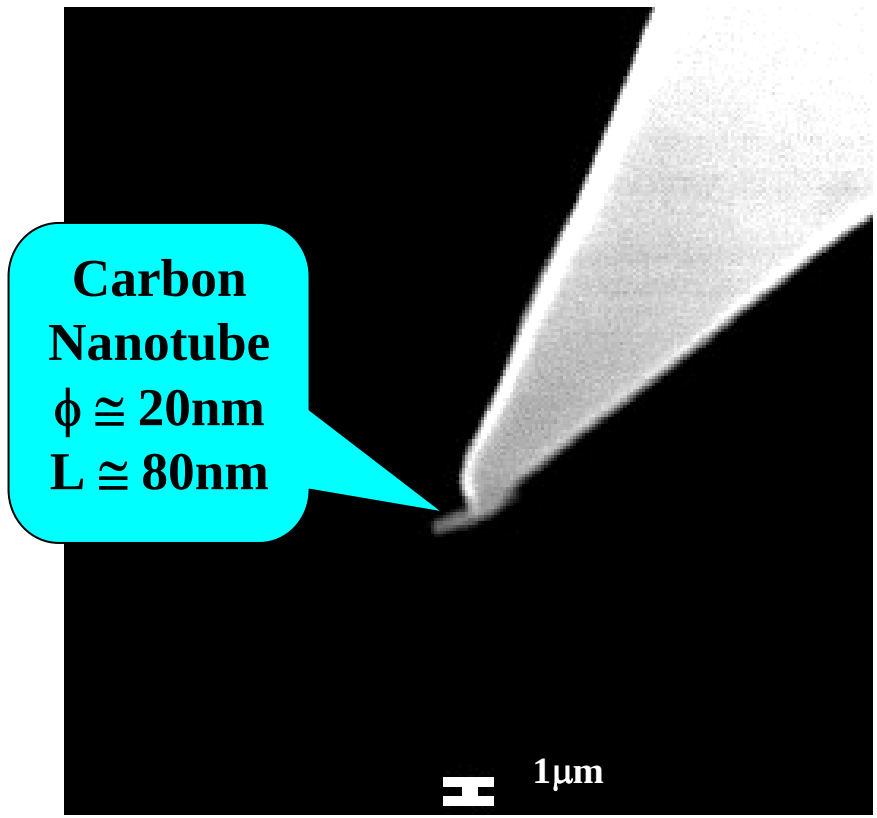



true imaging
conical
tip
path
of tip
path of tip
sample


tip imaging
pyramidal
tip
path
of tip
path of tip
sample

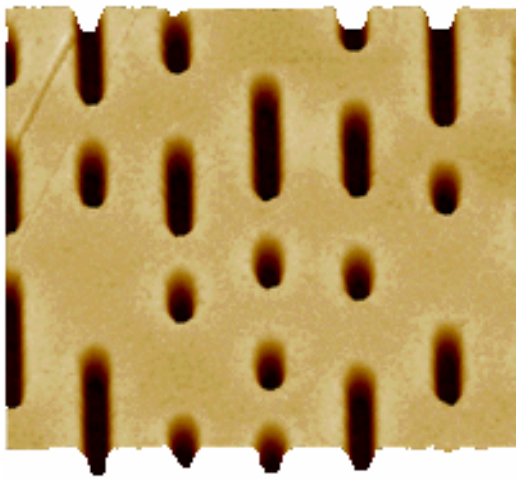
AFM Tip + Carbon Nanotube



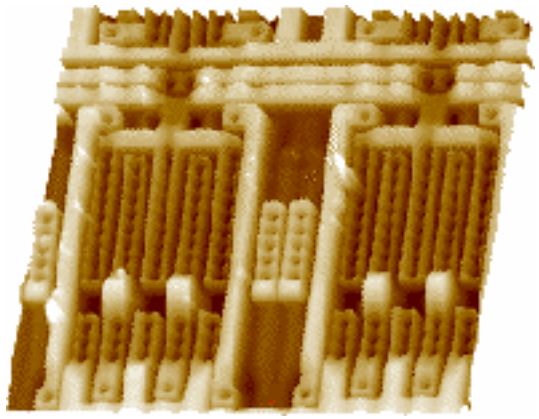


AFM images

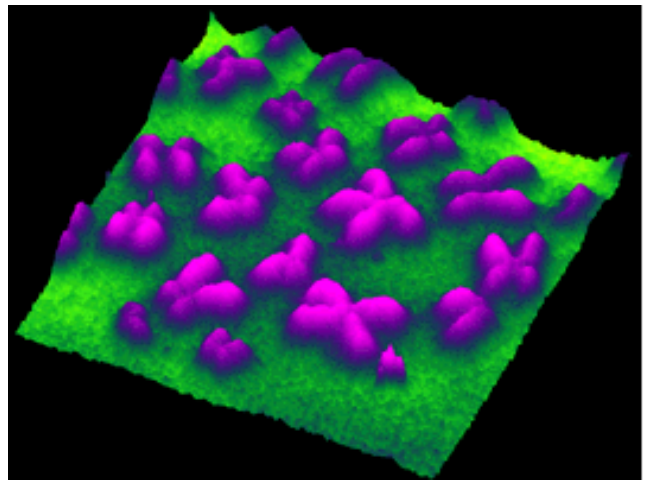
CD pits



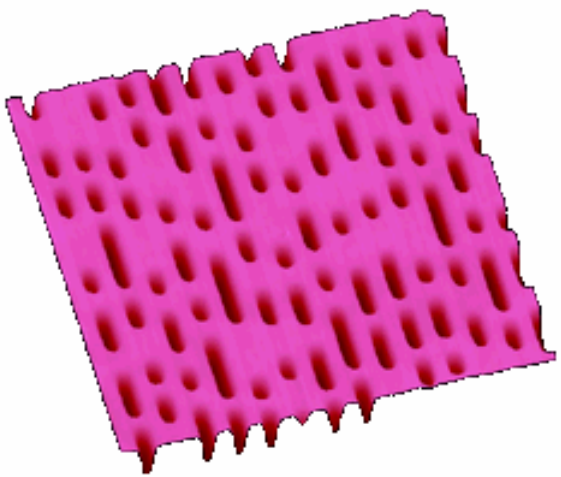
Integrated circuit



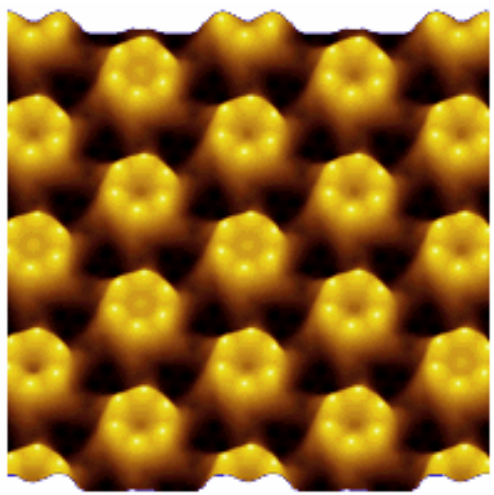
Chromosomes



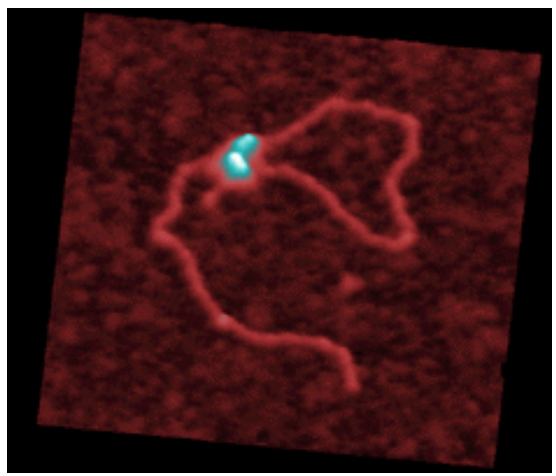
DVD pits



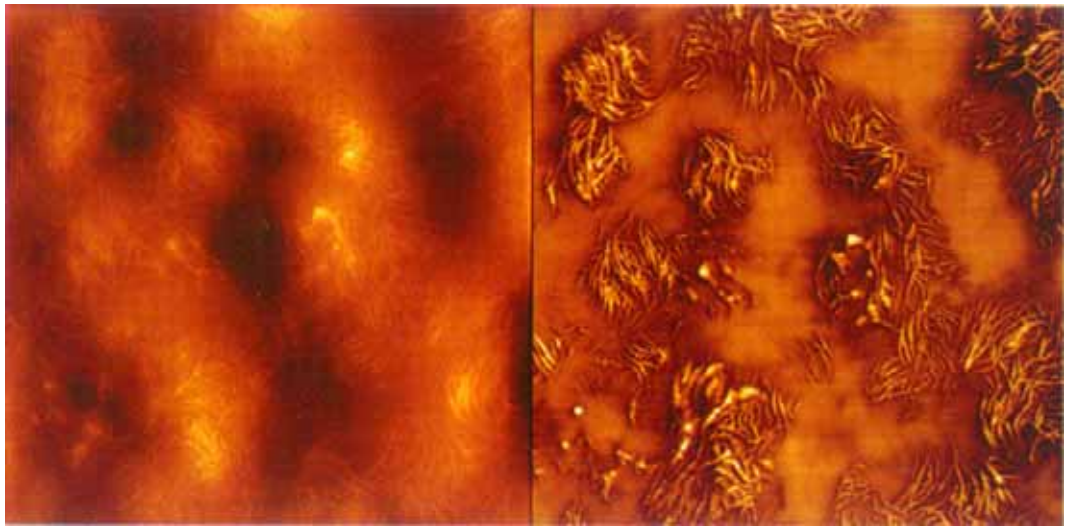
Bacteria



DNA



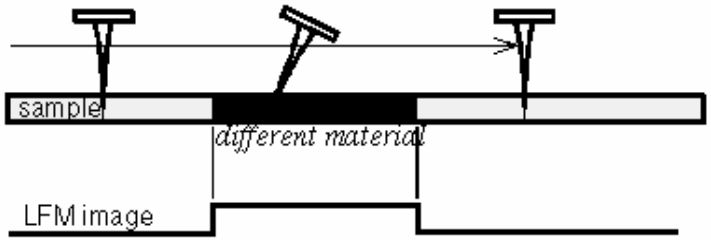
Height image **Phase Image**

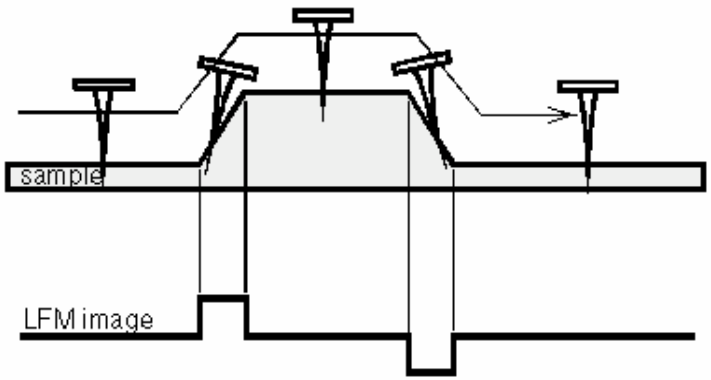


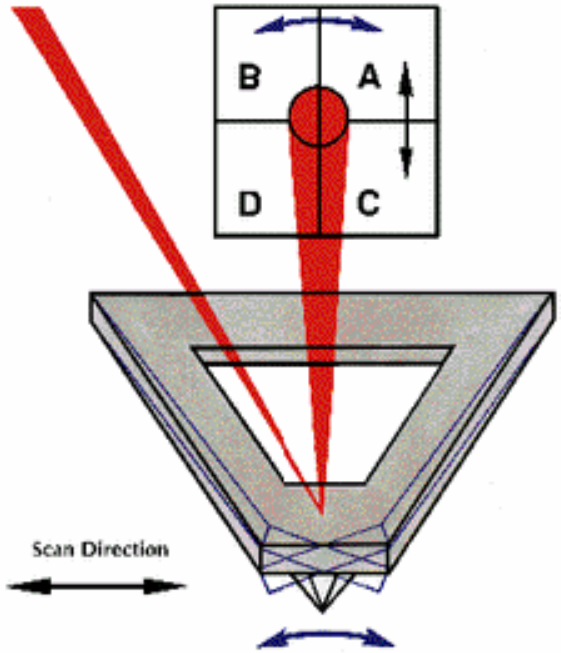
Phase image **Lateral force Image**

MoO_3 on MoS_2

Lateral Force Microscopy



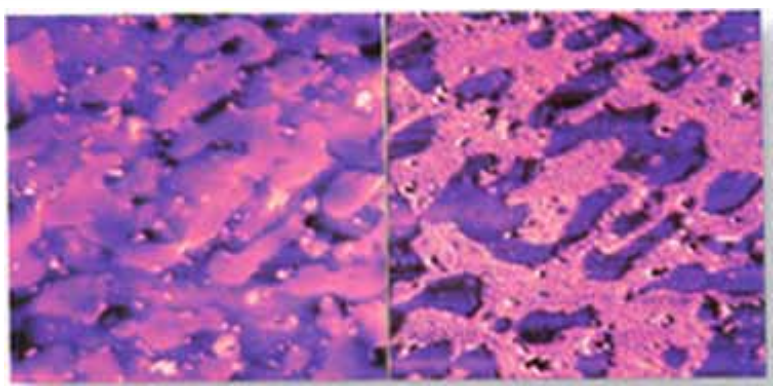




(A+C) – (B+D)

Topography

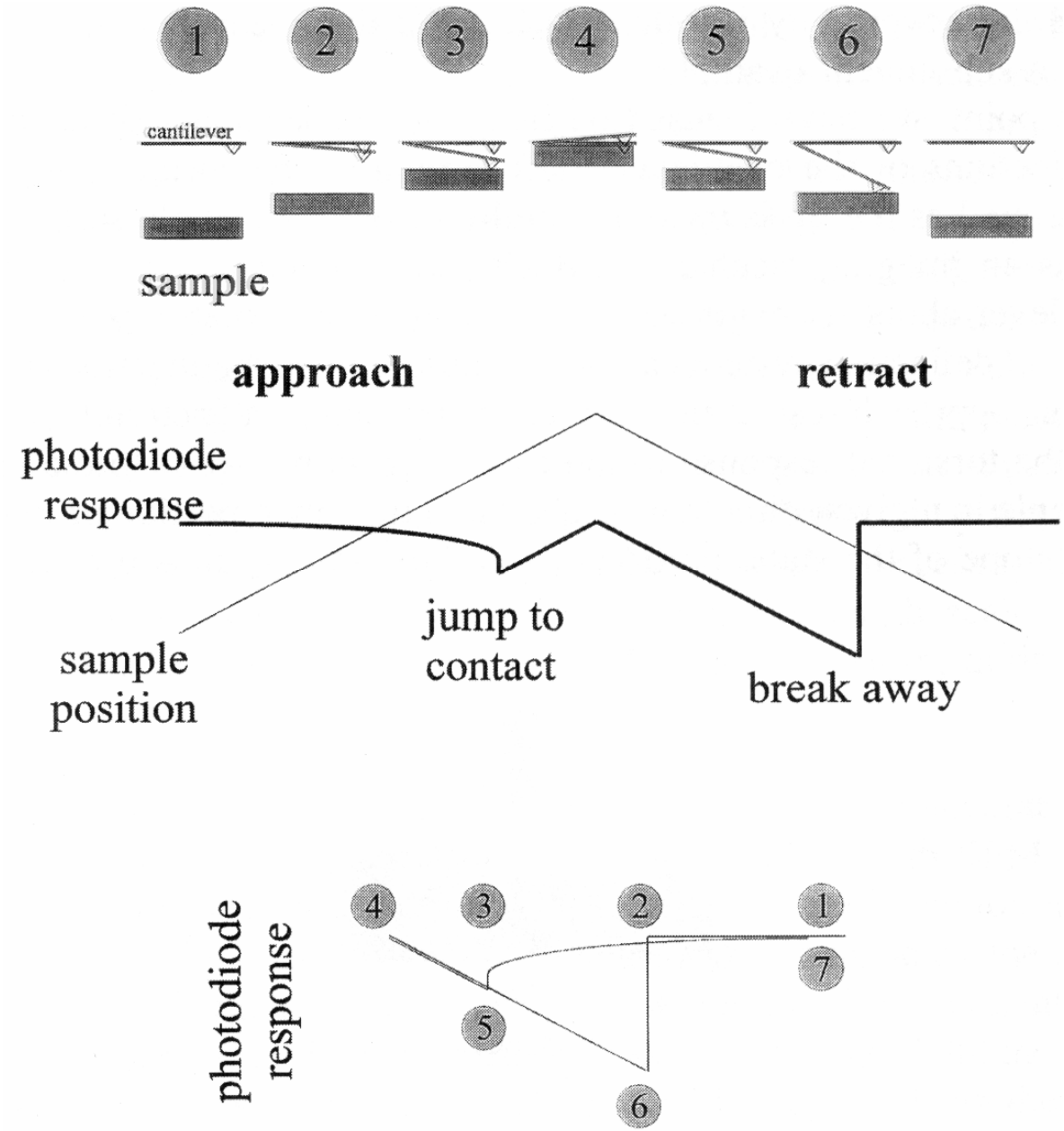
12 μm

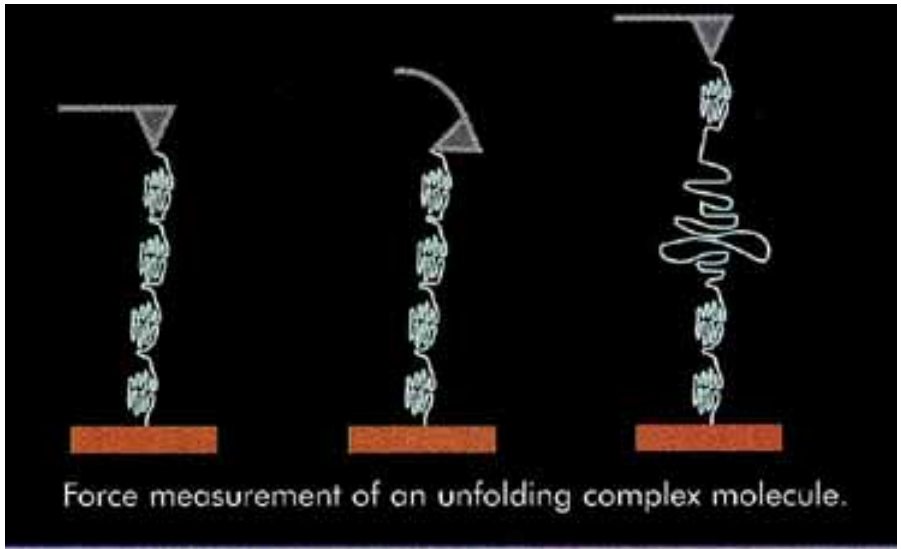


LFM image

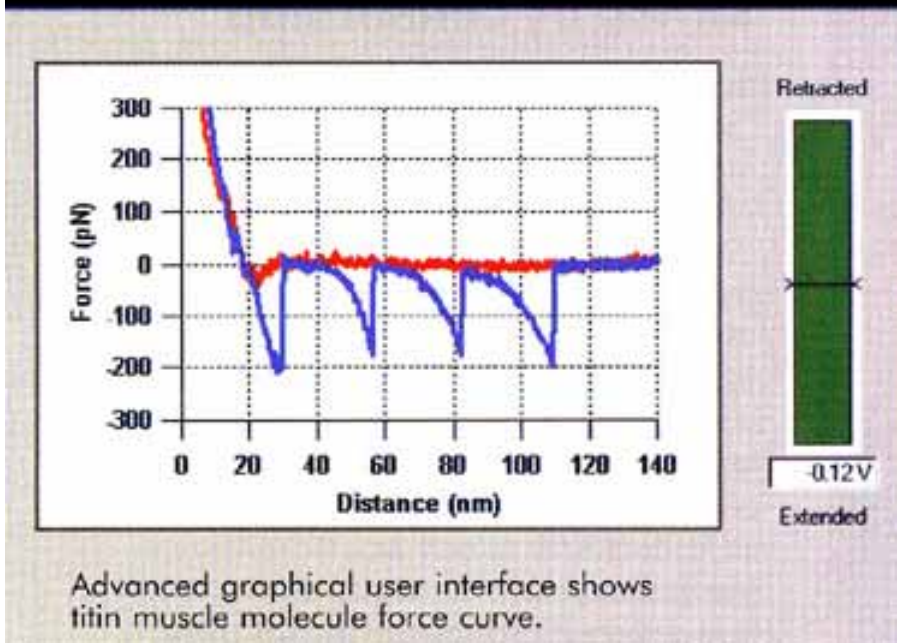
Nature rubber/EDPM blend

Force-Distance Curve



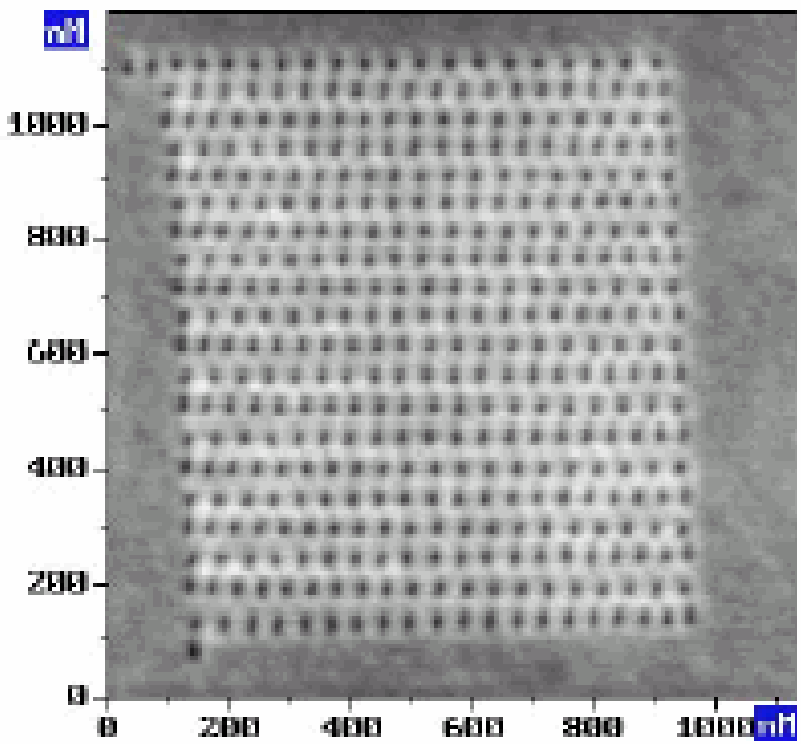


Force measurement of an unfolding complex molecule.

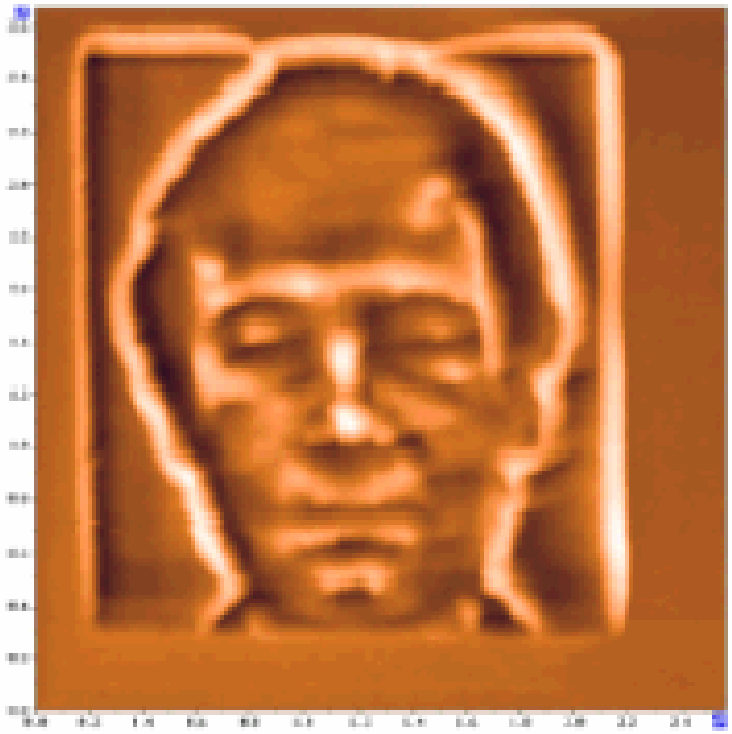


Advanced graphical user interface shows titin muscle molecule force curve.

Nanolithography of Tapping-Mode AFM



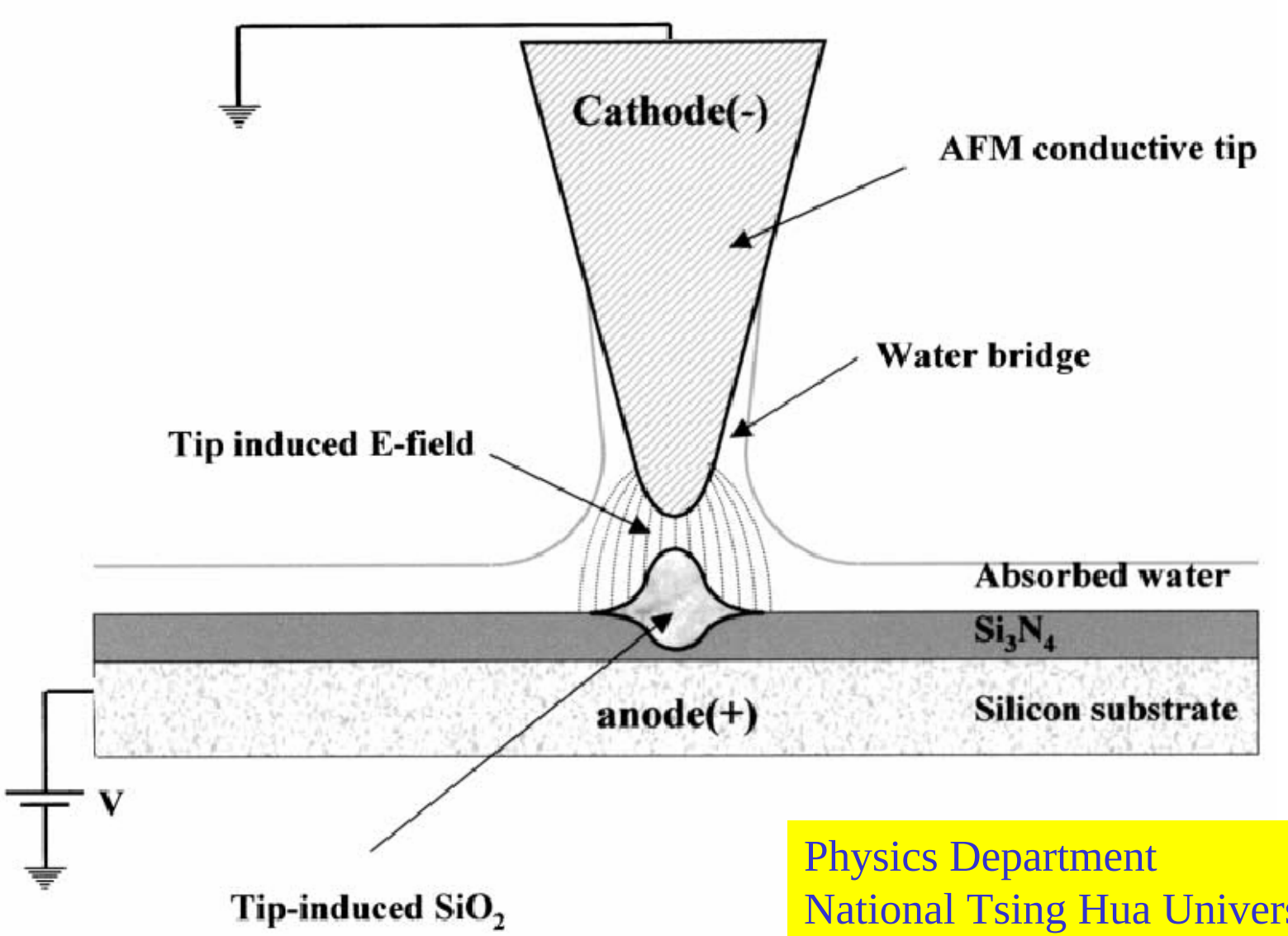
(1.2 μm× 1.2 μm)



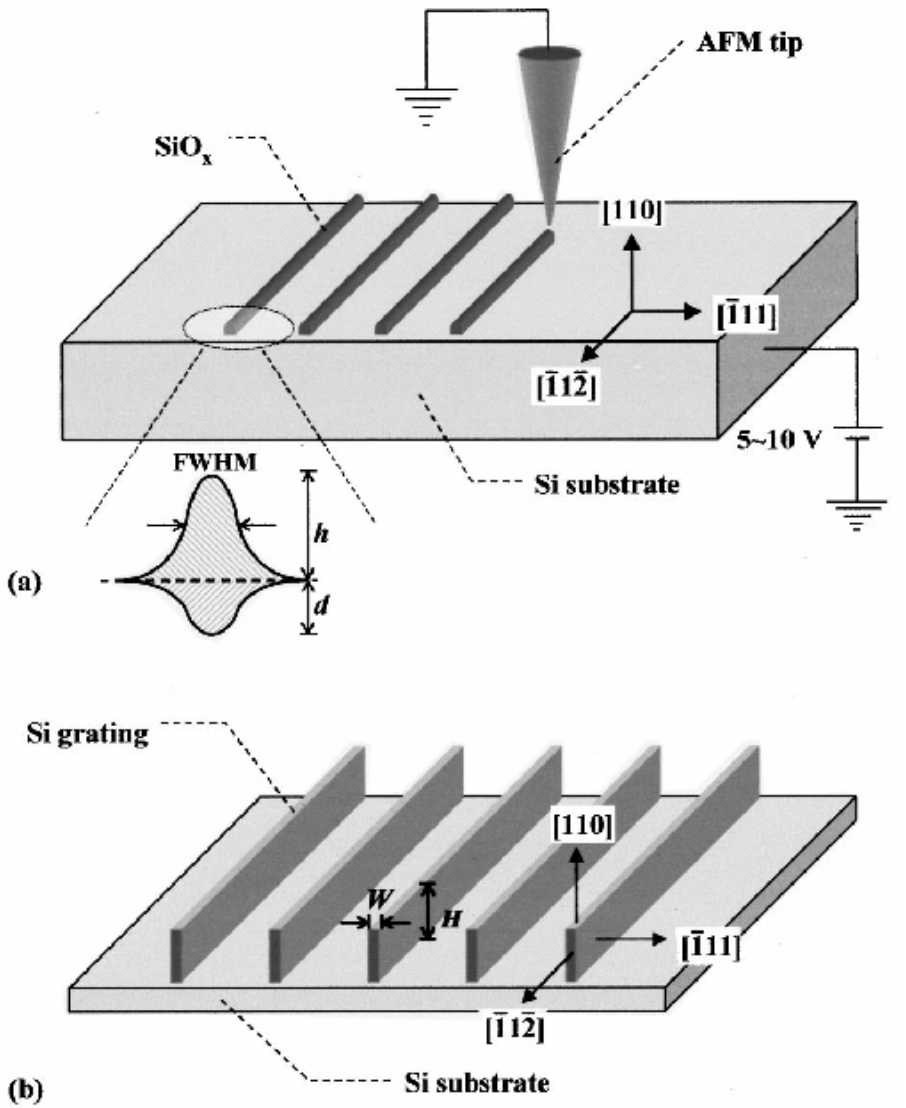
(2.5 μm× 2.5 μm)

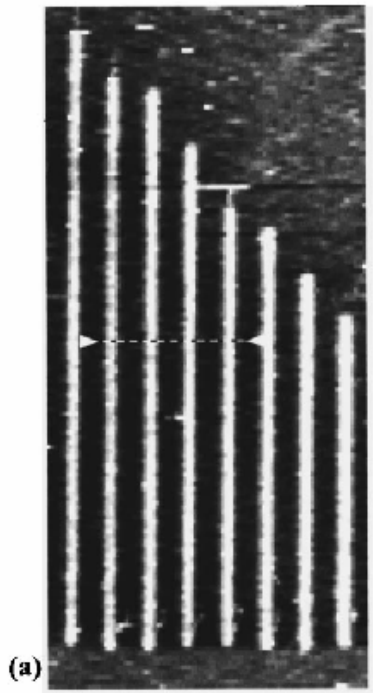
Image of polycarbonate film on silicon surface

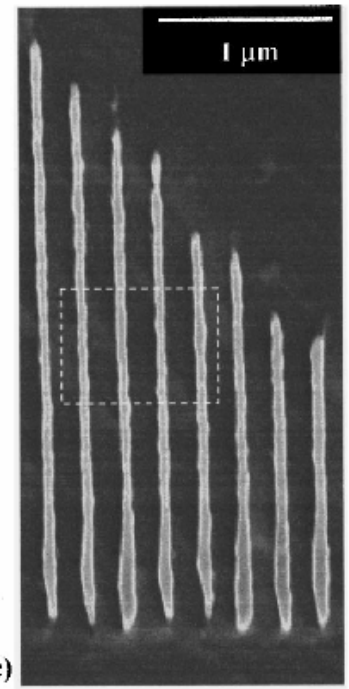
Nano-Lithography with an AFM tip

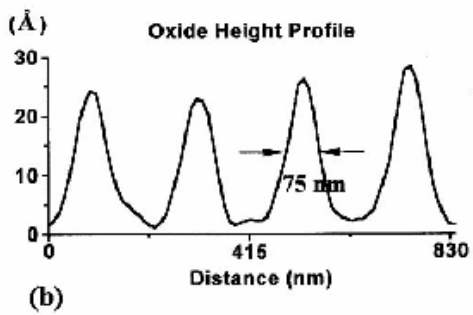


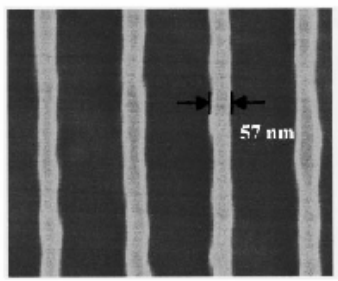
Physics Department
National Tsing Hua University



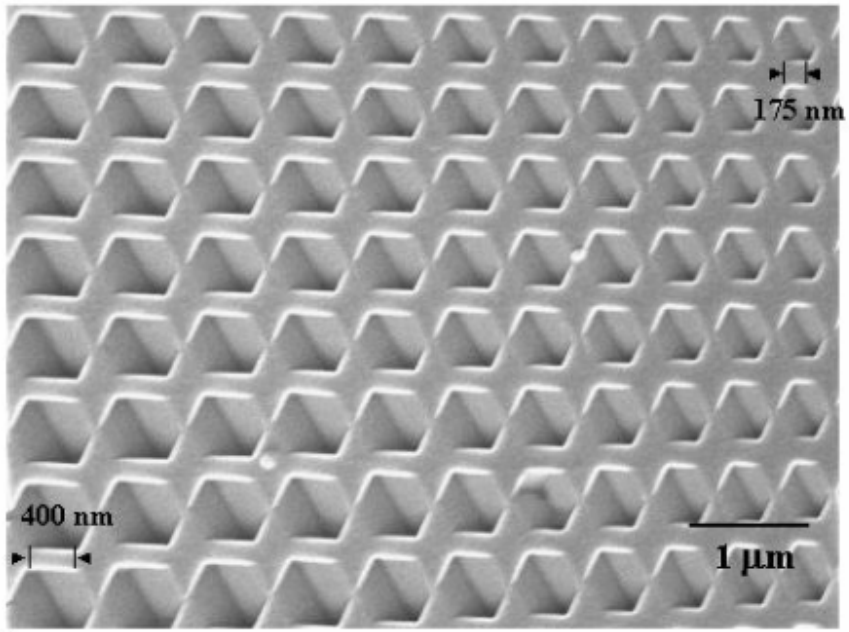


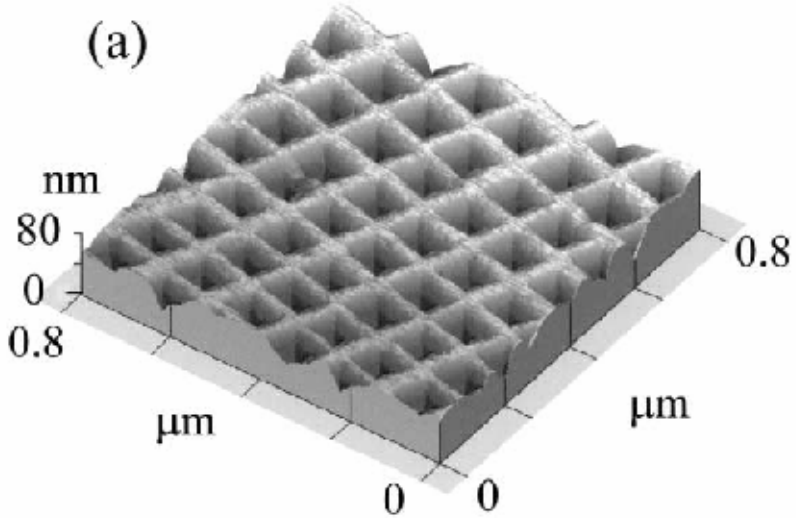


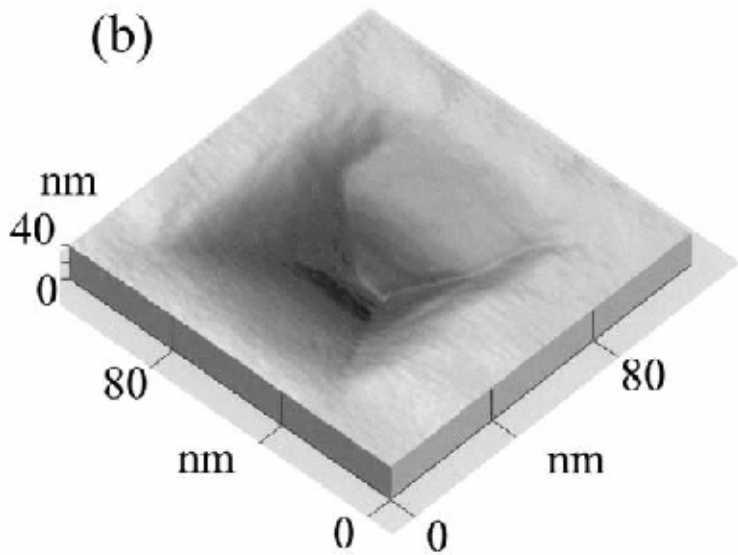


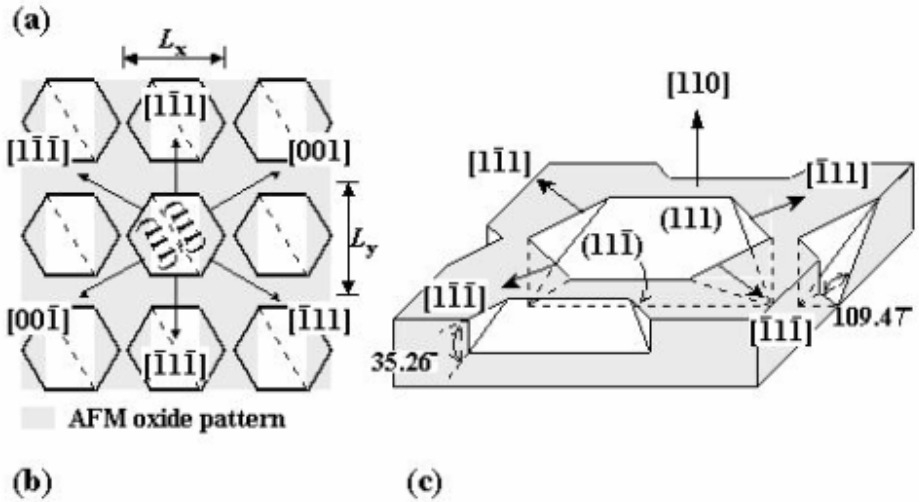


F.S.-S. Chien *et al.*, APL 75, 2429 (1999)



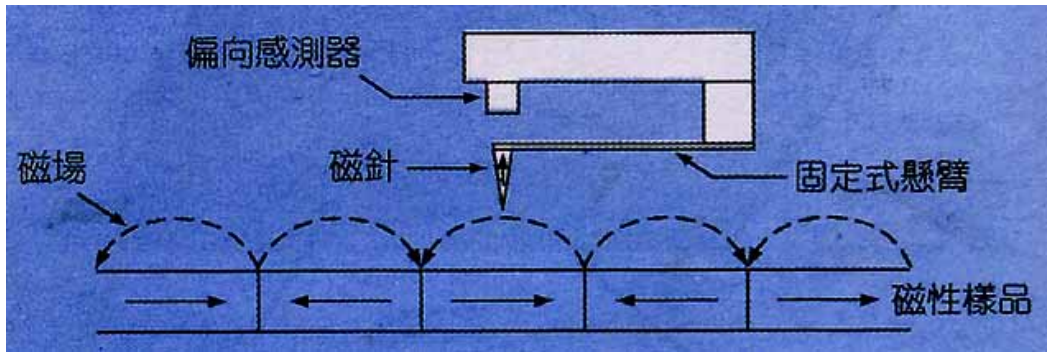






果尚志 , Physics Dept., National Tsing Hua University

Magnetic Force Microscopy (MFM)



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

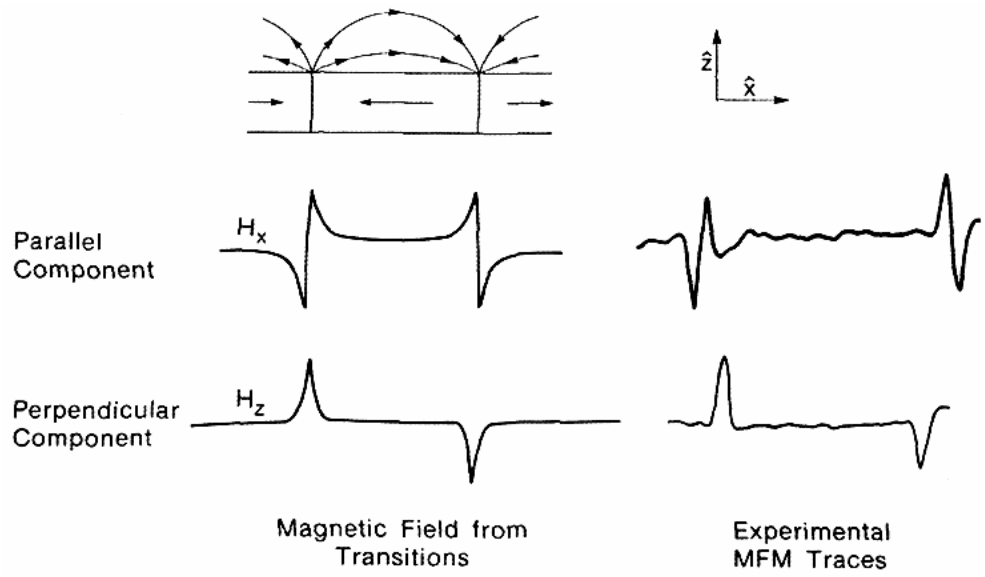
The tip is scanned several tens or hundreds of nanometers above the sample, avoiding contact. Magnetic field gradients exert a force on the tip's magnetic moment, and monitoring the tip/cantilever response gives a magnetic force image. To enhance sensitivity, most MFM instruments oscillate the cantilever 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.

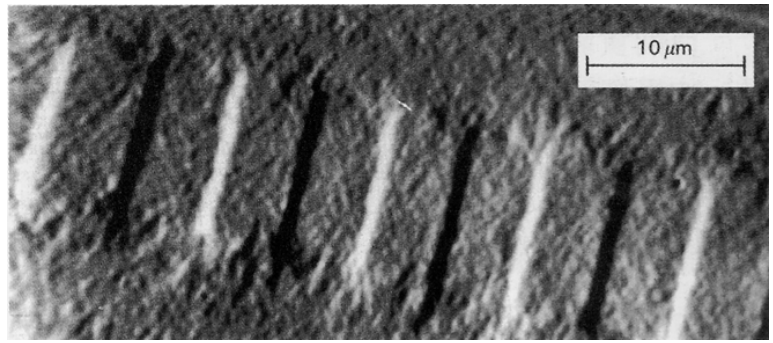
Tips: silicon probes are magnetically sensitized by sputter coating with a ferromagnetic material.

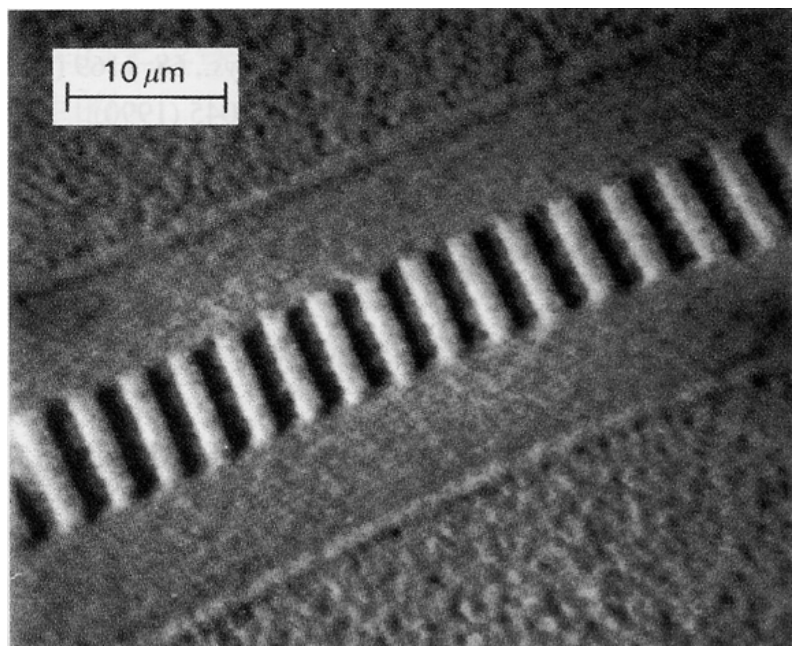
Resolution 10~25 nm.

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

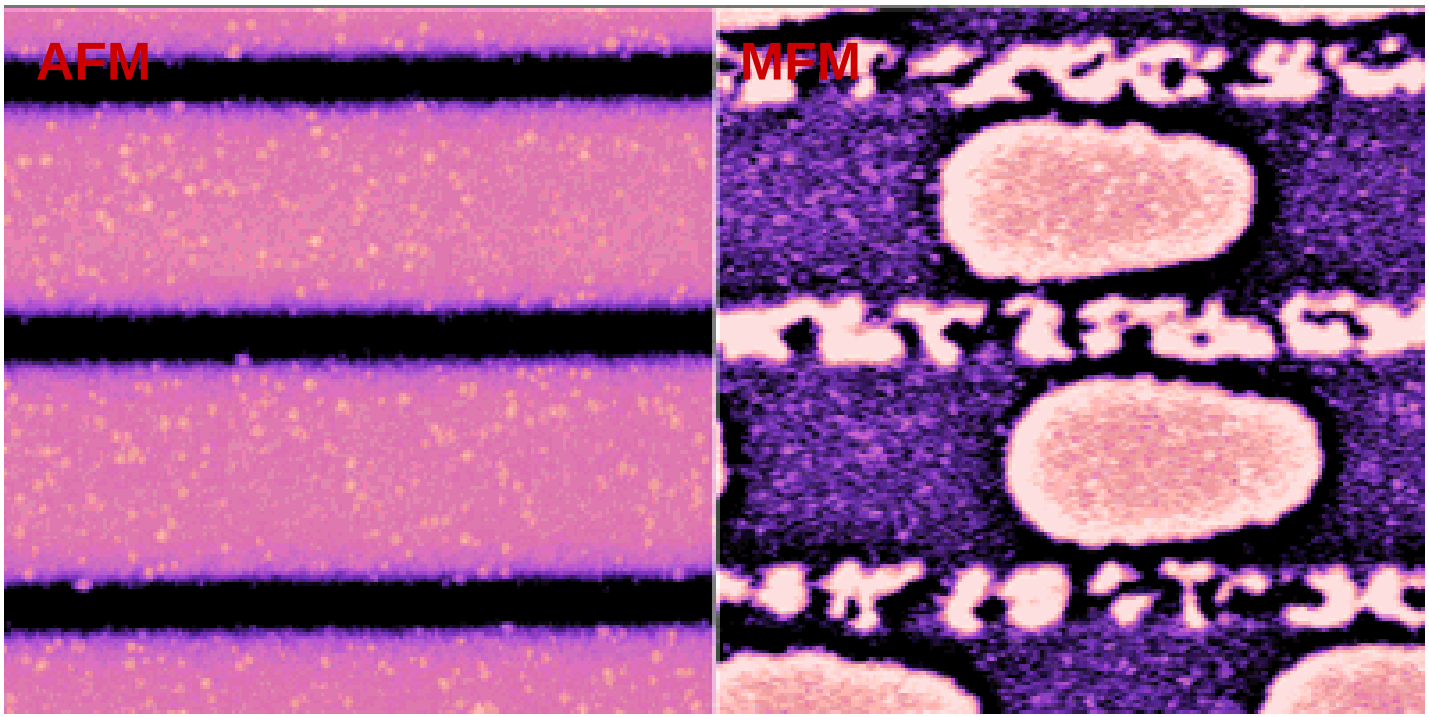
MFM Images


Parallel
Component
H_x
Perpendicular
Component
H_z
$\hat{z}$
$\hat{x}$
Magnetic Field from
Transitions
Experimental
MFM Traces


10 μm


10 μm

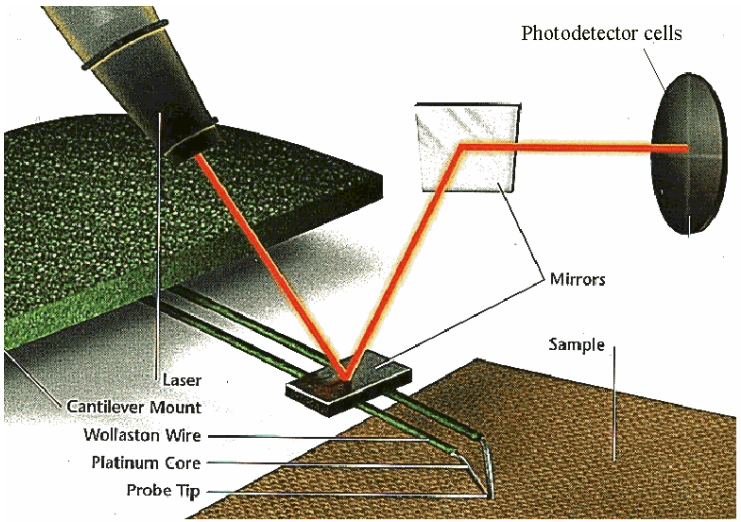
Magnetic Force Microscopy

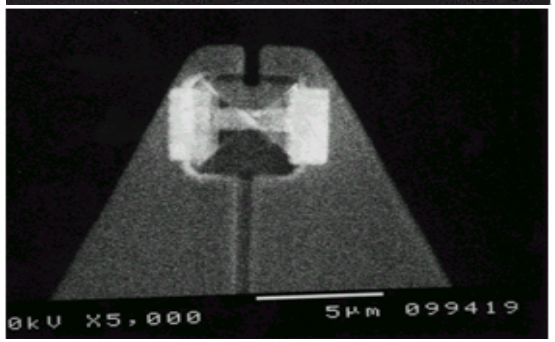


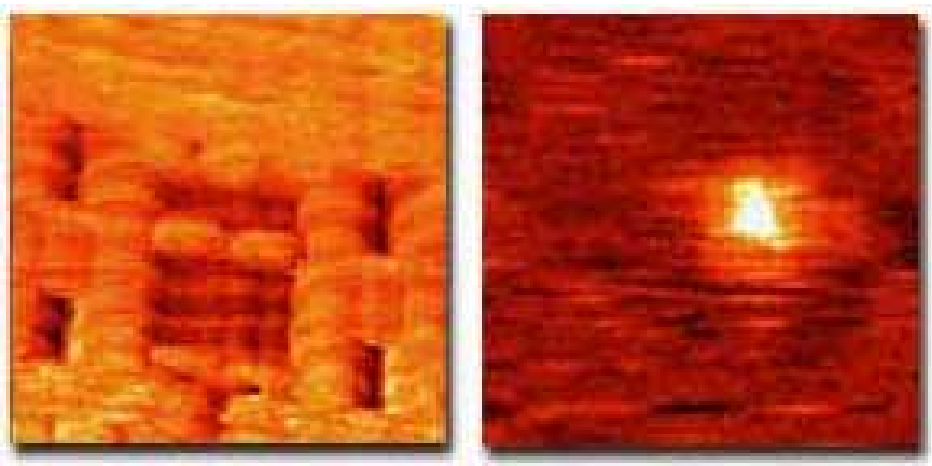
Bits (50 nm) on a magneto-optical disk.

Scan area (5 μm× 5 μm)

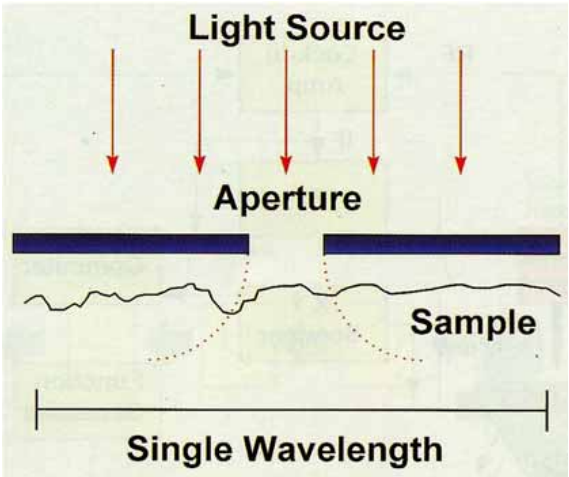
Scanning Thermal Microscopy (SThM)

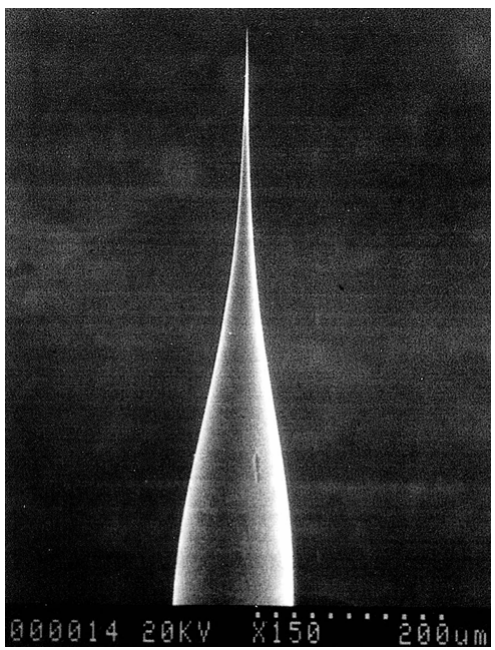


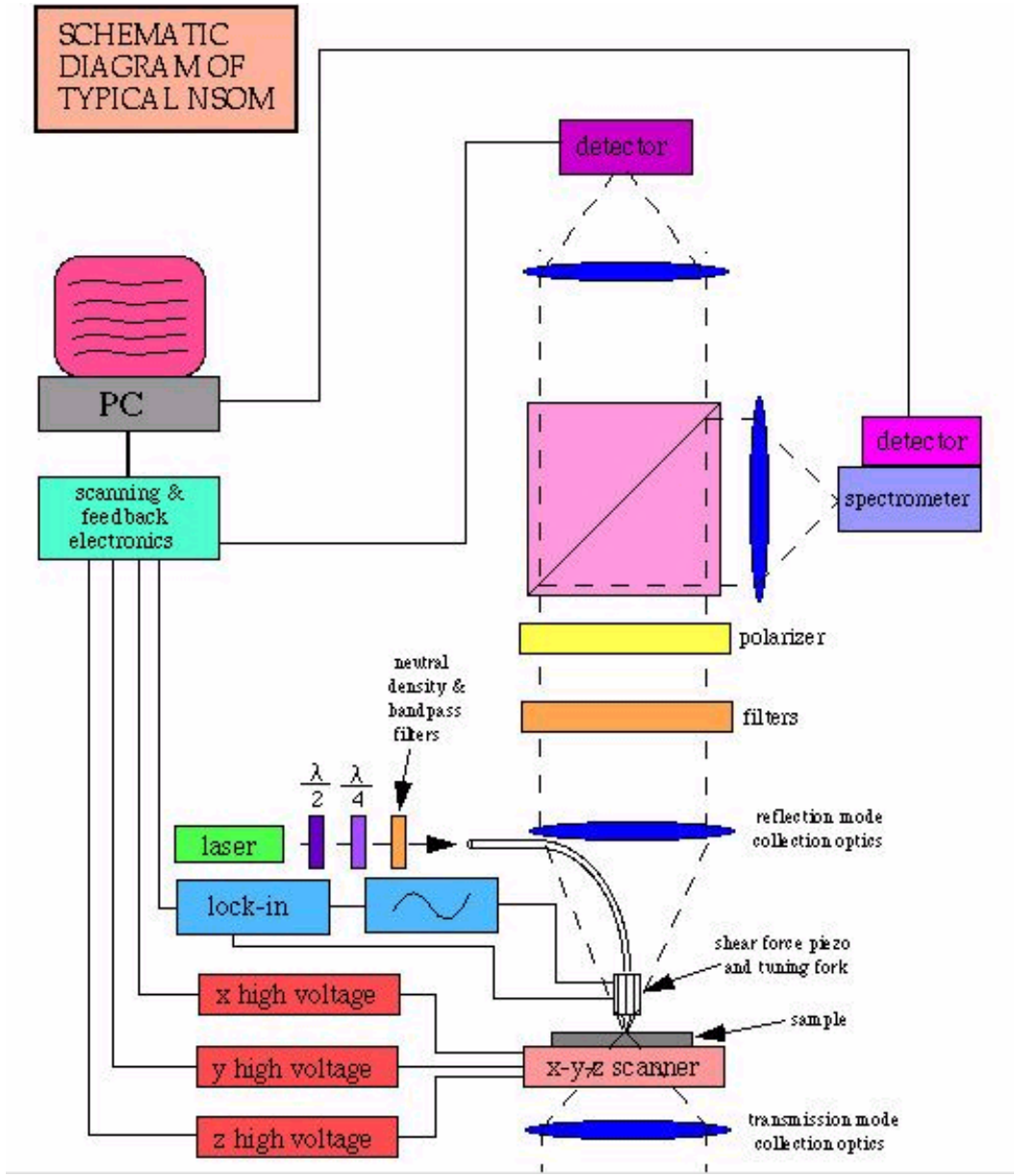




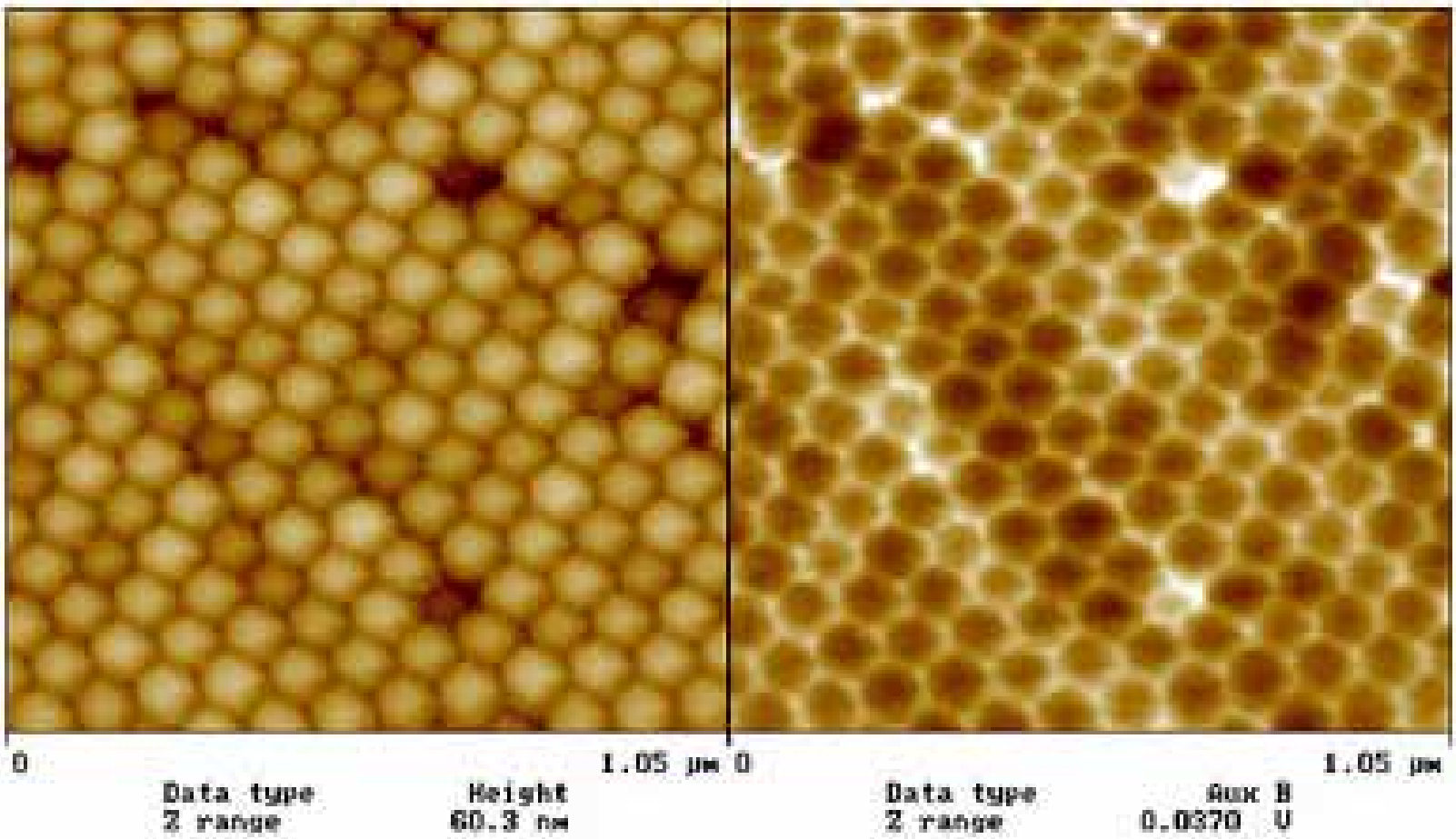
Near-field Scanning Optical Microscopy (NSOM)





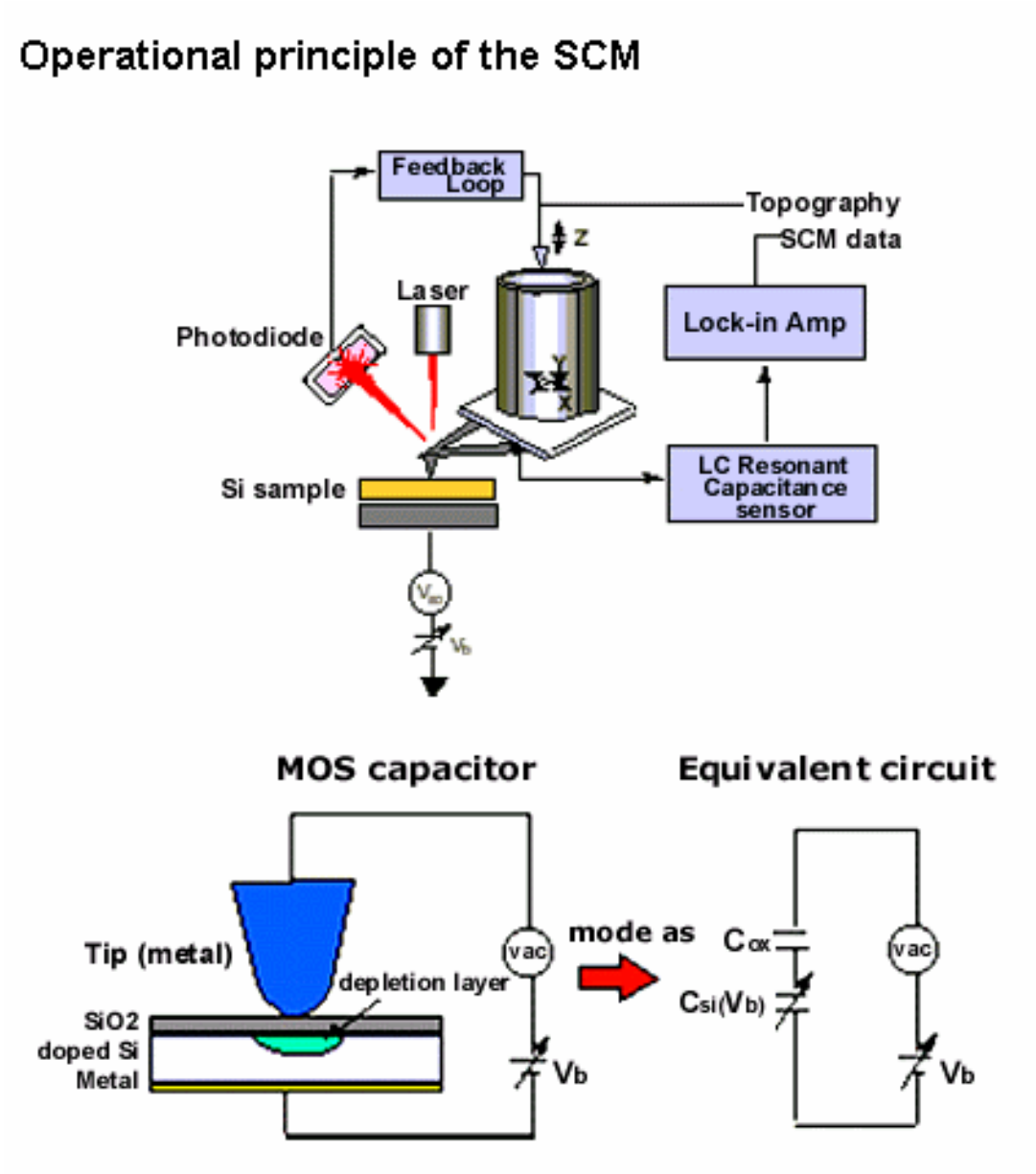


Topography **NSOM Image**



100 奈米直徑之聚苯乙烯顆粒球的原子力顯微 (AFM) 影像 (左) 及穿透式近場光學顯微影像 (右)

Sacnning Capacitance Microscopy (SCM)

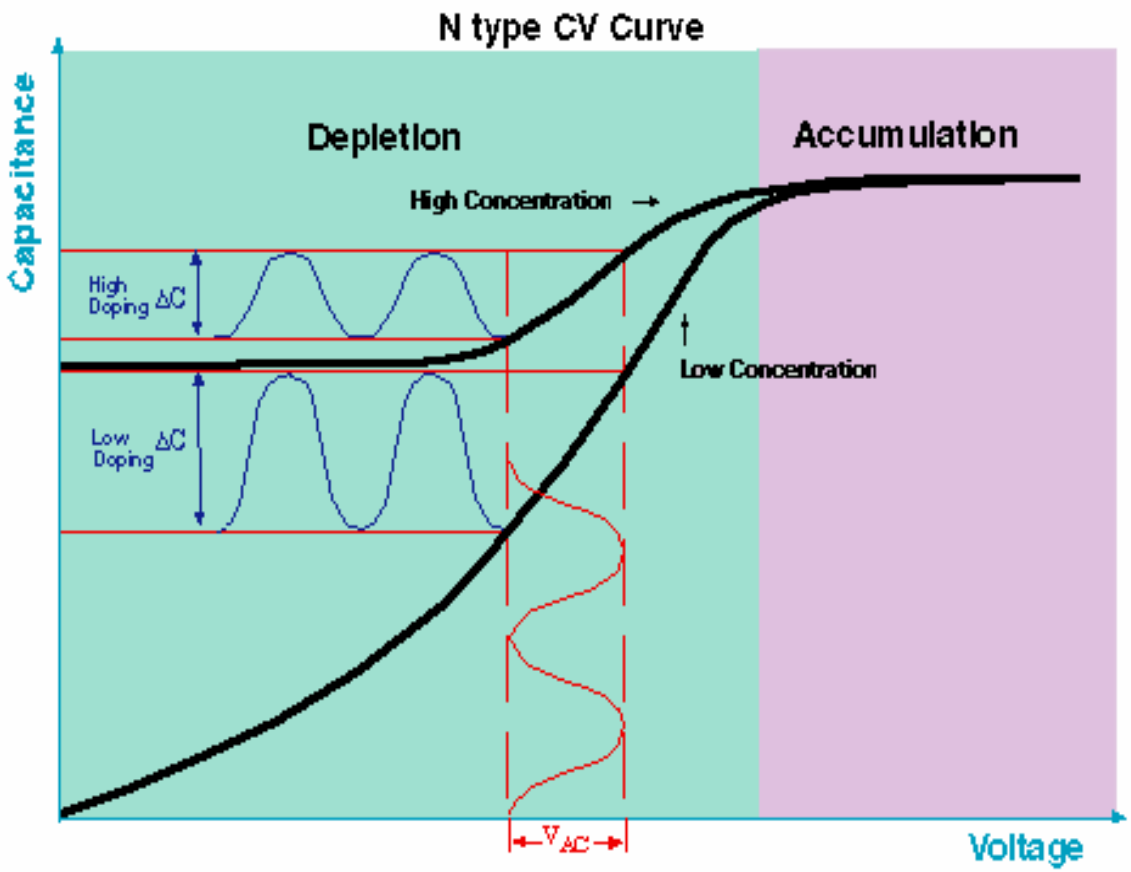


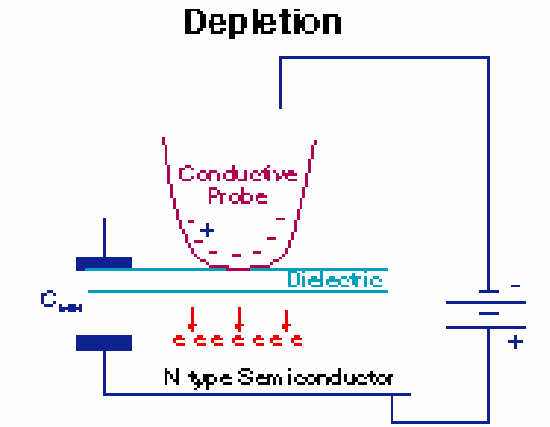
1. **Most SCMs are based on contact-mode AFM with a conducting tip.**
2. **In SCM, the sample (or the metallic tip) is covered with a thin dielectric layer, such that the tip-sample contact forms a MIS capacitor, whose C-V behavior is determined by the local carrier concentration of the semiconductor sample.**
3. **By monitoring the capacitance variations as the probe scans across the sample surface, one can measure a 2D carrier concentration profile.**
4. **One usually measures the capacitance variations (dC/dV), not the absolute capacitance values.**
5. **No signal is measured if the probe is positioned over a dielectric or metallic region since these regions cannot be depleted.**

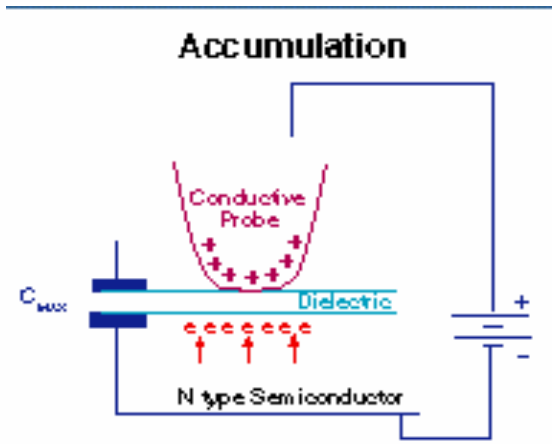
References:

1. C.C. Williams, Annu. Rev. Mater. Sci. **29**, 471 (1999).
2. P.D. Wolf et al., J. Vac. Sci. Technol. B **18**, 361 (2000).
3. R.N. Kleiman et al., J. Vac. Sci. Technol. B **18**, 2034 (2000).
4. H. Edwards, et al., J. Appl. Phys. **87**, 1485 (2000).
5. J. Isenbart et al., Appl. Phys. A **72**, S243 (2001).

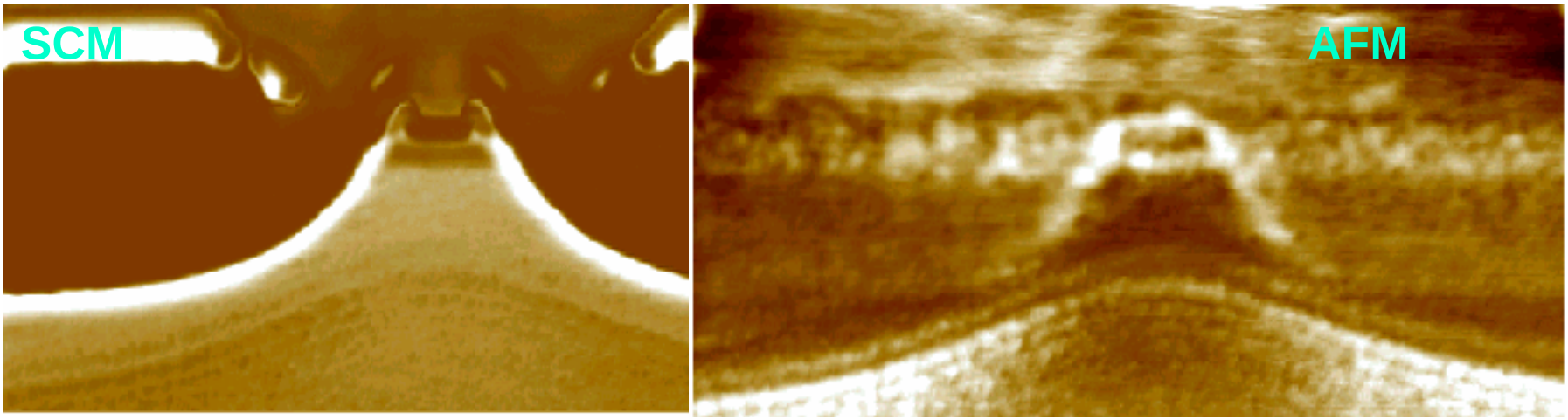
SCM CV Curve

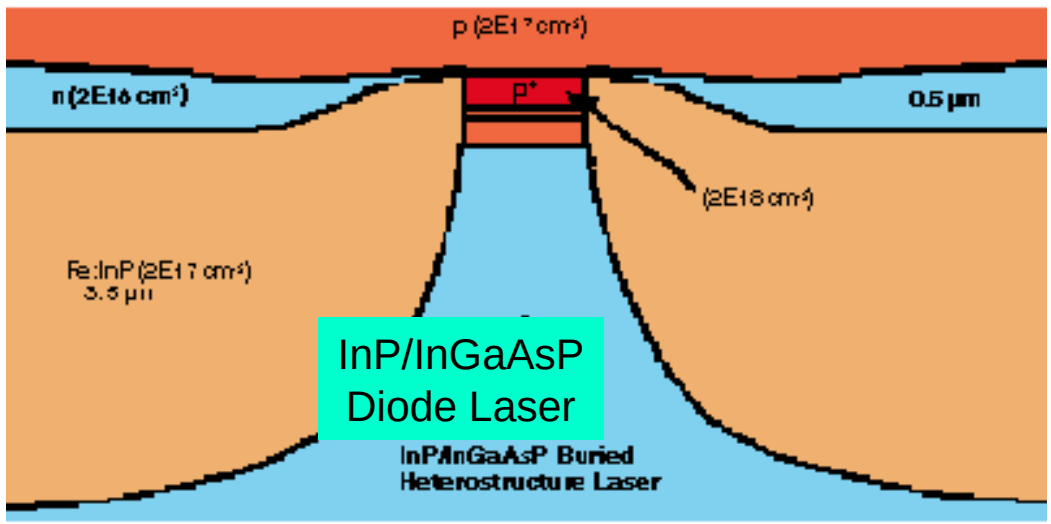

N type CV Curve
Capacitance
Depletion
Accumulation
High Concentration
Low Concentration
High Doping ΔC
Low Doping ΔC
V_{AC}
Voltage


Depletion
Conductive Probe
Dielectric
N type Semiconductor


Accumulation
Conductive Probe
Dielectric
N type Semiconductor

Scanning Capacitance Microscopy





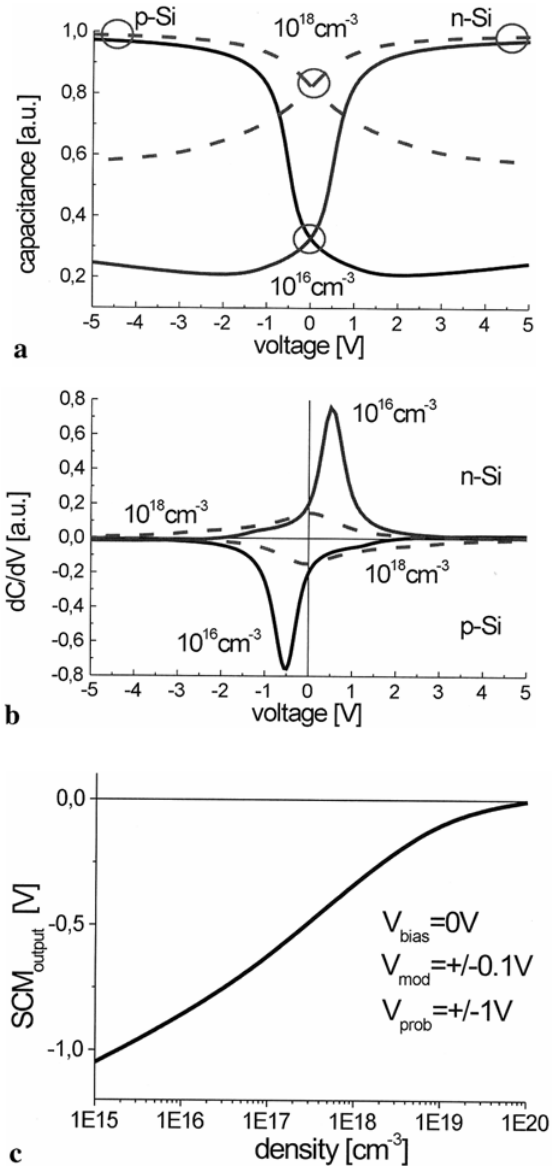


Fig. 2a–c. 3D simulations of SCM on homogeneously doped samples. The tip ($r_a = 25$ nm, $r_i = 25$ nm, $\alpha = 20°$) is modelled in cylindrical coordinates; $d_{Ox} = 10$ nm. **a** $C(V)$ curves on p- and n-doped silicon with dopant concentrations of $10^{16}\,cm^{-3}$ and $10^{18}\,cm^{-3}$, respectively. **b** The corresponding $dC/dV(V)$ curves are calculated analytically. **c** The calibration curve is calculated from $C(V)$-curve simulations. The SCM output is calculated as $\Delta C/\Delta V(V)$ at $V_{bias} = 0$ V taking $V_{mod} = \pm 0.1$ V and $V_{prob} = \pm 1$ V into account

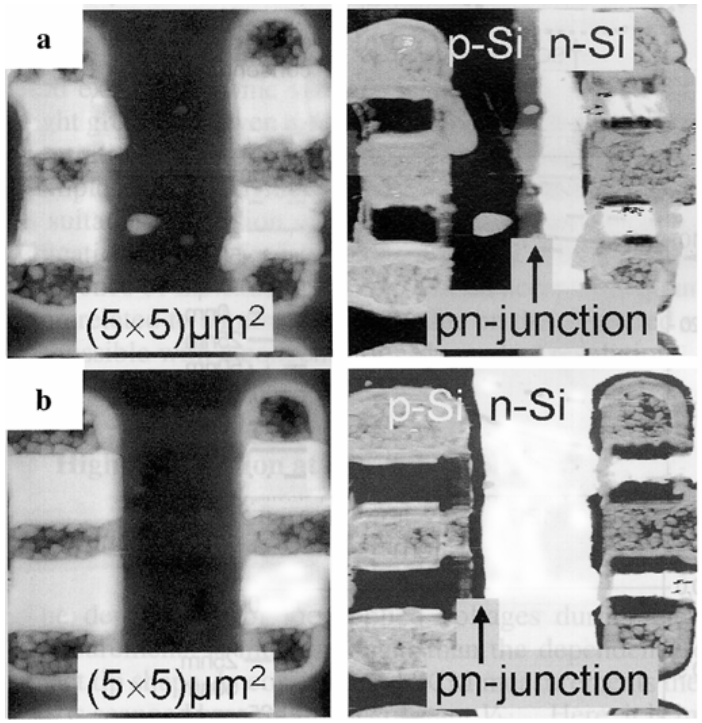


Fig. 3a,b. Failure analysis of an industrial device by means of SCM. Topography (*left-hand side*) and SCM image (*right-hand side*) are taken simultaneously. **a** Well-operating device with the *pn* junction implanted in the middle between the poly-silicon contacts. **b** Defective device with the *pn* junction shifted to the left-hand contacts. Both devices were measured at the same V_{bias} corresponding to the "zero voltage" (see text)

J. Isenbart et al., Appl. Phys. A **72**, S243 (2001).

1. **The SCM has proven its potential for the analysis of 2D dopant profiles on a scale down to less than 50 nm.**
2. **The quantification of a measured dopant profile is still difficult due to the influence of parameters of the sample, the tip shape, and the capacitance sensor including the applied voltages.**
3. **The properties of the sample, e.g. the roughness of the surface (fluctuation of the oxide thickness), the density of charged impurities and traps in the oxide layer and mobile surface charges, are mainly determined by the sample-preparation procedure.**
4. **The most important influence on the measurements is due to the probing voltage of the capacitance sensor and the applied bias voltage.**
5. **In SCM, not the dopant concentration, but rather the local charge-carrier concentration is measured because only the mobile carriers can contribute to C(V) and thus only the local charge-carrier distribution can be detected.**