Scanning Probe Microscopy

(SPM)

Dr. Benjamin Dwir

Laboratory of Semiconductor Materials (LMSC)

Benjamin.dwir@epfl.ch

PH.D2.397

Moodle:http://moodle.epfl.ch/course/view.php?id=13770

Outline:

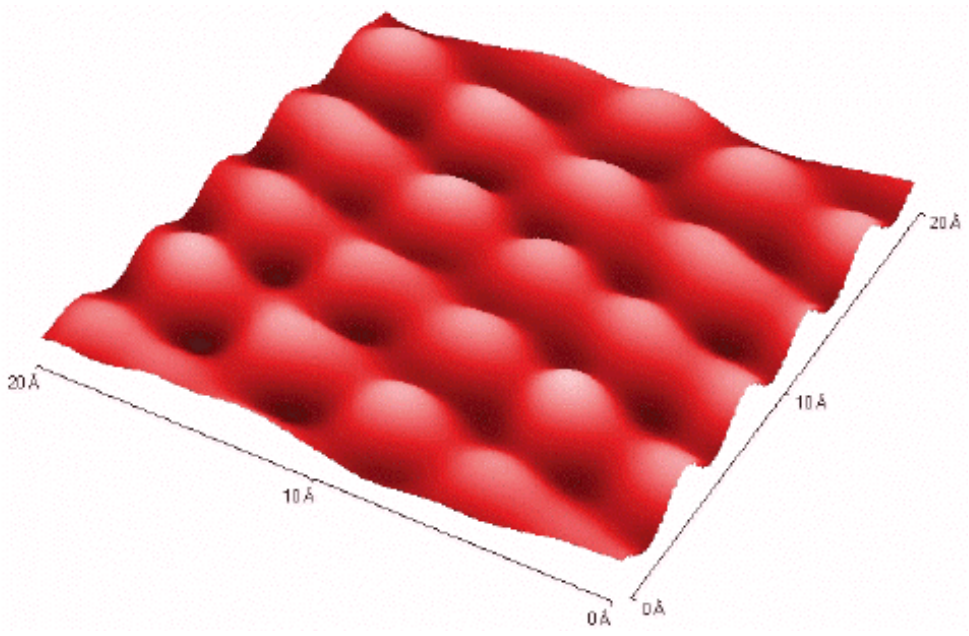
- Introduction: What is SPM, history
- STM
- AFM
- Image treatment
- Advanced SPM techniques
- Applications in semiconductor research and industry

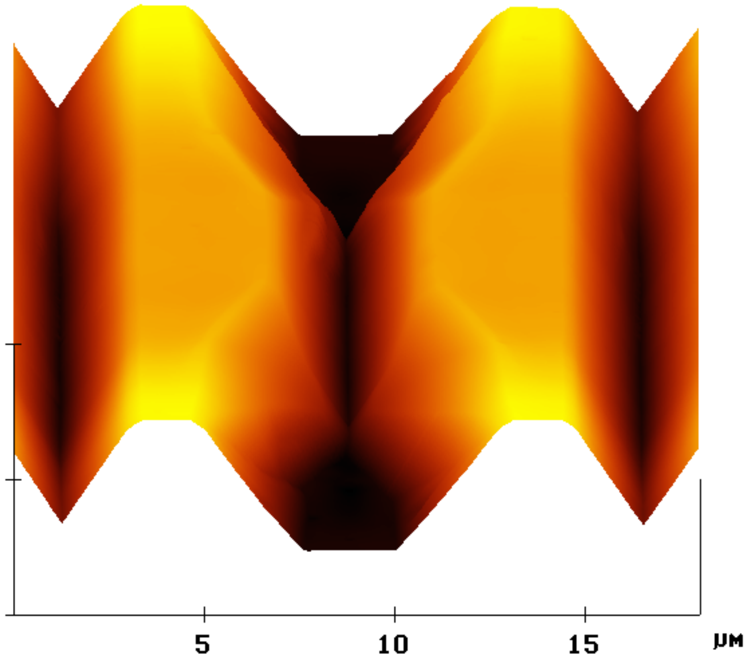
What is SPM ?

- **Scanning Probe Microscopy :**

The characterization of a sample by scanning its surface with a probe, at a small distance

Usually, only surface properties are observable





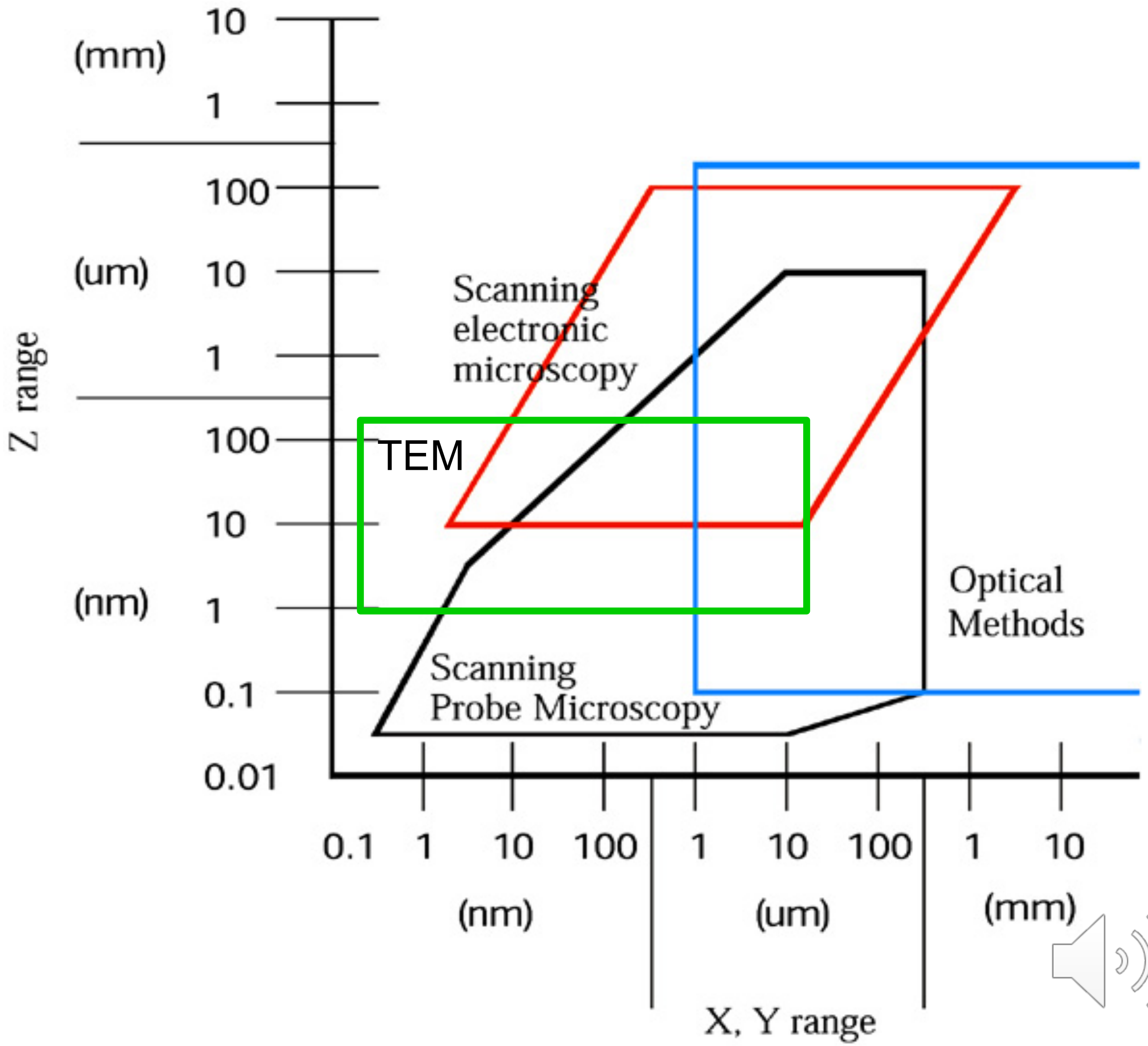
How does SPM compare with other microscopy techniques ?

Microscope	Optical	Confocal	Interference	SEM	TEM	STM	AFM	SNOM
XY resolution	400 nm	150 nm	250 nm	1 nm	0.05 nm	0.1 nm	(<)1-10 nm	<50 nm
Z resolution	-	1 nm	0.1 nm	-	-	0.01 nm	0.01 nm	(0.01nm)
Ambience	air (liquid)	air (liquid)	air (liquid)	vacuum	vacuum	vacuum (air,liq.)	air (liquid)	air (liquid)
Sample preparation	none	none	none	none / coating	polishing, ion milling	none / UHV cleaving	none	none
Damage to sample	none	none	none	Contami-nation,(heating)	Contami-nation, heating	none	none (scratch)	none
Price (kFr)	5-30	50-200	50-200	200-700	500-5000	70-300	50-300	70-300

Advantages of SPM

- 3D imaging
- High spatial and vertical resolutions
- No sample preparation
- Simple to operate
- Low-cost

- Main disadvantage : slow (5-20 min/image)



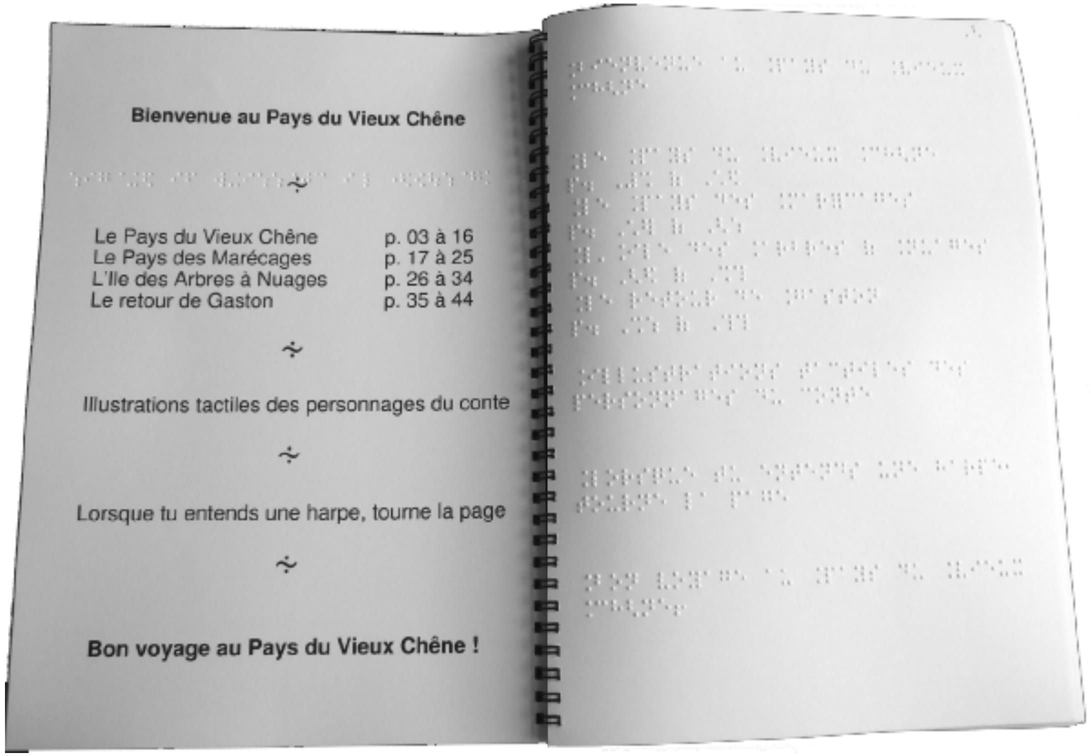
A (short) history of SPM

To get an idea of the surface of a sample, we can:

- Observe it (optical imaging)

Or:

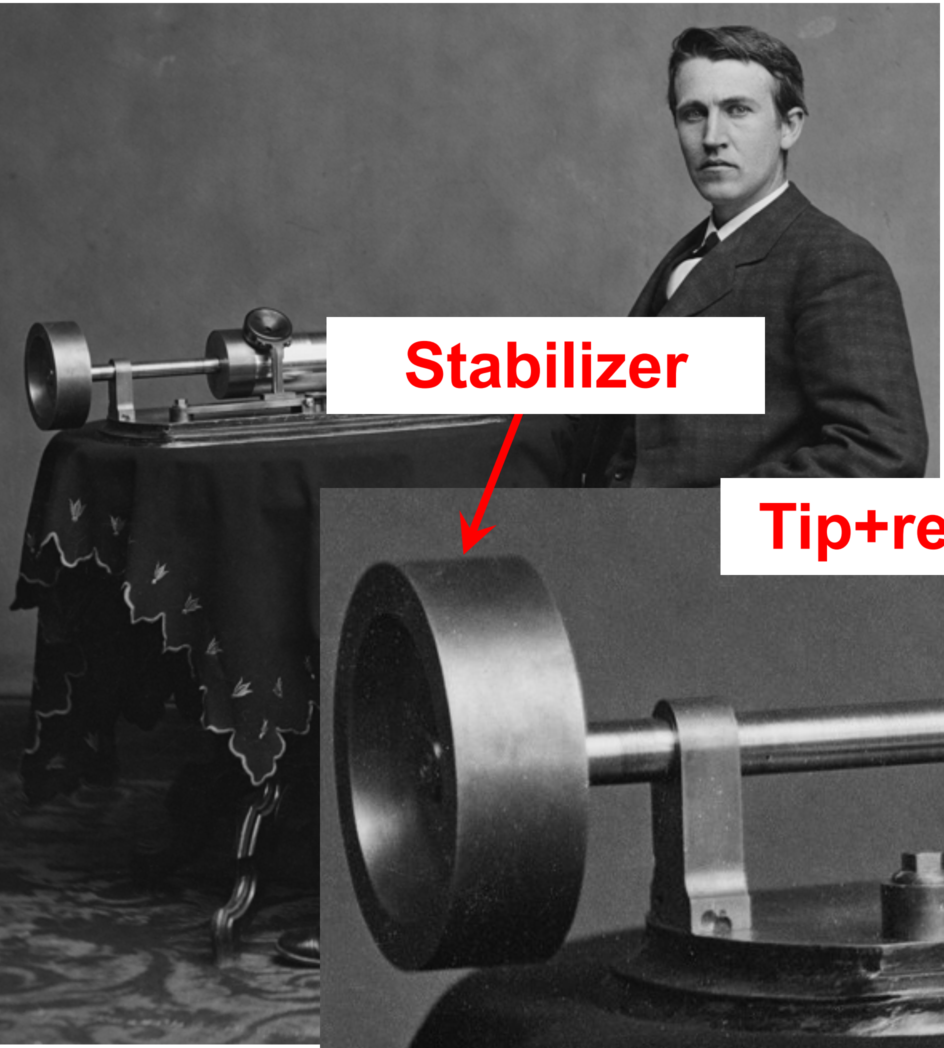
- Touch it (mechanical scanning)

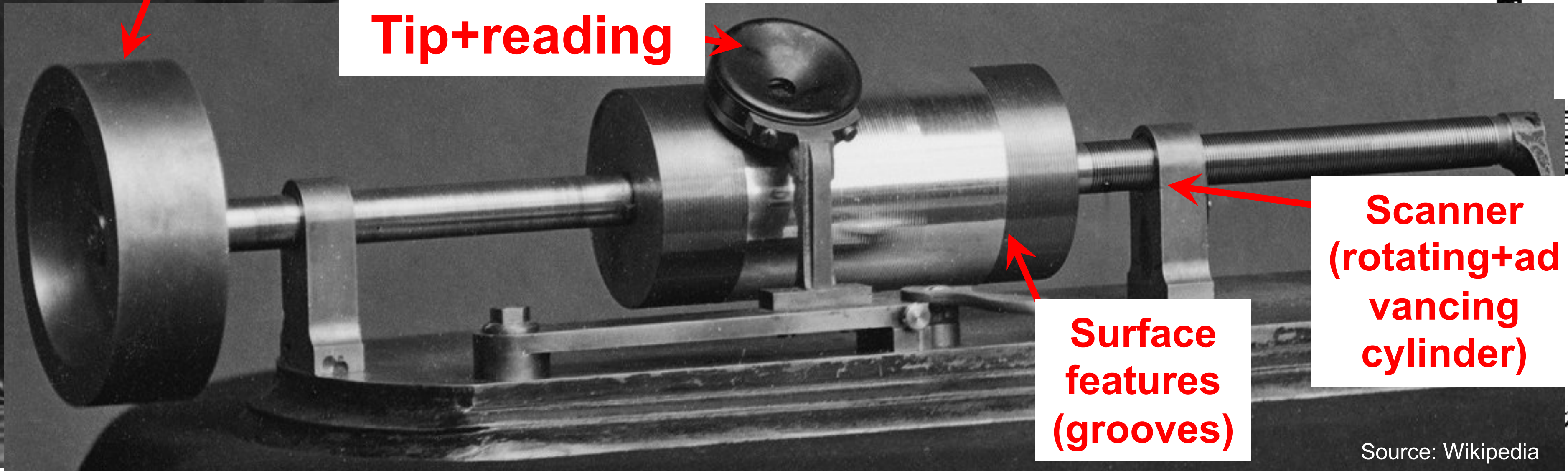


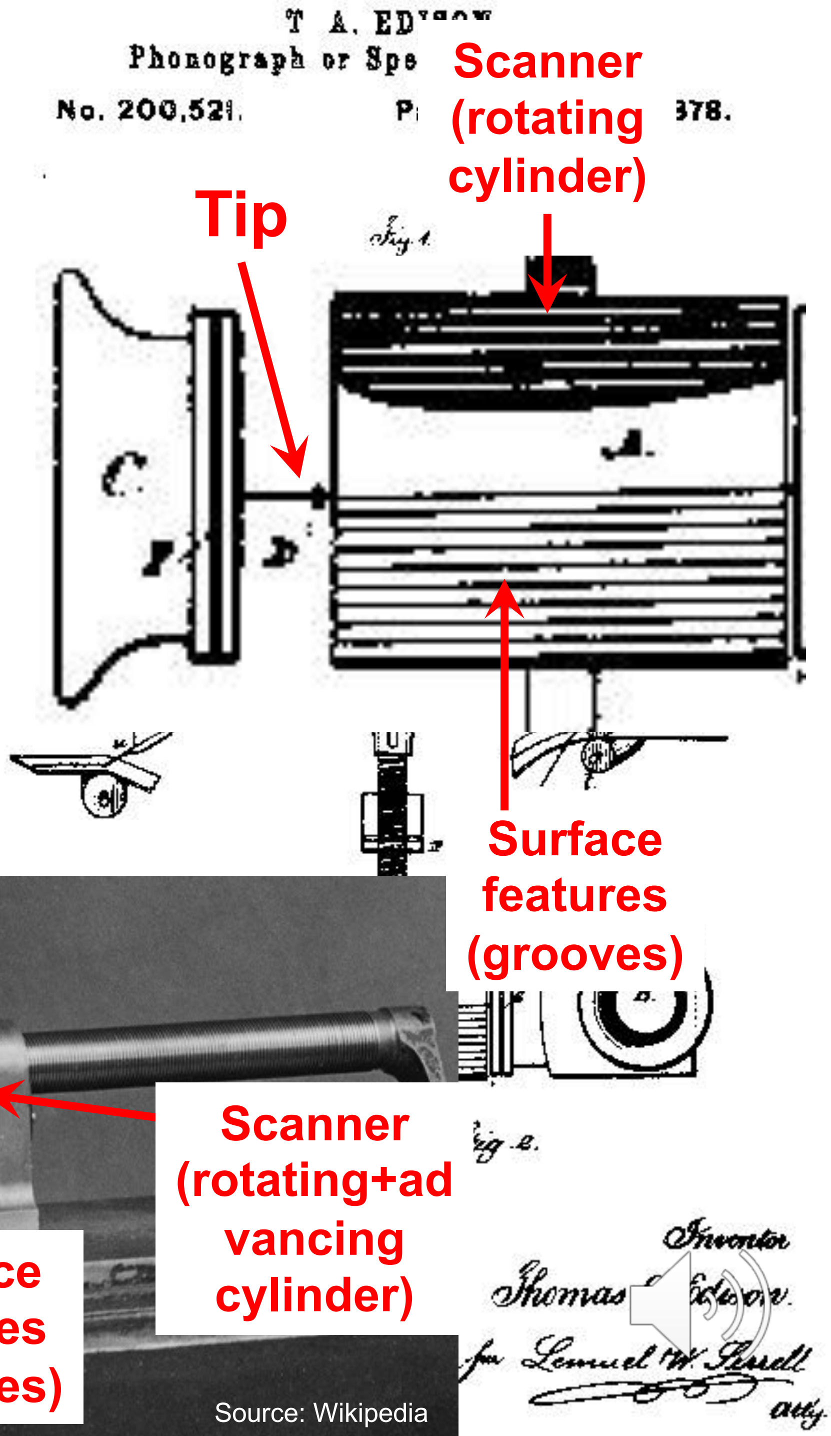
- Parallel reading
- (High resolution)

- Serial reading
- (Low resolution)

Another old type of SPM: reading data by mechanical probe

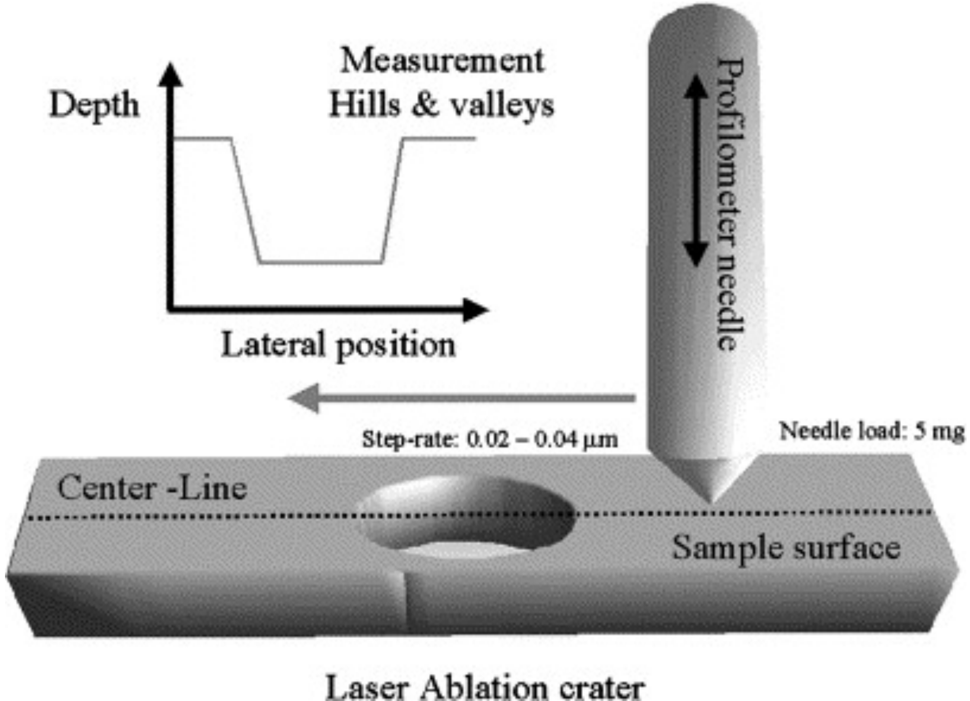






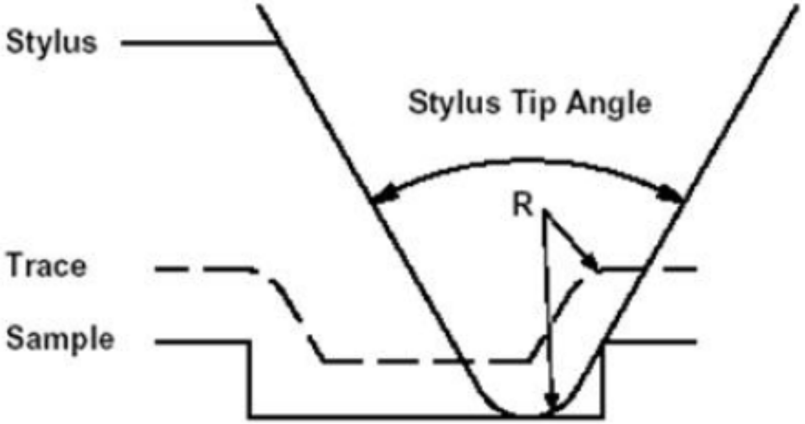
A more modern instrument: The Stylus Profilometer ("Alpha-step")

- Scans a line profile of the surface with a mechanical tip at a low force
- Measures the height profile across the line scan

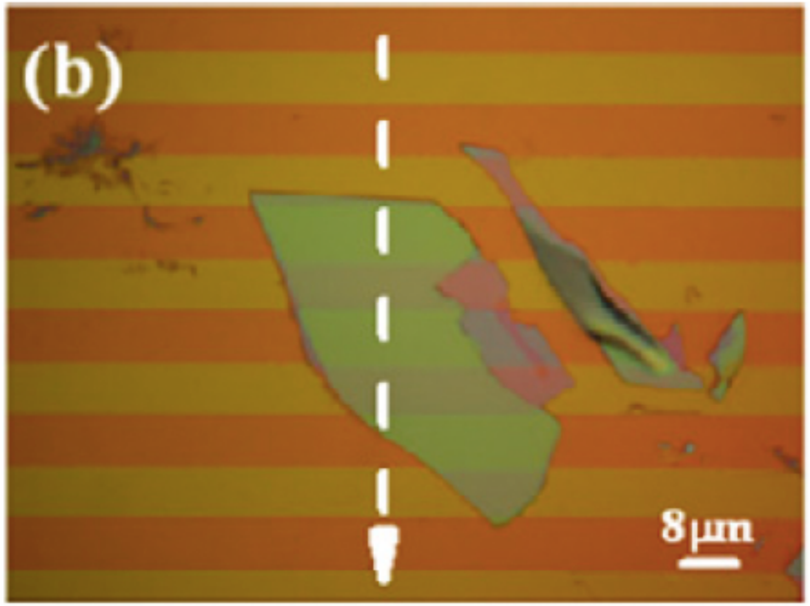


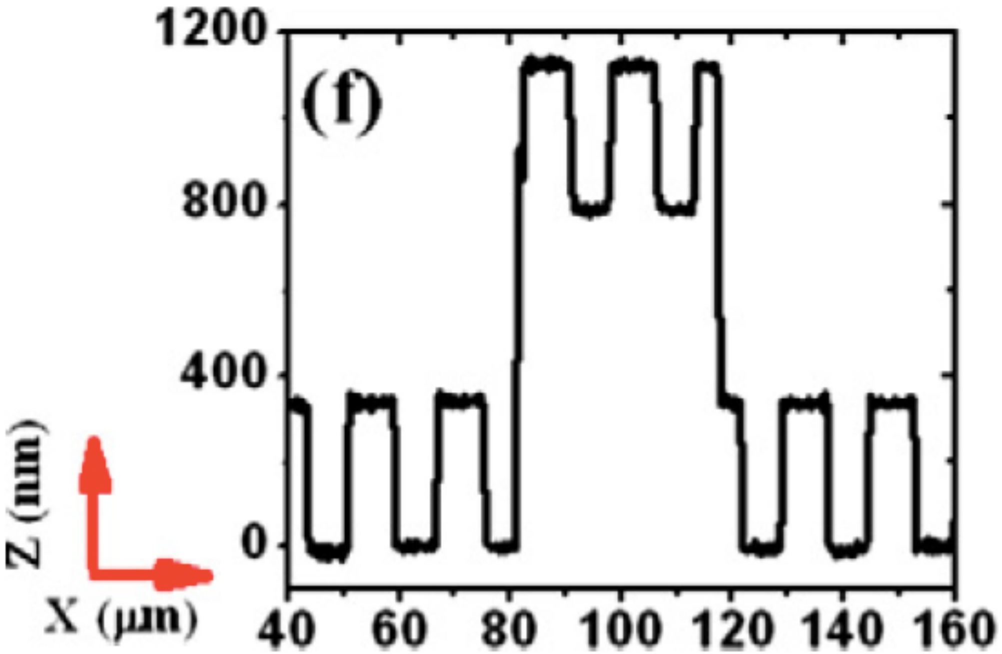
Typical height profiles

- Scan length: up to 100 mm
- Z-resolution: 5-10 nm
- X-resolution: ~10 μm (due to tip size)
- Scan time: 10-100 s



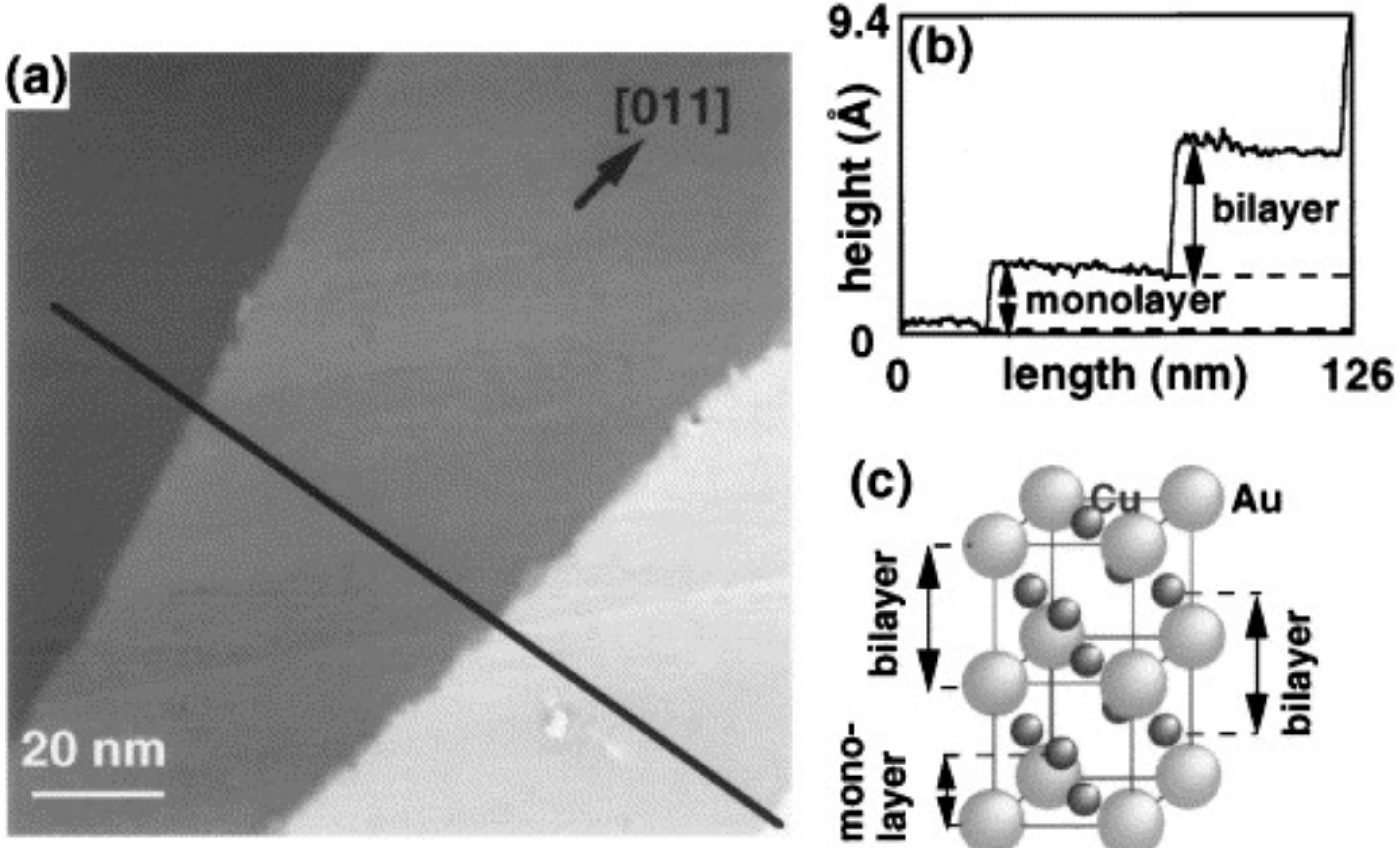
Stylus Tip Angle = 60 degrees
R = 5 micons





X. Wanga, L.X. You, D.K. Liu, C.T. Lin, X.M. Xie, M.H. Jiang, Physica C 474, 13 (2012)

The challenge of modern SPM: How to get nm resolution in all dimensions (X,Y,Z)?



M.-T Lin, J Shen, W Kuch, H Jenniches, M Klaua, C.M Schneider, J Kirschner, Surface Science 410, 2–3, 290 (1998)

First attempt: The Topografiner (1972)

Student presentation:

R. Young, J. ward, F. Scirer, Rev. Sci. Inst. **43**, 999 (1972)
“A noncontacting instrument for measuring the microtopography of metallic surfaces”

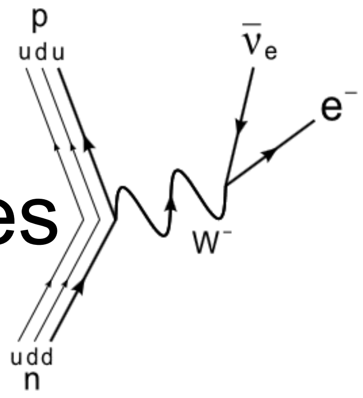
Let's think: How to get nm resolution?

Potential problems:	Solutions:
1. Tip size	1. Short-range interactions
2. High-resolution XY scanning	2. Piezo scanner
3. Non-destructive	3. Non-contact
4. Keep distance from sample	4. Height feedback
5. Vibrations	5. Rigid structure, isolation
6. Thermal stability	6. Compensation

How to get nm resolution:

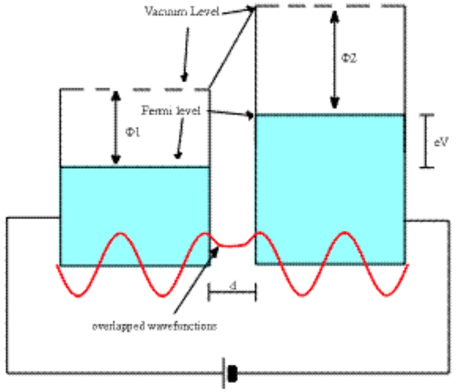
1. Short-range interactions: Do you know any?

- Nuclear (strong) forces

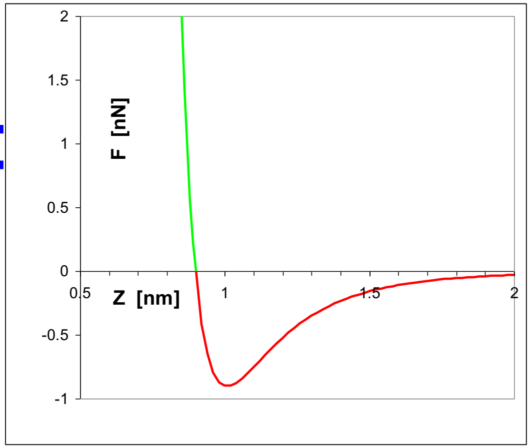


But range is too short!

- Quantum-mechanical electron tunneling: STM



- Van-der-Waals forces: AFM



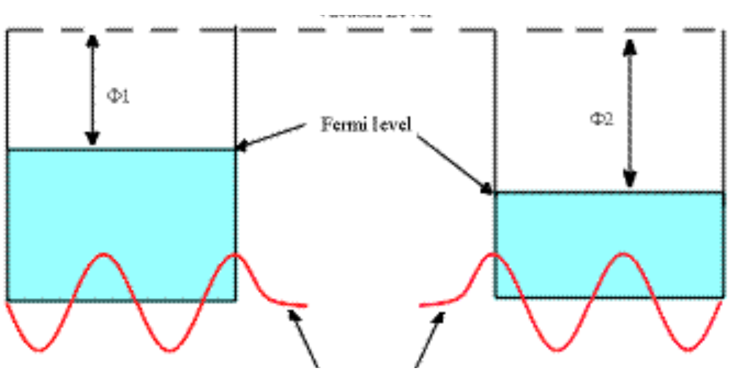
First working STM:
Binnig & Rohrer, 1982

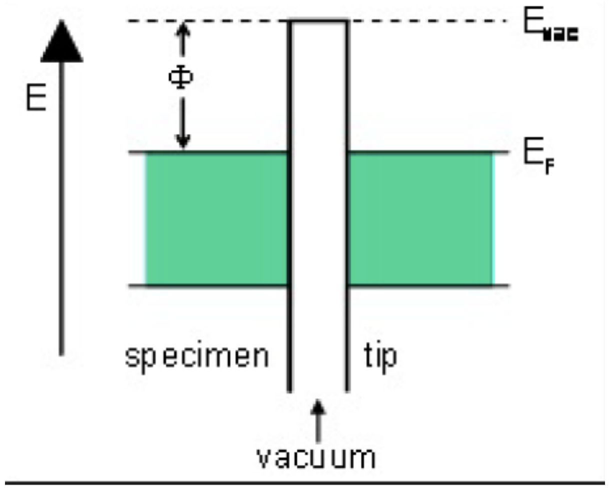
Student presentation:

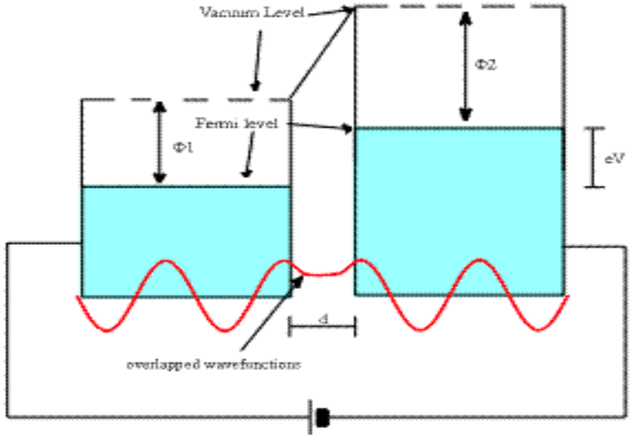
G. Binning, H. Rohrer, Ch. Gerber, and E. Weibel,
Phys. Rev. Lett. **49**, 57 (1982)
"Surface Studies by Scanning Tunneling Microscopy"

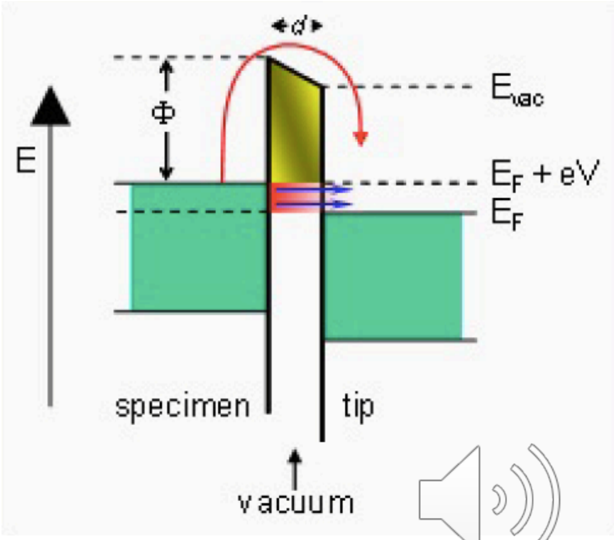
Quantum Tunneling between metals

- Electrons in metals fill up energy levels to the Fermi level, which is about 5 eV (the work function) below the Vacuum level Φ.
- External potential between metals shifts the relative Fermi levels, so that electrons could pass from full (left) to empty (right) levels, but… the energy barrier is too high!
- When the metals are close enough, electron wavefunctions can overlap and tunneling current flows

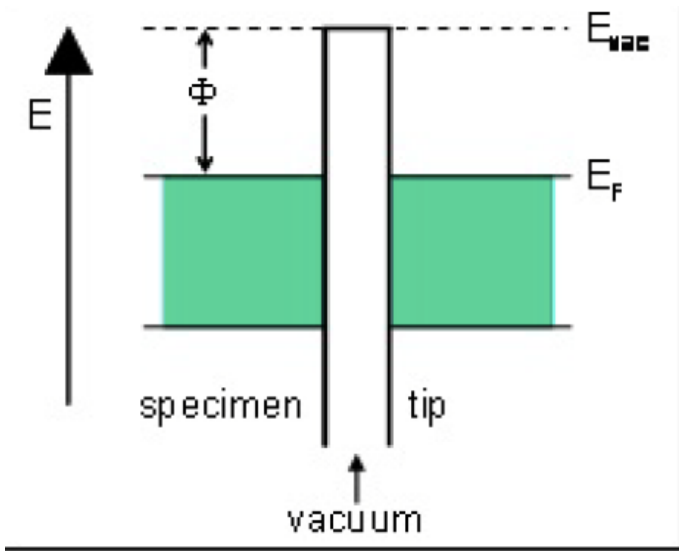


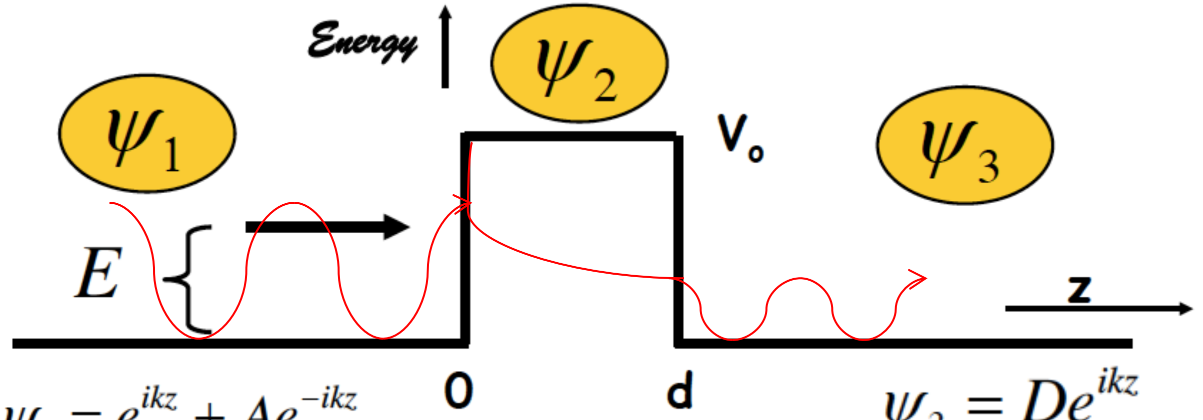






Quantum Tunneling: wavefunctions





$$\psi_1 = e^{ikz} + Ae^{-ikz}$$
$$U(z) = 0$$
$$k^2 = \frac{2mE}{\hbar^2}$$

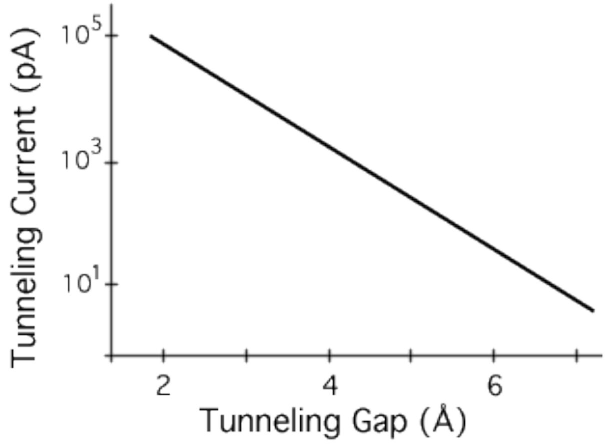
$$\psi_2 = Be^{-\alpha z} + Ce^{\alpha z}$$
$$U(z) = V_o$$

$$\psi_3 = De^{ikz}$$
$$U(z) = 0$$
$$k^2 = \frac{2mE}{\hbar^2}$$

- Electron wavefunction is propagating in metal, but exponentially decaying in the vacuum barrier.
- Typical decay coefficient: $\alpha = \frac{\sqrt{2mV_0}}{\hbar} = \frac{\sqrt{2m\Phi}}{\hbar}$ = 11 nm^{-1}
- The transmission coefficient is: $T = \left(\frac{4k\alpha}{k^2+\alpha^2}\right)^2 e^{-2\alpha d} \propto e^{-2d\sqrt{2m\Phi}/\hbar}$

Quantum Tunneling: current flow

- When we apply a potential *V* between the metals, current will flow across the barrier.
- The current from the left metal to the right is given by (*f* = Fermi distribution):

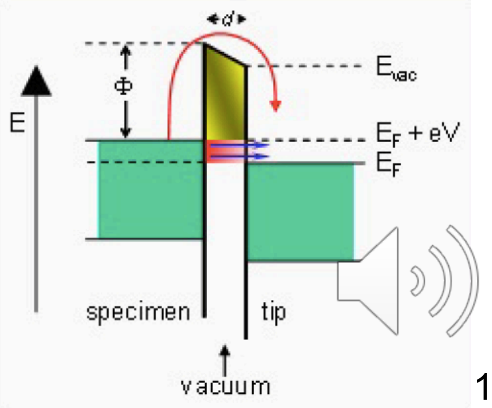


$$J_{l\to r} = \frac{4\pi e m^2}{h^3}\int_0^\infty f(E)D_l(E)D_r(E+eV)T(E)\,dE$$

- The current from the right metal to the left is given by:

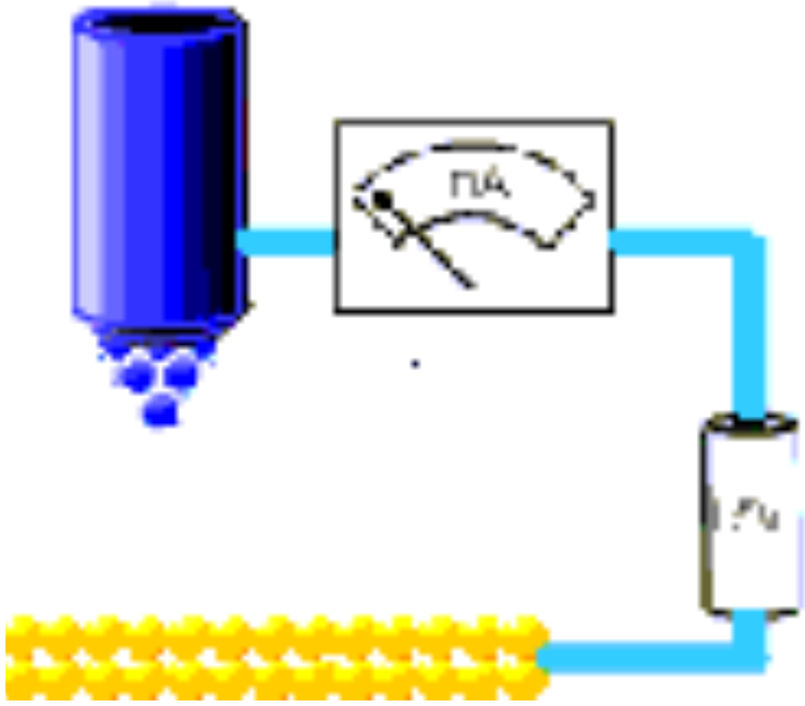
$$J_{r\to l} = \frac{4\pi e m^2}{h^3}\int_0^\infty f(E+eV)D_l(E)D_r(E+eV)T(E)\,dE$$

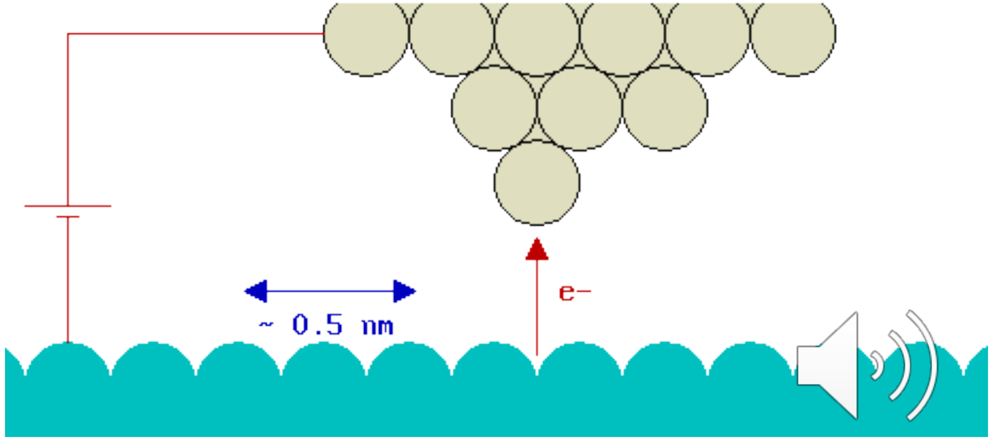
- The net current is the difference: $J = \frac{4\pi e m^2}{h^3}\int_0^\infty \left[f(E)-f(E+eV)\right]D_l(E)D_r(E+eV)T(E)\,dE$
- If the voltage is small relative to the barrier, we can use a 1st order expansion for the Fermi distribution function and get: $J = \sigma_0 V e^{-2d\sqrt{2m\Phi}/\hbar} \propto V e^{-2\alpha d}$, with: $\alpha = \frac{\sqrt{2m\Phi}}{\hbar}$ $\sigma_0 = \frac{e^2\sqrt{2m\Phi}}{h^2 d} D_l(E_F)D_r(E_F)$
- The I-V curve is linear, as in an Ohmic contact
- Wavefunction decay length is very short: $\ell = \frac{\hbar}{\sqrt{2m\Phi}}$ ~ 0.1 nm!
- This makes the current very sensitive to the distance: a change of distance of one atomic monolayer = 0.3 nm, gives change of current by x1000!



Tunneling as surface probe:

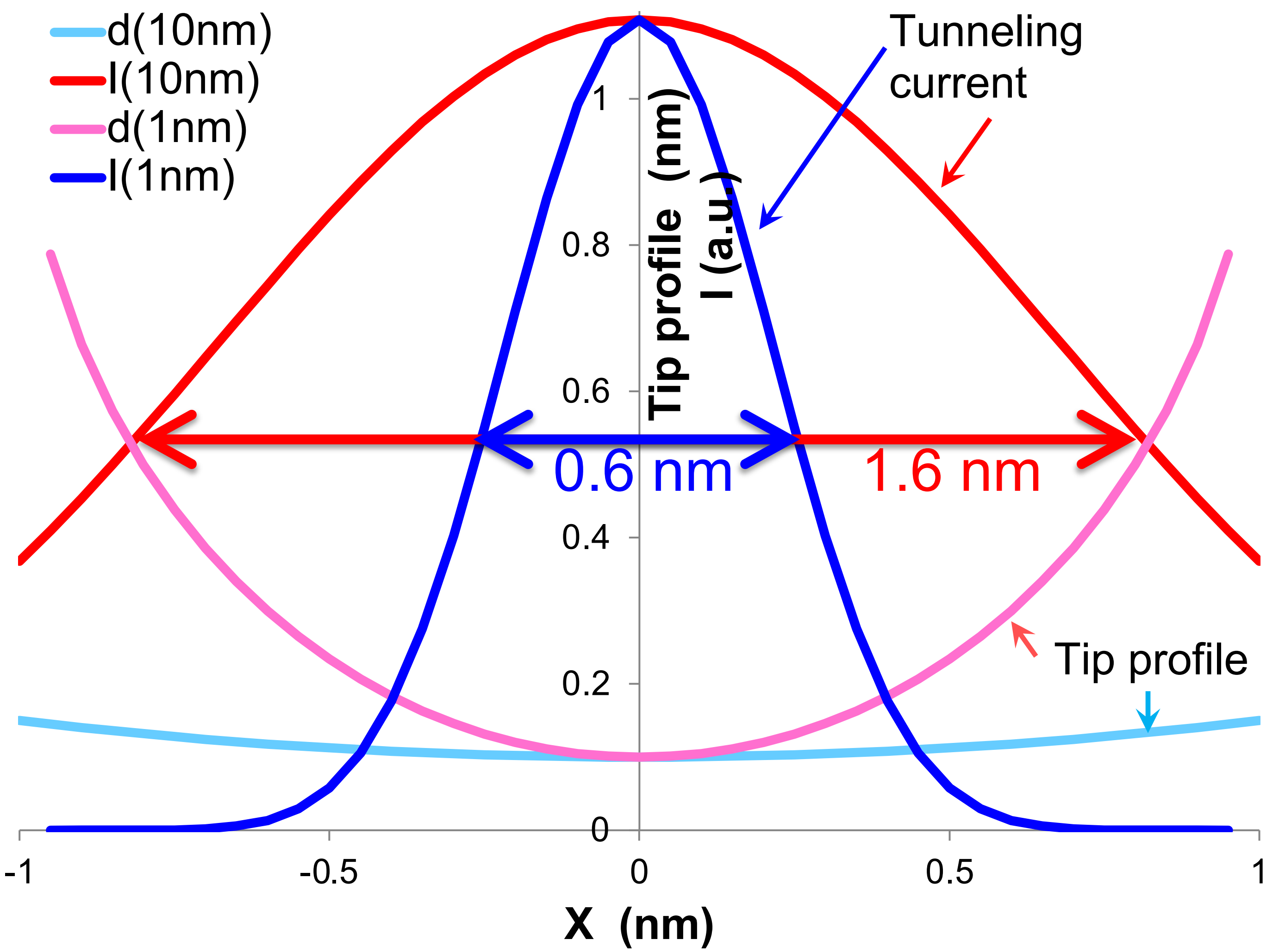
- We approach the sample with a sharp metallic tip, biased to a small potential (1-1000 mV)
- At a very close distance, tunneling current will start to flow between the tip's atoms and the samples' surface atoms
- This current is measurable (nA) at a tip-sample distance of 1Å





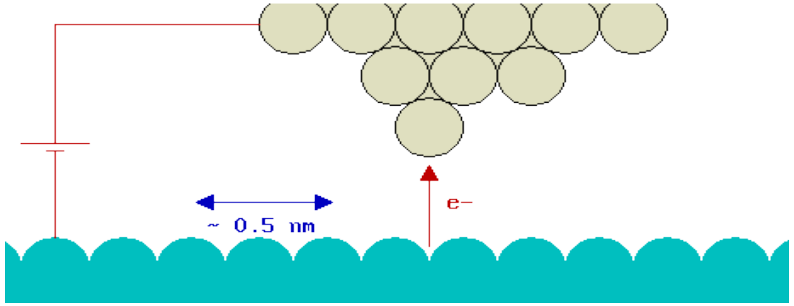
Tunneling between plane and tip

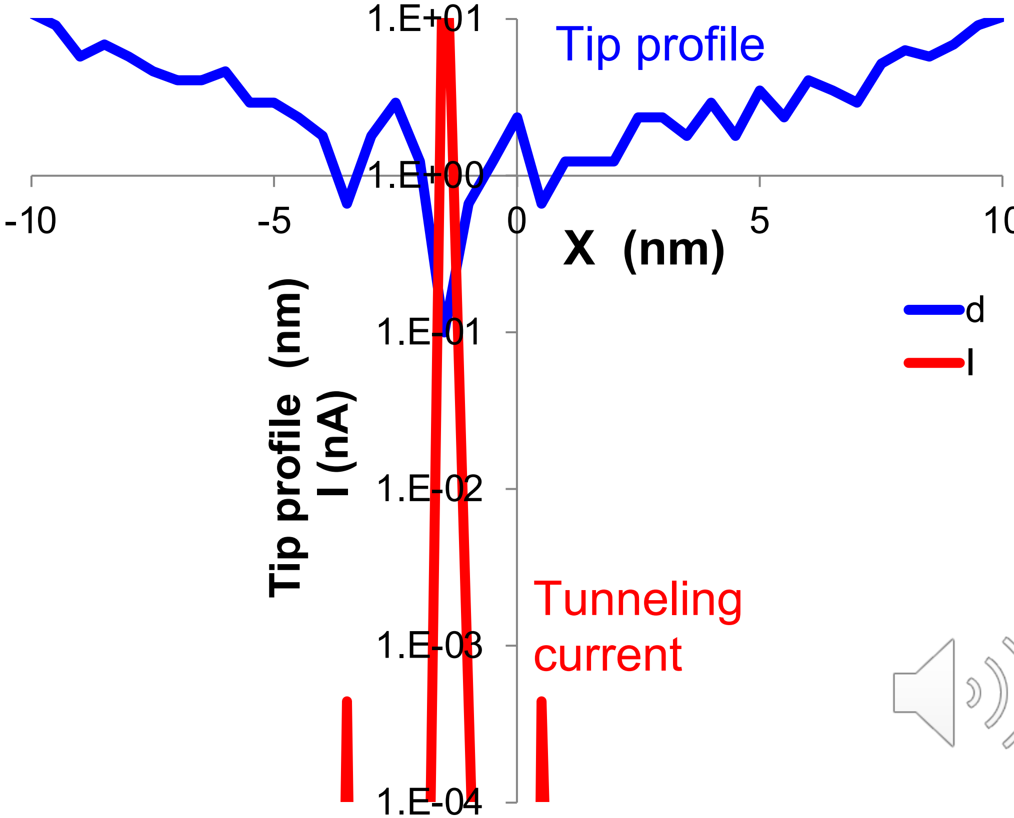
- Calculation of tunneling current between plane and half-spherical tip of identical metals, for tip radii of 1 and 10 nm: apparent width is much smaller!



Tunneling between plane and tip

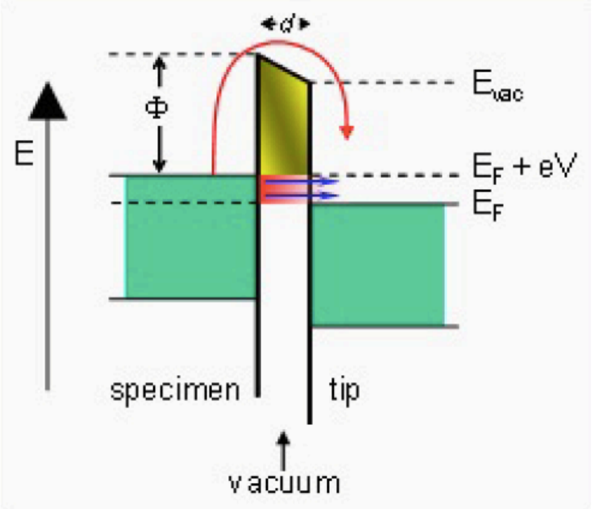
- In a more realistic case, the random atomic nature of the tip will "promote" one atom to produce most tunneling current. Here the tip R=10 nm, h=0.1 nm, lattice constant 0.56 nm
- The current through the lowest atom is bigger by 10^4 than the current from the next one!
- The real "tip" (atom) is not at the position X=0, but it doesn't matter! It's only a small fixed shift in the image





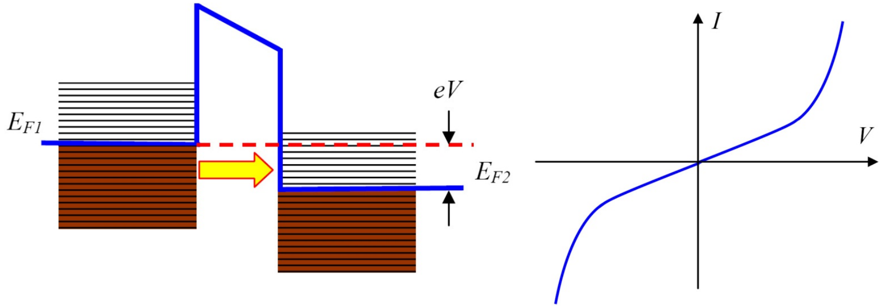
Tunneling between non-identical materials

- The tunneling current is given by: $J = \frac{4\pi e m^2}{h^3}\int_0^\infty [f(E) - f(E+eV)] D_l(E) D_r(E+eV) T(E) dE$
- In tunneling between different materials, the electron transmission probability depends on the electron density of states (DOS) at the Fermi level $D(E_F)$. This gives tunneling current: $J = \propto V D(E_F) e^{-2\alpha d}$
- There is still exponential dependence on tip-sample distance
- The DOS of the sample can be measured

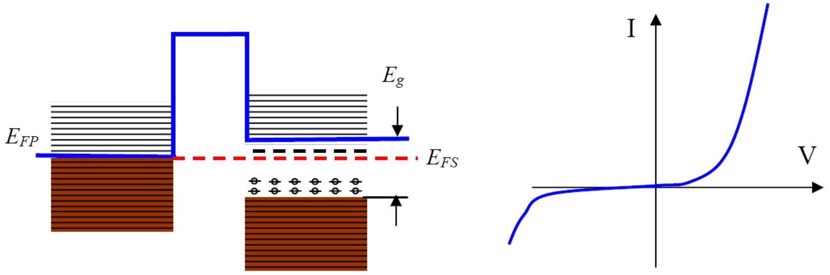


STS: Scanning Tunneling Spectroscopy

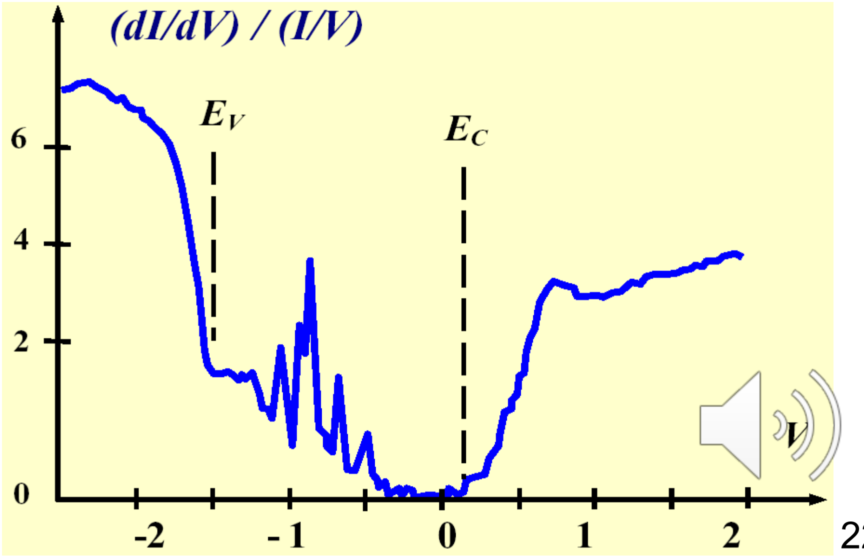
- Tunneling between the metallic STM tip and a metal shows a gapless (Ohmic) I/V curve



- Tunneling between the metallic STM tip and a semiconductor shows the energy gap in the I/V curve (diode-like)
- Similar behavior in superconductors, where pair tunneling can be measured



- In many cases the derivative dI/dV is plotted vs. V to show more clearly the DOS, states in the gap etc.
- Surface states (oxidation) can pin the Fermi level – UHV is needed
- These measurements are often done at low temperatures (reduce phonons)



The main problem: How to get nm resolution?

Potential problems:

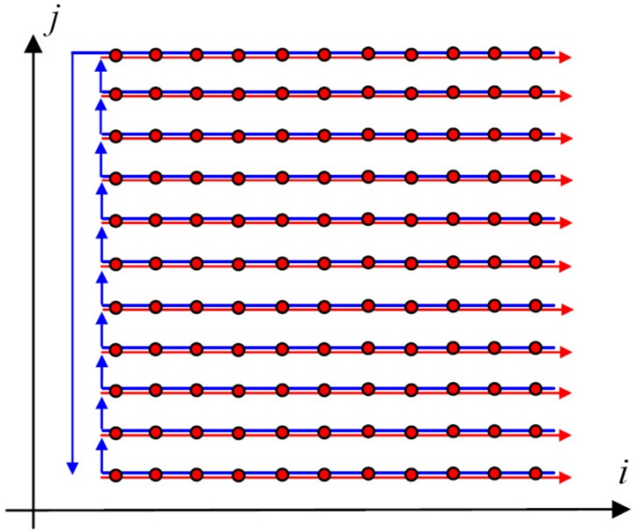
1. Tip size
2. High-resolution XY scanning
3. Non-destructive
4. Keep distance from sample
5. Vibrations
6. Thermal stability

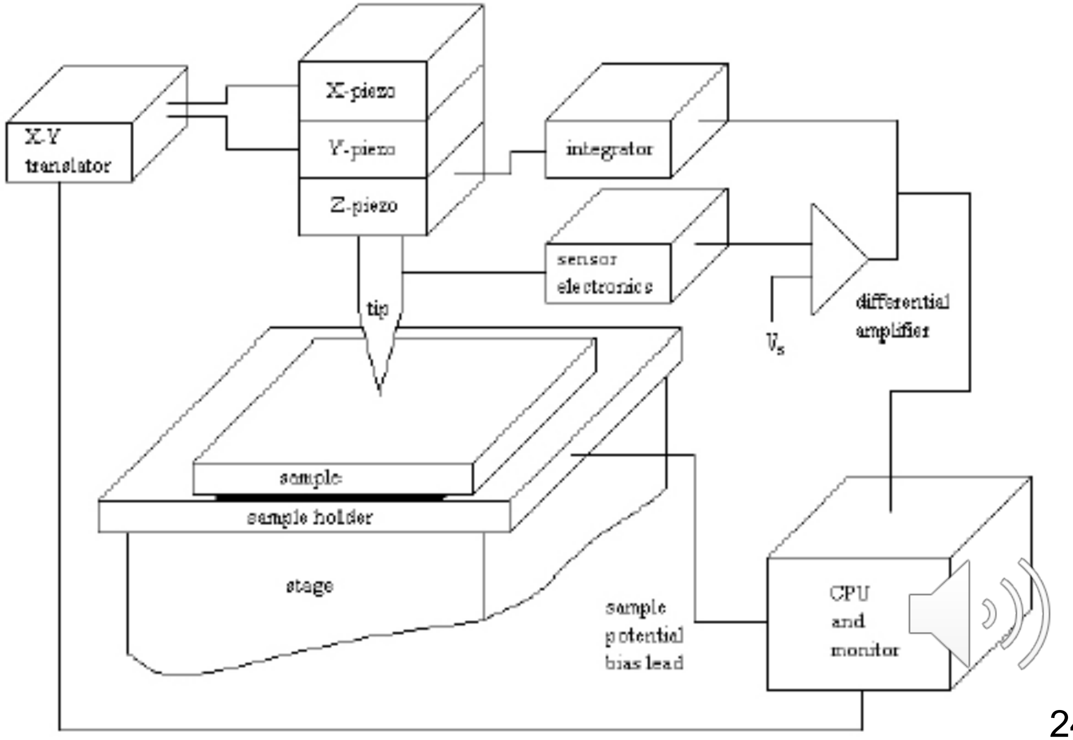
Solutions:

1. Short-range interactions
2. Piezo scanner
3. Non-contact
4. Height feedback
5. Rigid structure, isolation
6. Compensation

High resolution: the piezo scanner

- The X-Y-Z relative movement between tip and sample is controlled by a Piezoelectric Scanner with < 0.1nm precision
- During the scan, we need to measure and stabilize **tip height**:
  - Measured through tunneling current (very sensitive!)
  - Can be used to control tip height by a **feedback loop**
  - Height is displayed as a 3D image



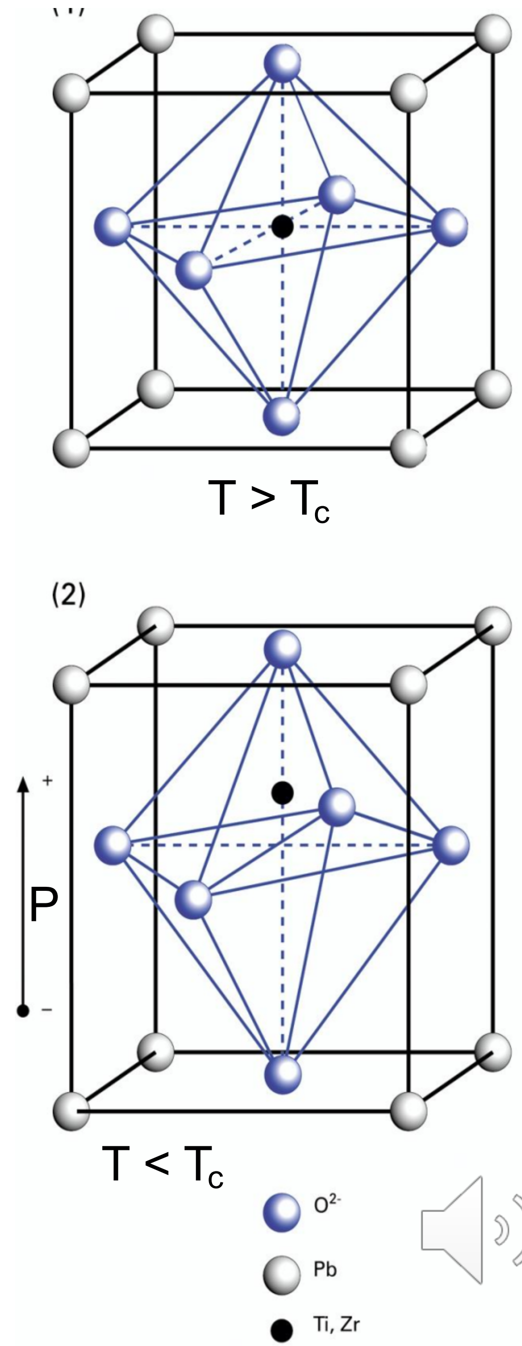


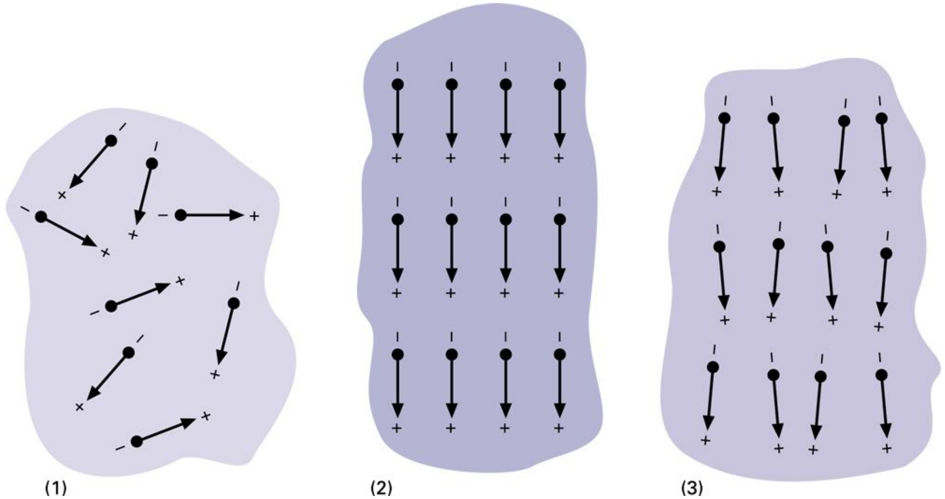
The piezoelectric effect

What is the piezoelectric effect?

- Change in length induced by electric field (also the reverse)
- Atomic structure of PZT: cubic crystal becomes tetragonal at low temperatures, producing a dipole (Ti^+/Zr^+ ion is above the O^{-2} ions) .
- Dipoles in domains can be ordered by an external field, applied during cooling (poling)

$PbZr_{0.52}Ti_{0.48}O_3$





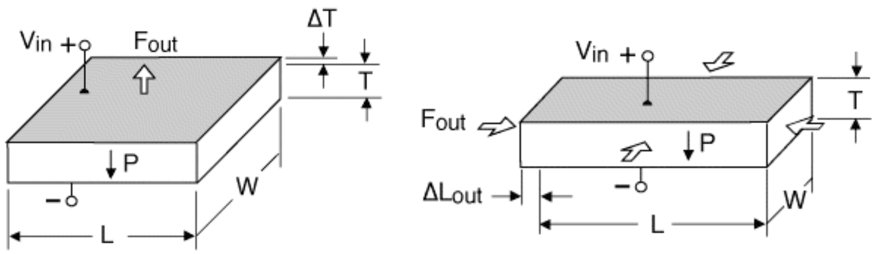
Natural Under field poled

Source: http://www.physikinstrumente.com

The piezo scanner

The displacement of the piezo element: $\frac{\Delta L_i}{L_i} = d_{ij}E_i$ *i,j*=1,2,3

The most interesting directions:



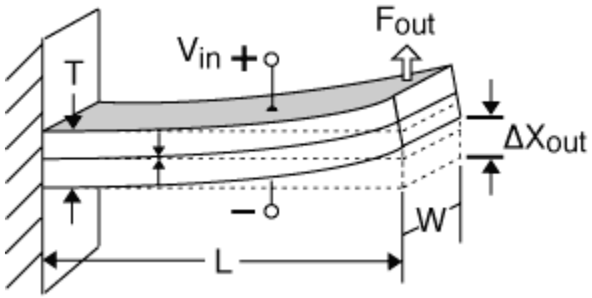
Source: http://piezo.com

- i=j=3 (z), used in linear motion
- i=1, j=3, used in flexing motion

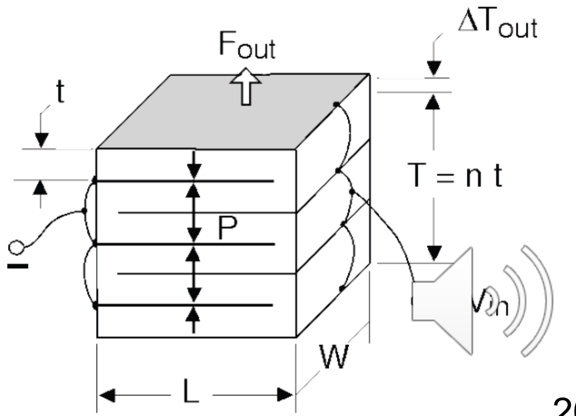
Typical values: d_{33} = $5 \cdot 10^{-10}$ m/V (Small!)

d_{13} = $-2 \cdot 10^{-10}$ m/V

Ways to extend the motion:

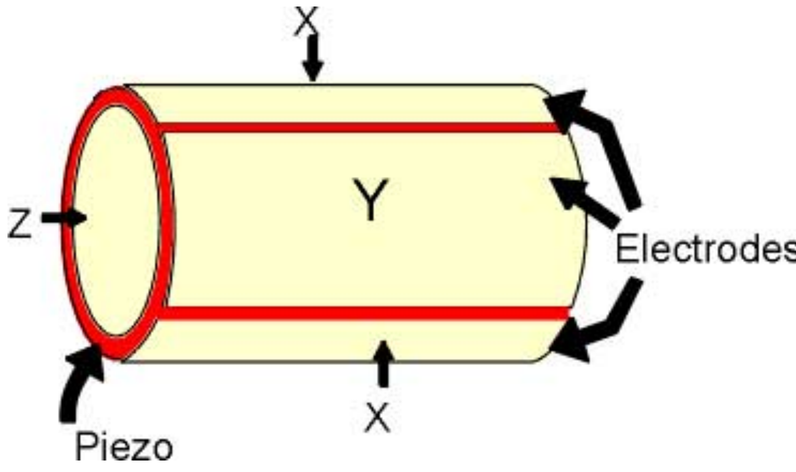


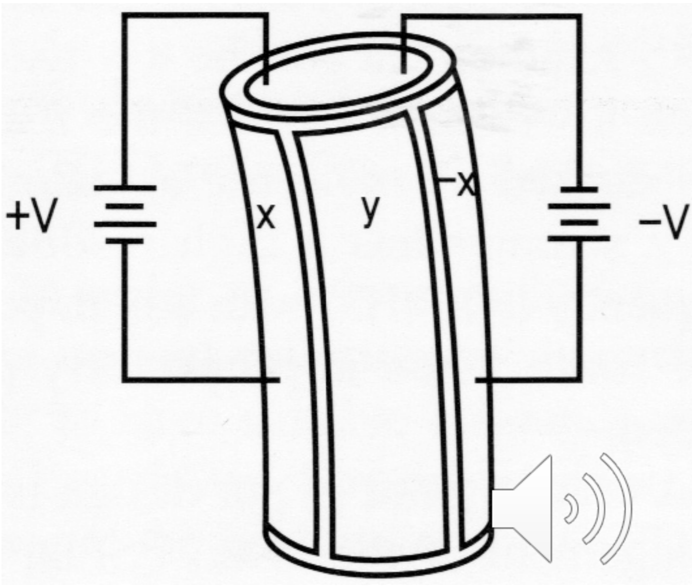
- Levering system
- Multi-layer stack, same voltage applied to many piezo elements in series
- Can reach 100μm movement with a voltage of 100-1000V



Types of piezo scanners: Tube

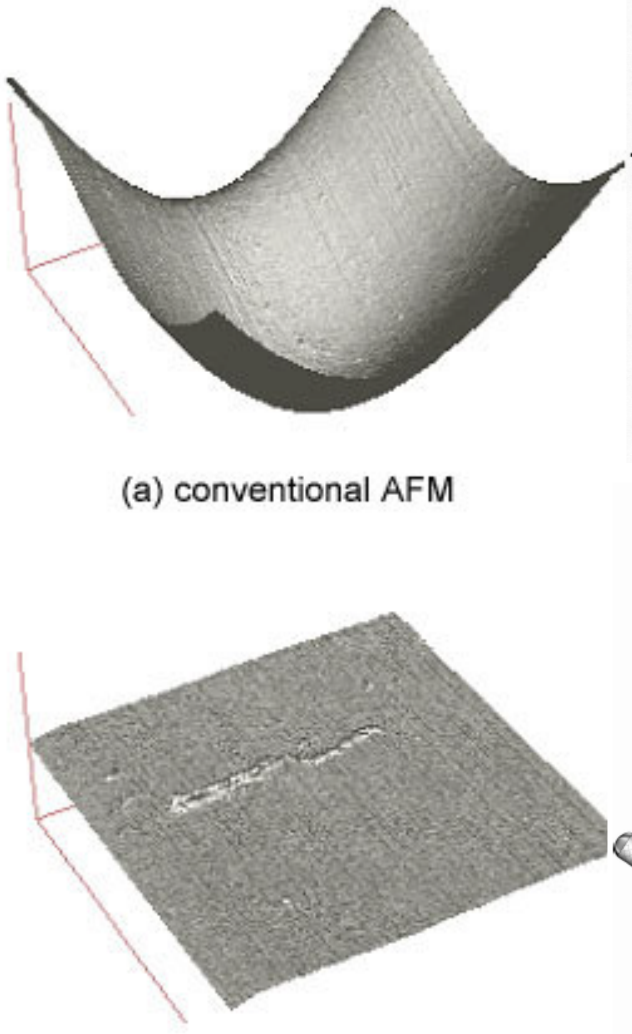
- All movements (X-Y-Z) can be achieved by a single tube scanner:
  - Applying opposite voltages to pairs of electrodes bends the tube in one direction (X,Y)
  - Applying voltage to the inner electrode makes the tube contract/expand (Z)
- Advantages of tube scanner:
  - Simple, small, rigid, cheap (single part does all)
- Disadvantages of tube scanner:
  - Non-linear (especially XY)
  - Difficult to add position sensors
  - All scan axes linked



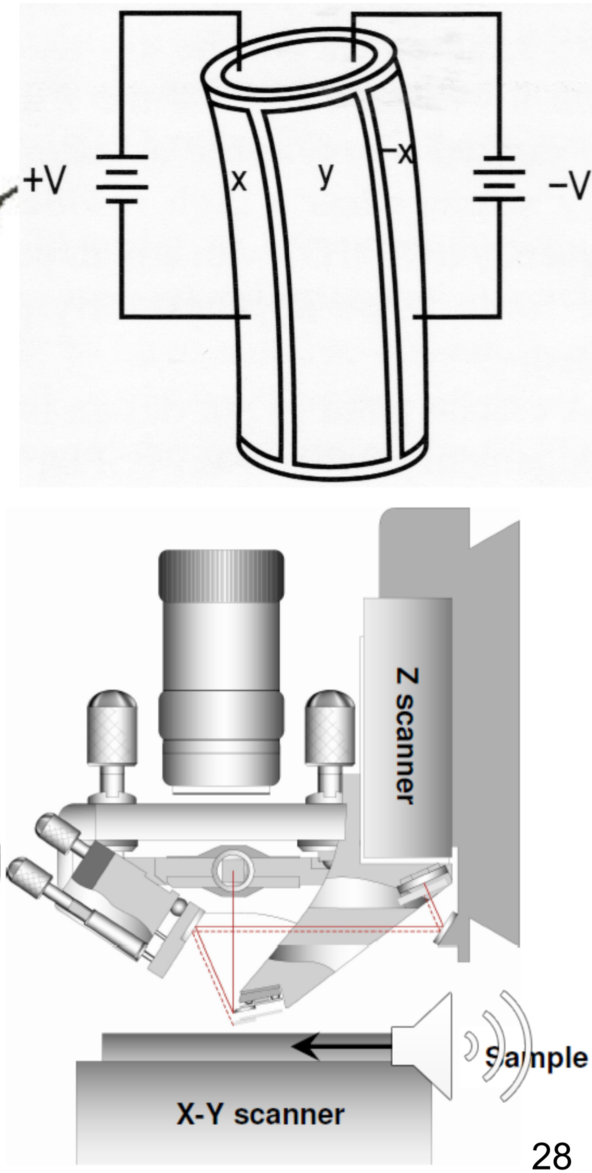


Types of piezo scanners: XY/Z

- Cartesian movement is often achieved by using separate Z and XY scanners
- High-quality XY scanners are available, with high-resolution position sensors to achieve **linear scan**
- Z piezo (used for the feedback!) is uncoupled from the XY scan


(a) conventional AFM

(b) new scan system of XE



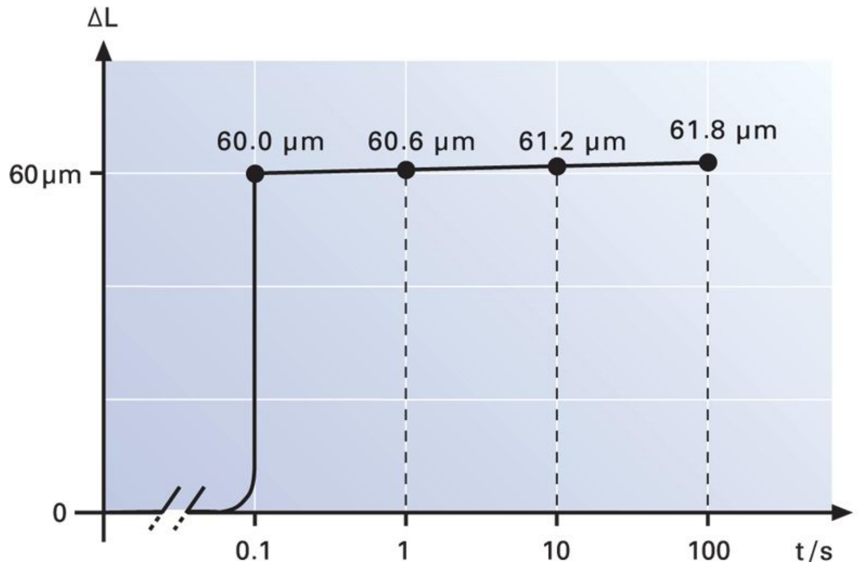
Problems of piezo scanners

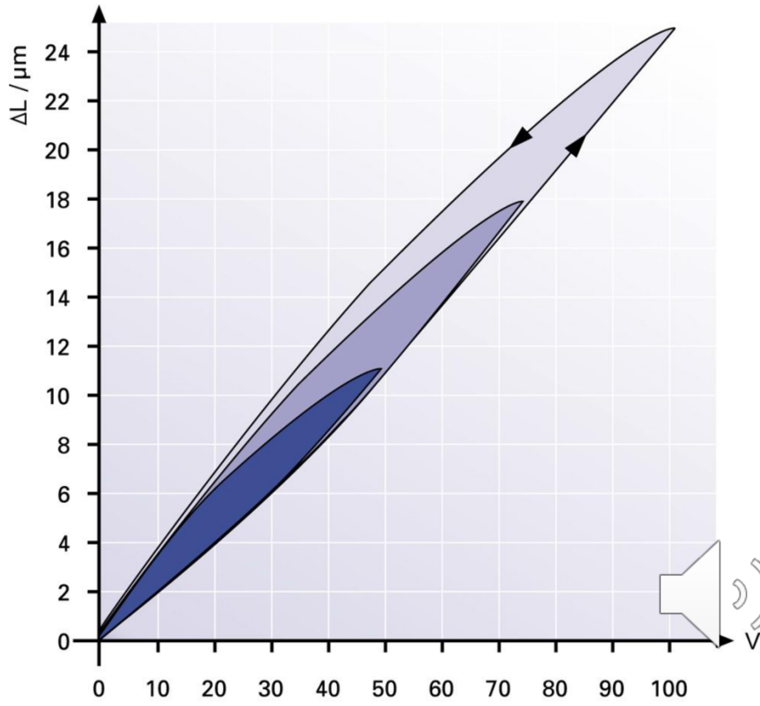
- Creep: The displacement of the piezo element continues slowly after a (large) step:

$$\Delta L(t) = \Delta L(t_0)\left[1+\gamma \ln\left(t/t_0\right)\right] \qquad \gamma\text{=1-2\%}$$

- Hysteresis: The displacement does not follow the same curve when moving back and forth

- Non-linearity: The displacement is non-linear with applied voltage

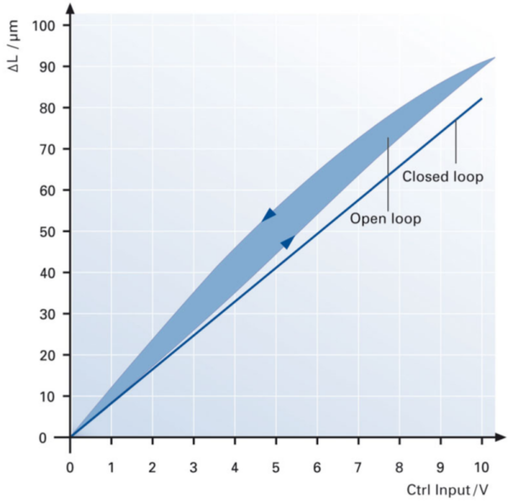




Source: http://www.physikinstrumente.com

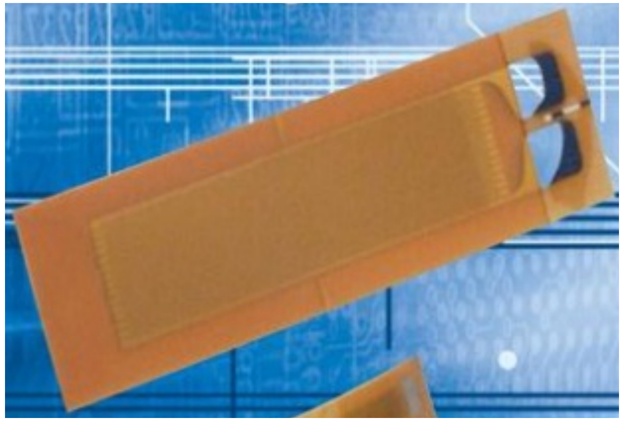
Improving the piezo scanner

The piezo does not give precise positioning. We need sensors to get precise position readout / correction

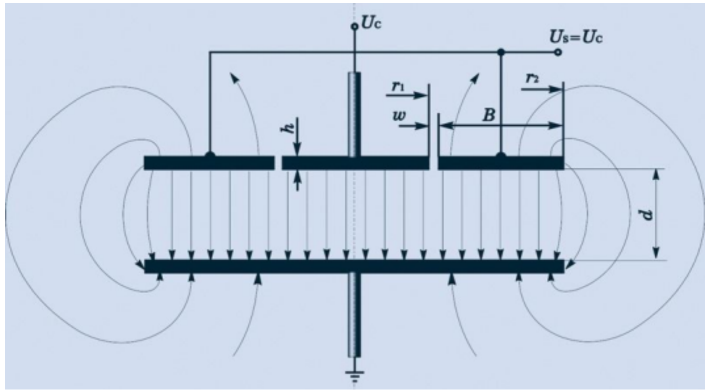


Types of sensors:

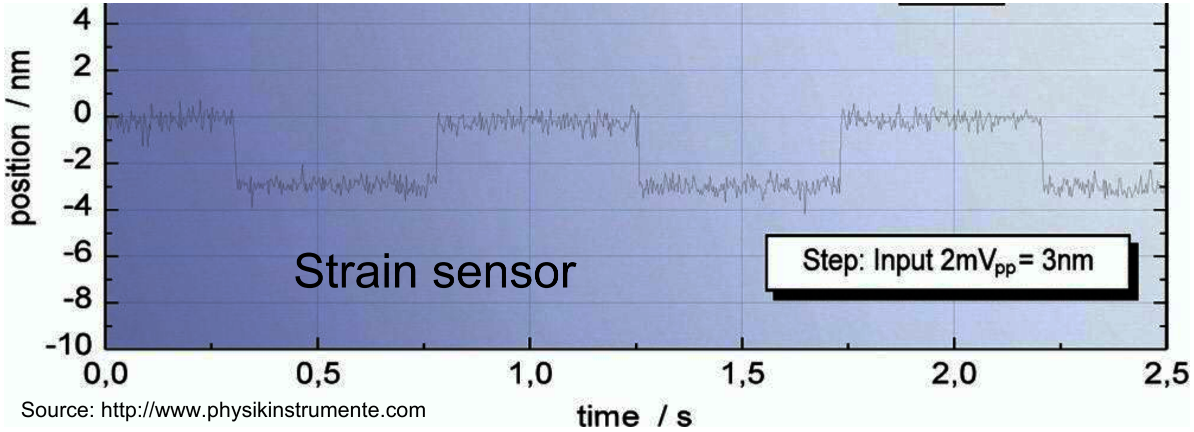
- Strain



Capacitive

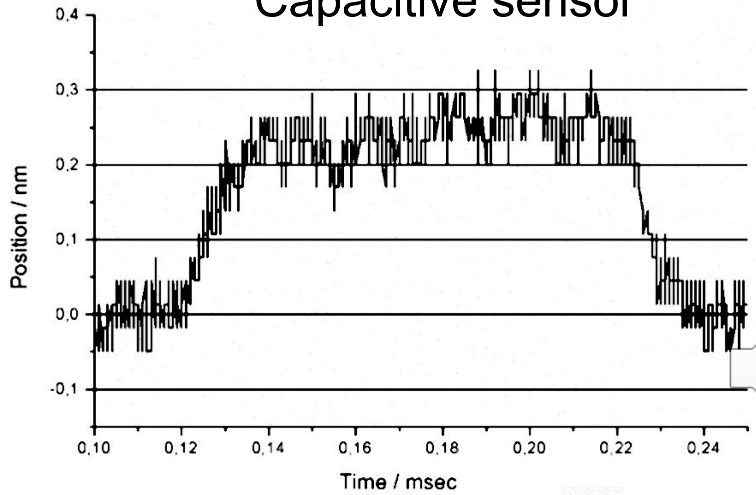


The limiting factor: noise (also in driver)!



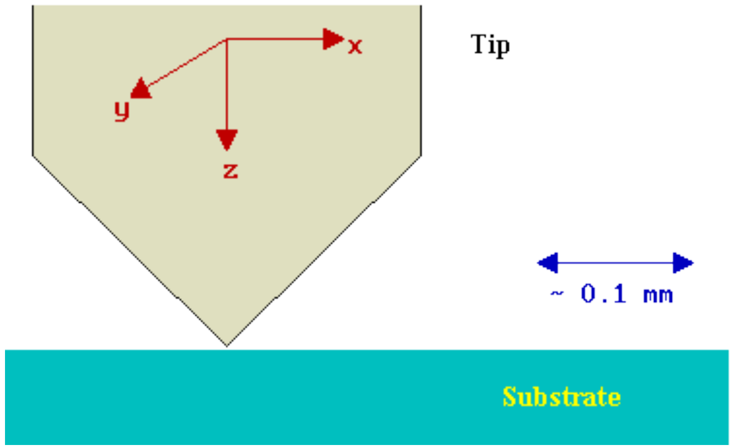
Source: http://www.physikinstrumente.com

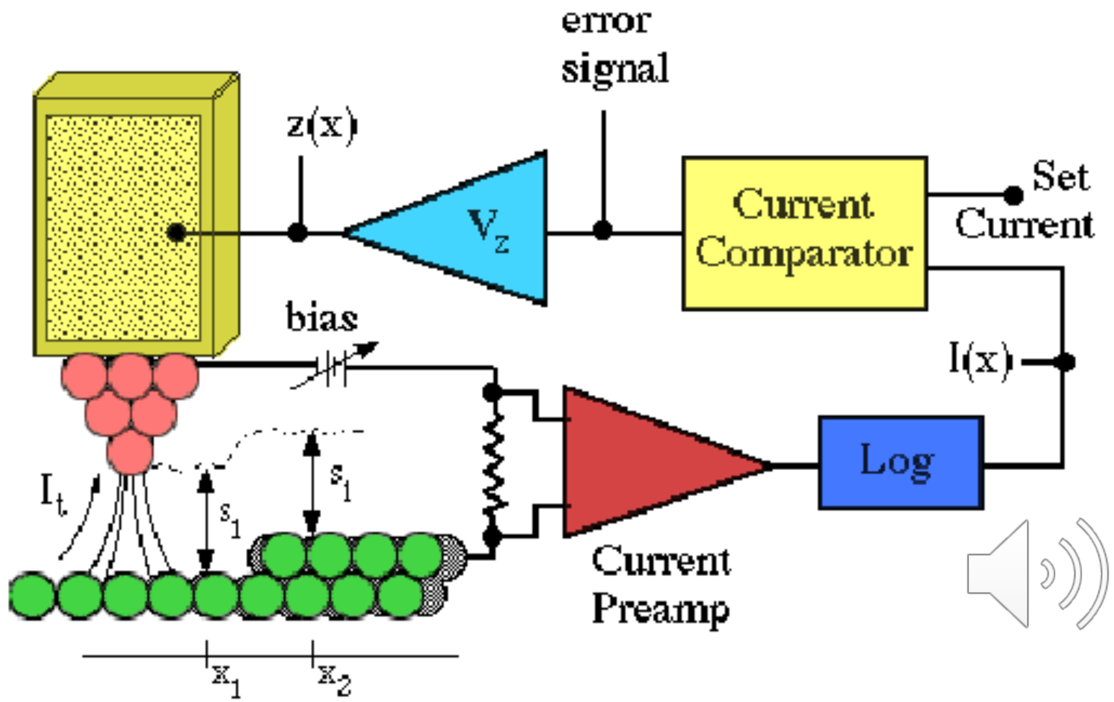
Capacitive sensor



The use of feedback :

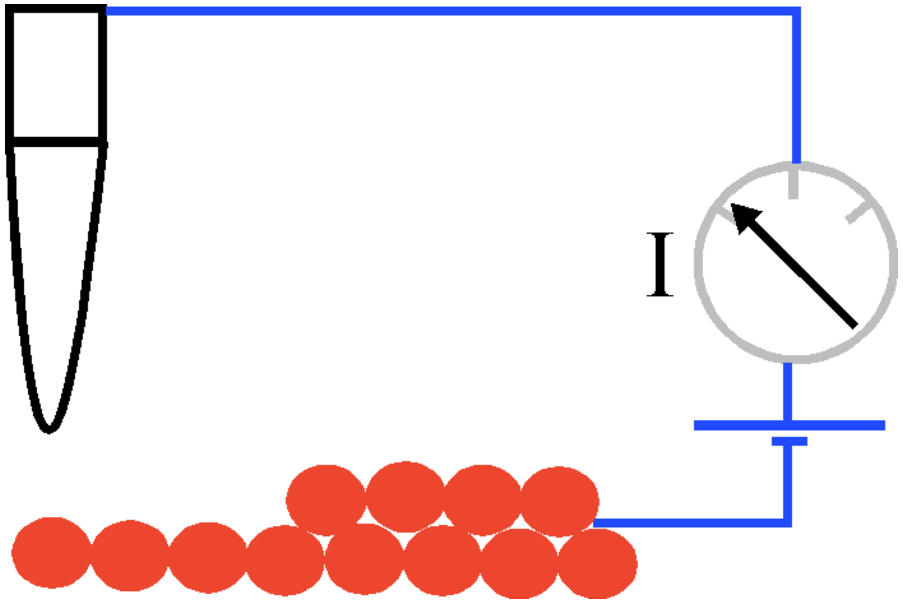
- In STM, current varies exponentially with tip-sample distance
- A log amp gives signal inversely proportional to distance
- The signal is fed back to a Piezoelectric actuator, to keep the same current = same distance
- The piezo tracks the surface of the sample, giving a high-resolution height map

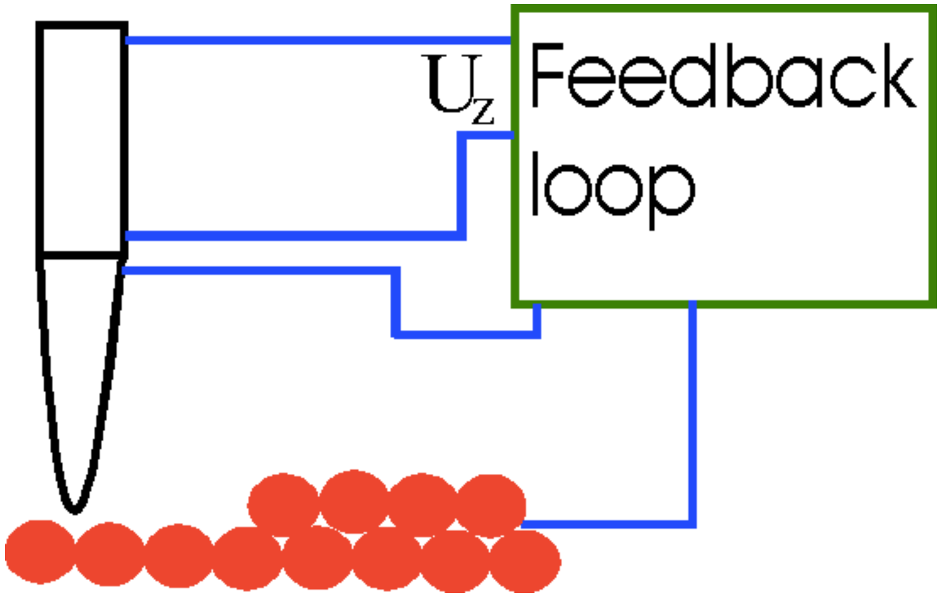




Two ways to scan:

- Constant tip height: Imaging the different surface atoms (due to their different work functions), revealing the surface composition or defects.
- Constant current: Imaging the surface topography at atomic resolution if the surface is composed of the *same* atoms.



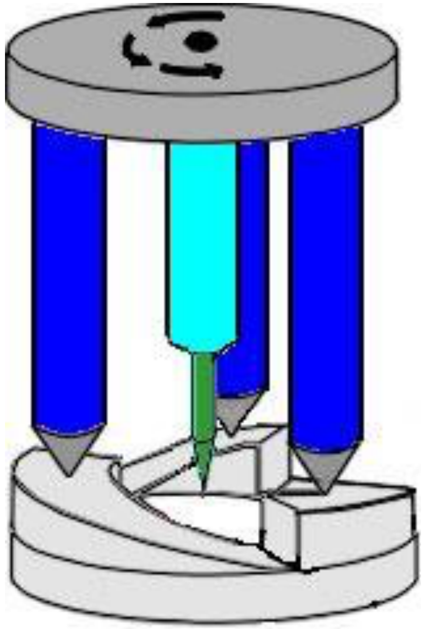


The main problem: How to get nm resolution?

Potential problems:	Solutions:
1. Tip size	1. Short-range interactions
2. High-resolution XY scanning	2. Piezo scanner
3. Non-destructive	3. Non-contact
4. Keep distance from sample	4. Height feedback
5. Vibrations	5. Rigid structure, isolation
6. Thermal stability	6. Compensation

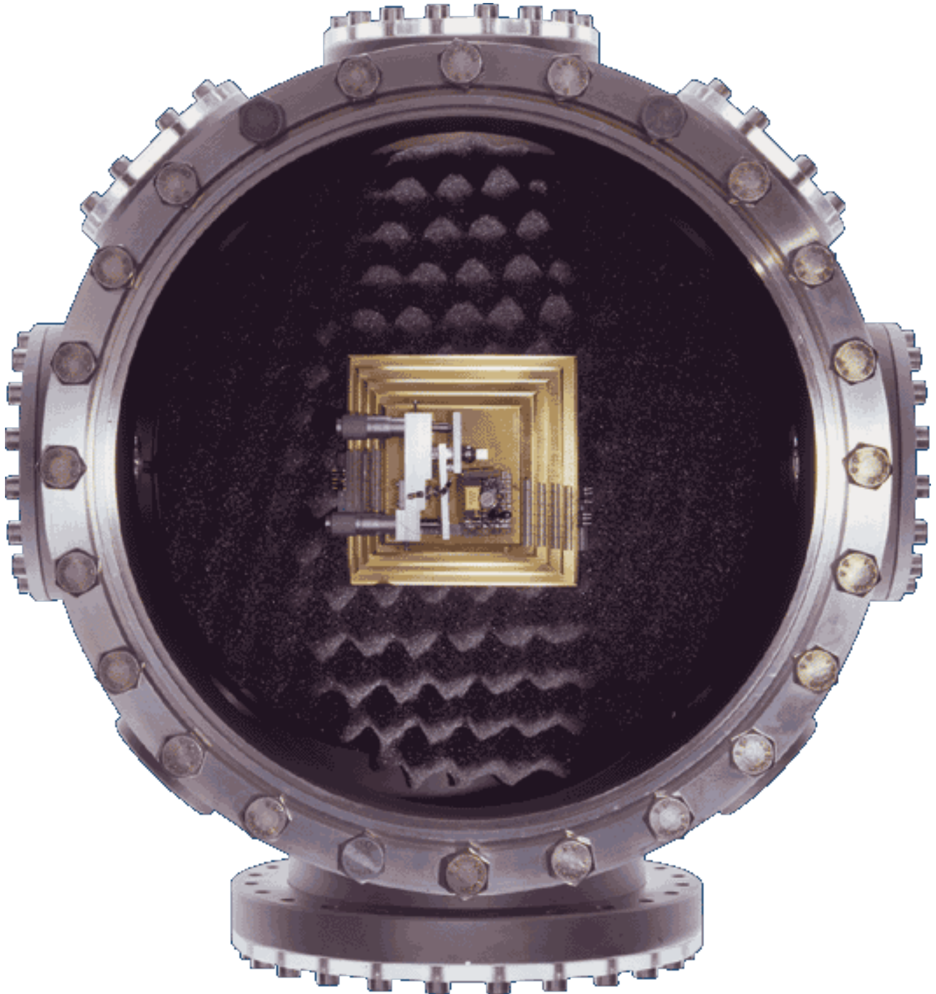
STM construction

- On top of the scanner and tip, we need:
- Mechanical stabilization (vibrations!)
- Environment control (vacuum)
- Sample positioning



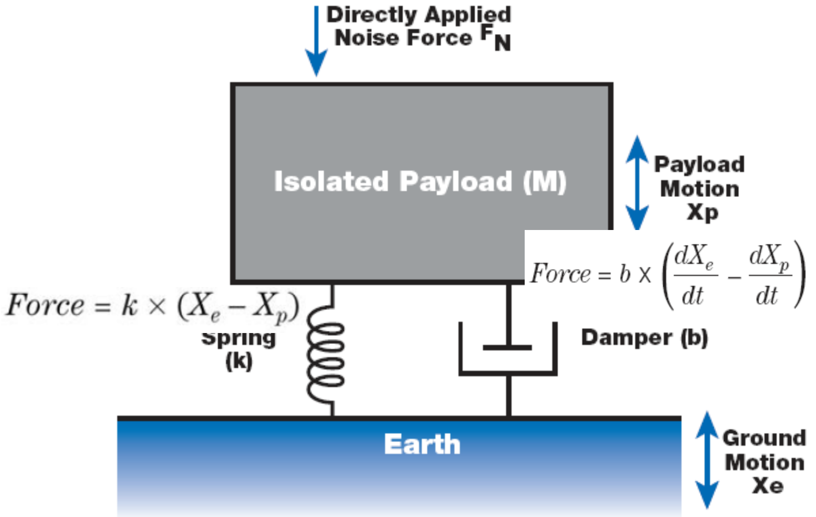
Basic STM structure

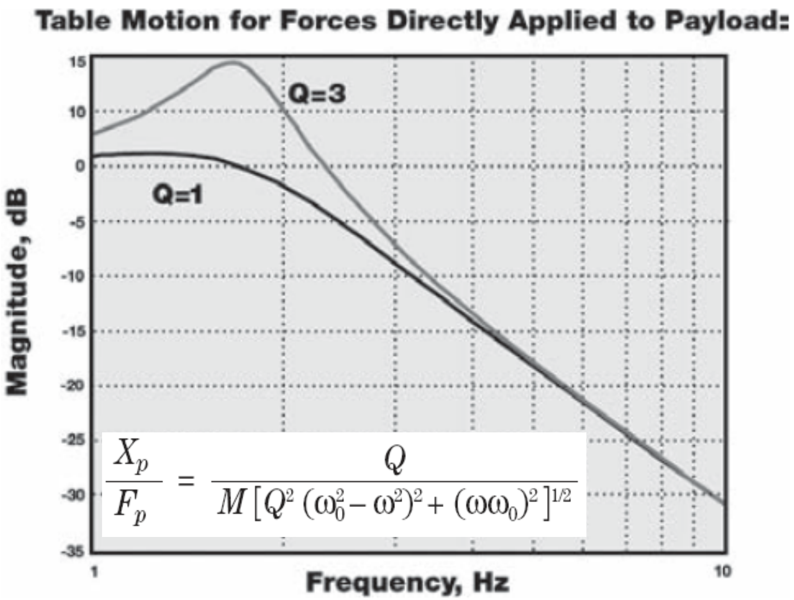
UHV STM

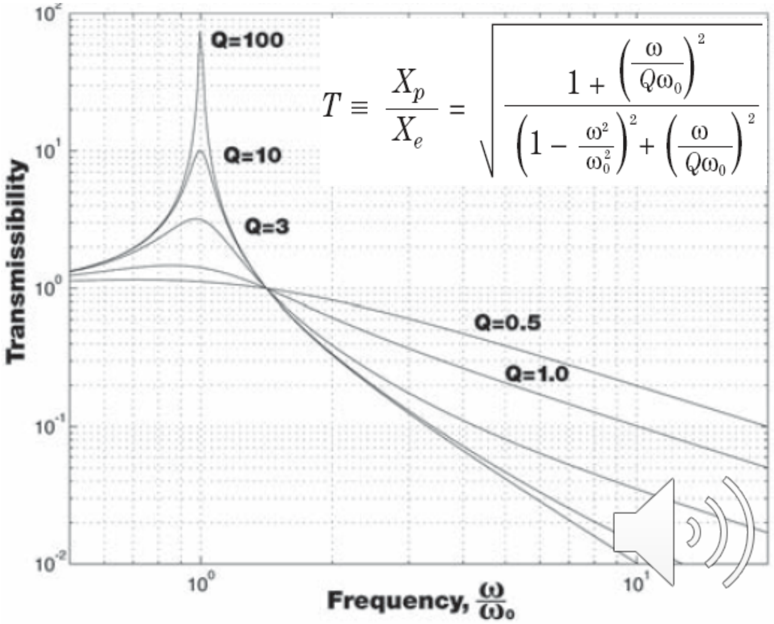


Vibrations

- Sources of vibrations:
  - Ground vibrations
  - Directly coupled vibrations (acoustic)
- Model of vibration isolation: mass, spring, damper
- Resonant system with characteristic frequency ω and quality factor Q



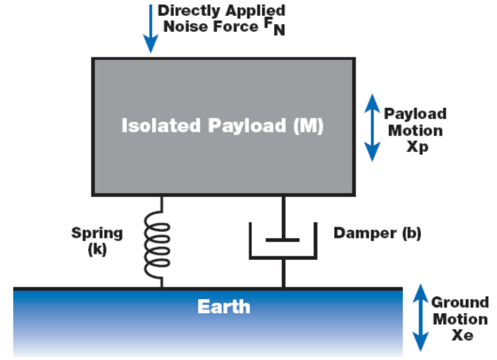




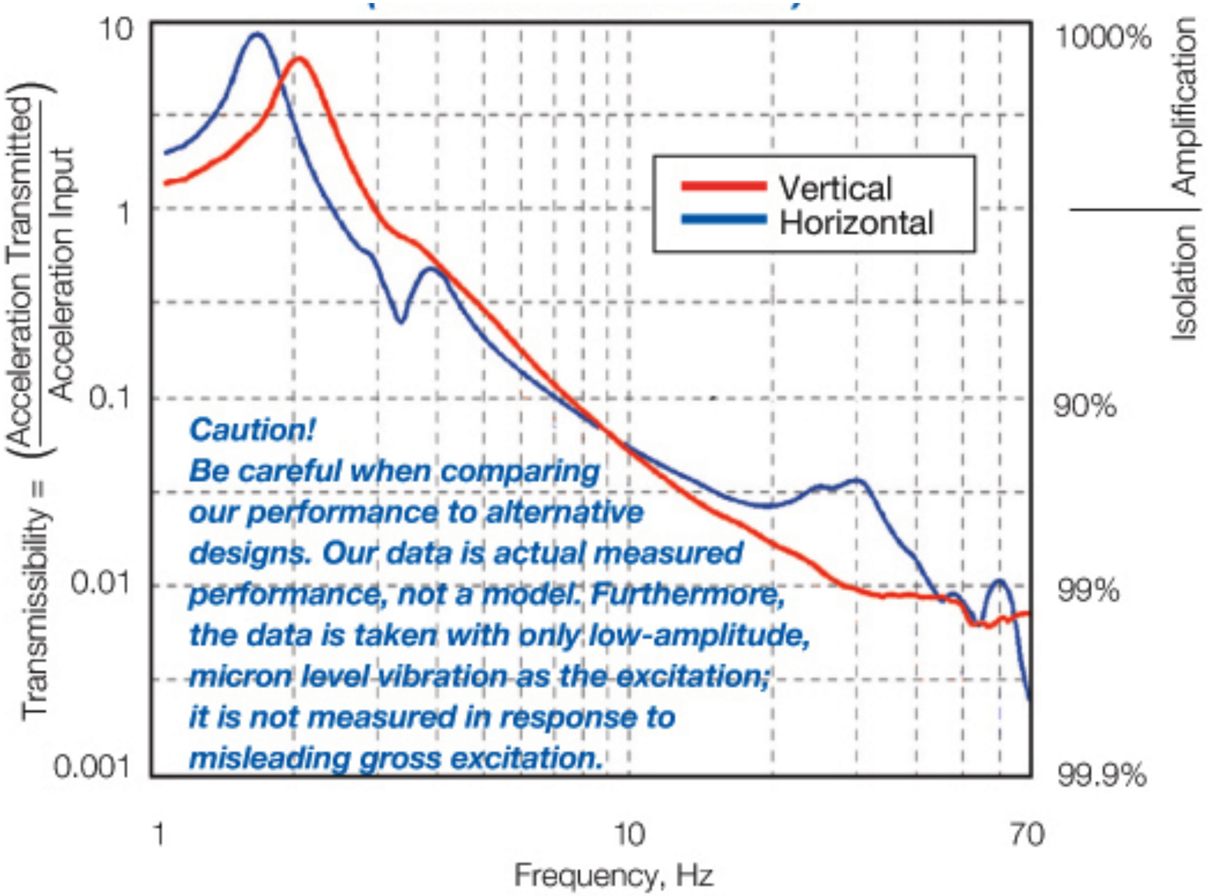
Source: TMC corp., http://www.techmfg.com

Vibrations

- Performance of a real passive table:
  - No damping (even amplification…) below 2-3 Hz
  - Performance increases with frequency T ~ ω^{-2}
  - Secondary resonances at 3.2, 30, 53, 70 Hz

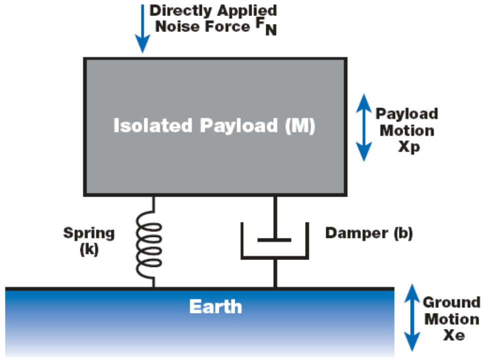


$$\frac{X_p}{F_p} = \frac{Q}{M\left[Q^2\left(\omega_0^2 - \omega^2\right)^2 + \left(\omega\omega_0\right)^2\right]^{1/2}}$$

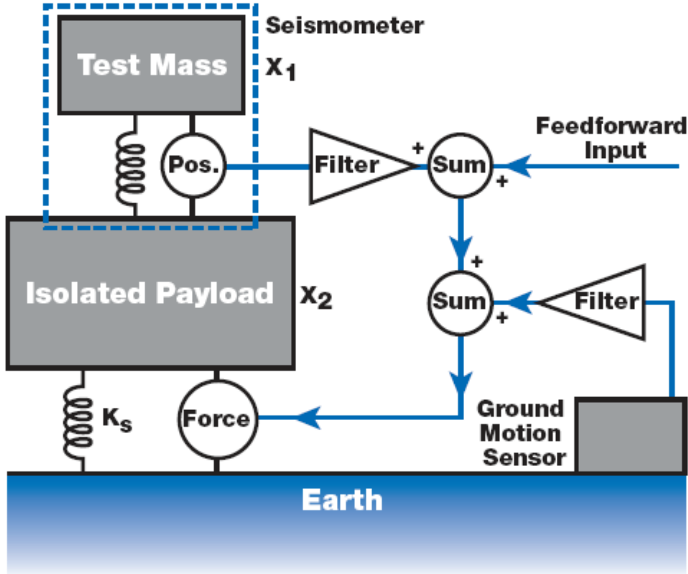


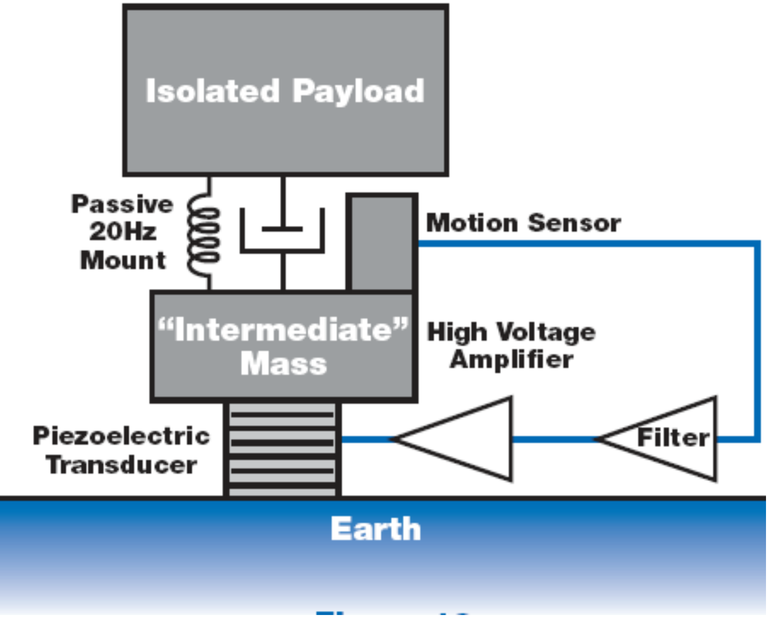
Source: TMC corp., http://www.techmfg.com

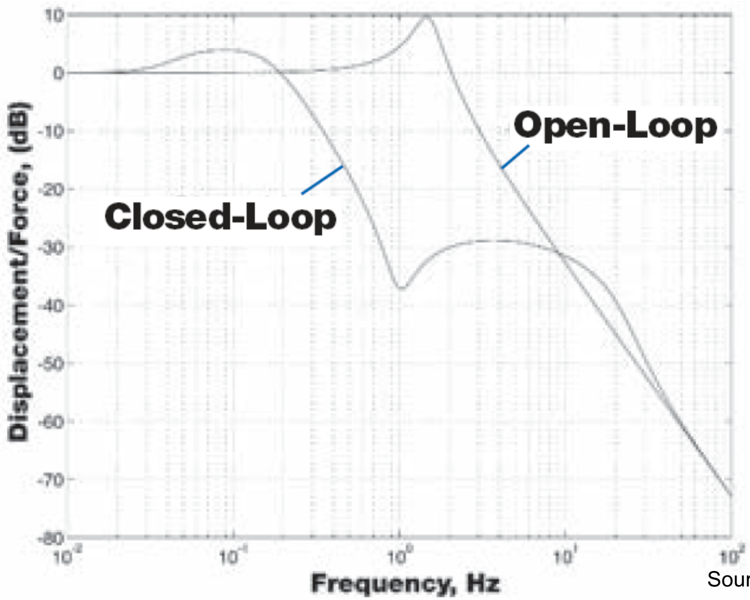
Vibrations



- Active tables: feedback system
  - Motion sensor
  - Piezo or motor to counteract external forces
- Combination: active+passive



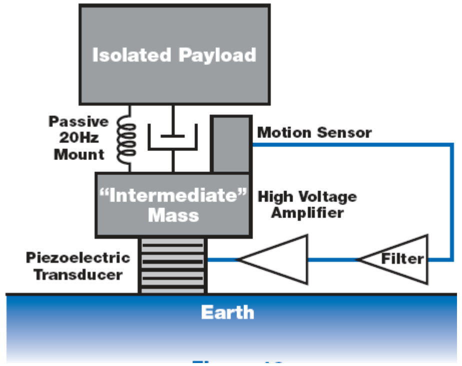


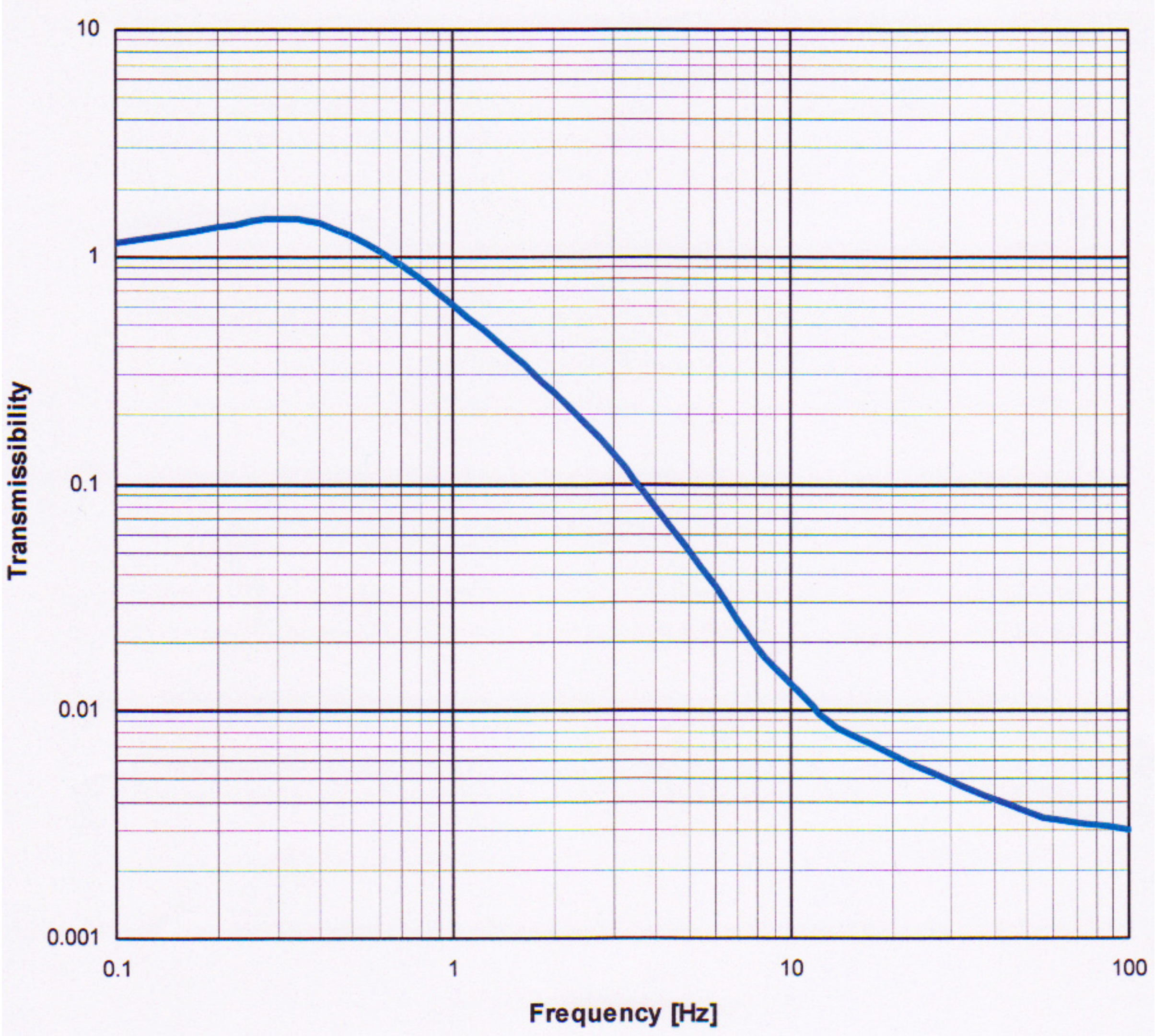


Source: TMC corp., http://www.techmfg.com

Vibrations

- Active tables:
  - Small size, light weight
  - (almost) no amplification at low frequencies

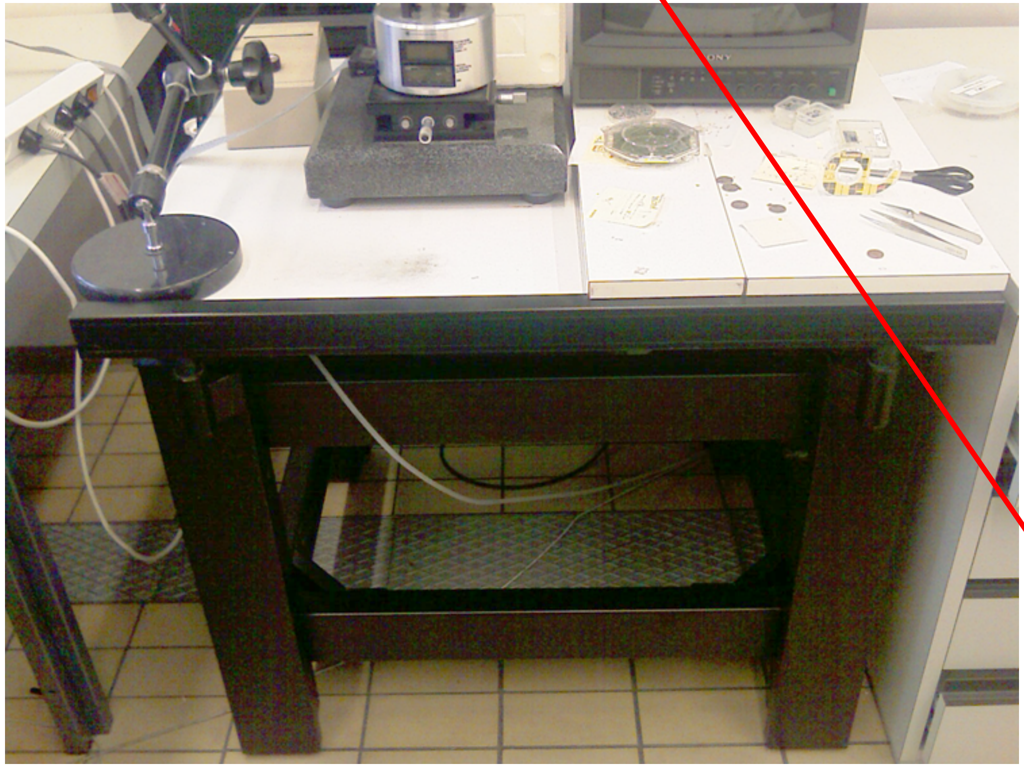


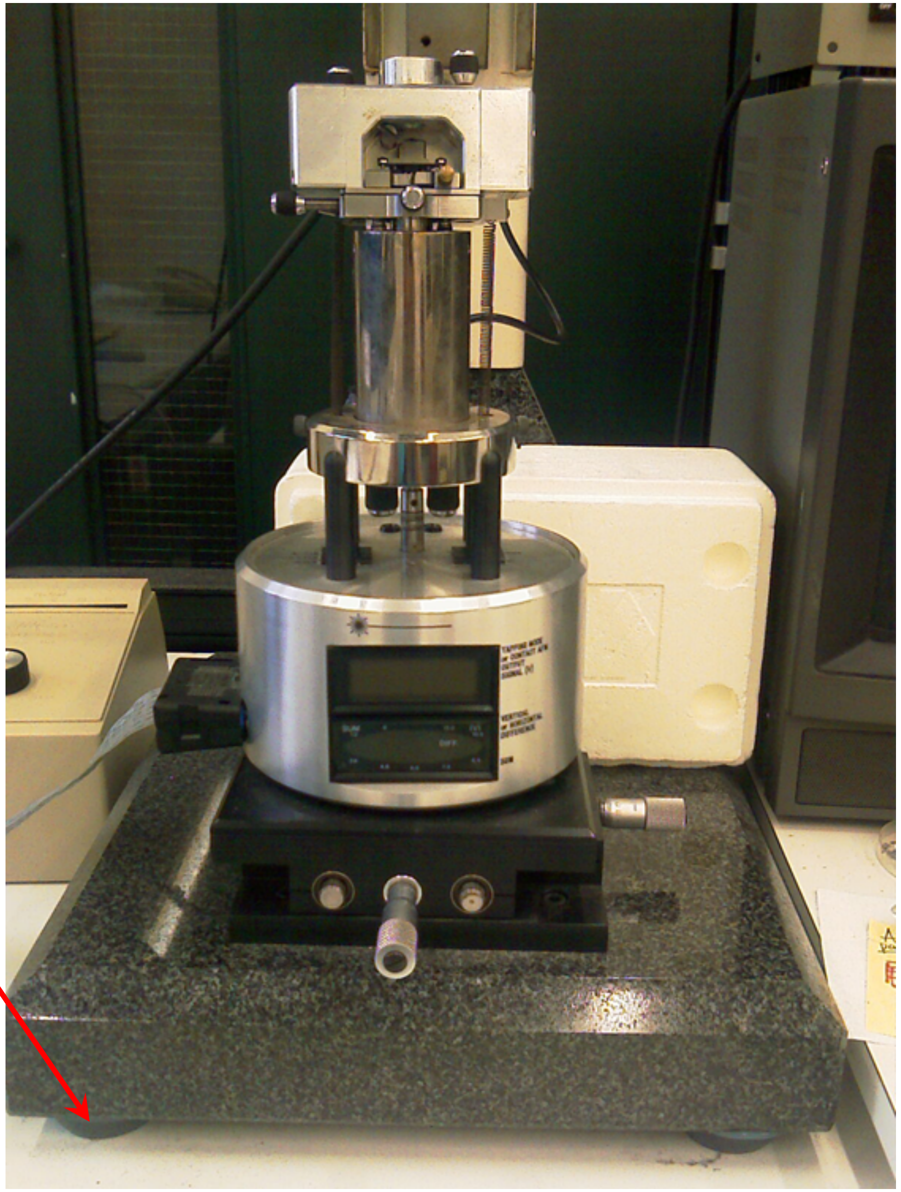


Source: TMC corp., http://www.techmfg.com

Vibrations: examples

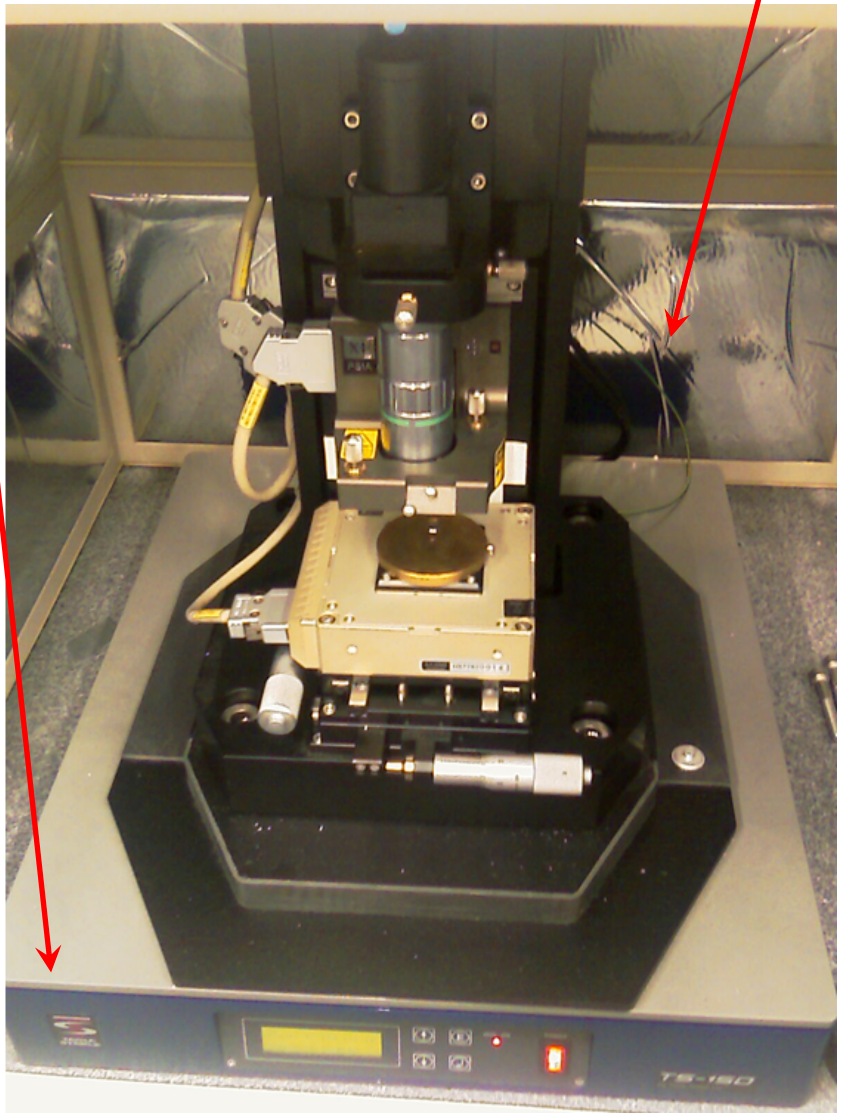
- Passive isolation
  - Floating table
  - AFM mounted on granite slab with rubber feet (secondary passive isolation)

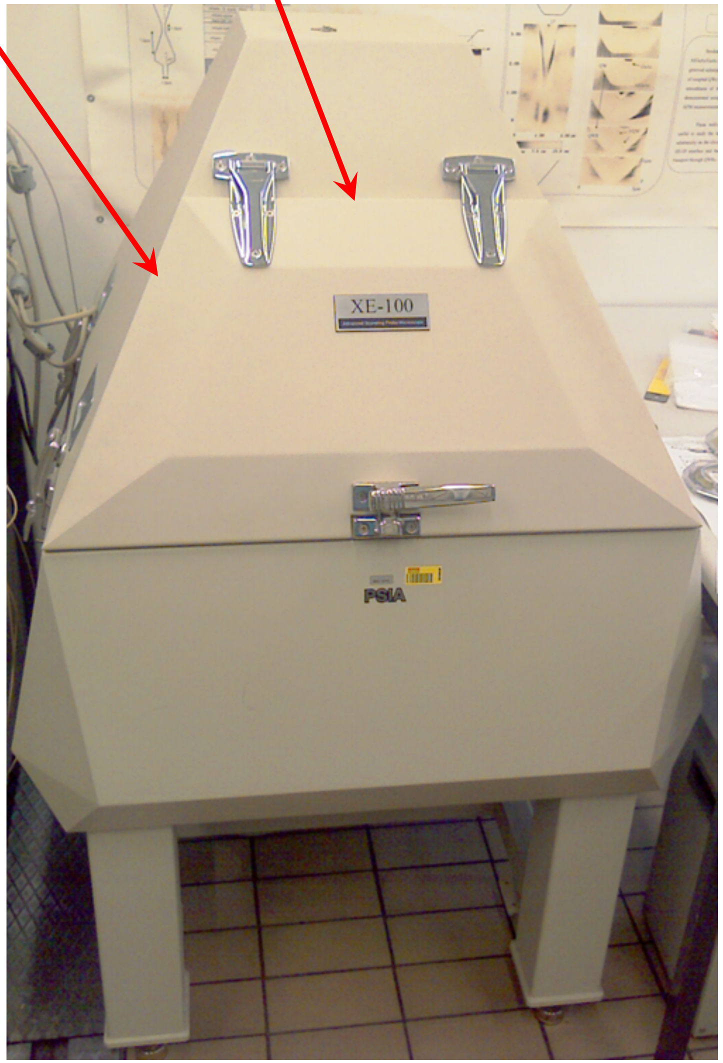




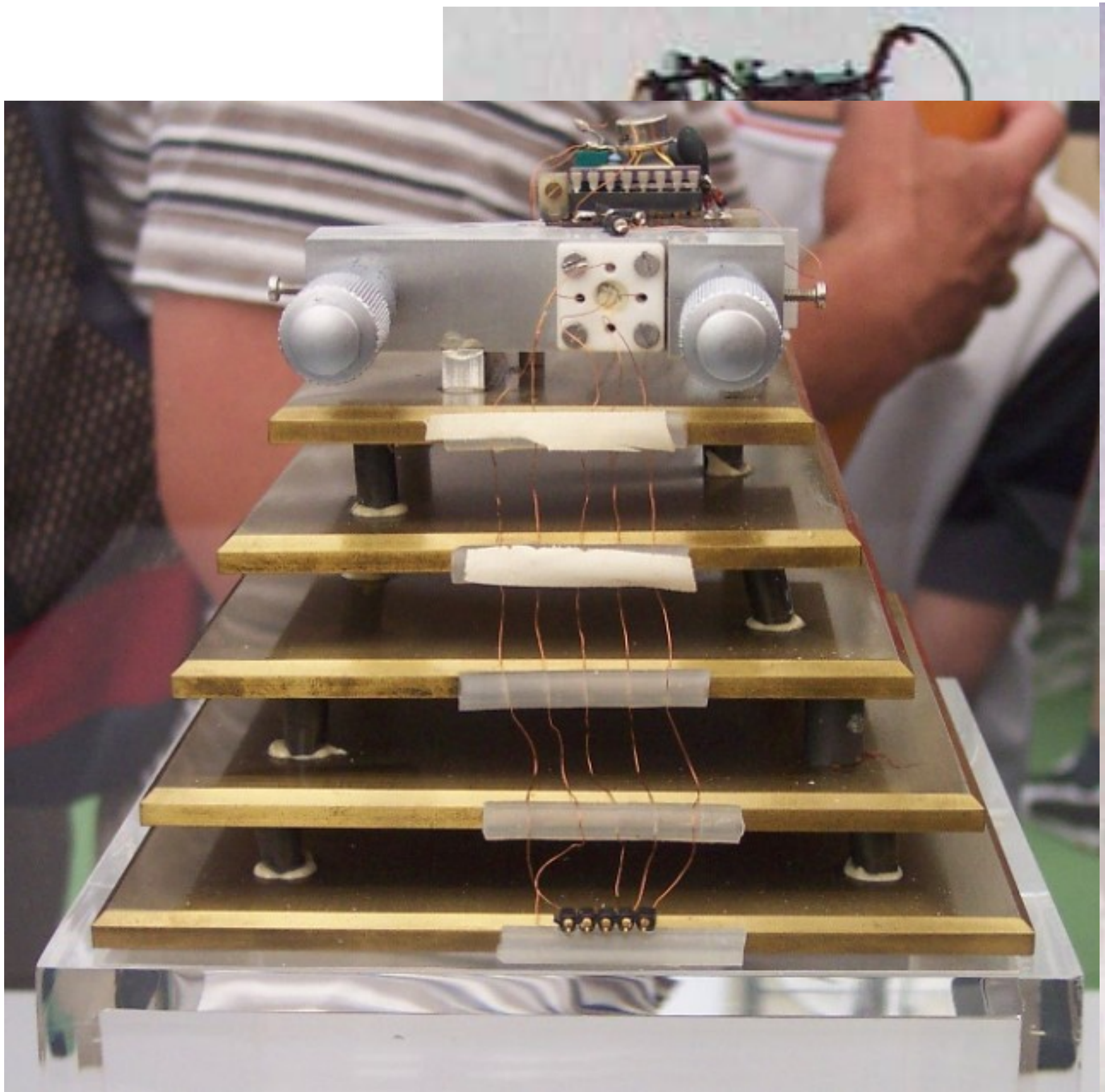
Vibrations: examples

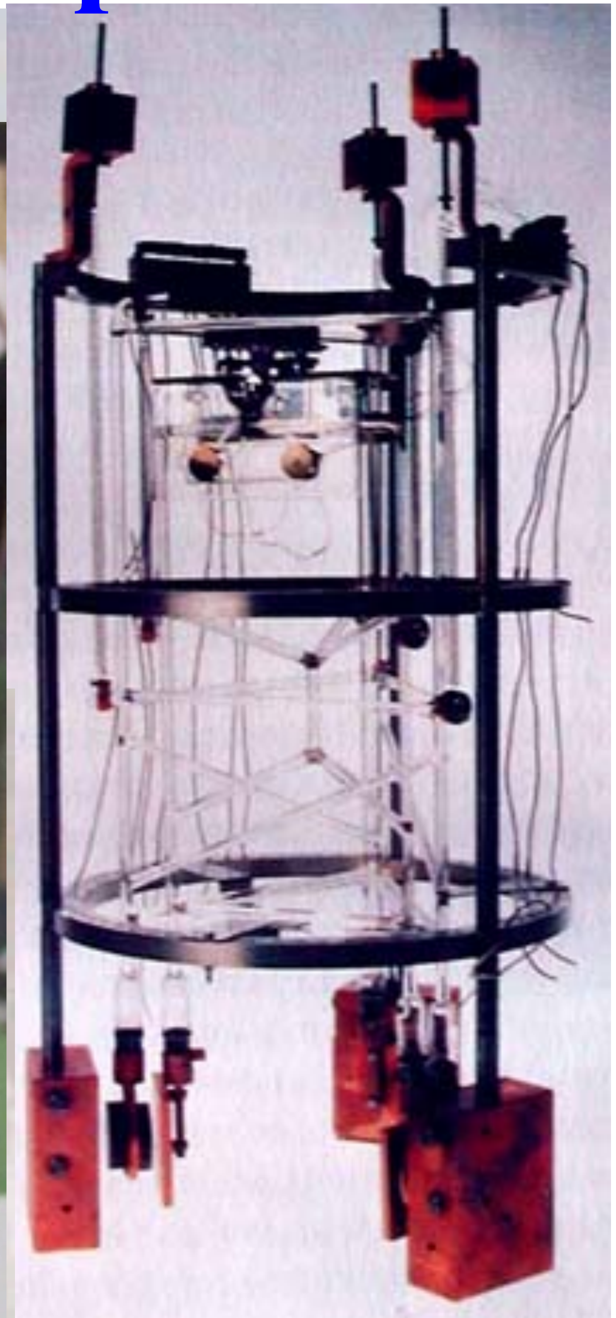
- Active isolation table inside passive metal enclosure
- Acoustic isolation (inside lining)





Vibrations: STM examples



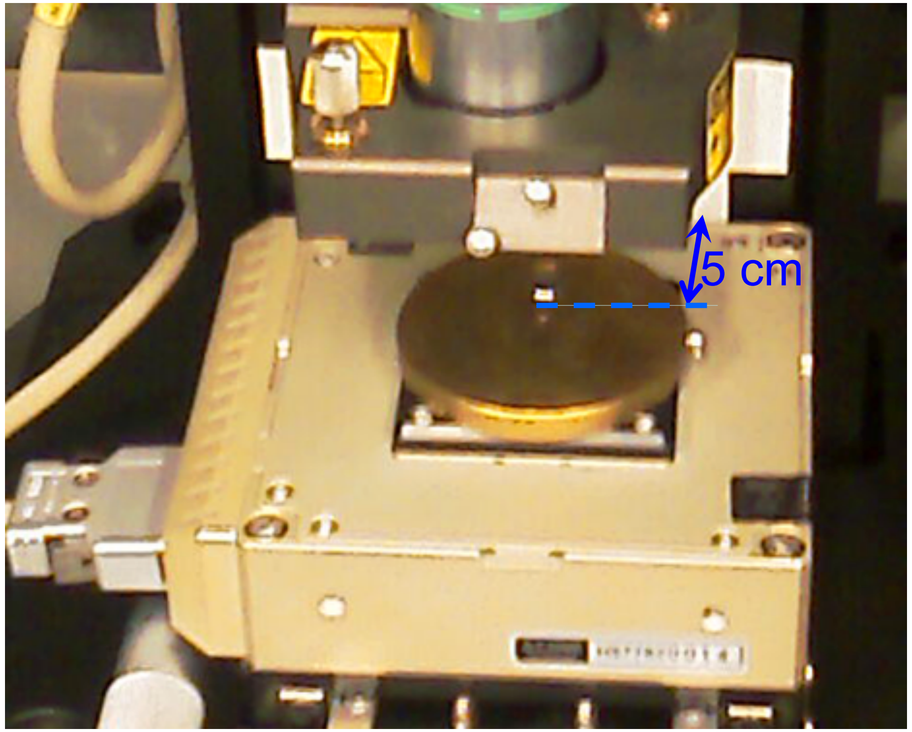


Thermal stability

Example 1:

- AFM structure made of Al (thermal expansion coeff. $23 \cdot 10^{-6}$ °C^{-1})
- Distance between sample and support: 5 cm
- Temperature change of 1°C
- By how much would the sample move?

Answer: by 1.06 μm !



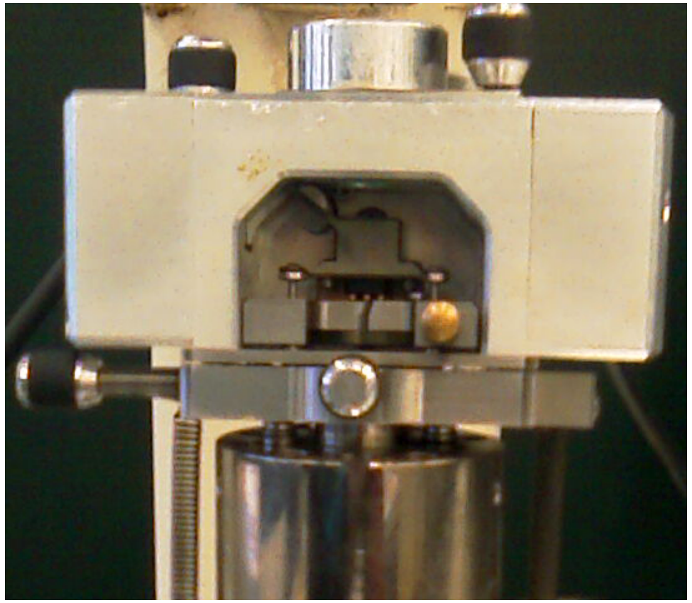
Not very good for measuring atoms…

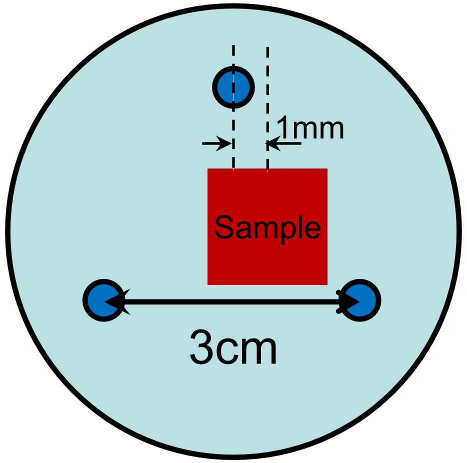
Thermal stability

Example 2:

- AFM head made of Fe (thermal expansion coeff. $12 \cdot 10^{-6}$ °C^{-1})
- Distance between supporting screws: 3 cm
- Sample is offset by 1mm from center of support
- Temperature change of 1°C
- By how much would the sample move?

Answer: by 12 nm !



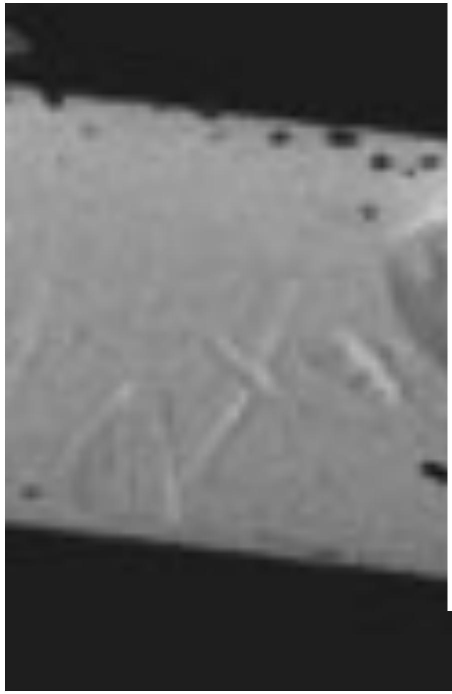


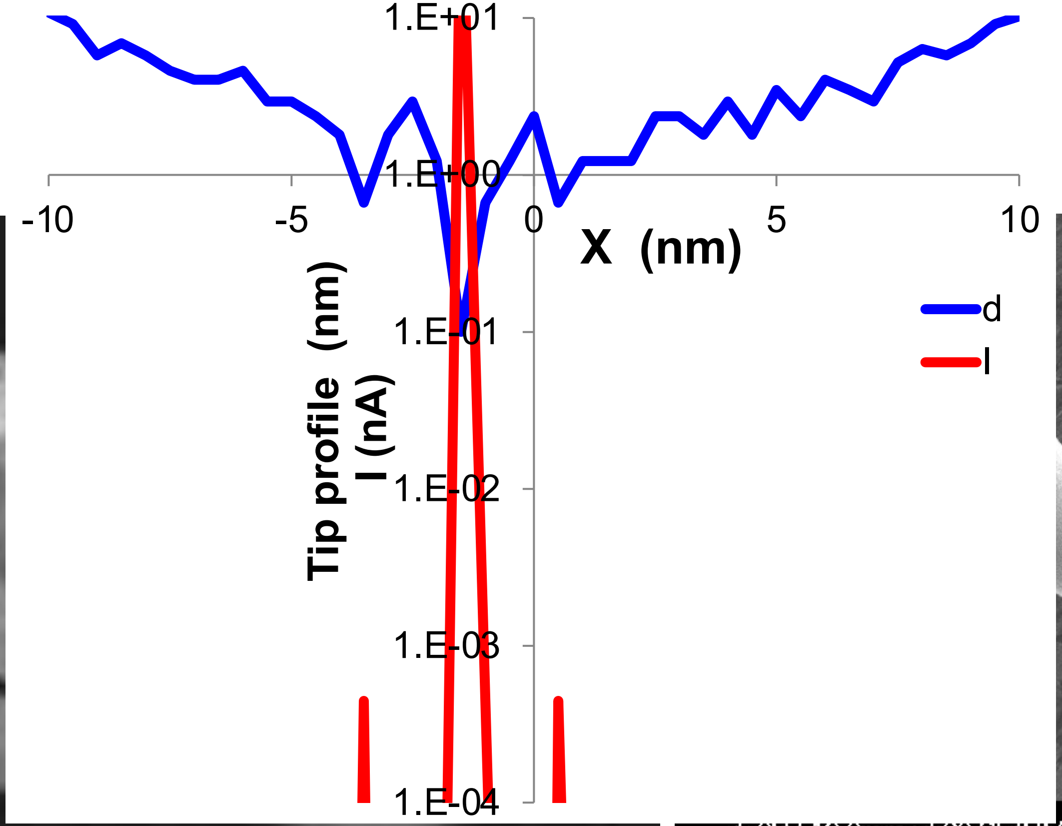
AFM base

- We need to stabilize room temperature, but also:
  - To use materials with small expansion coeff. (Invar)
  - To construct the AFM in a self-compensating, symmetrical way

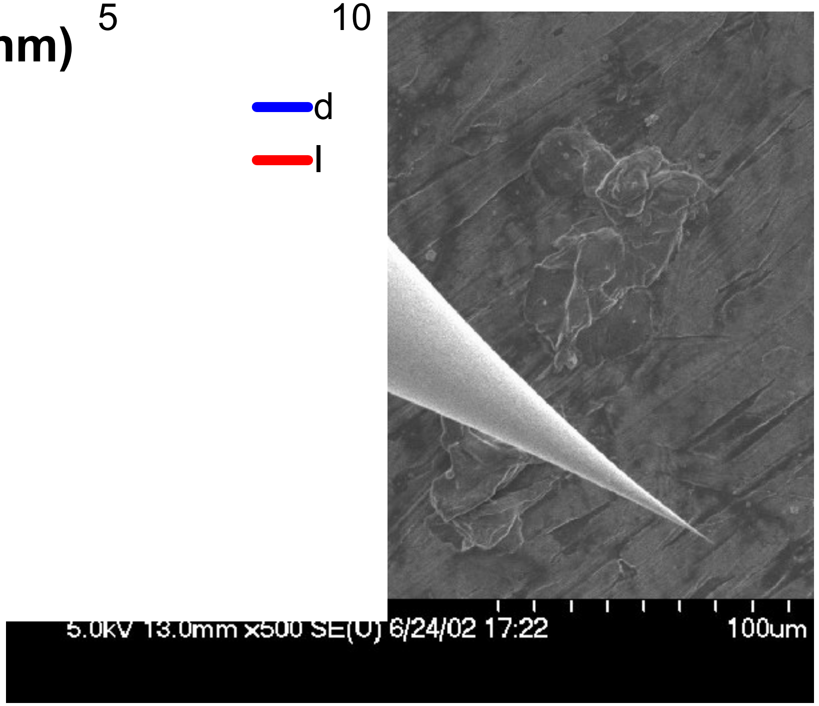
STM tips

Hint: remember this curve?





Pt/Ir wire, diameter 0.2 mm, cut with wire cutter

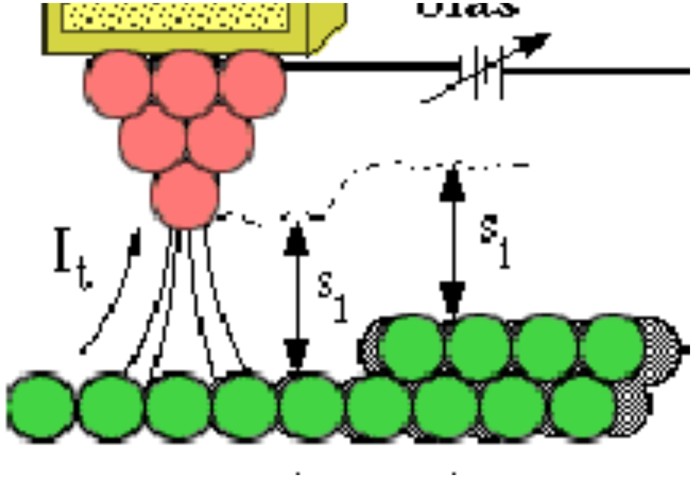


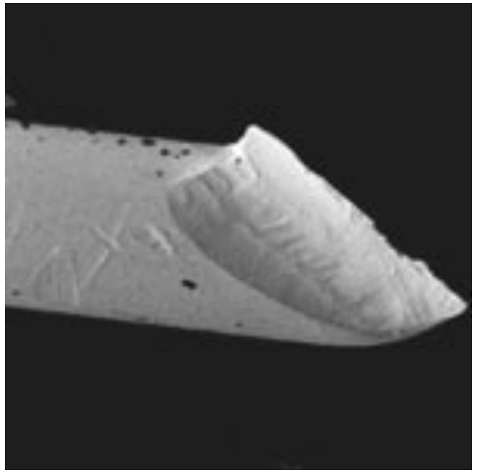
W wire, diameter 0.2 mm, electro-etched in KOH solution

STM tips

Answer: They give the same performance!

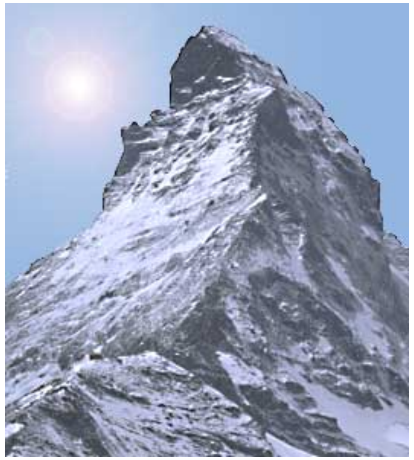
- Tip radius is not very important: rigidity is more important than tip radius!
- Exponential tunneling current dependence “selects” that only the very last atoms of the tip participate in the imaging



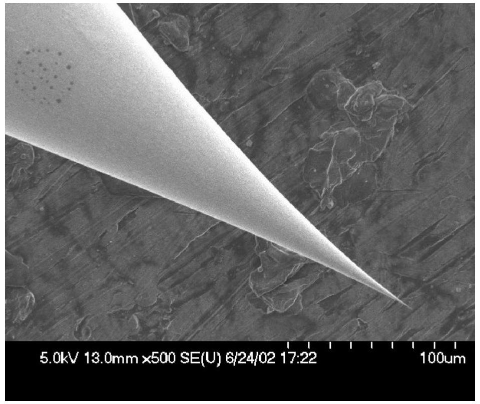


Cut STM tip

"Swiss" STM tip



(Same, enlarged x10^8)



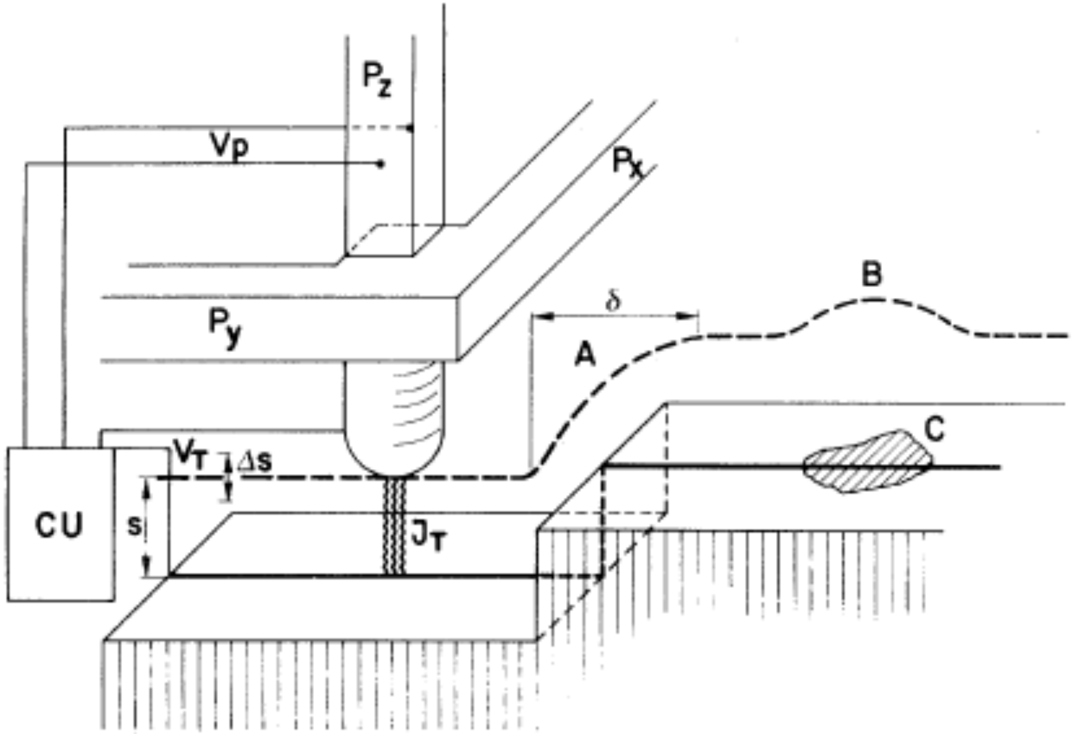
Etched STM tip

The first STM (1982)

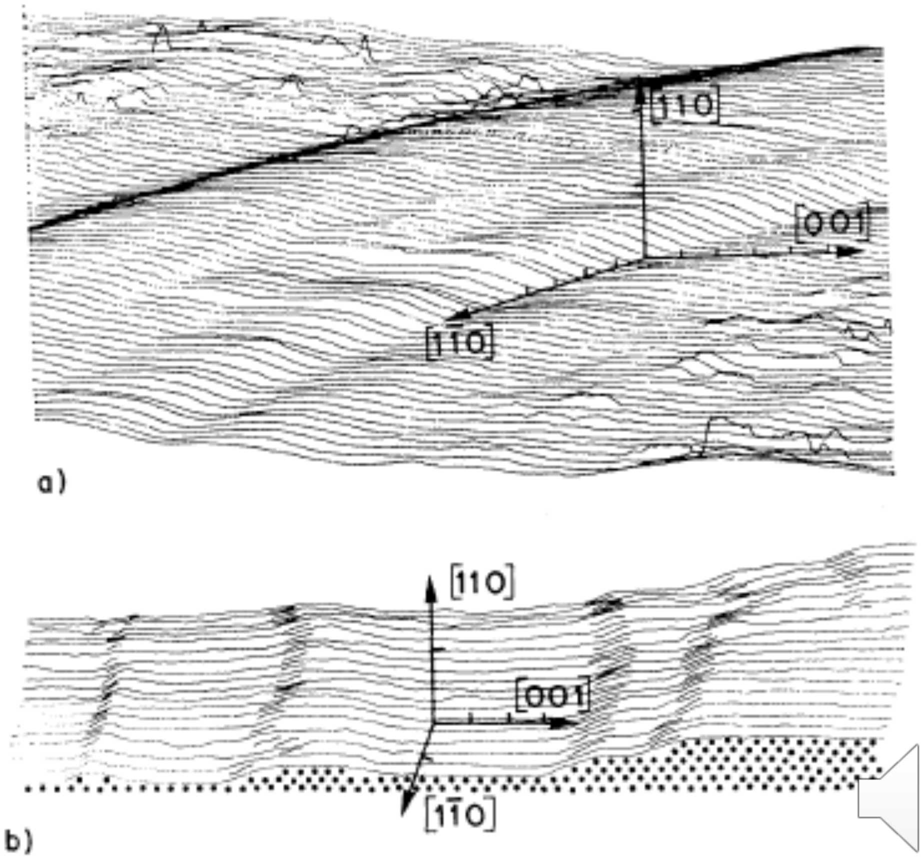
Surface Studies by Scanning Tunneling Microscopy

G. Binning, H. Rohrer, Ch. Gerber, and E. Weibel
IBM Zurich Research Laboratory, 8803 Rüschlikon-ZH, Switzerland
(Received 30 April 1982)

emission microscopy. However, since suppression of vibrations is evidently more vital for the STM, long and narrow field-emission tips might not be satisfactory. Instead, we used solid metal rods of 1 mm diameter, and ground 90° tips with a conventional grinding machine. This yielded overall tip radii of only some thousand angstroms to 1 μm, but with some rather sharp minitips. The extreme sensitivity of the tunnel current on gap width then selects the longest of the minitips for operation of the STM. The lateral resolution



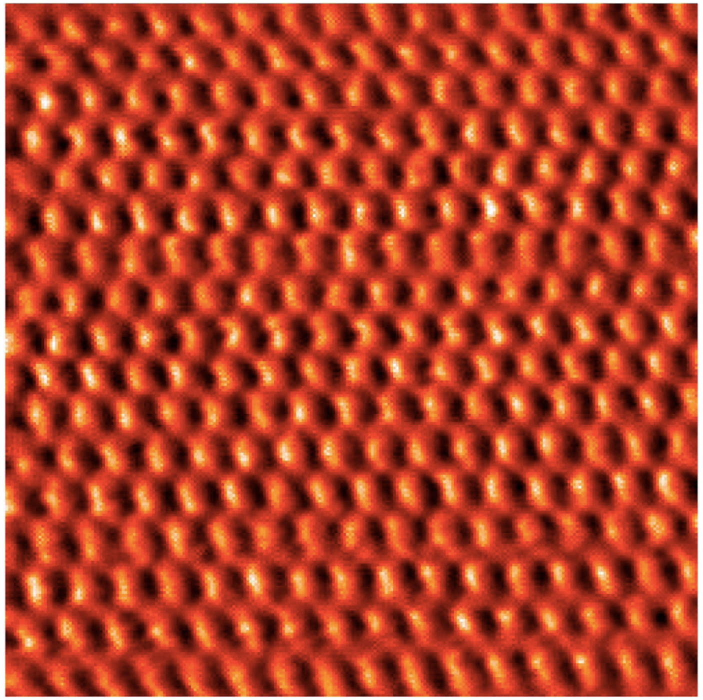
Schematic structure of the STM



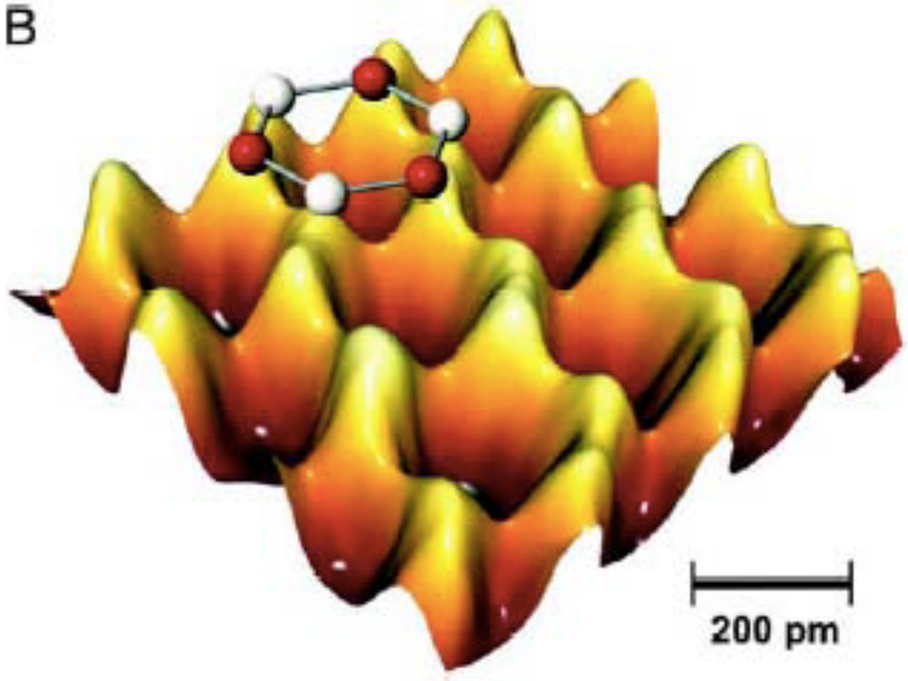
STM Image of Au surface (b: after annealing)

STM Images

- STM images can resolve individual atoms, or parts of molecules, on surfaces – preferably under vacuum



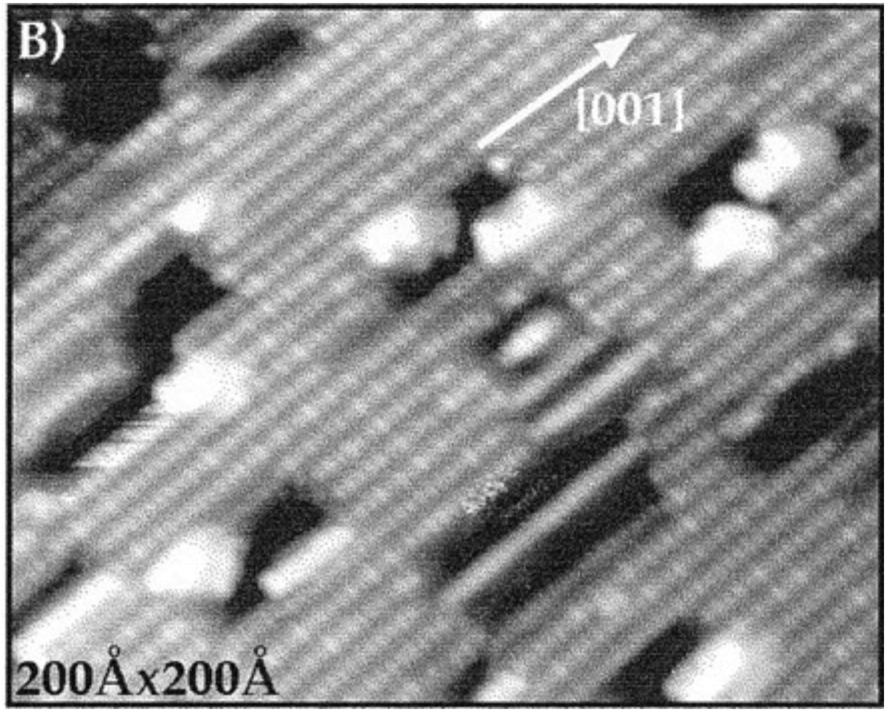
STM Image of pyrolitic graphite atoms



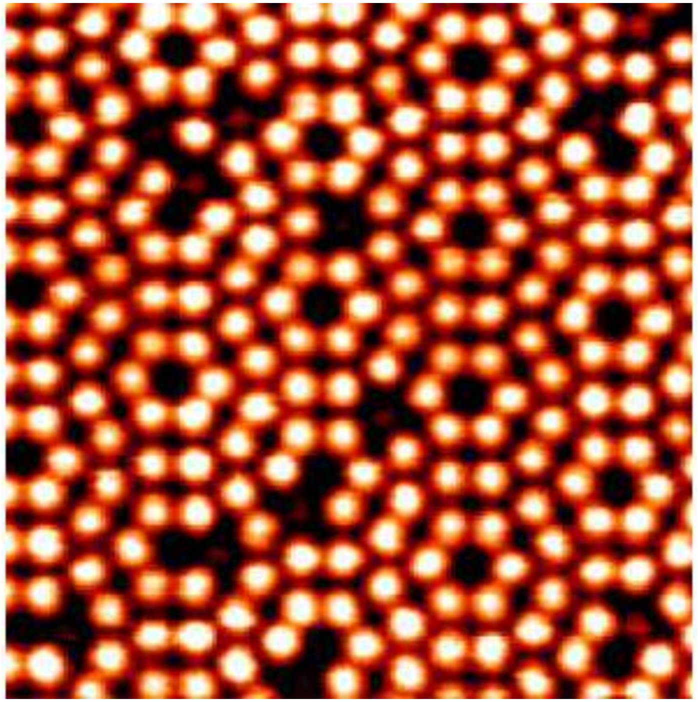
STM Image of Graphite, and the carbon ring underlying (top)

STM Images

- STM images can resolve individual atoms, or parts of molecules, on surfaces – preferably under vacuum



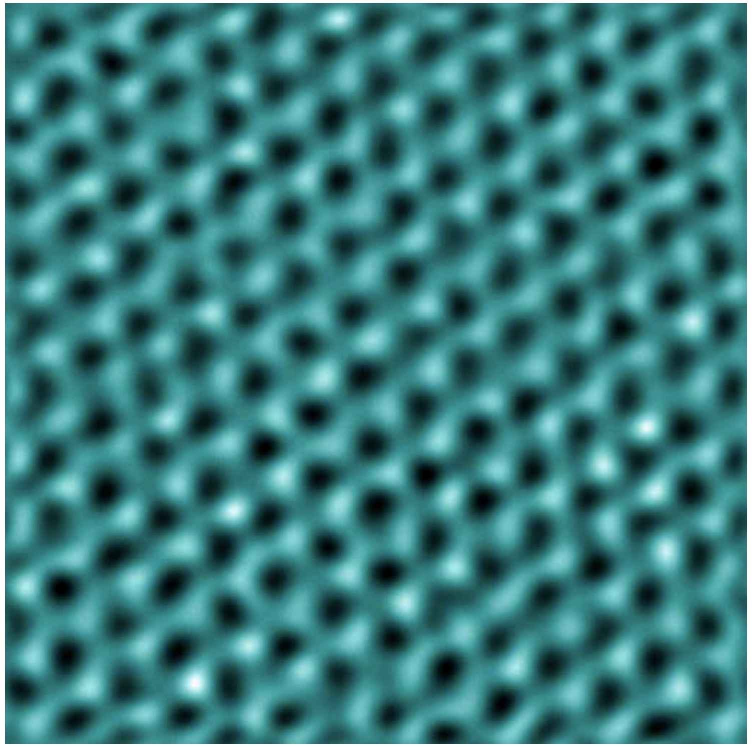
STM Image of CO molecules on RuO_2 crystal



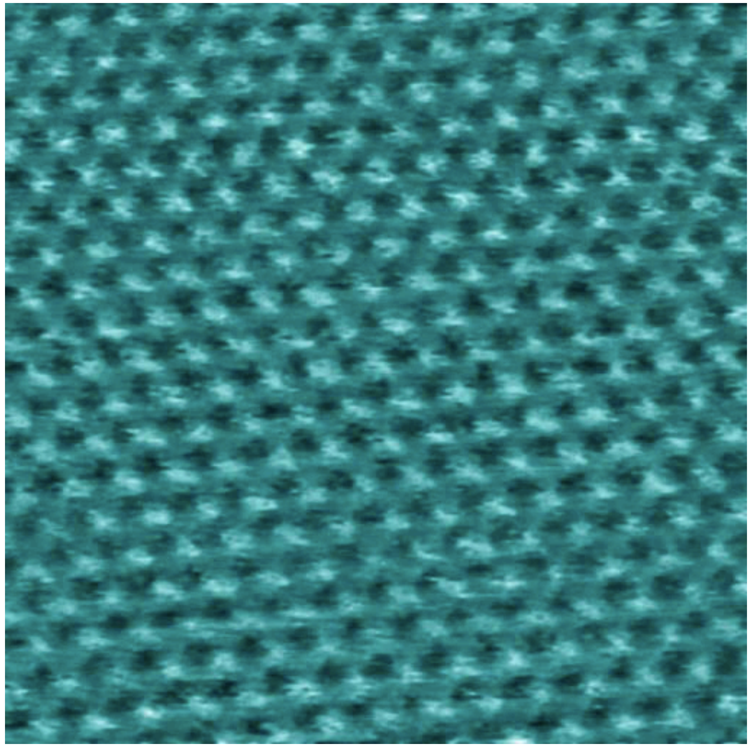
STM Image of Si atoms

The effect of temperature

- STM images are sensitive to thermal atomic distance fluctuations, so low-T STM is essential for atomic studies



Graphite atoms, 77K



Graphite atoms, 295K

More STM Images later …

Outline:

- Introduction: What is SPM, history
- STM
- AFM
- Image treatment
- Advanced SPM techniques
- Applications in semiconductor research and industry

Back to our solutions:

The main problem: How to get nm resolution?

Potential problems:

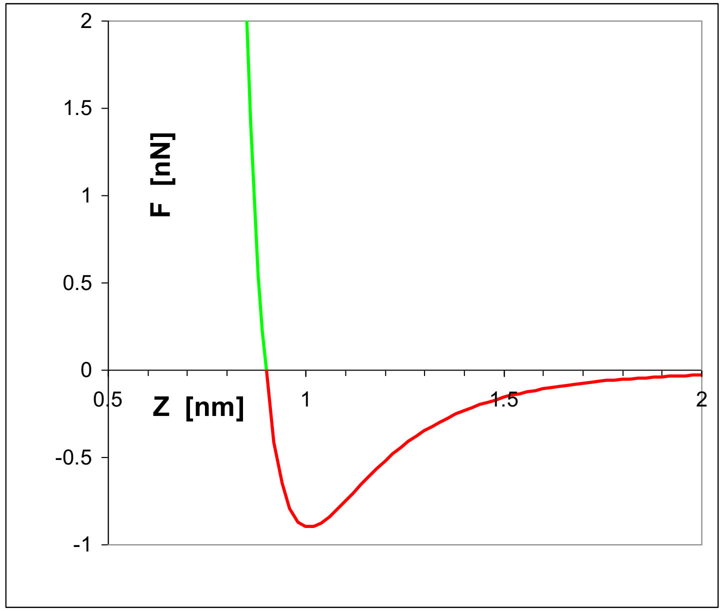
1. Tip size
2. High-resolution XY scanning
3. Non-destructive
4. Keep distance from sample
5. Vibrations
6. Thermal stability

Solutions:

1. Short-range interactions
2. Piezo scanner
3. Non-contact
4. Height feedback
5. Rigid structure, isolation
6. Compensation

Short-range interactions:

- Van-der-Waals forces



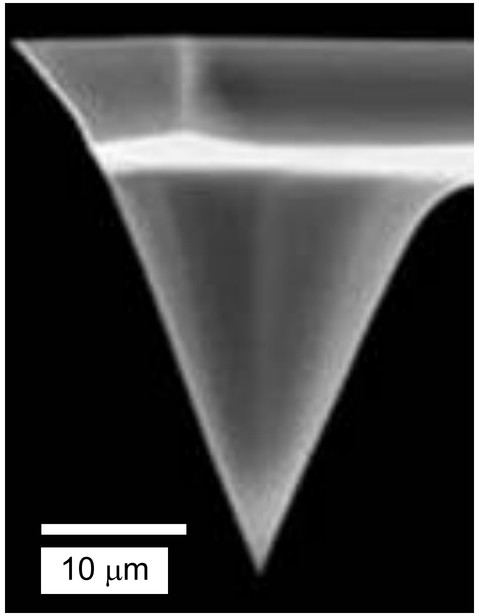
Atomic Force Microscope: AFM

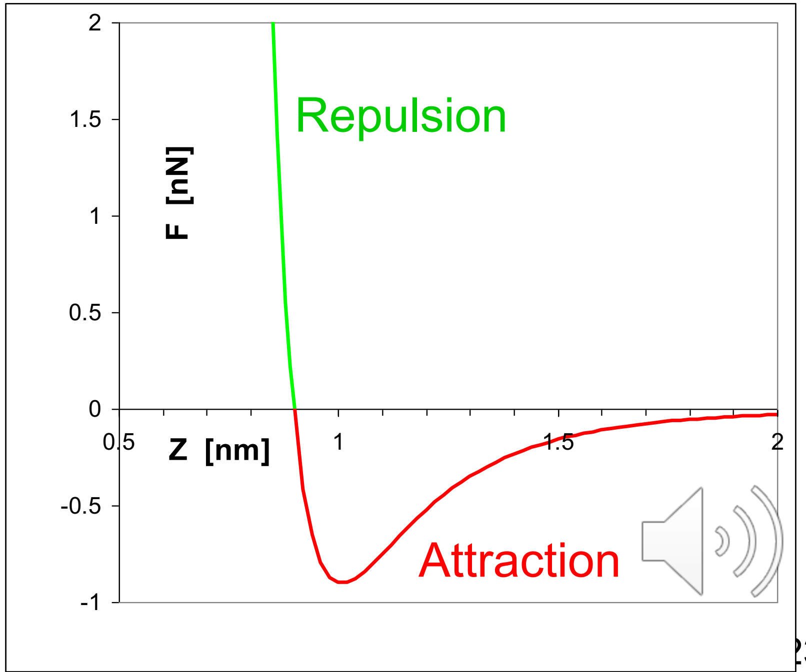
- Developed by Gerd Binnig (1984)
- Uses the Van-der-Waals force between tip and sample as short-range interaction
- Especially the repulsion force is very sensitive to distance:

$$F \sim z^{-12} \,!$$

(almost as good as exponential) and short-range (<1 nm)

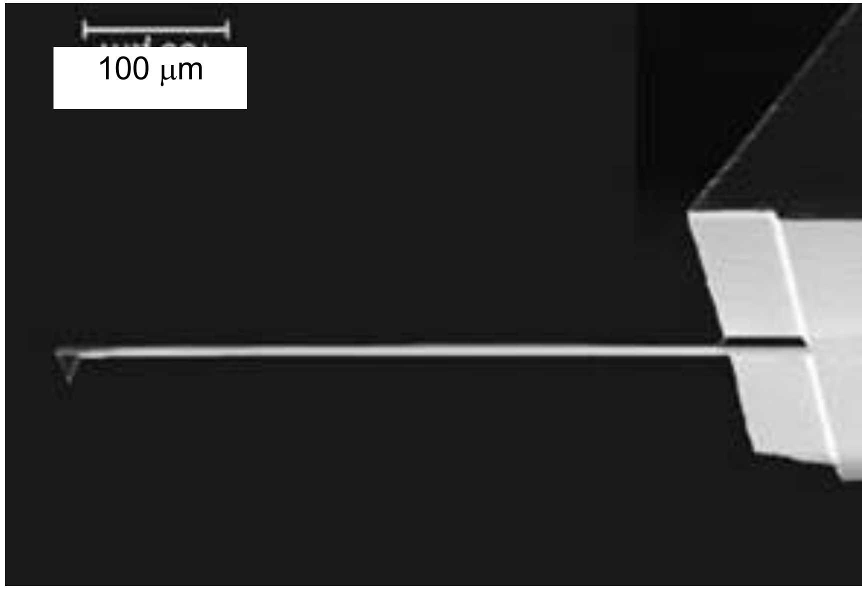
- But: Van-der-Waals force are small: order of nN
- We need a sensitive force sensor

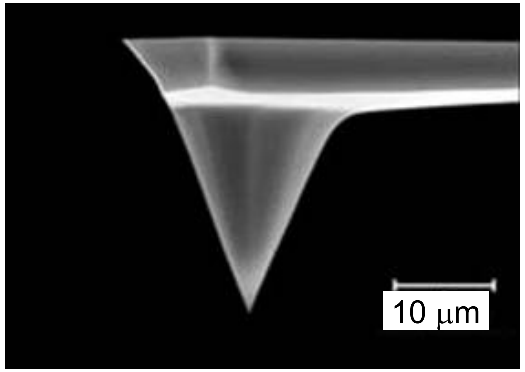


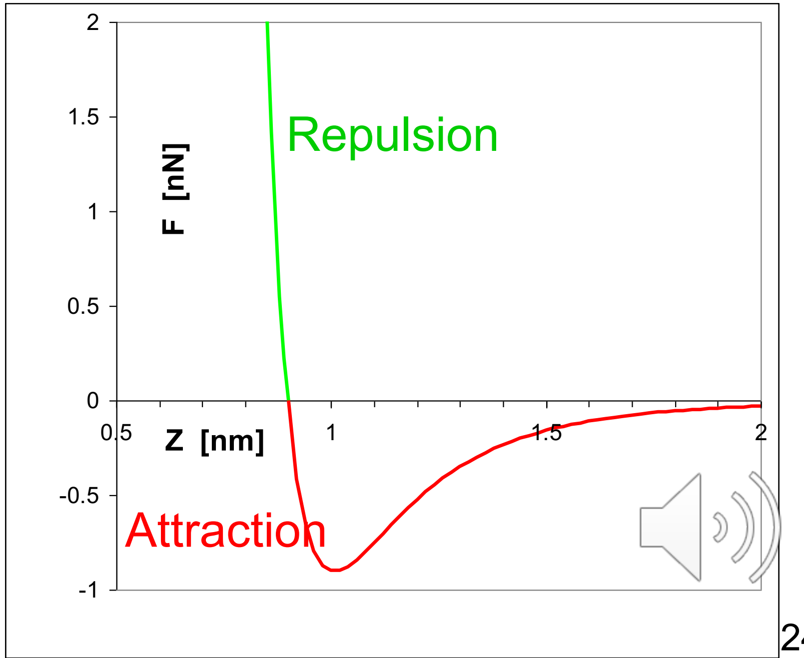


AFM: How do we measure small forces (nN)?

- Solution: use the flexibility of the tip-carrying cantilever
- Material: Si
  - Tough, flexible E= $2{\cdot}10^5$ N/cm^2
  - Easy to structure by photo-lithography and chemical etching
- The force on the tip moves (flexes) the cantilever.



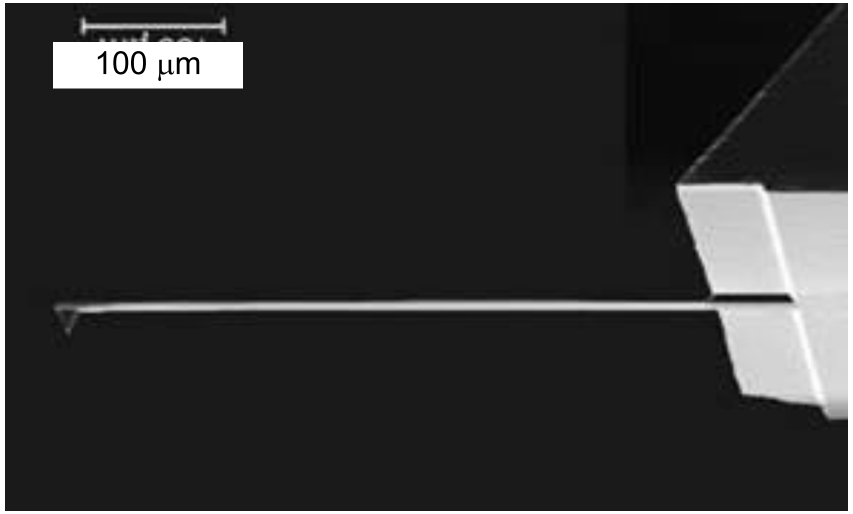


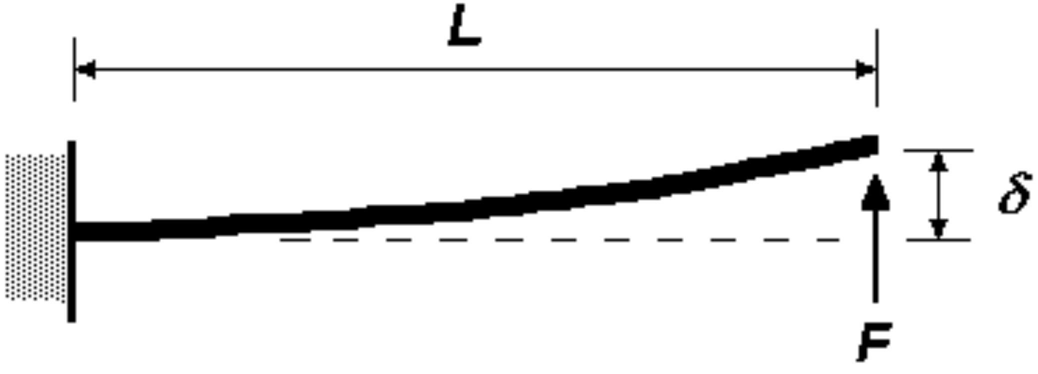


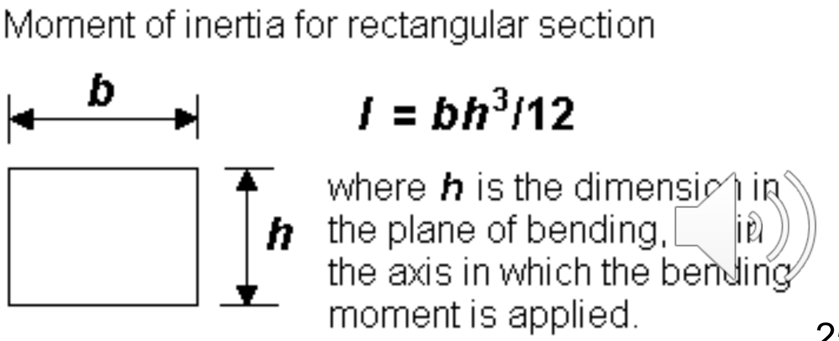
How do we measure small forces (nN)?

- Deflection of a beam: $\delta = FL^3/3EI$
- For a typical cantilever (L=400 µm, b=20 µm, h=2 µm): δ = 0.2 µm/nN
- The angular deflection is:
- $\alpha = F/Lk$, where $k = 3EI/L^3$
- Typical value: 0.6 °/nN
- Next question:

How do we measure a small deflection?



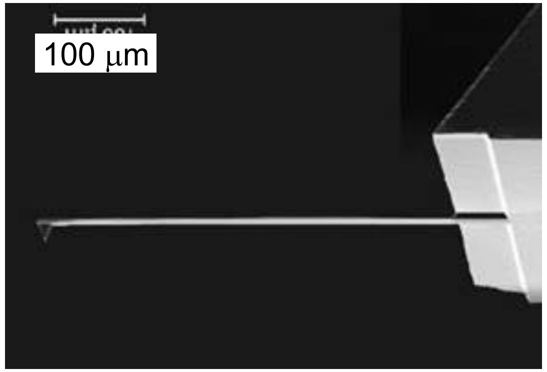




http://www.clag.org.uk/pics/beams/moment1.gif

How do we measure small deflections?

- First solution (1986): By an STM!
- Use the stm tip to sense the z-position of the AFM tip on the cantilever (used as a spring)
- Complicated !



PHYSICAL REVIEW LETTERS

Atomic Force Microscope

G. Binnig[a] and C. F. Quate[b]

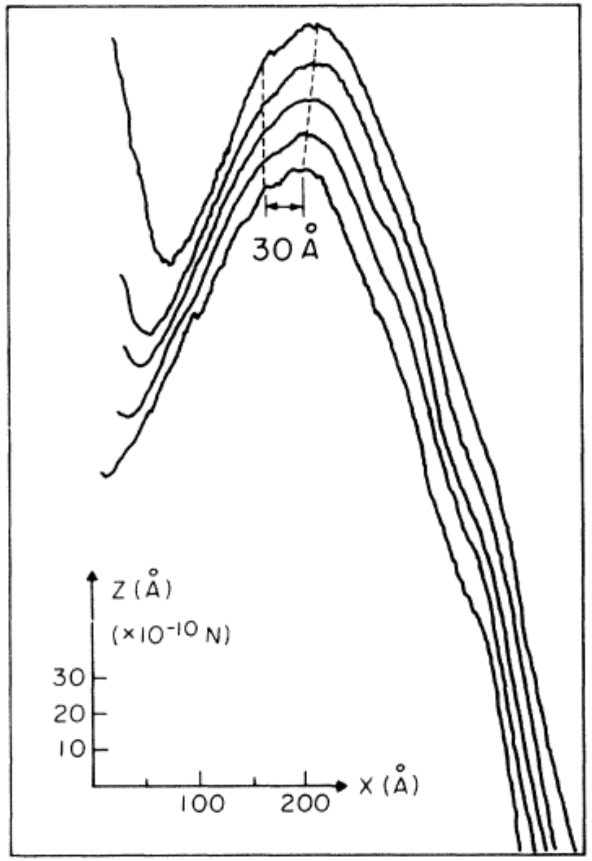
Edward L. Ginzton Laboratory, Stanford University, Stanford, California 94305

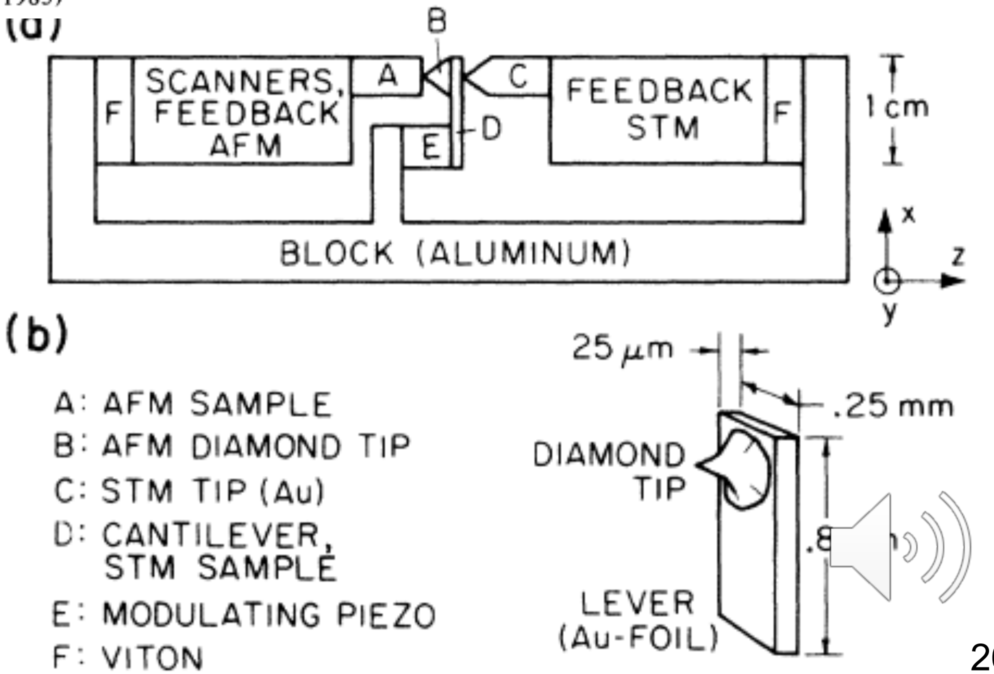
and

Ch. Gerber[c]

IBM San Jose Research Laboratory, San Jose, California 95193

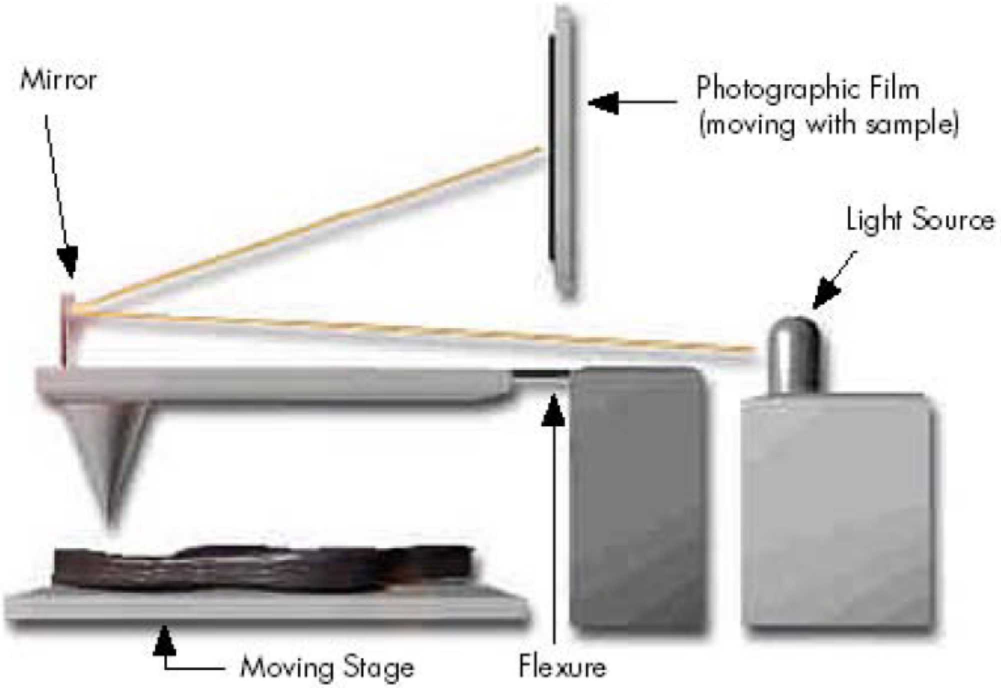
(Received 5 December 1985)



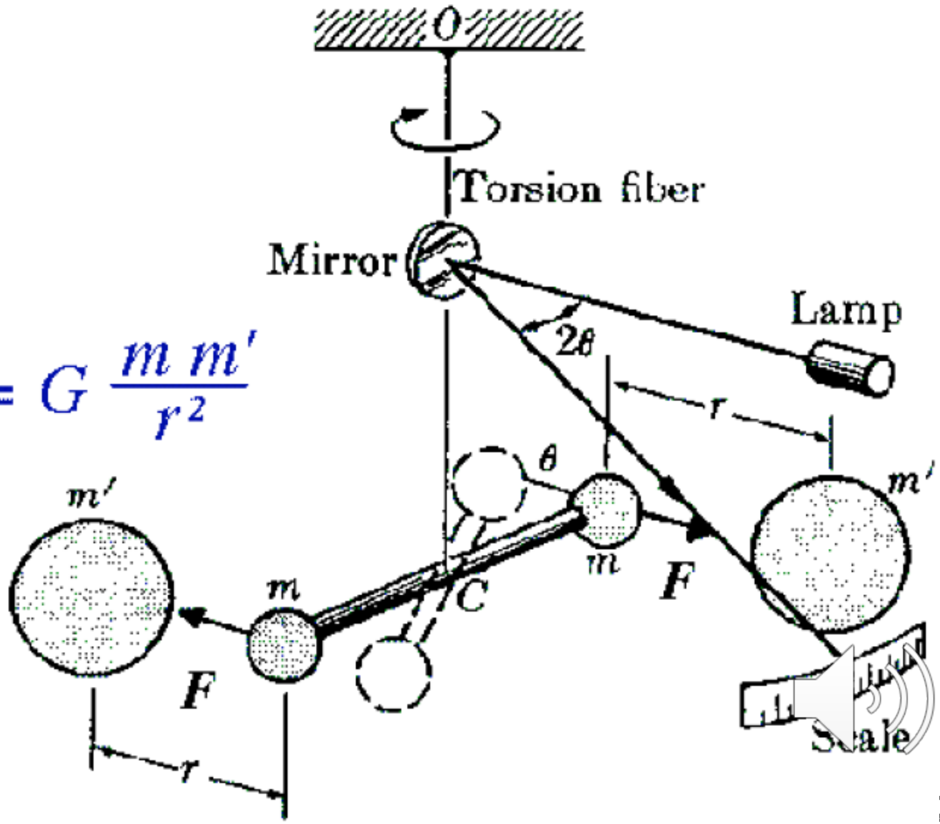


How do we measure small deflections (nm)? With light!

- Light beams have been used to measure small deflection, e.g. by Cavendish in his measurement of G (1798) and surface profilometer of Schmaltz (1929)
- The light beam serves as a long weightless lever

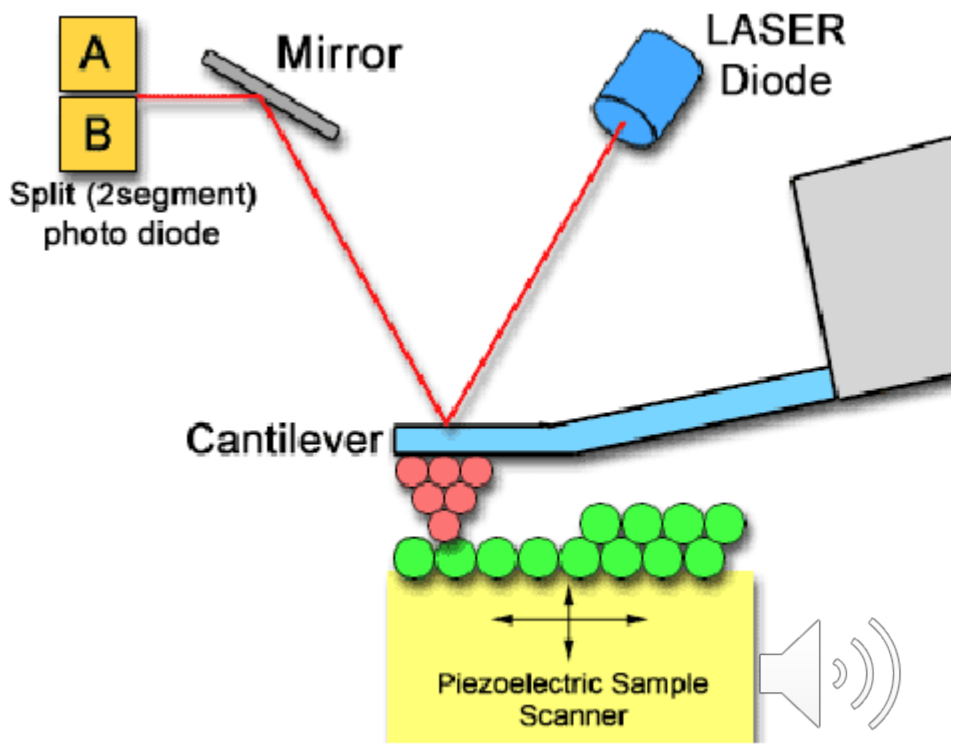


$$F = G\frac{m\,m'}{r^2}$$



How do we measure small deflections (nm)? With a laser!

- A laser beam is reflected from the cantilever to a position-sensitive photodetector
- The detector signal is proportional to the tip displacement, which is proportional to the force
- The tip is scanned over the sample (as in STM) to produce the image



Operation of contact AFM

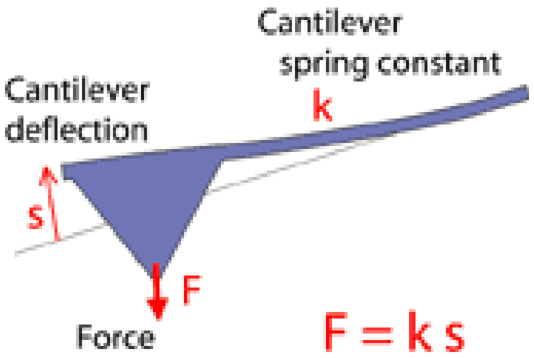
- We saw that the deflection of the cantilever is:

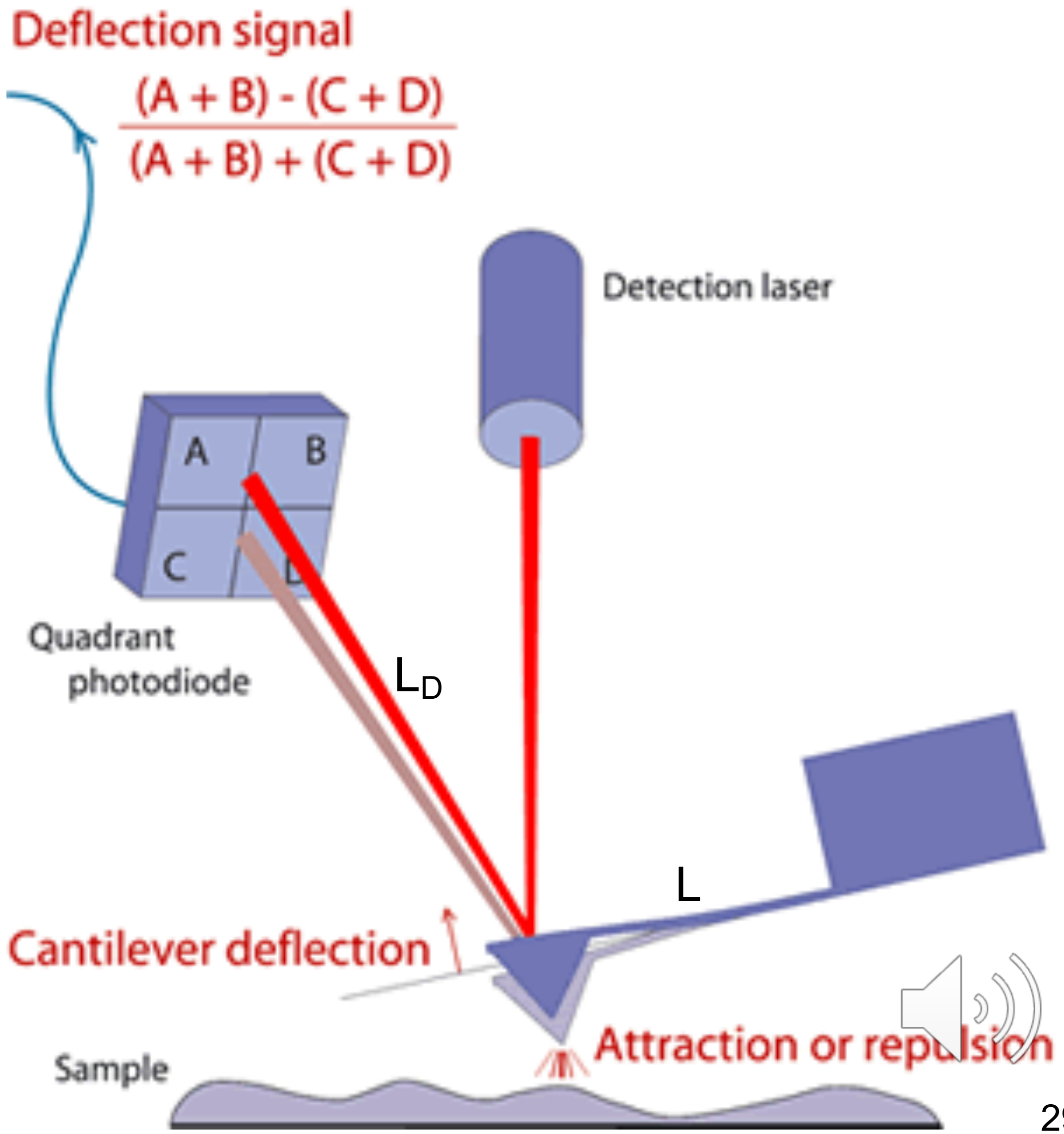
  $\delta = FL^3/3EI$, typical $0.2\ \mu m/nN$

- The reflected laser beam moves by a distance:

  $\delta L_D = \delta L/L_D = FL^2/3EIL_D$

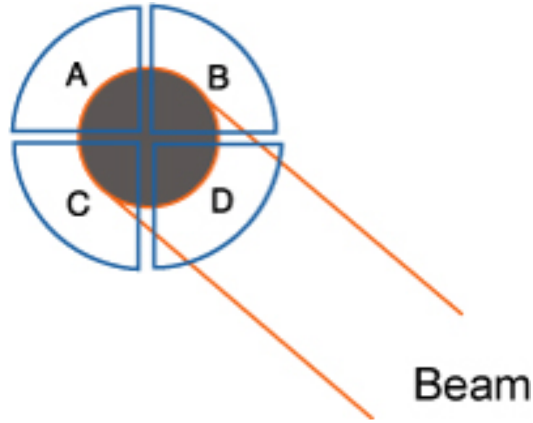
- Typical value (L_D~20 mm): $\delta L_D = 10\ \mu m/nN$





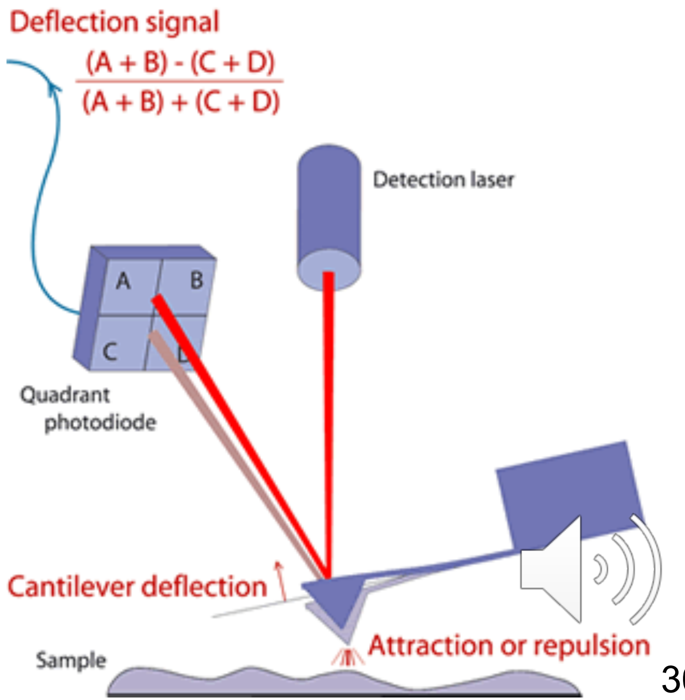
Operation of contact AFM

- The laser beam movement (10 μm/nN) is easily detectable by a 4-quadrant photodetector:



$$X = \frac{(A+C)-(B+D)}{(A+B+C+D)} = \frac{X_{Diff}}{SUM} \qquad Y = \frac{(A+B)-(C+D)}{(A+B+C+D)} = \frac{Y_{Diff}}{SUM}$$

- SUM signal is used for laser beam alignment on the cantilever
- Y signal is used to detect the cantilever movement (zeroed before contact)
- X signal used to detect lateral forces
- Typical values: Beam diameter 1 mm, P_{refl}=10μW, gives a SUM signal of 10V. Difference of 10 μm (1%, corresponding to a force of 1 nN) gives a difference signal of 0.1 V

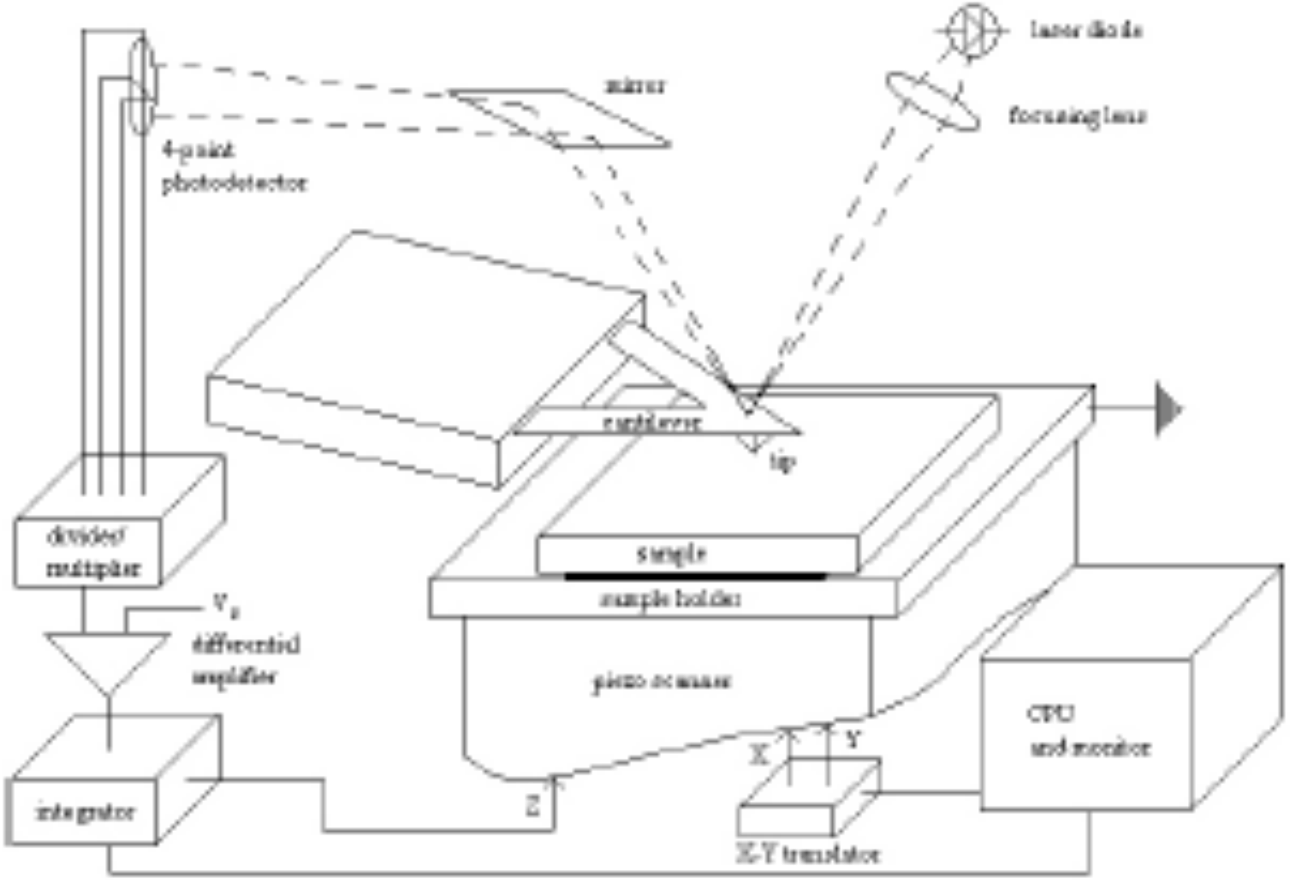


AFM feedback

- As in STM, feedback is used to keep the tip at a constant force from the sample, the height is plotted as image.
- On flat surfaces (to a few nm), constant height can be maintained, and the force is displayed

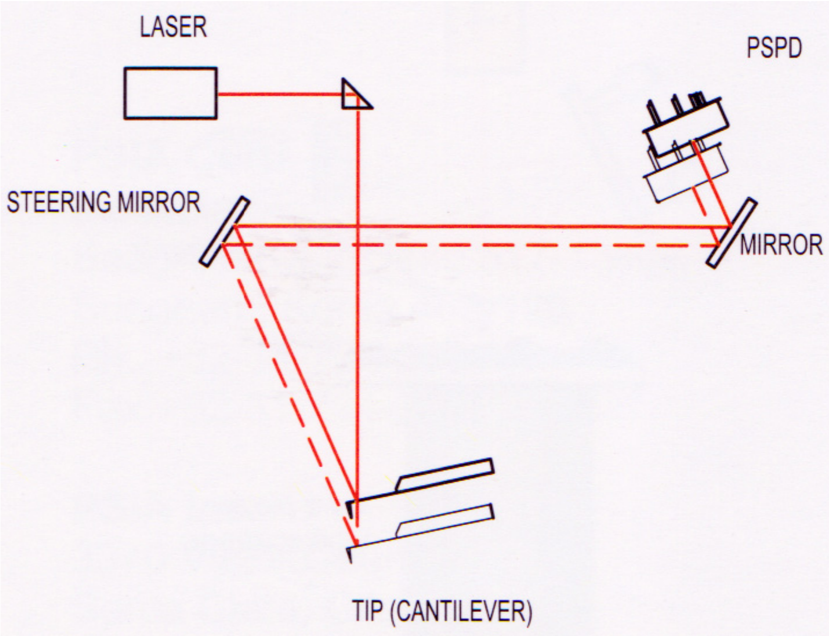
Solutions:

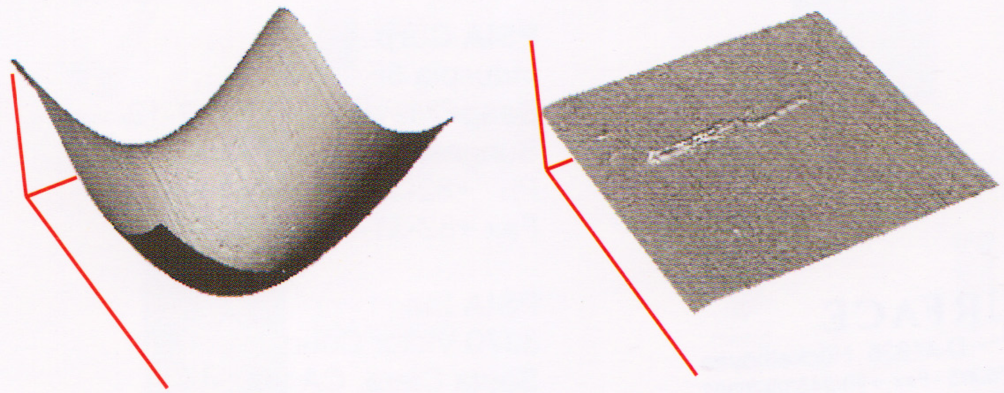
1. Short-term interactions
2. Piezo scanner
3. Non-contact
4. Height feedback
5. Rigid structure, isolation
6. Compensation

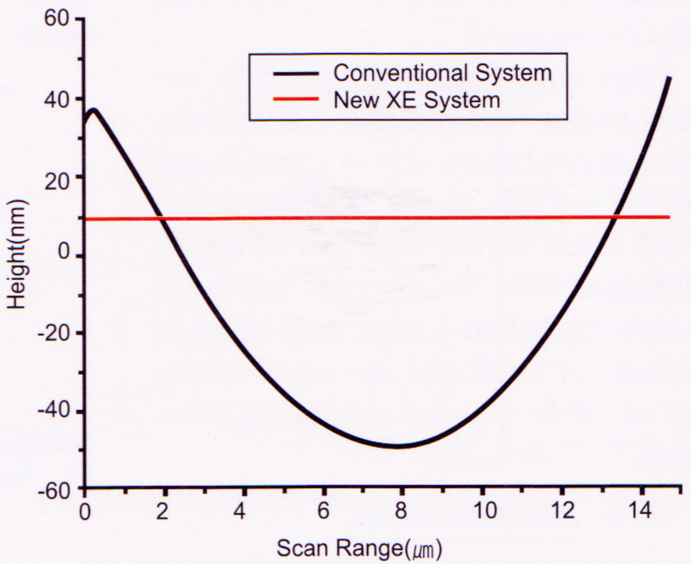


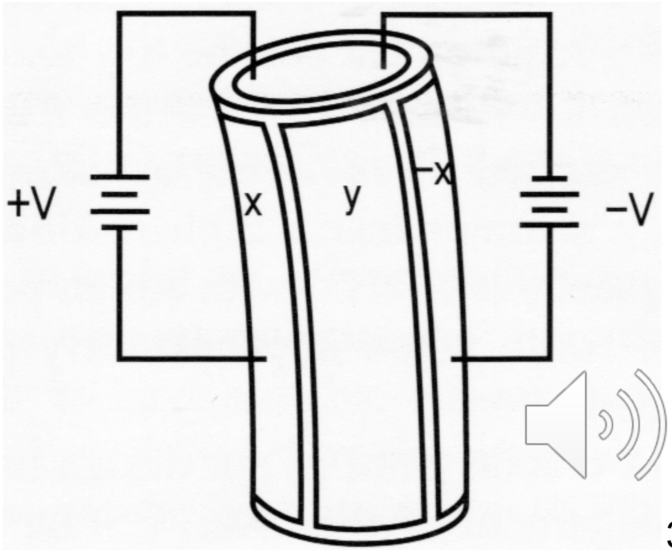
Scanner types

- As in STM, there are two scanner types: tube and separate (XY-Z)
- The separate XY-Z scanner is more linear, and has no Z-distortion
- Linearization is provided by sensors



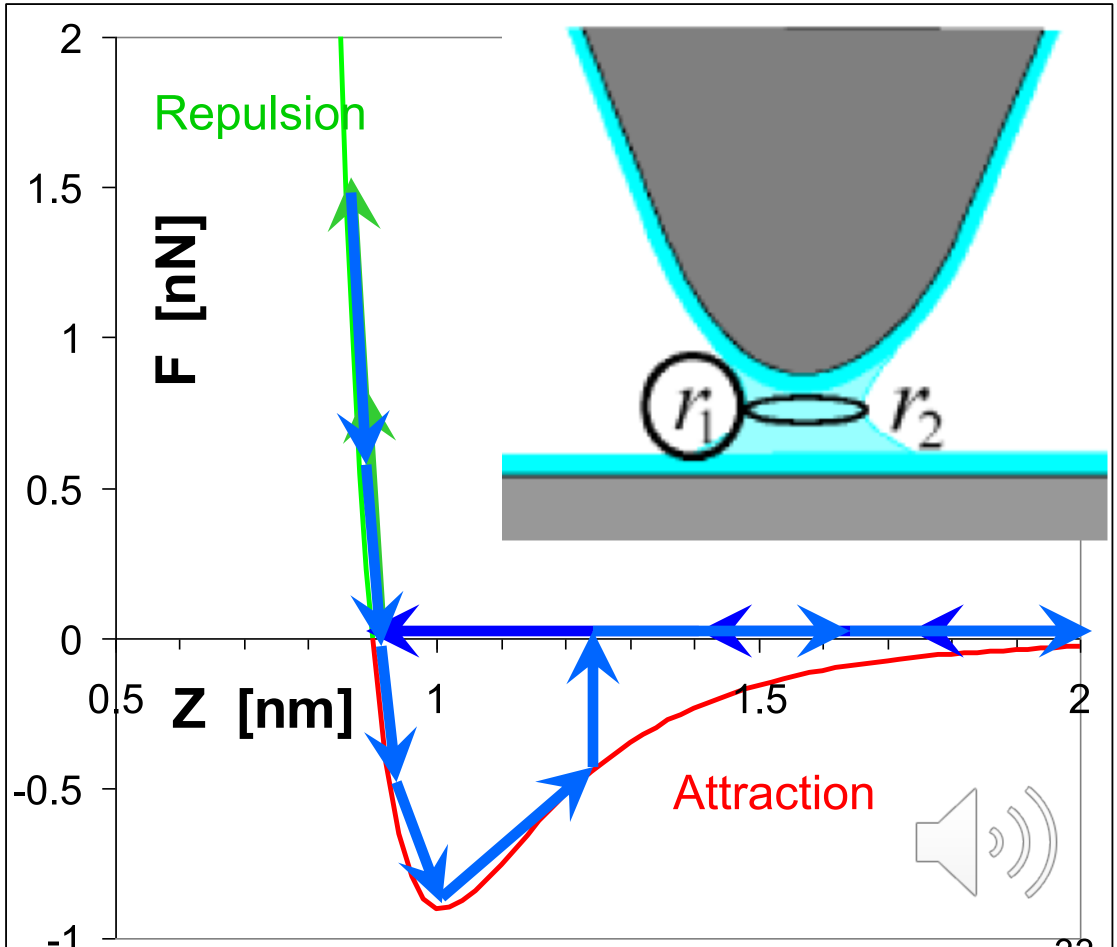






The other side of the force …

- The Van-der-Waals force between tip and sample: $F \propto \left(\frac{1}{z^6} - \frac{1}{z^{12}} \right)$
- When the tip approaches, the force is attractive, then strongly repulsive
- The attractive force:
  - Makes the tip "jump" to touch the surface quickly when approaching the sample surface.
  - Makes the tip "stick" to the surface when retracting.
- Result: hysteresis in tip movement !
- This is most problematic in ambient air, as the sample and tip are covered by a thin (1 nm) water layer.



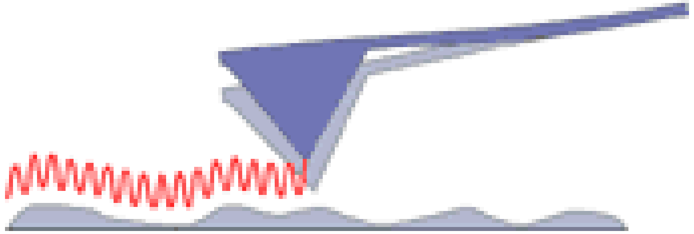
How to avoid contact sticking in AFM ?

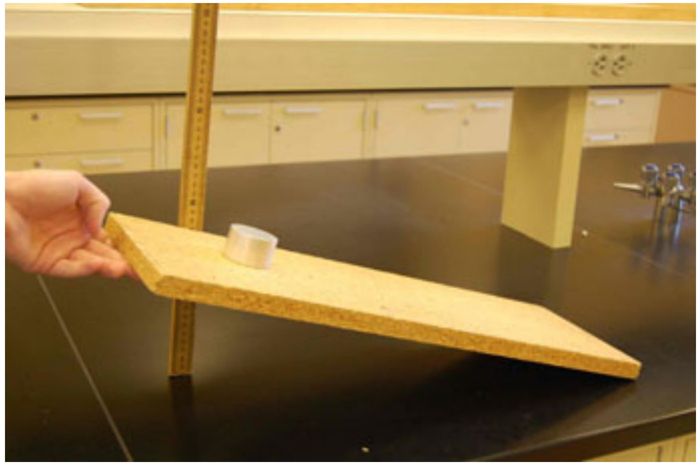
- Let's get inspired by the study of friction:

- We know that dynamic friction is smaller than static friction

- Let's try to make the AFM tip dynamic!

- In AFM: vibrate the tip to avoid sticking

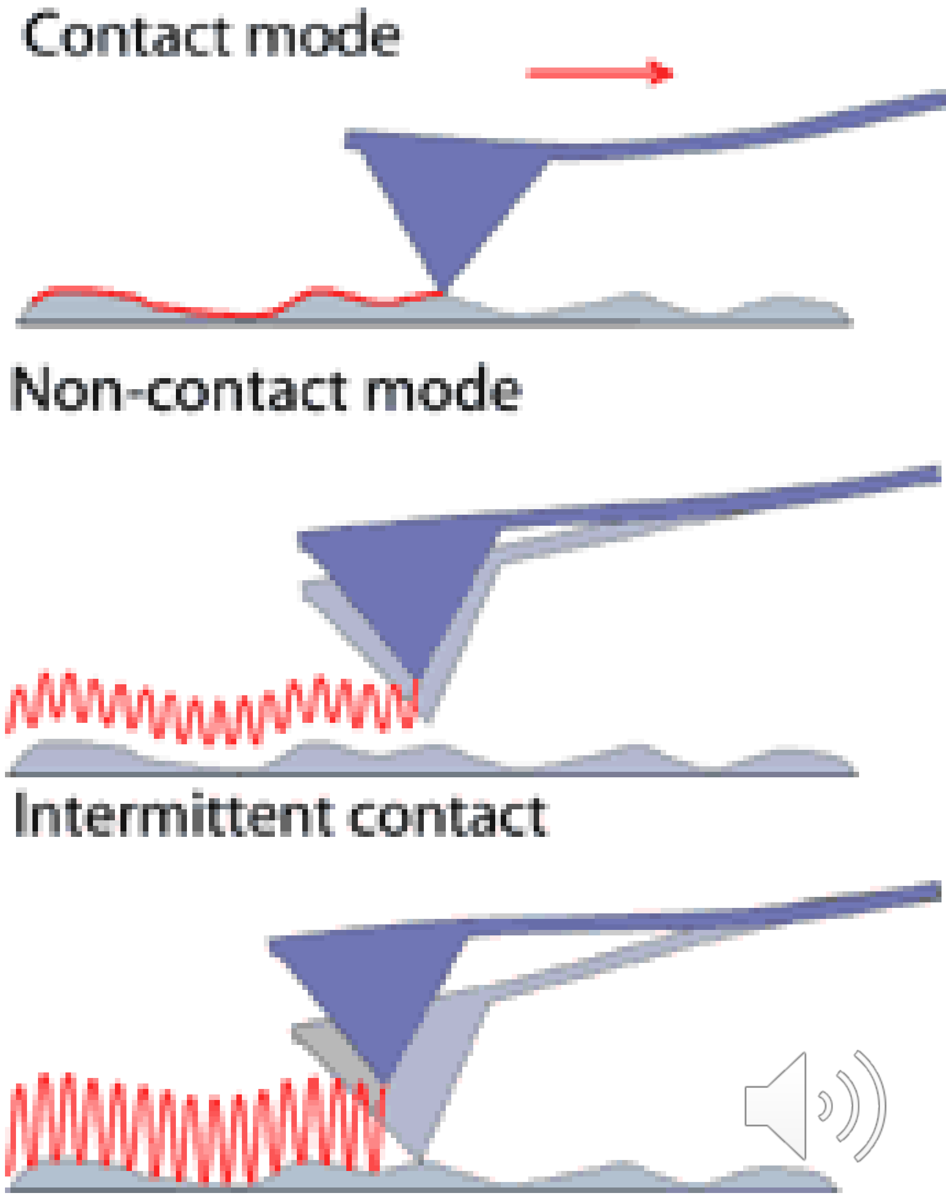




http://www.ehow.com/how_7529403_calculate-kinetic-friction.html http://www.sciencecontrol.com/static-friction-vs-kinetic-friction.html

Non-contact AFM: no sticking!

- "Classical" contact-mode AFM is prone to tip sticking problems.
- To avoid the problems of tip sticking, non-contact AFM modes are used:
  - "Pure" non-contact: tip never touches the sample, oscillation amplitude is small.
  - Intermittent contact, or tapping: large amplitude, at every oscillation cycle the tip touches the sample.

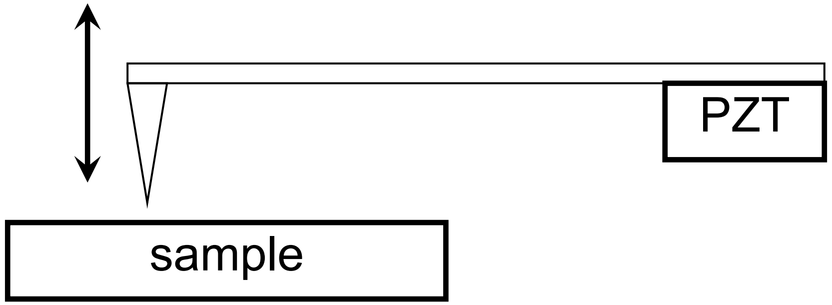


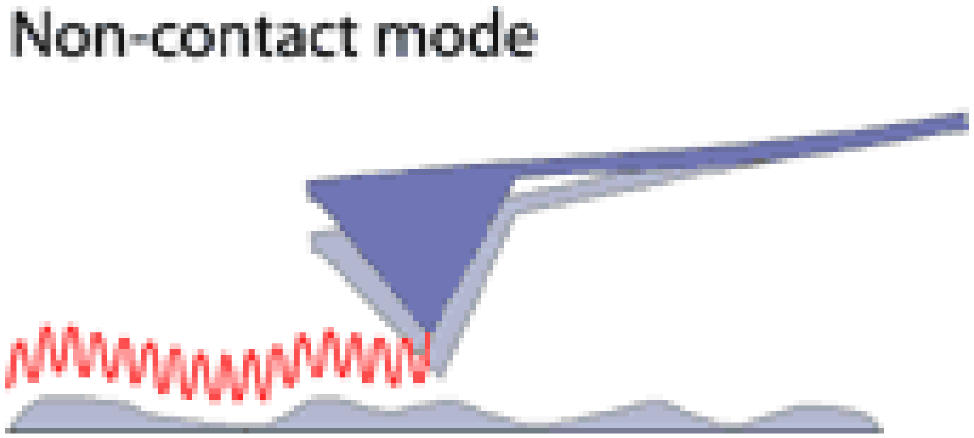
Operation of non-contact AFM

- The cantilever is vibrated by a special piezo at its resonance frequency: $f_0 = \sqrt{K/\mu}$.

  where K = force constant, μ = cantilever mass, both per unit length.

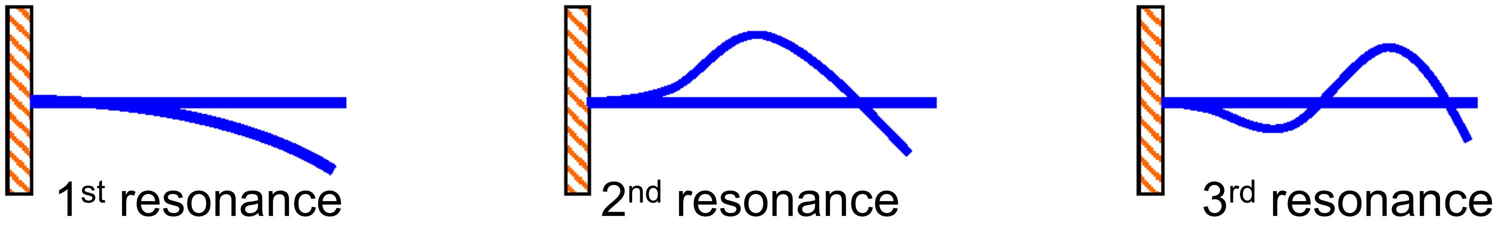
- The laser beam reflected onto the position-sensitive detector vibrates at the resonance frequency
- The PSD signal has an AC component, showing the tip's oscillatory motion.
- At resonance, the transducer needs to supply minimum energy to maintain oscillations.



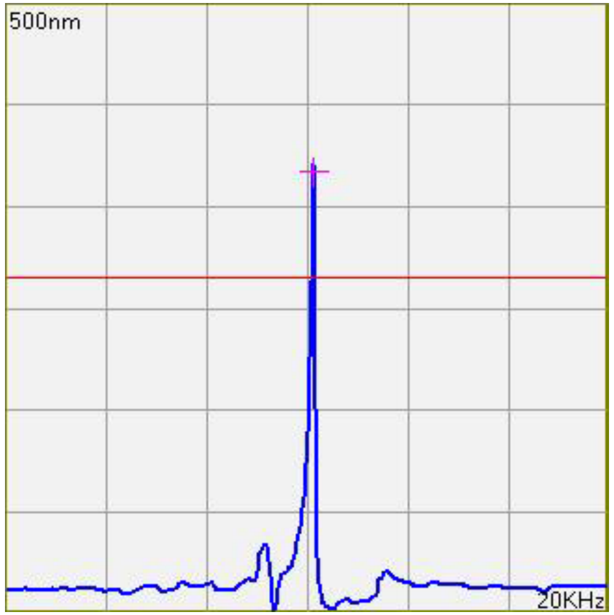


Resonances of the cantilever

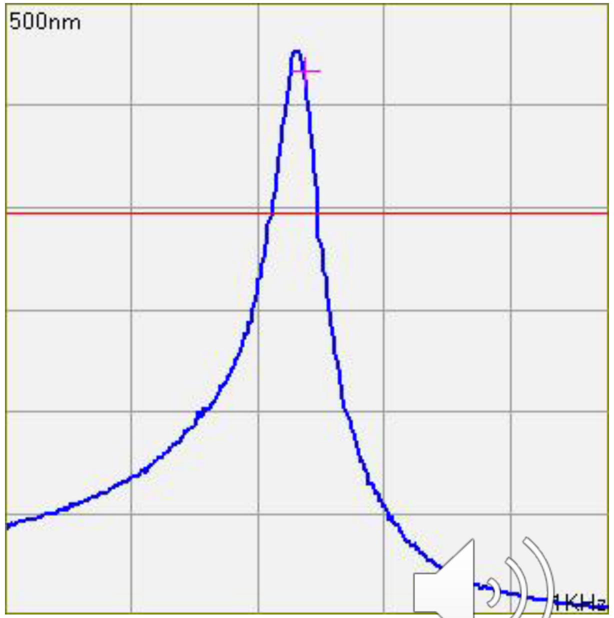
- The cantilever can have several resonances:
- The resonance frequency of the i^{th} mode of the cantilever is: $f_i = \frac{\lambda_i}{L^2}\sqrt{\frac{EJ}{\rho S}}$, where E = Young's modulus, ρ = material density, L = cantilever length, S = cantilever cross-section, I = cantilever moment of inertia, λ_i = numerical coefficient dependent on the mode number: $\lambda_1 \sim 0.5$, $\lambda_2 \sim 3$, etc.)
- Usually the first (highest-Q) resonance is used



First three cantilever resonances



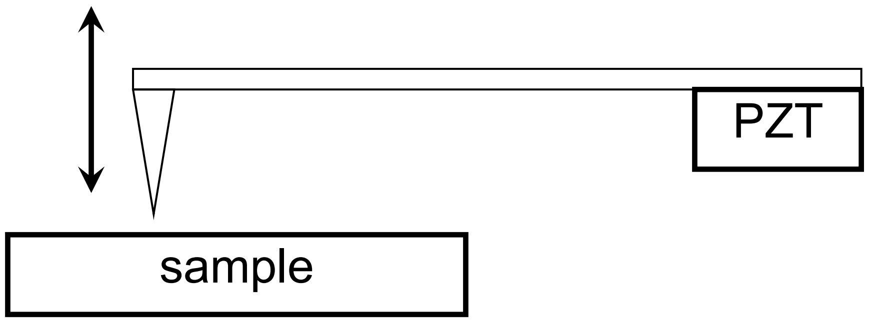
Scan over a large frequency range

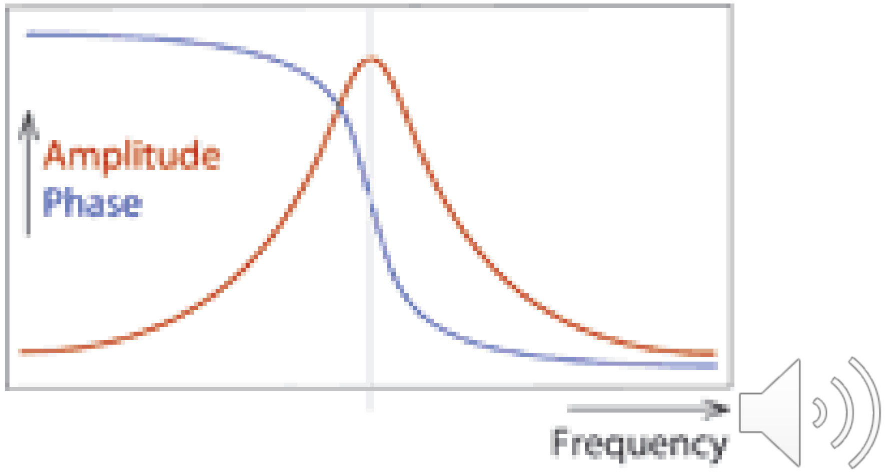


Zoom on the main resonance

Feedback in non-contact AFM

- What changes by tip-sample forces ?
- Changes in the vibrations’
  - Frequency
  - Phase
  - Amplitude
- In NC-AFM, usually frequency is used for feedback. In IC-AFM, usually the amplitude change is used
- Sometimes lock-in (phase) detection is used, e.g. to plot height + phase images

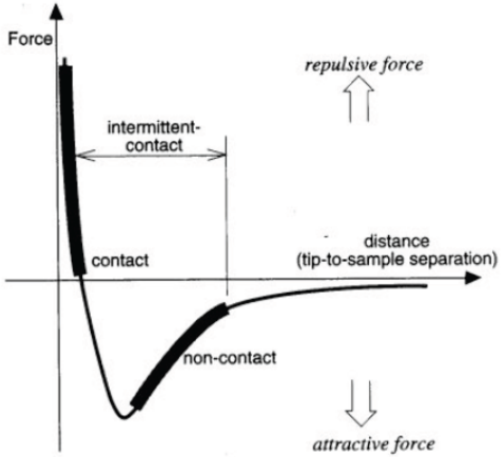


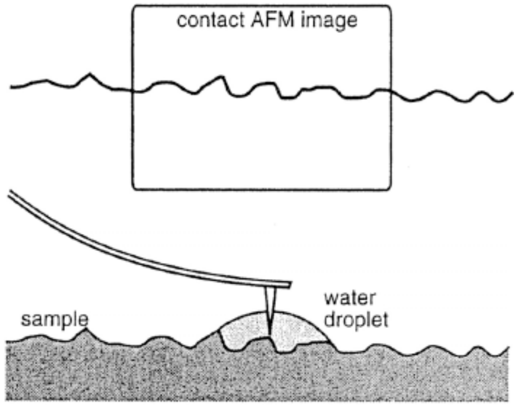


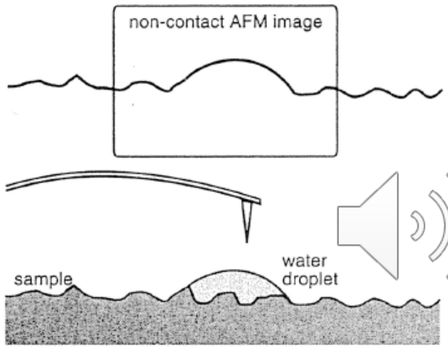
Amplitude and phase near a resonance

Force, resolution in non-contact AFM

- NC and IC AFM use different force regimes:
  - Contact AFM works with repulsive forces, at close distance (<0.5 nm)
  - NC-AFM works with the attractive force, at a larger tip-sample distance (1-10 nm)
  - IC_AFM works with the repulsive force, at smaller distance, like contact AFM (0.5-2 nm). However the force is applied only for a short time during the cycle
- Results:
  - Contact AFM has the highest resolution (atomic, like STM), but uses high forces (1 nN - 1 μN) which can scratch the surface
  - NC-AFM uses less force (1 pN - 1 nN), good for delicate surfaces (polymers), but has lower resolution
  - IC-AFM uses higher force (0.1 - 100 nN), but for a short time in the cycle. good for all surfaces, has higher resolution

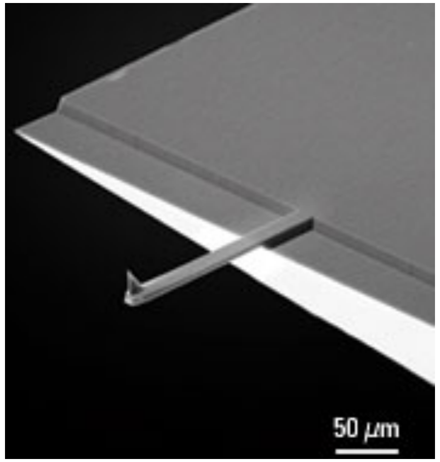


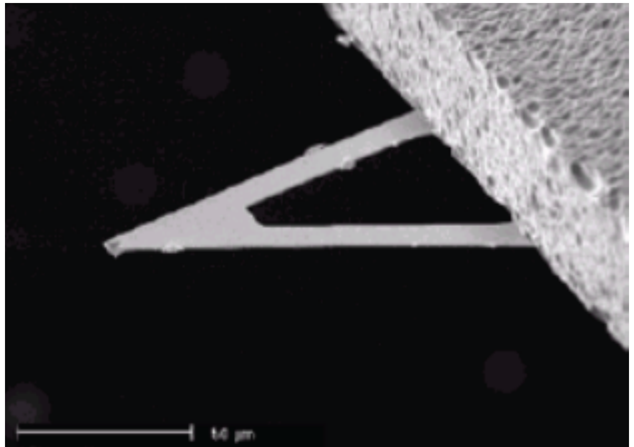




Types of AFM cantilevers

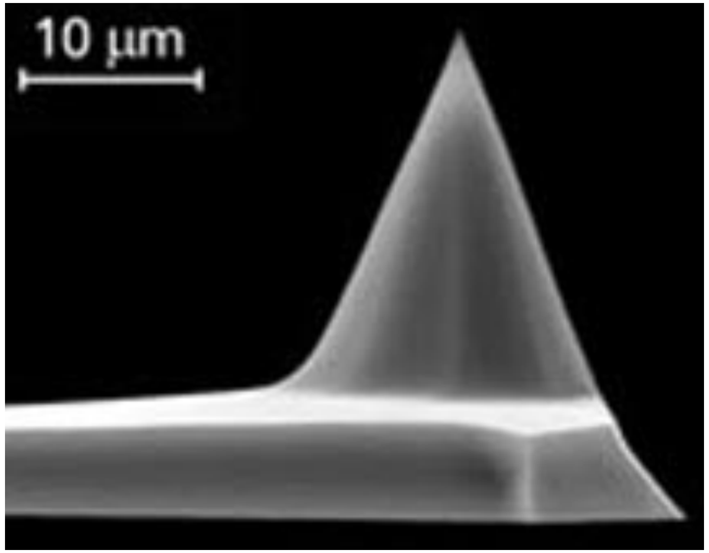
- For contact mode, usually a long cantilever is used to increase sensitivity. Remember: $\delta = FL^3/3EI$
  - Typical values: K = 0.1-1 N/m, L = 250-400 μm
  - Resonance frequency is low (50 kHz)
- For non-contact mode, usually a short cantilever is used to increase the resonance frequency: $f = \frac{\lambda}{L^2}\sqrt{\frac{EJ}{\rho S}}$
  - Typical values: K=10 N/m, L = 100 μm
  - f_0 = 200-400 kHz
- Sometimes, two-beam cantilevers are used, e.g. to measure lateral forces.



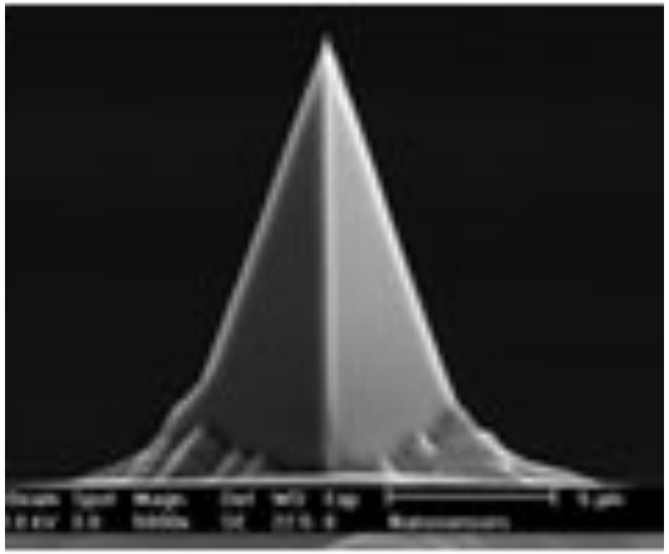


Standard AFM tips

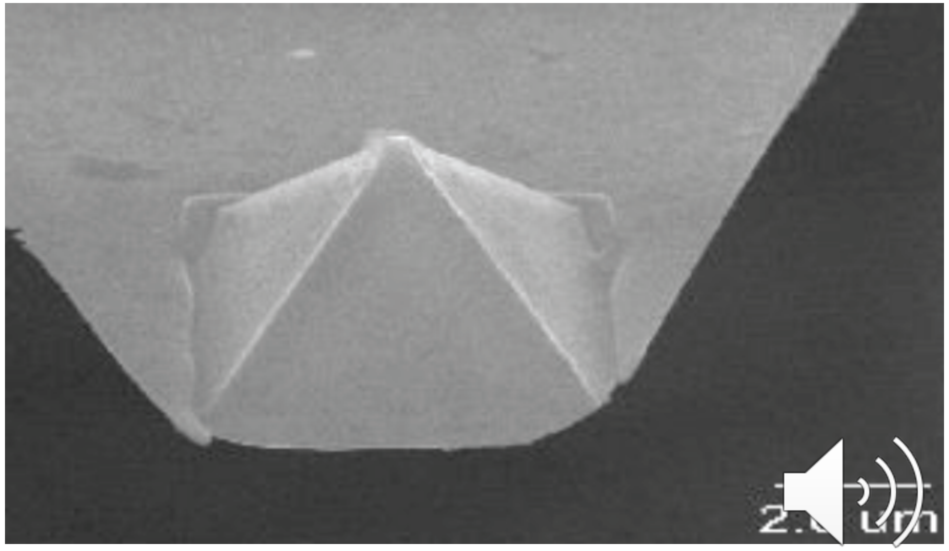
- Most AFM tips are made from Si, by photolithography and directional etching.
- The tip is pyramidal in shape, with height ~20 μm and sidewall angles of ~20° to the normal
- The standard tip radius is on the order of 5-10 nm
- In some cases Si_3N_4 is used: has longer life but larger tip radius



Si tip: Side view



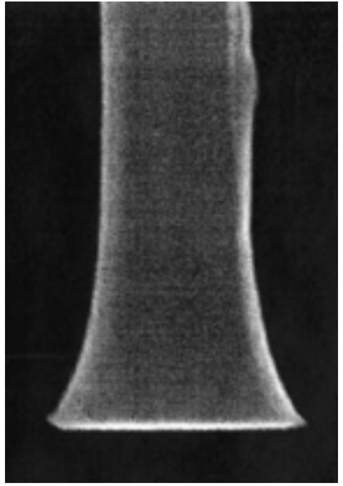
Si tip: Front view



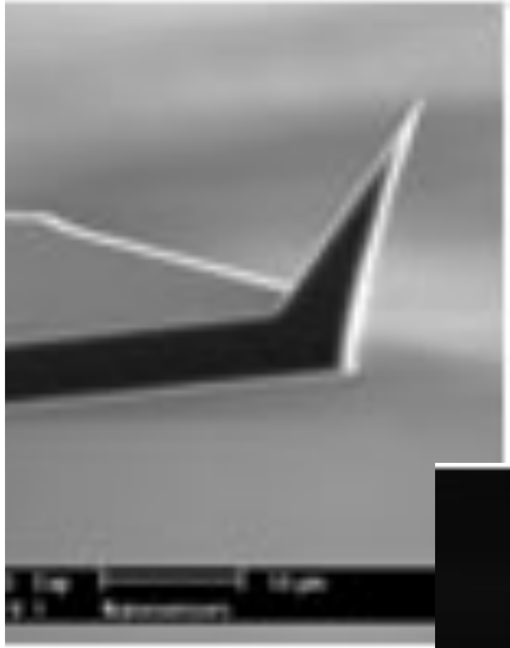
Si_3N_4 tip: Oblique view

Special AFM tips

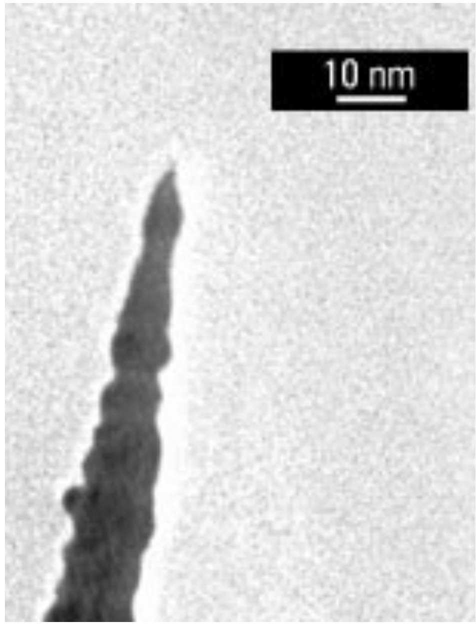
- For metrology : "elephant foot" to measure sidewalls:

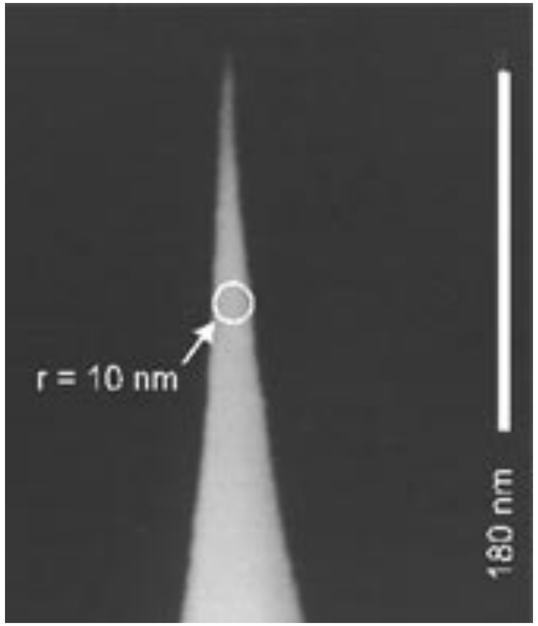


- Inclined tips to probe edges:

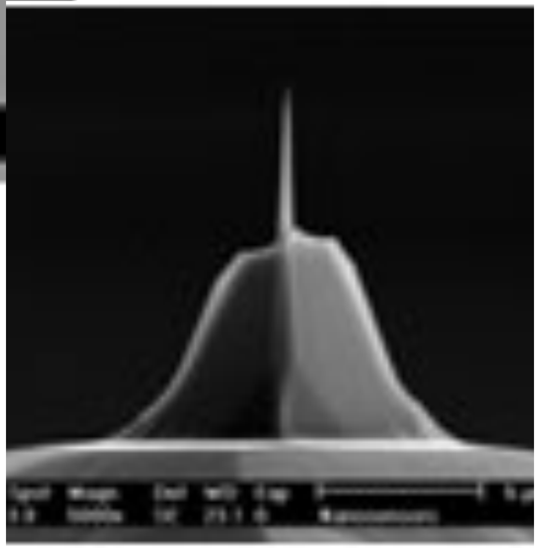


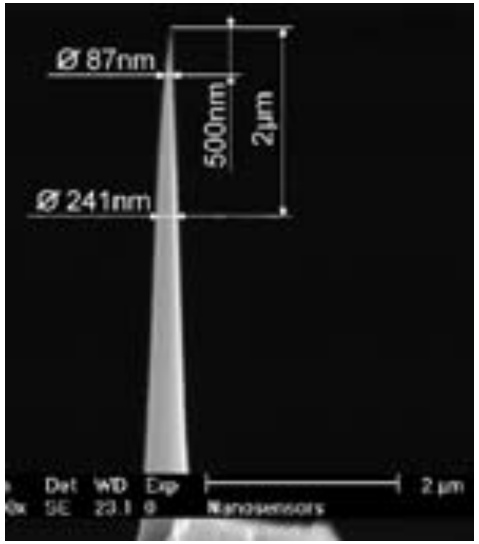
- Ultra-sharp tips, down to 1 nm





- High aspect-ratio tips to probe trenches and holes



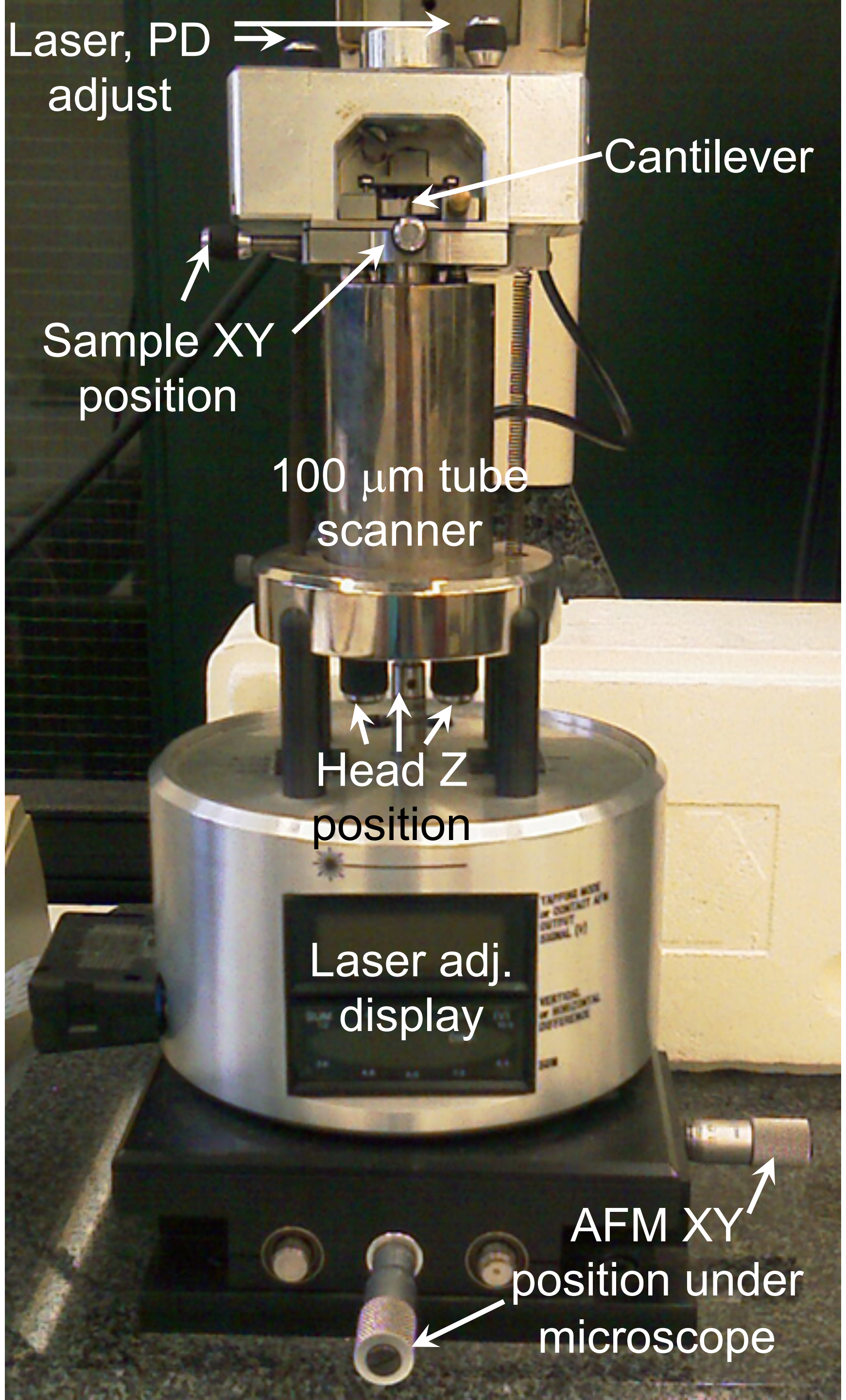


- Diamond tips for hardness testing and long life (low resolution!)
- Different coating on tips : conducting, magnetic etc.

AFM construction

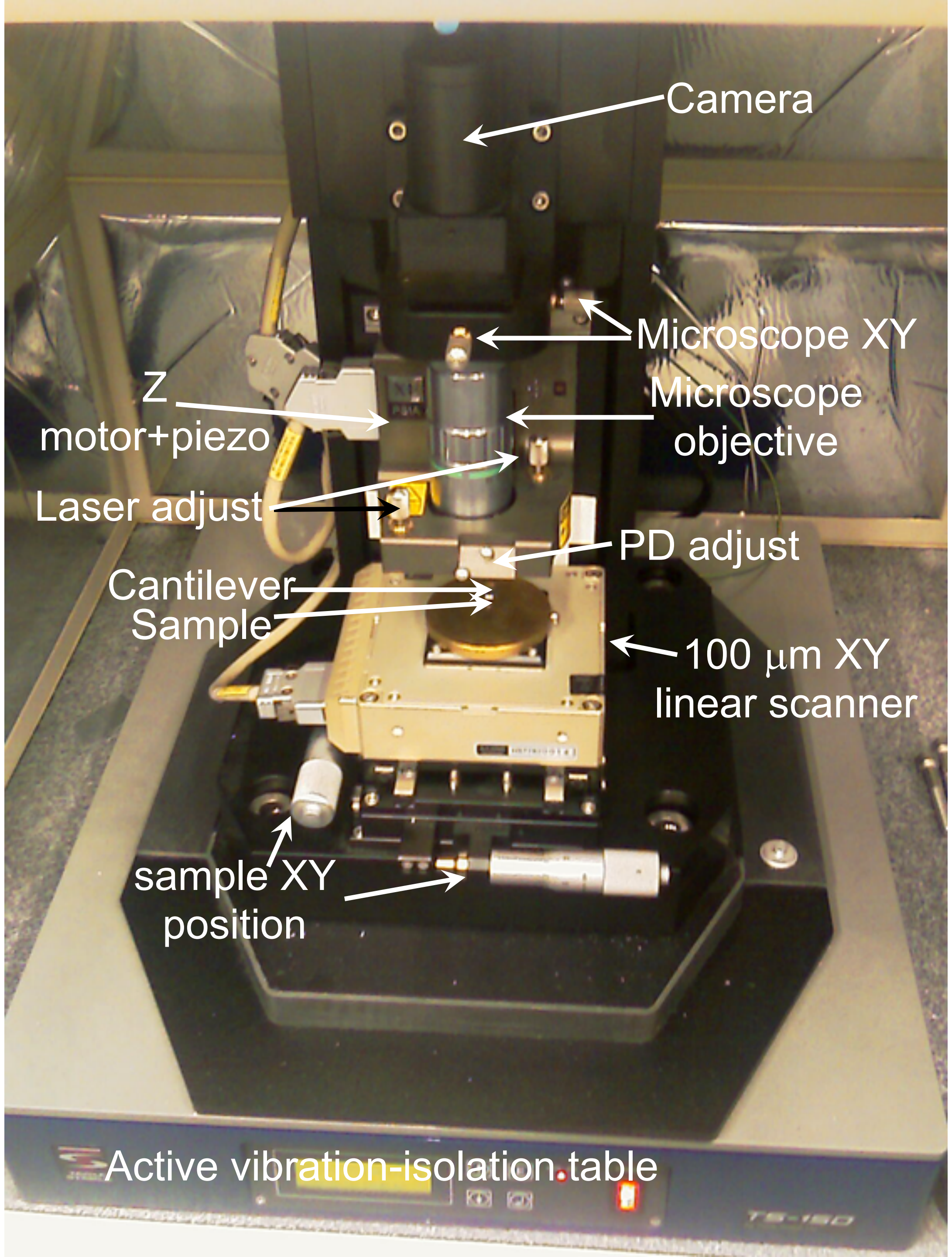
Small-sample AFM, tube scanner:

Electronics cable



AFM construction

Big-sample AFM, XY/Z linear scanners:



Outline:

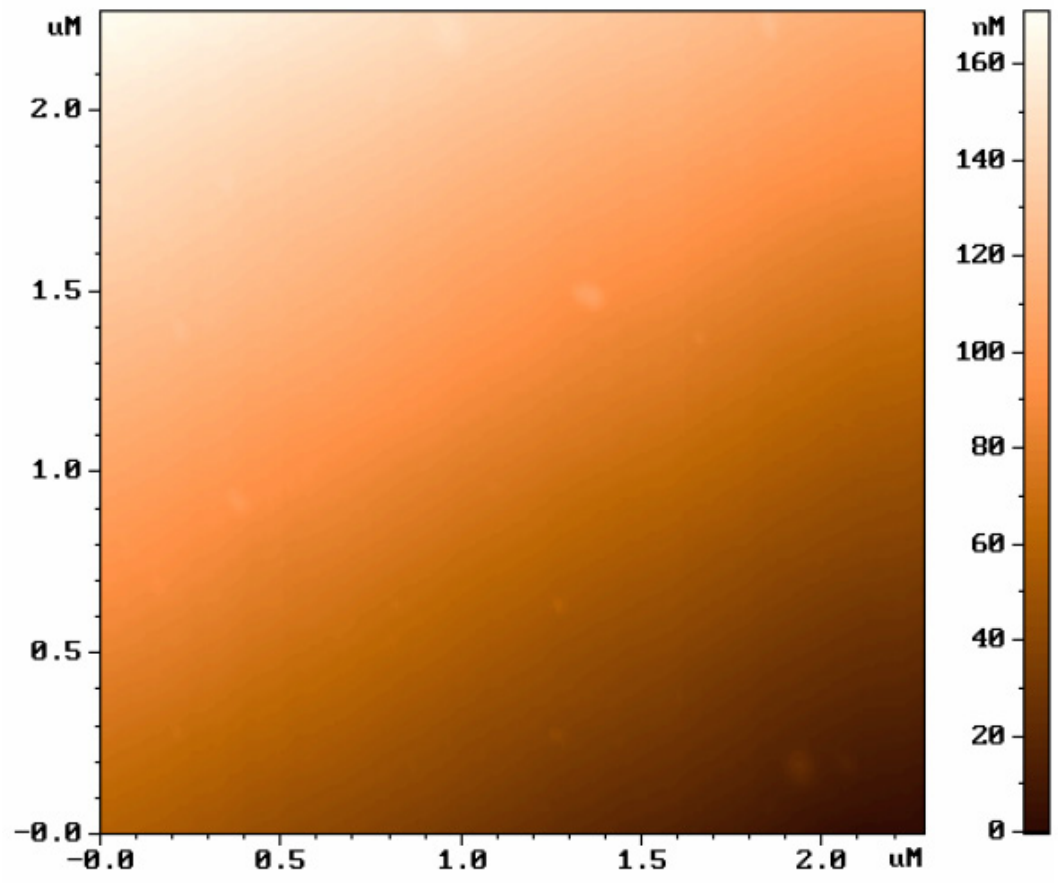
- Introduction: What is SPM, history
- STM
- AFM
- Image treatment
- Advanced SPM techniques
- Applications in semiconductor research and industry

Image processing

- SPM images are rarely perfect “as taken”
- “Basic” image processing:
  - Removing sample tilt, scanner non-linearity, tip jumps, noise
- “Advanced” image processing:
  - Filtering, deconvolution, finding & characterizing objects
- Measurements:
  - Size, distance of features
  - Line profiles & their characterization
  - Roughness
- Calibration
  - Scan (axes) calibration
  - Tip characterization

Basic Image Treatment

A newly-taken AFM image of a flat sample looks like this:

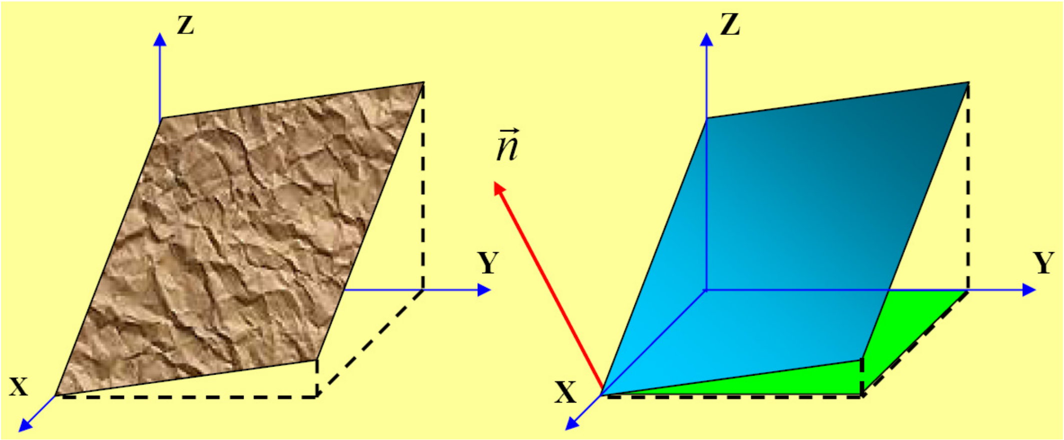


WHY ?

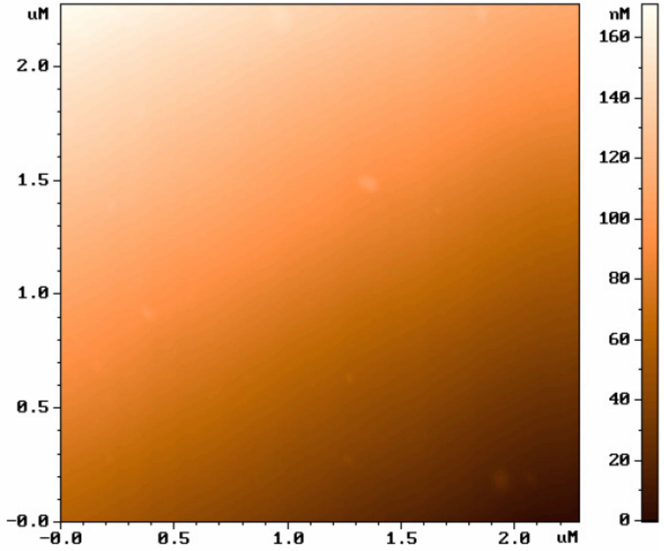
Basic Image Treatment: plane-fit

The sample is never horizontal! A 10mm sample mounted with one side higher than the other by 0.1mm, will give an image slope of 100nm over a 10 μm scan!

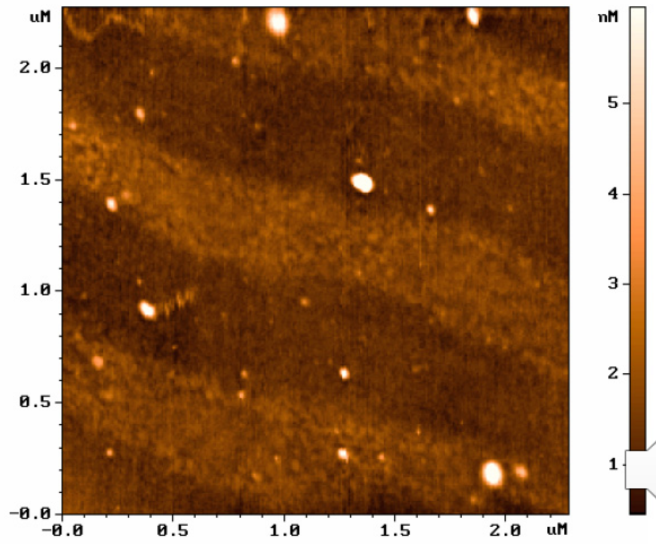
The plane-fit correction: An average plane is calculated by LSQ fit of the image to: ax+by+cZ=0



This plane is subtracted from the image, to “planarize” it:



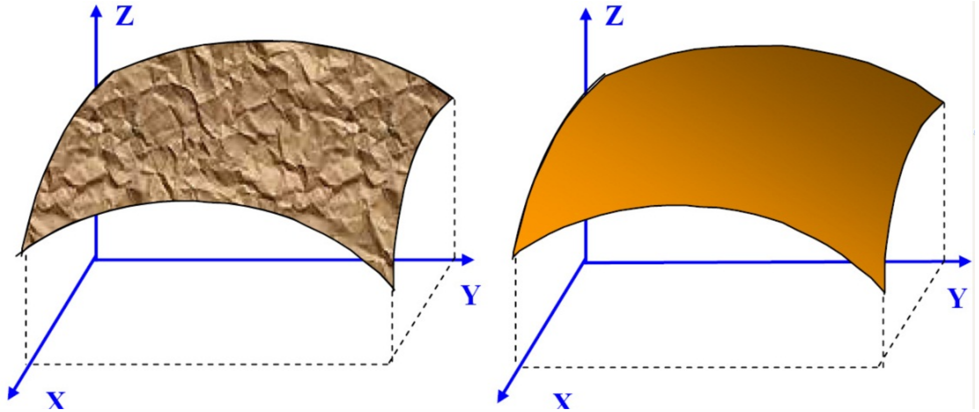
"Before"

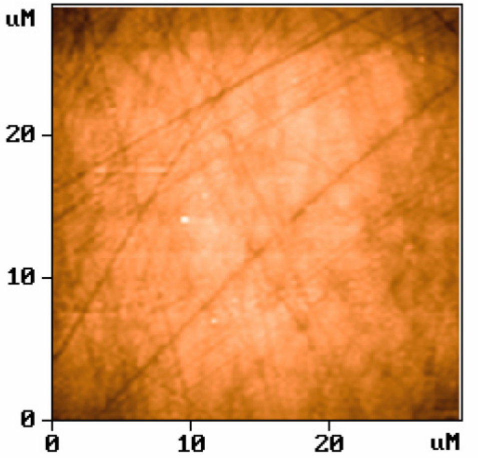


"After"

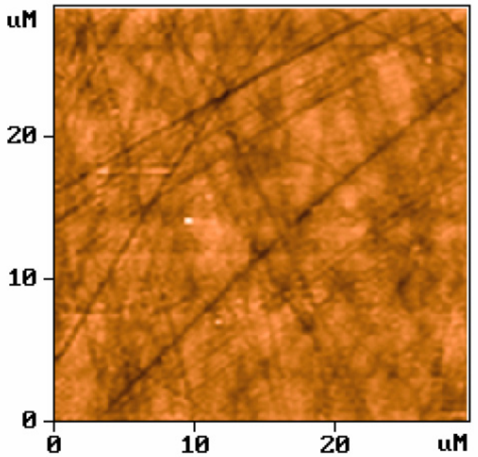
2^{nd} order plane-fit

- The piezo scanner can have non-linearities (especially tube scanners), leading to changes in Z values across the scanned plane
- In this case, a simple plane fit is not enough to correct the image, which is curved.





After 1st order planefit

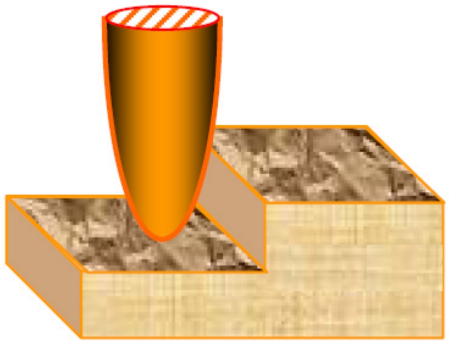


After 2nd order planefit

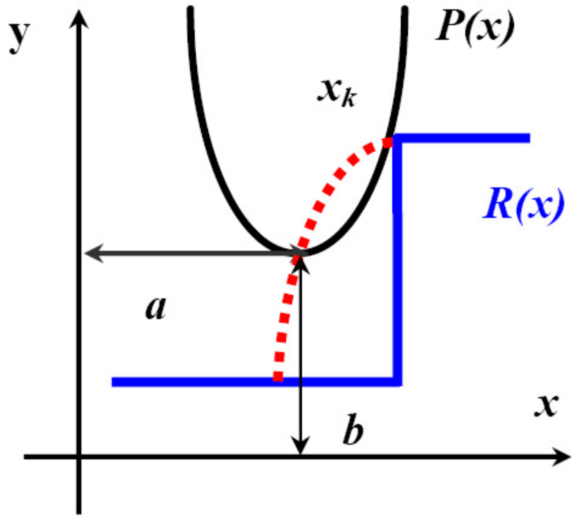
The 2nd-order (and sometimes even higher order) plane-fit correction subtracts from the image a LSQ-fitted curved plane

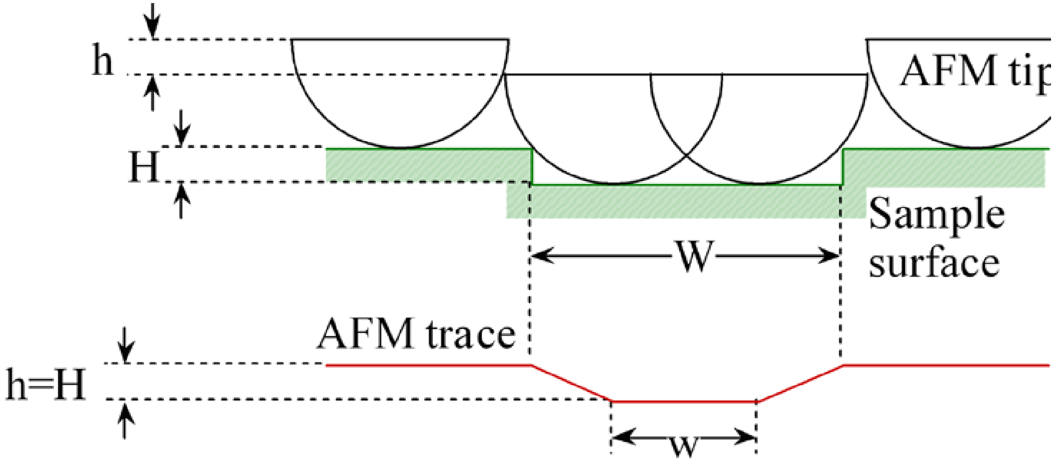
Caution: in some cases, high-order plane-fit correction can remove real image features (e.g. sample undulations)

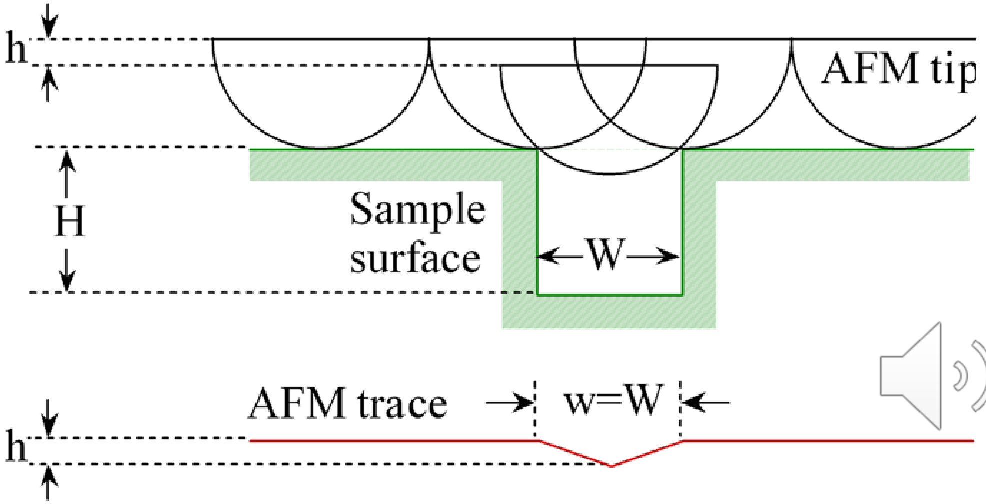
Effect of the tip size on the Image



- The AFM tip is never atomically sharp (standard R~10 nm), especially if it's broken !
- The image is the result of a geometrical convolution of the tip and sample
- A blunt tip will not penetrate a deep trench – a triangular image will result, shallower than the real depth. The width is correct (at the top) !

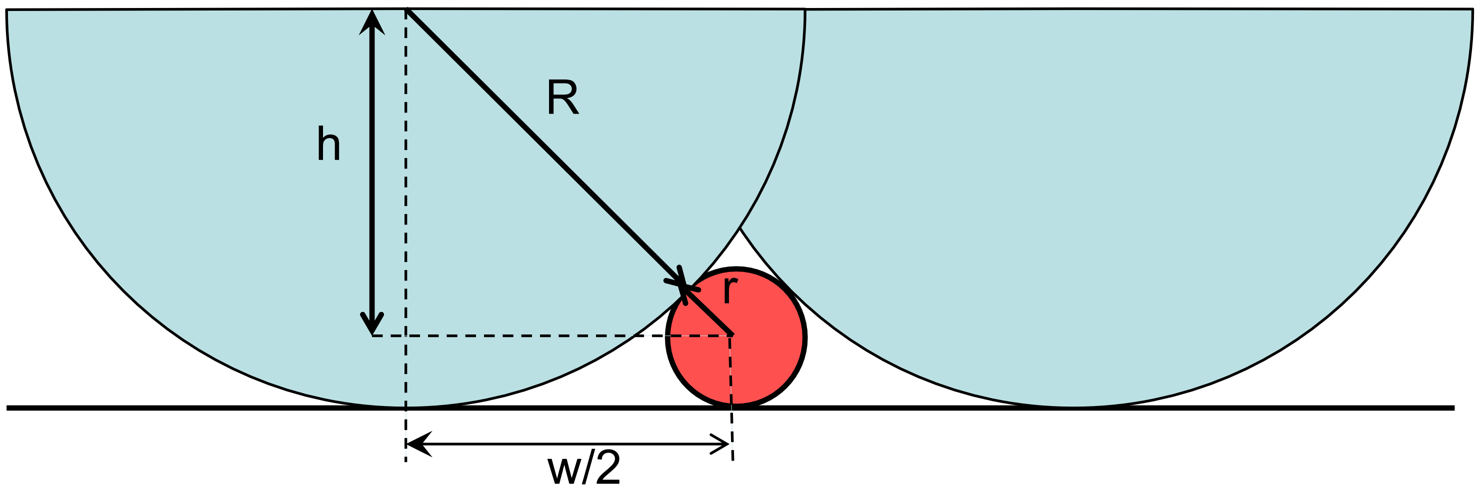






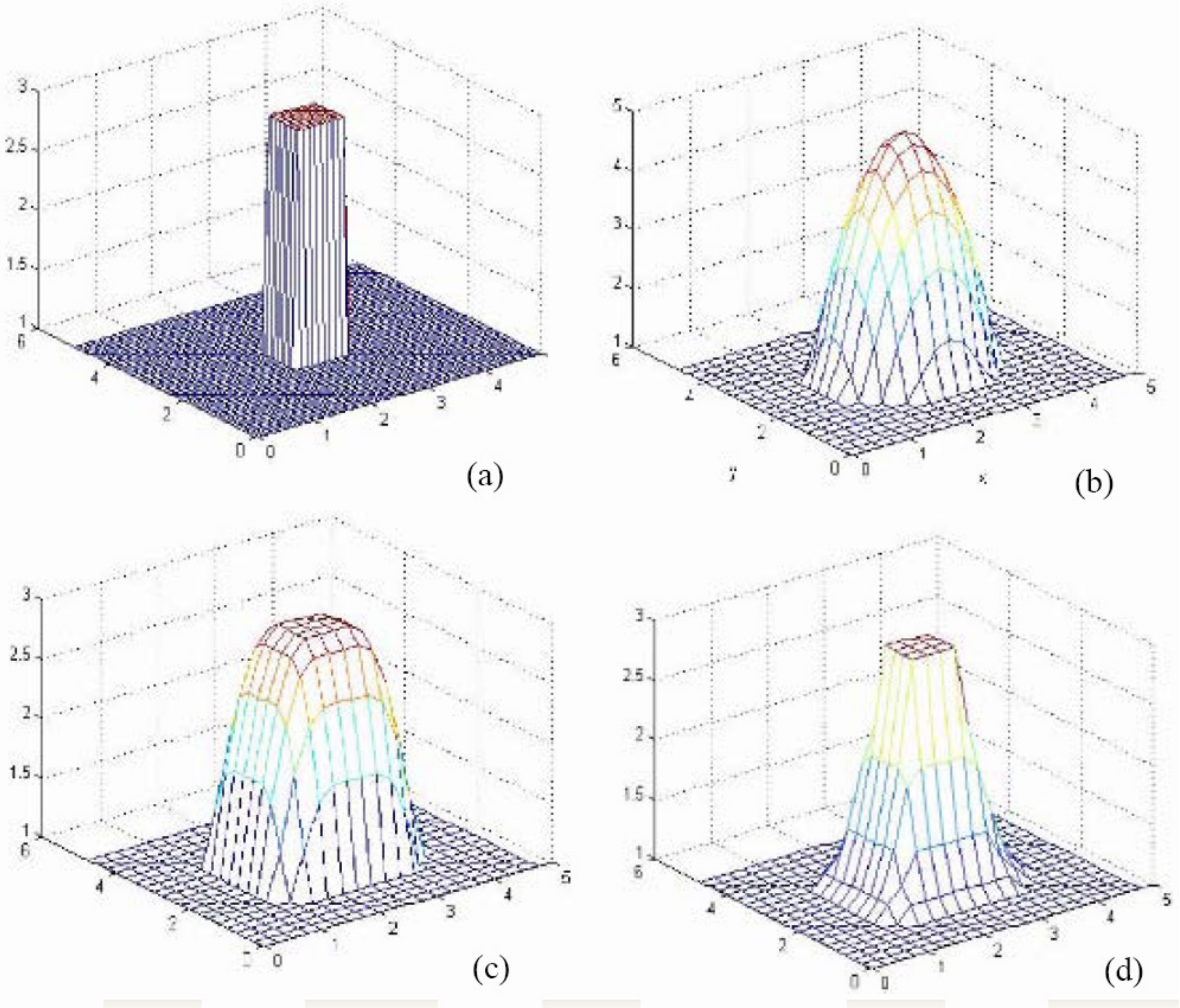
Effect of the tip size on the Image

- Example: Semi-circular tip, radius R, measures a molecule (or particle), radius r < R
- The apparent width is measures between the points where the tip touches the molecule from each side
- Geometrical calculation shows: $w = 2\sqrt{(R+r)^2 - (R-r)^2} = 4\sqrt{Rr}$
- Typical values: r = 1 nm, R=10 nm, giving w = 12 nm!
- The tip size will increase the apparent step width, but the height is correct!



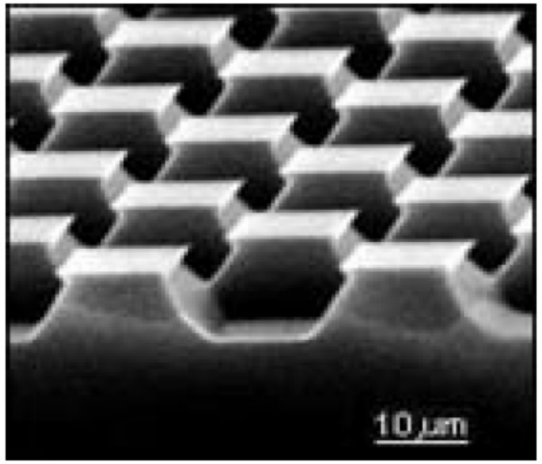
Example of tip deonvolution

- A square object (a) is scanned with a similar-size rounded tip (b).
- The resulting image (c) combines features of both tip and sample
- The object can be partially restored by deconvolution (d)

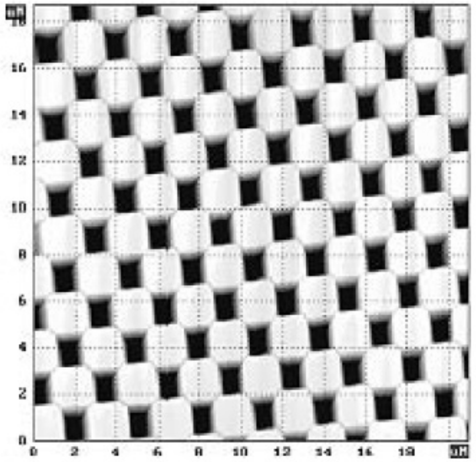


AFM calibration

- Special "calibration standards"
  - Checkerboard pattern to calibrate XY scale, linearity:

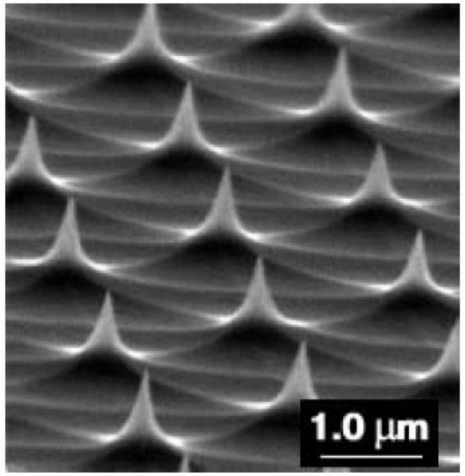


SEM picture of sample

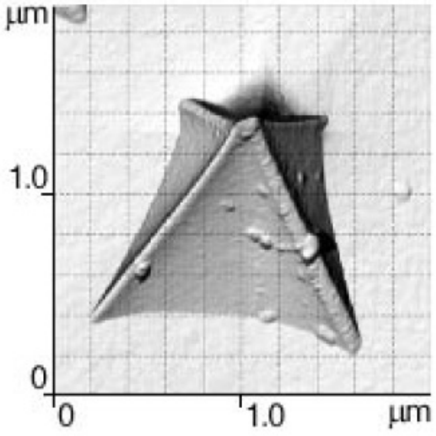


AFM image

  - Sharp “tips” to calibrate tip shape:



SEM picture of sample



reconstructed tip shape

- It's time-consuming to calibrate every tip – useful only for critical applications (metrology)

Outline:

- Introduction: What is SPM, history
- STM
- AFM
- Image treatment
- Advanced SPM techniques
- Applications in semiconductor research and industry

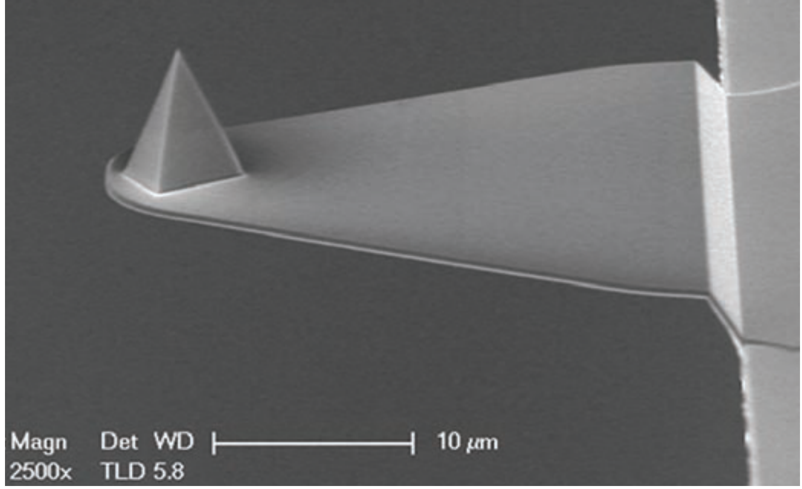
Advanced modes - SPM

- The AFM can measure small forces (< 1 nN), so any phenomenon that can be translated to force can thus be measured by the AFM
- The tip is very close to the sample, so it can be used to interact with the sample while scanning
- The general name : Scanning probe microscopy - SPM

- Friction : LF-AFM
- Electric field : EFM
- Voltage : KF-AFM
- Current : I-AFM, CAFM
- (Spreading) Resistance : SSRM
- Capacitance : SCM
- Magnetic field : MFM
- Temperature
- Magnetic field (Hall)
- Chemical interaction
- Optical excitation and detection : SNOM
- Lithography

Faster AFM

- Usually, AFM is slow! >5 mim/image
- Speed limits of AFM:
  - Cantilever resonance
  - Electronic feedback speed
  - Z piezo speed (resonance)
  - XY scanner speed (resonance)
- To get higher speed, we need to improve all parameters:
  - Short, wide cantilever: resonance 1.3 MHz in air
  - Faster scanner: 2.5 mm/s
  - High speed electronics
- Results: scan speed of 6-1200 Hz!



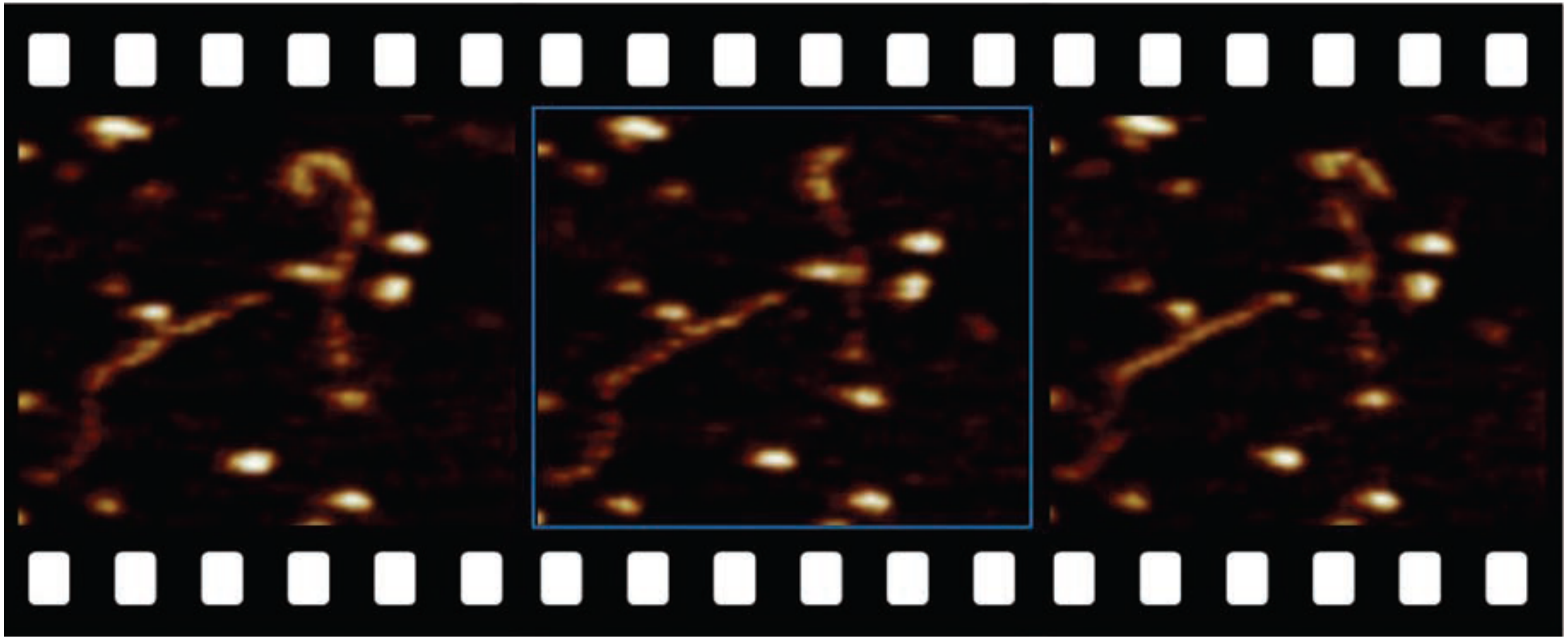
High resonance-frequency cantilever

High-speed scanner

http://www.bruker-axs.com/dimension_fastscan_atomic_force_microscope.html

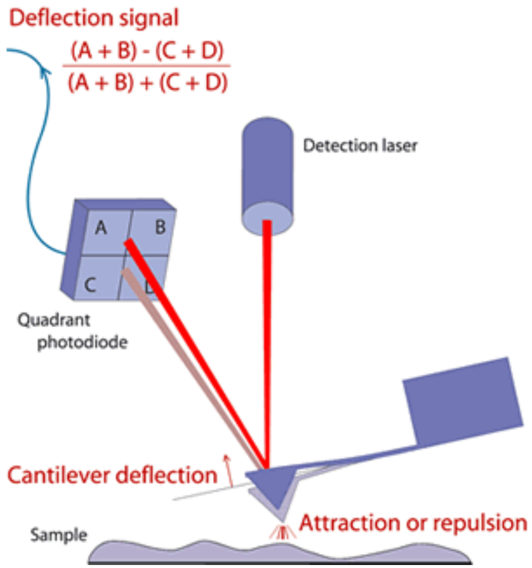
Faster AFM: example of use

- Sample: DNA on Mica in fluid
- Scan speed : 1 sec / image
- Result: “film” showing DNA movement
- Real-time video (10 Hz) is now possible



http://www.bruker-axs.com/dimension_fastscan_atomic_force_microscope.html

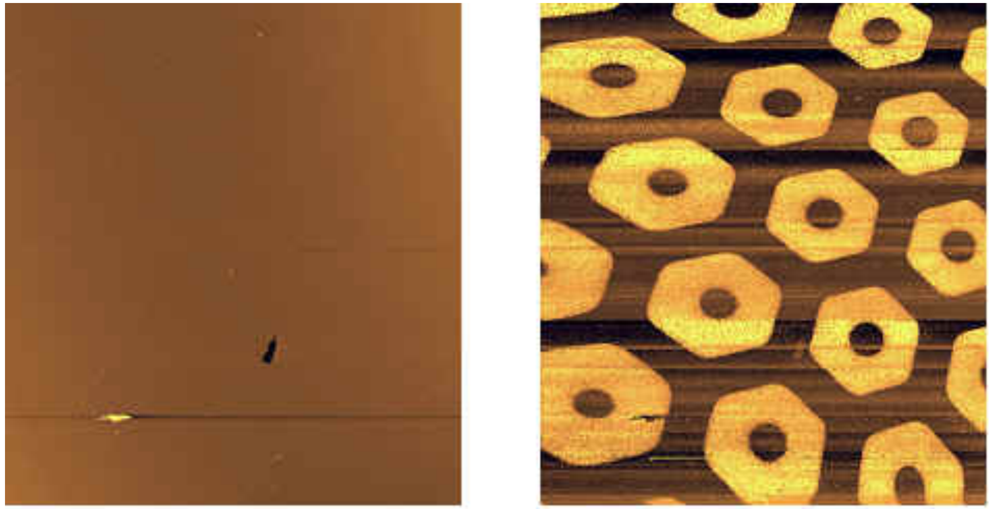
Lateral Force AFM



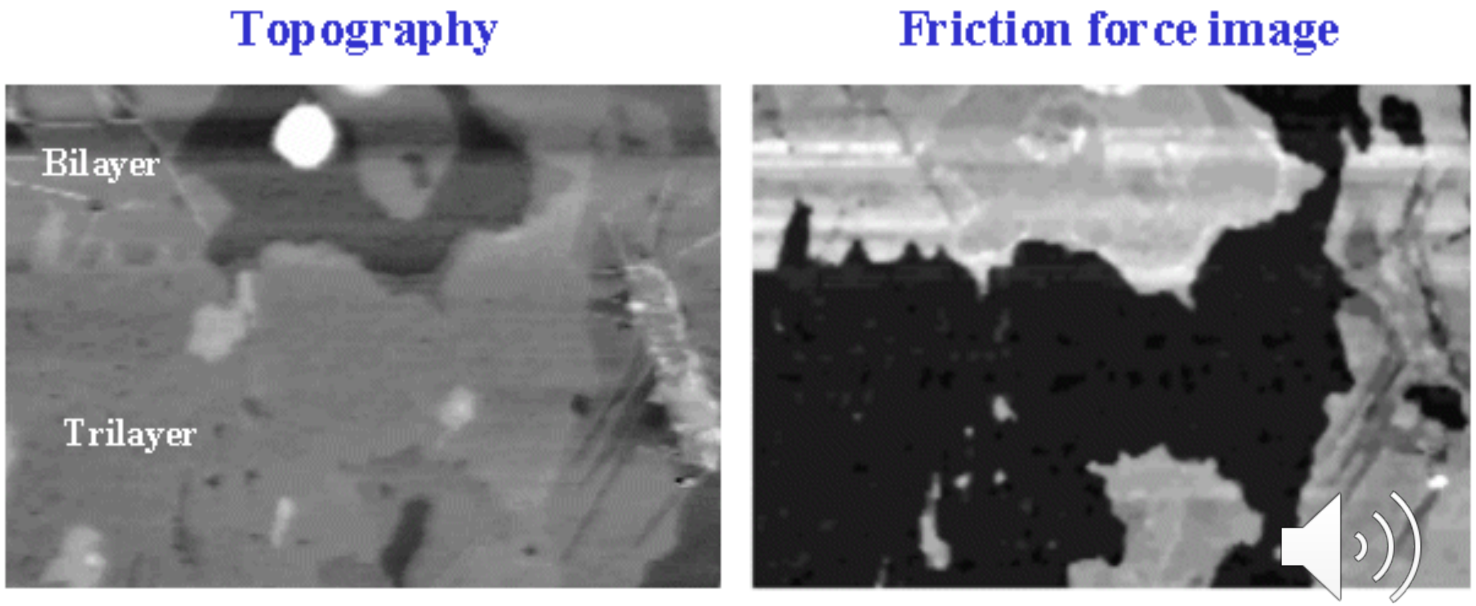
- Lateral movements of the cantilever are measured by the photodetector:

$$\frac{(A+C)-(B+D)}{(A+C)+(B+D)}$$

- Useful to measure friction and material contrast on planar structures.



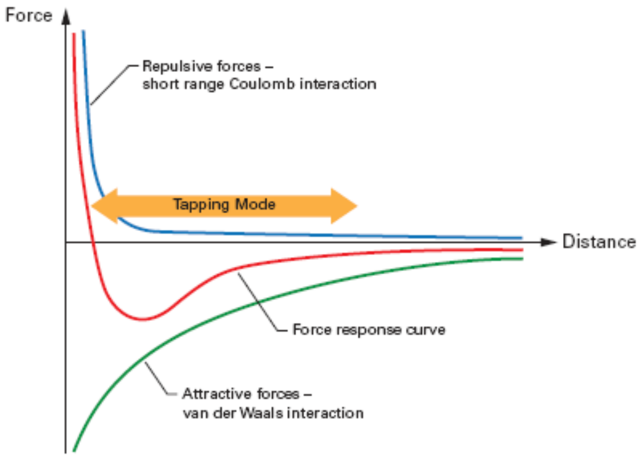
Patterned alkanethiol on Au
(topography and LFM)

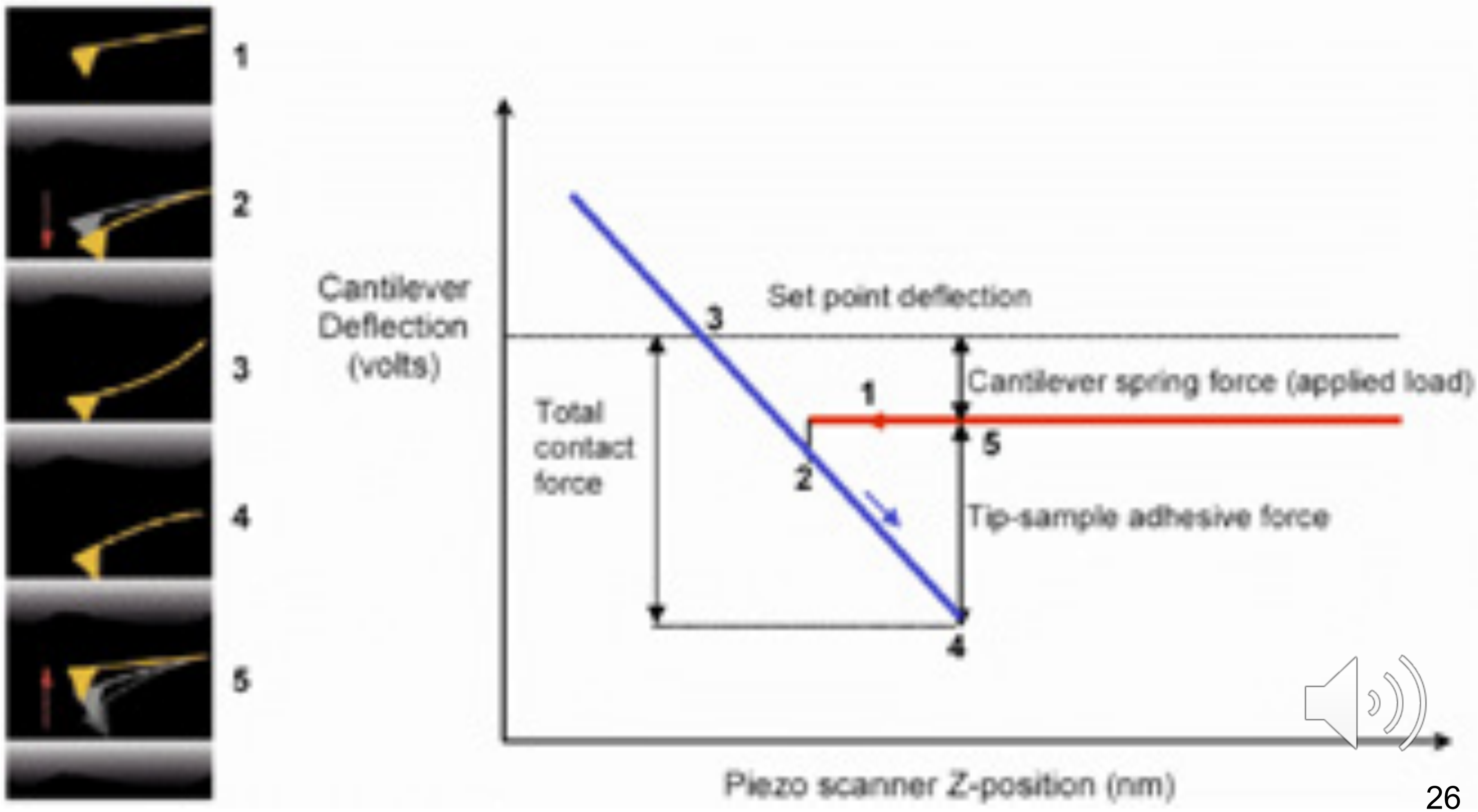


Si tip distinguishes hydrophilic and hydrophobic layers

Force curves: contact mode

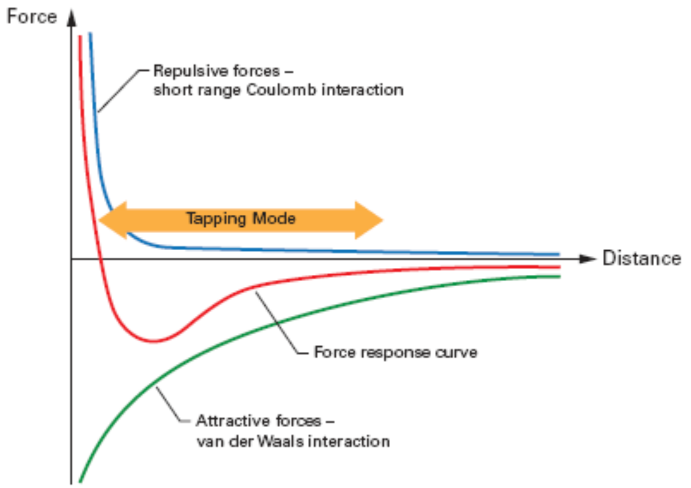
- In contact mode: Sweeping the tip up-down can show the force – distance curve, useful for analyzing mechanical properties (polymers, bio samples…)
- The van-der-Waals curve can not be fully traced due to tip jumps (hysteresis)

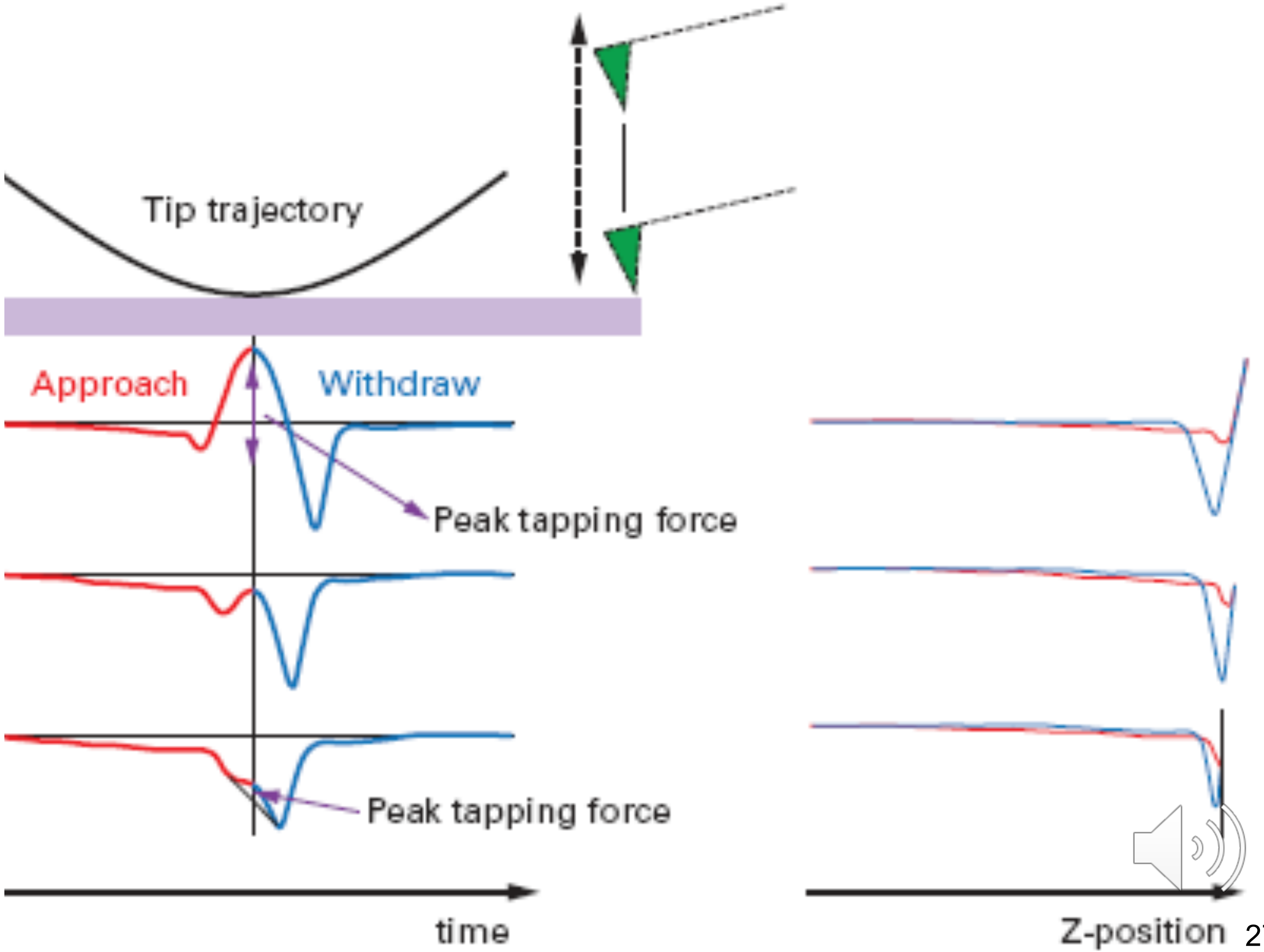




Force curves: intermittent contact

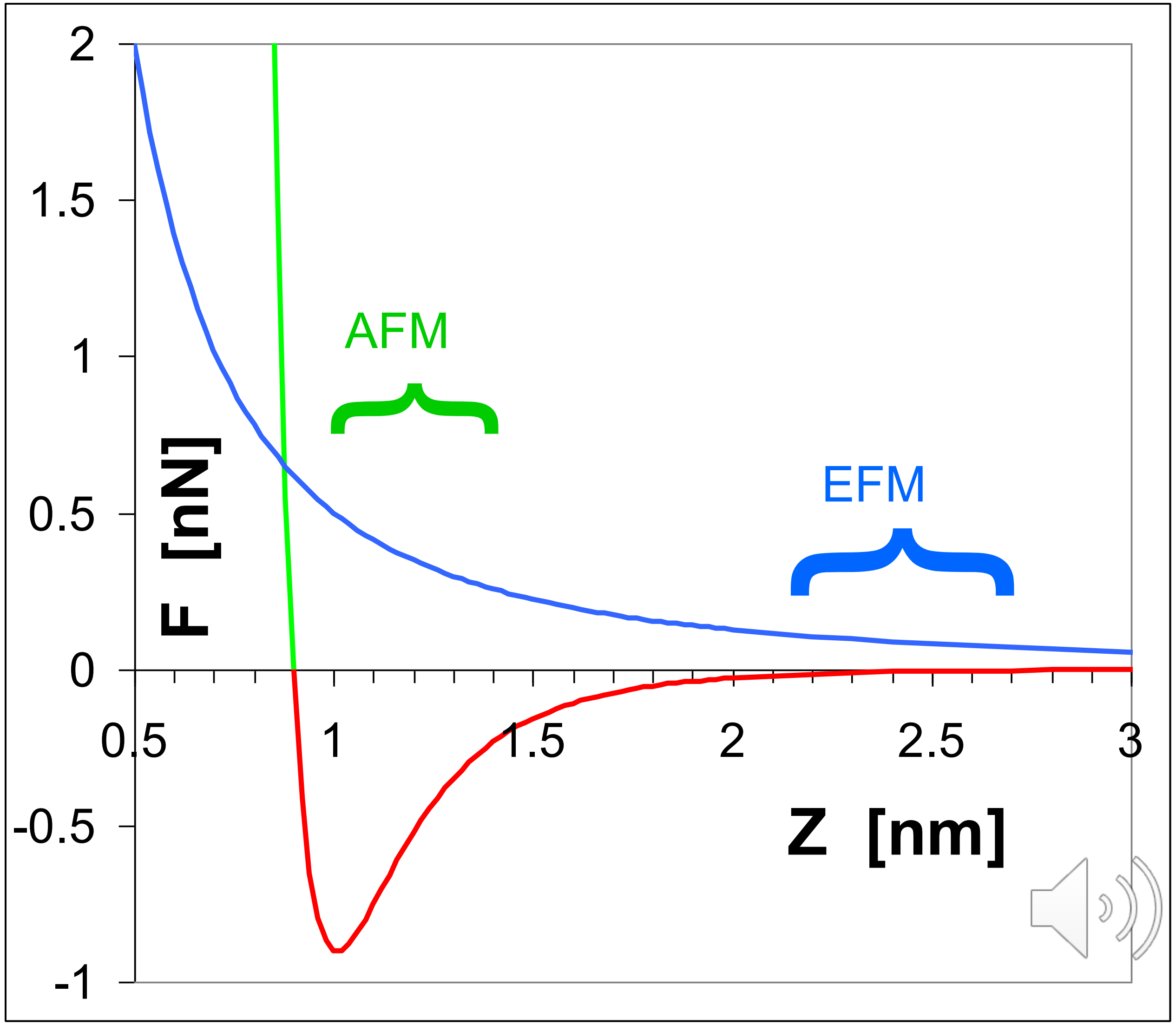
- New fast AFM can measure force-distance curve during each oscillation cycle of the tip
- Good control of peak force, reconstruction of curve





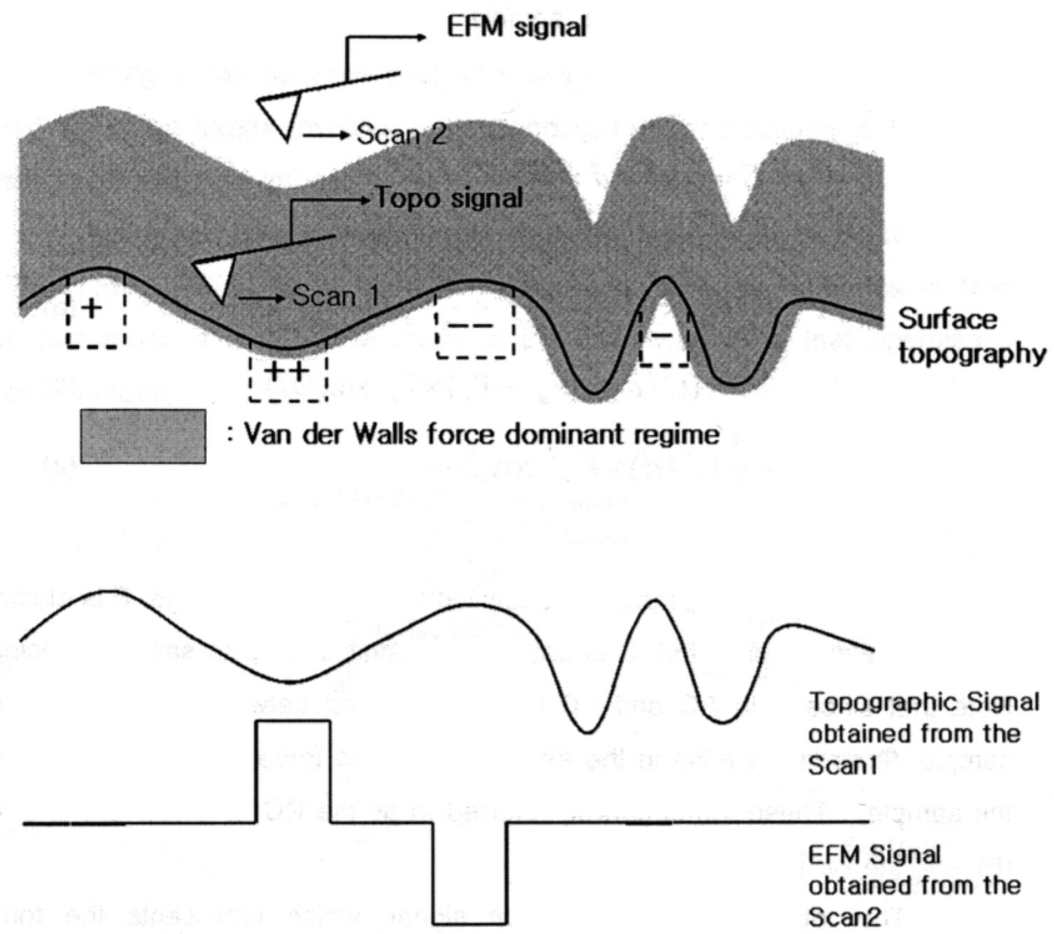
Electric Field – EFM: know your force …

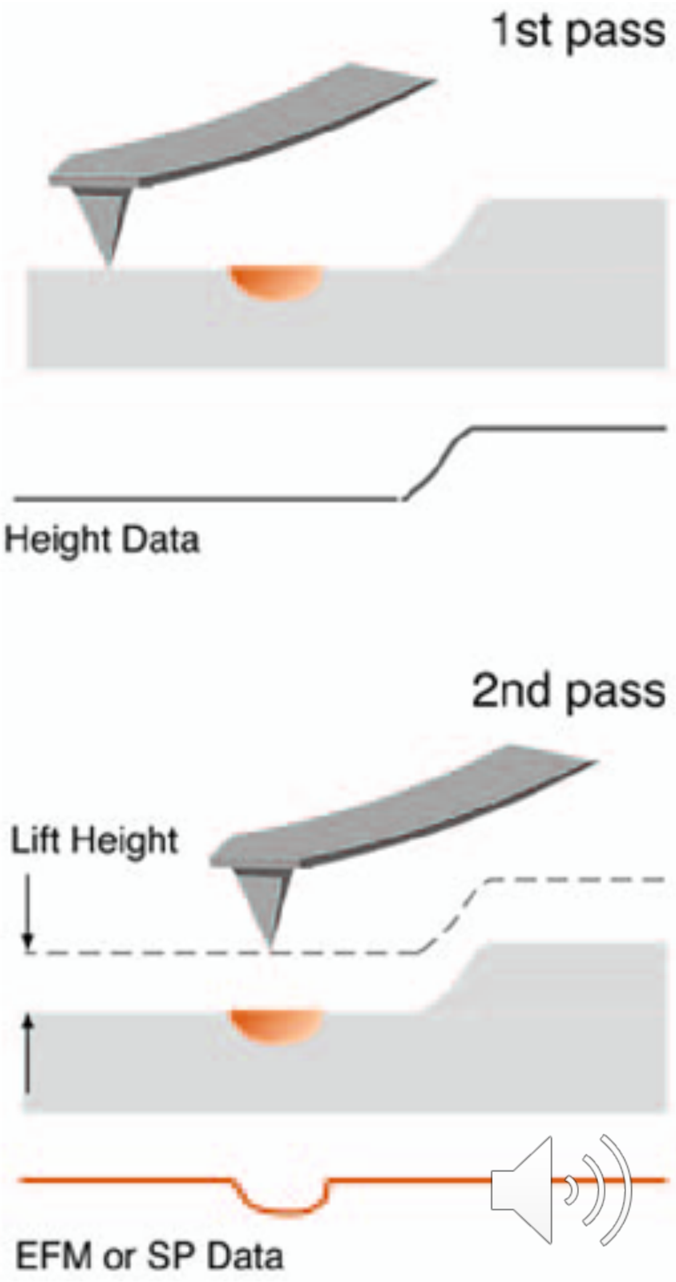
- When a voltage is applied between sample and tip, electric (Coulomb) forces are present
- Electric forces are long-range ($1/r^2$): can be separated from the short-range Van der Waals force ($1/r^6$) by scanning at a higher Z position

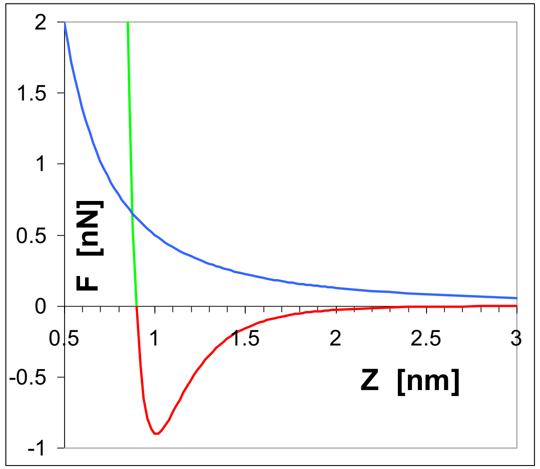


Electric Field – EFM : DC

- Drawback of scanning at great distance : lower resolution
- A better solution :Taking differential image at 2 distances ("lift mode")

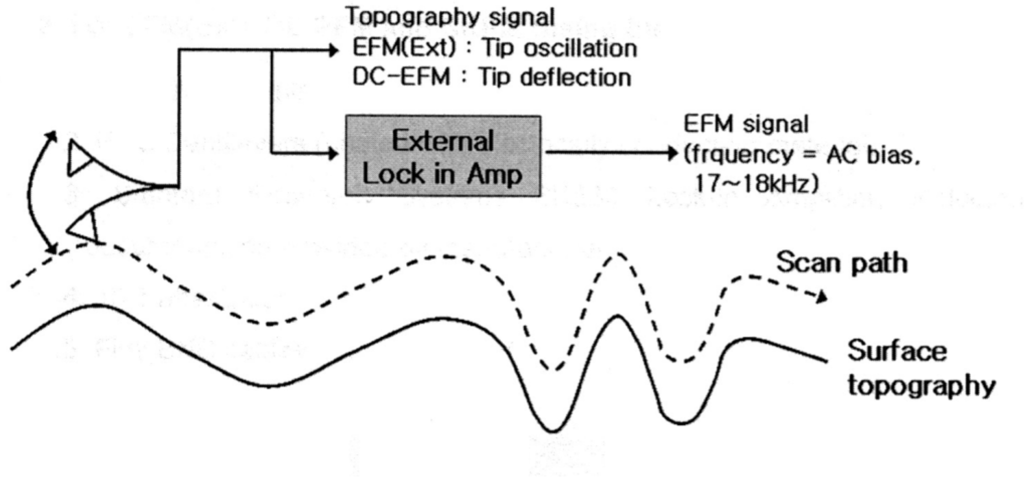




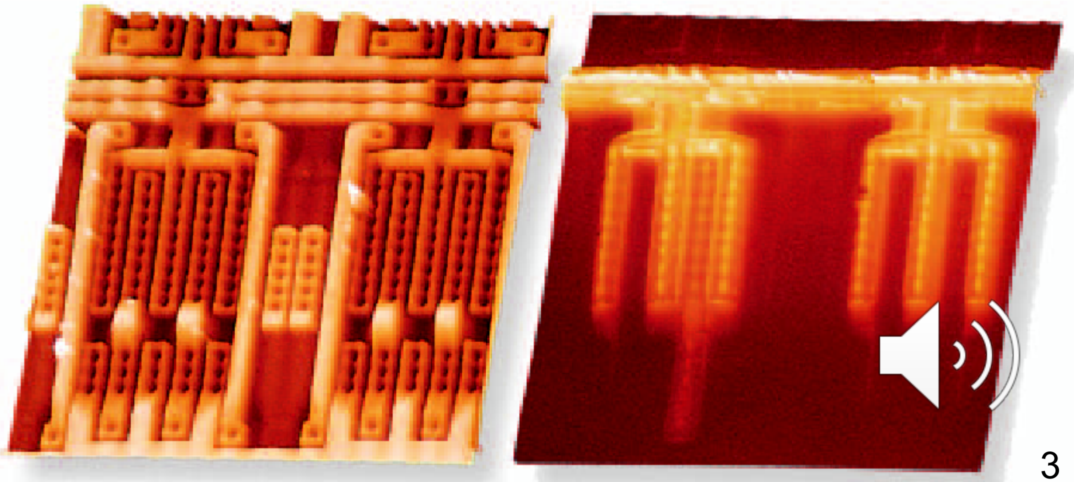


EFM : AC for high sensitivity

- In a parallel-plate geometry, the electric force is: $F_e = CV^2/d$; C = tip-sample capacitance ,d = tip-sample distance
- The tip-sample voltage is : $V = V_{dc} + V_{ac}\sin(\omega t)$



- The force is : $F_e = \frac{C}{d}\left[V_{dc}^2 + \frac{1}{2}V_{ac}^2 + 2V_{dc}V_{ac}\sin(\omega t) - \frac{1}{2}V_{ac}^2\cos(2\omega t)\right]$
- We can use the AC component at ω by lock-in detection



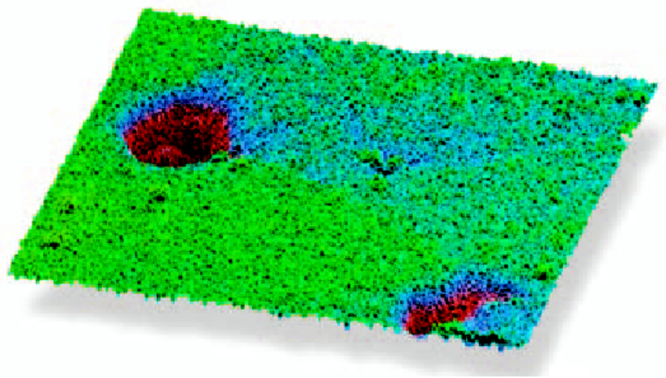
Si transistors : Topography and EFM

Voltage – Kelvin Force (KF)-AFM

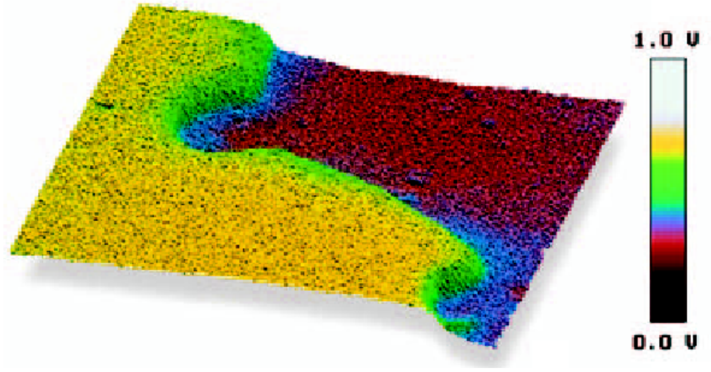
- AC-EFM can be used to measure the voltage at the surface of the sample
- A feedback loop is used to keep the EFM signal constant by changing the sample bias
- The resulting signal is the surface potential at the sample

Topography

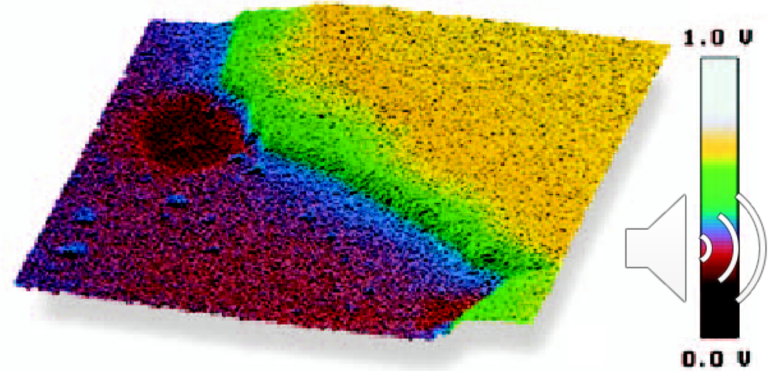
(10x10μm)



Surface potential V=+4V

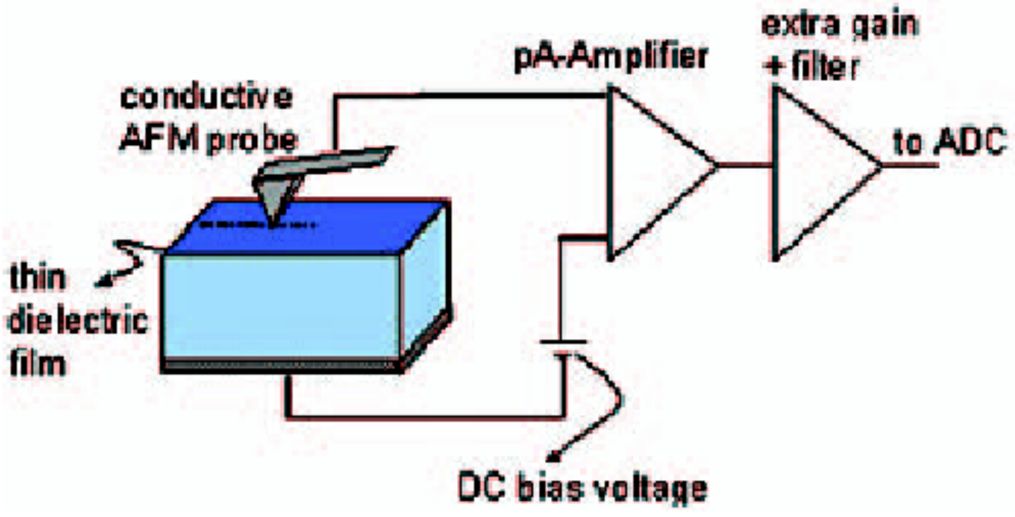


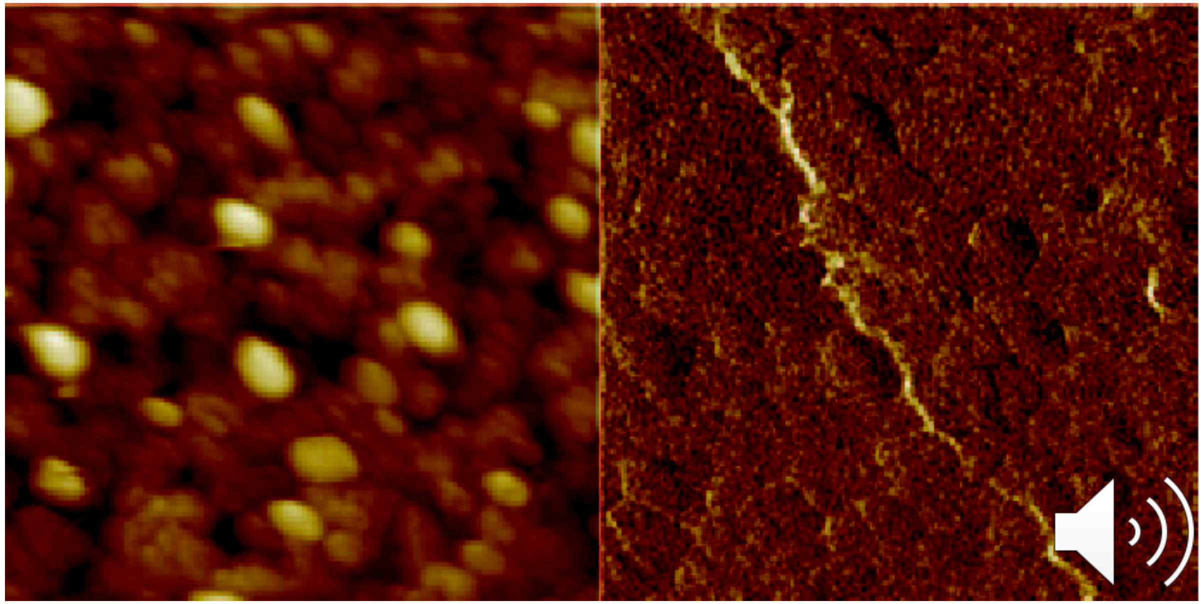
Surface potential V=-4V



Current – I-AFM, CAFM

- Contact AFM with a metal-coated tip can be used to pass current between tip and sample
- For semiconductors and insulators a sensitive current preamplifier should be used
- Low currents (<1 pA) can be measured





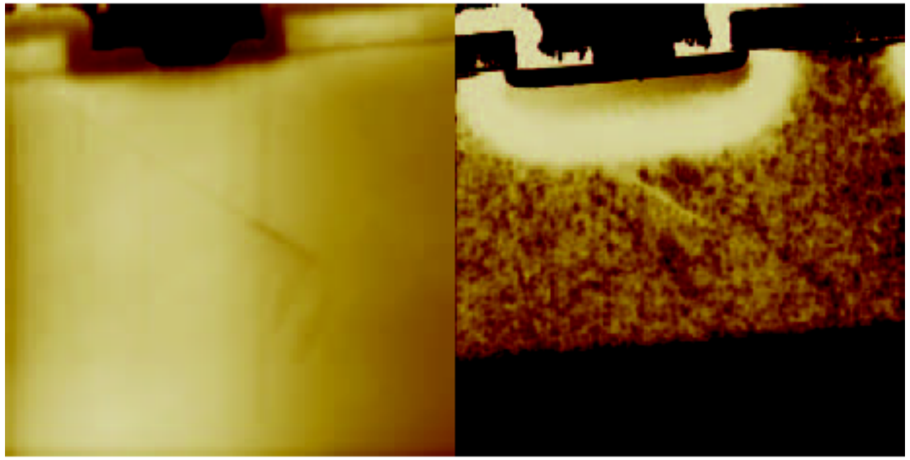
$BaTiO_3$ film, 2x2 μm, 2 pA (topography and current)

Spreading-resistance – SSRM

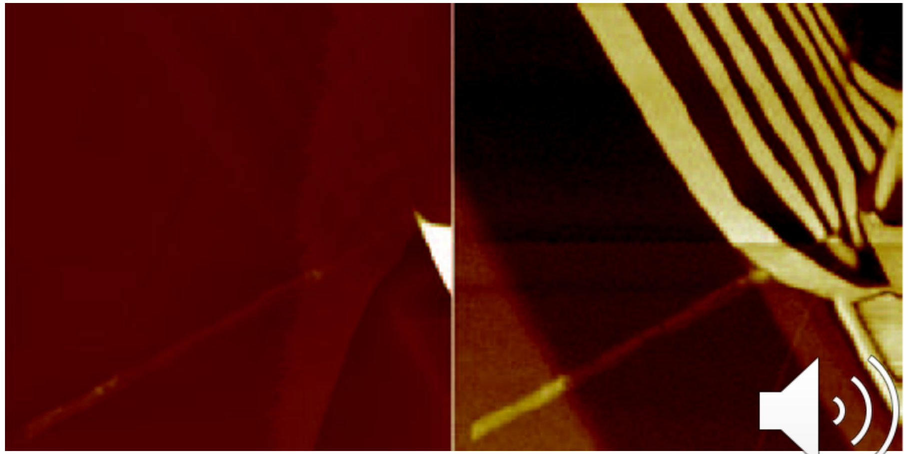
- I-AFM can be used to measure resistivity : supposing a circular tip-sample contact of radius r, the local resistivity is given by:

  $\rho = 4rV/I$

- Local resistivity is linked to doping concentration, leakage
- In air, high forces (μN) are needed – diamond tips



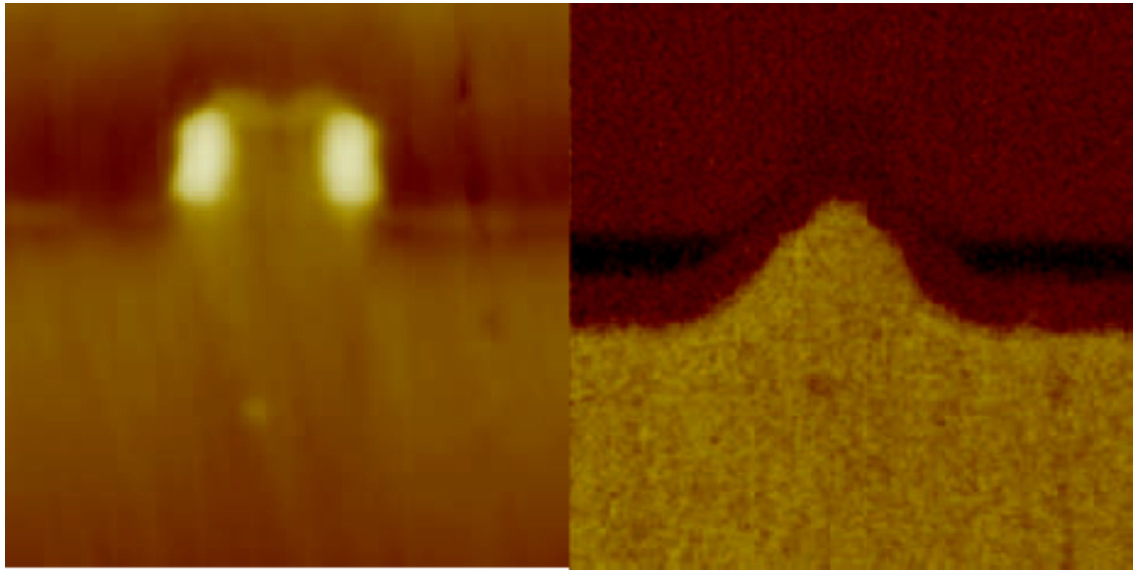
Si DMOS transistor, 12x12 μm (topography and resistance)



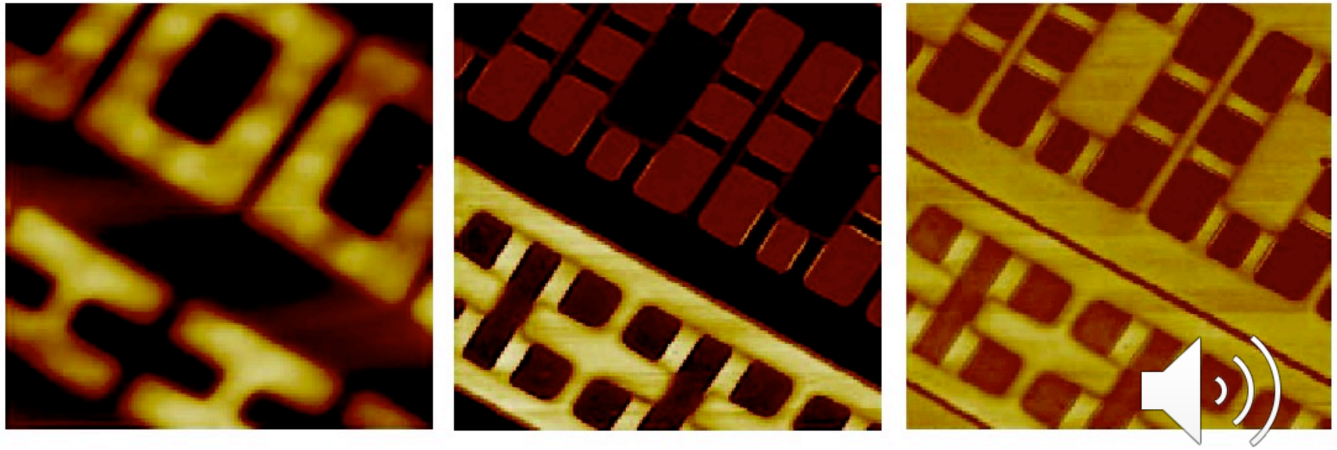
InP transistor, 7x7 μm (topography and resistance)

Capacitance – SCM

- An AC voltage applied between tip and sample leads to the flow of AC current
- Using high frequency (~1 GHz), small capacitance (<1 aF) can be measured
- SCM can be useful for measuring doping in semiconductors

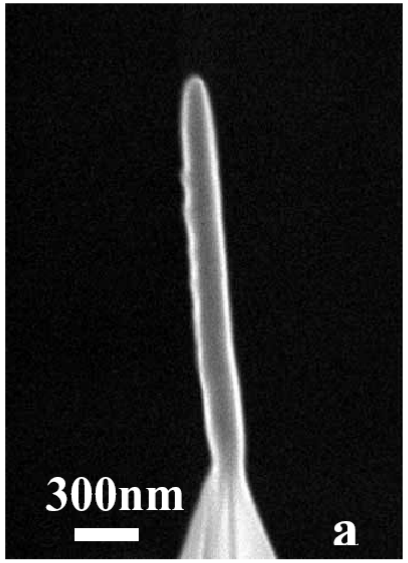


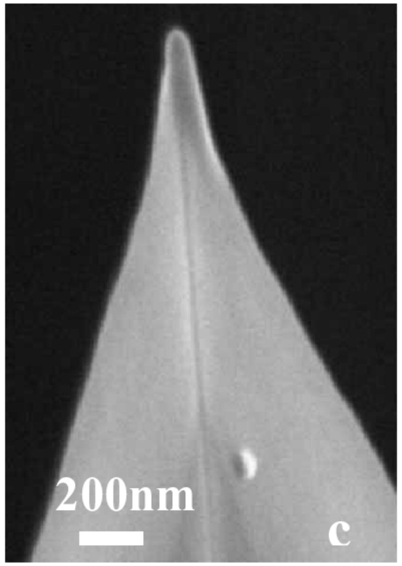
Si MOS transistor, 1.25x1.25 μm (topography and dC/dV)



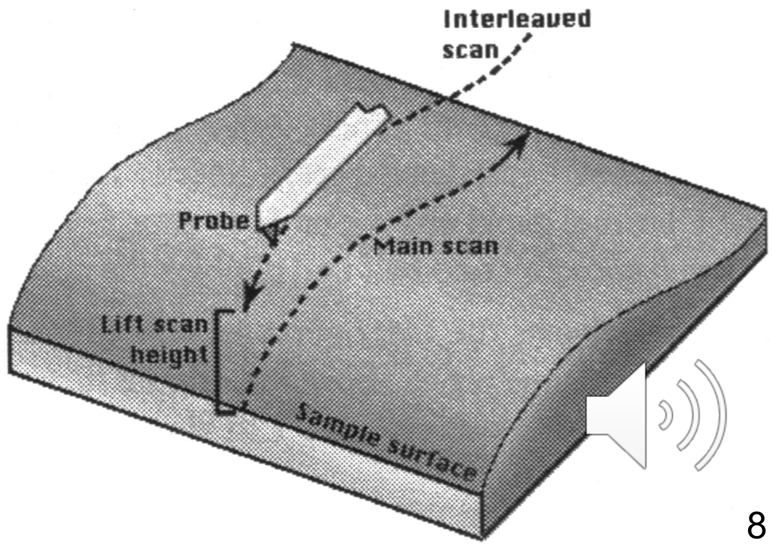
Si DRAM cell (topography and dC/dV amplitude and phase)

Magnetic Force - MFM



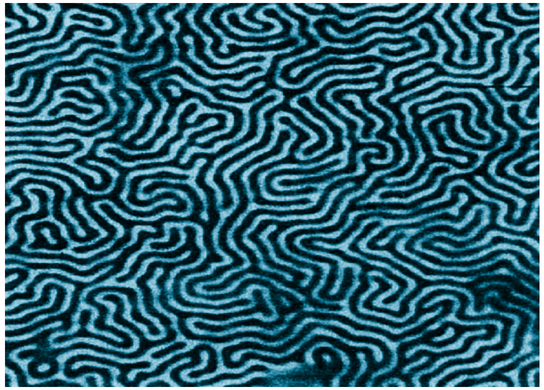


- AFM tip made from or coated with magnetic materials (Co, Ni)
- Magnetic forces are long-range: can be separated from Van der Waals force ($1/r^6$) by:
  - Scanning at greater distance – only magnetic forces remain
  - Taking differential image at 2 distances ("lift mode")
  - Looking at phase in non-contact mode

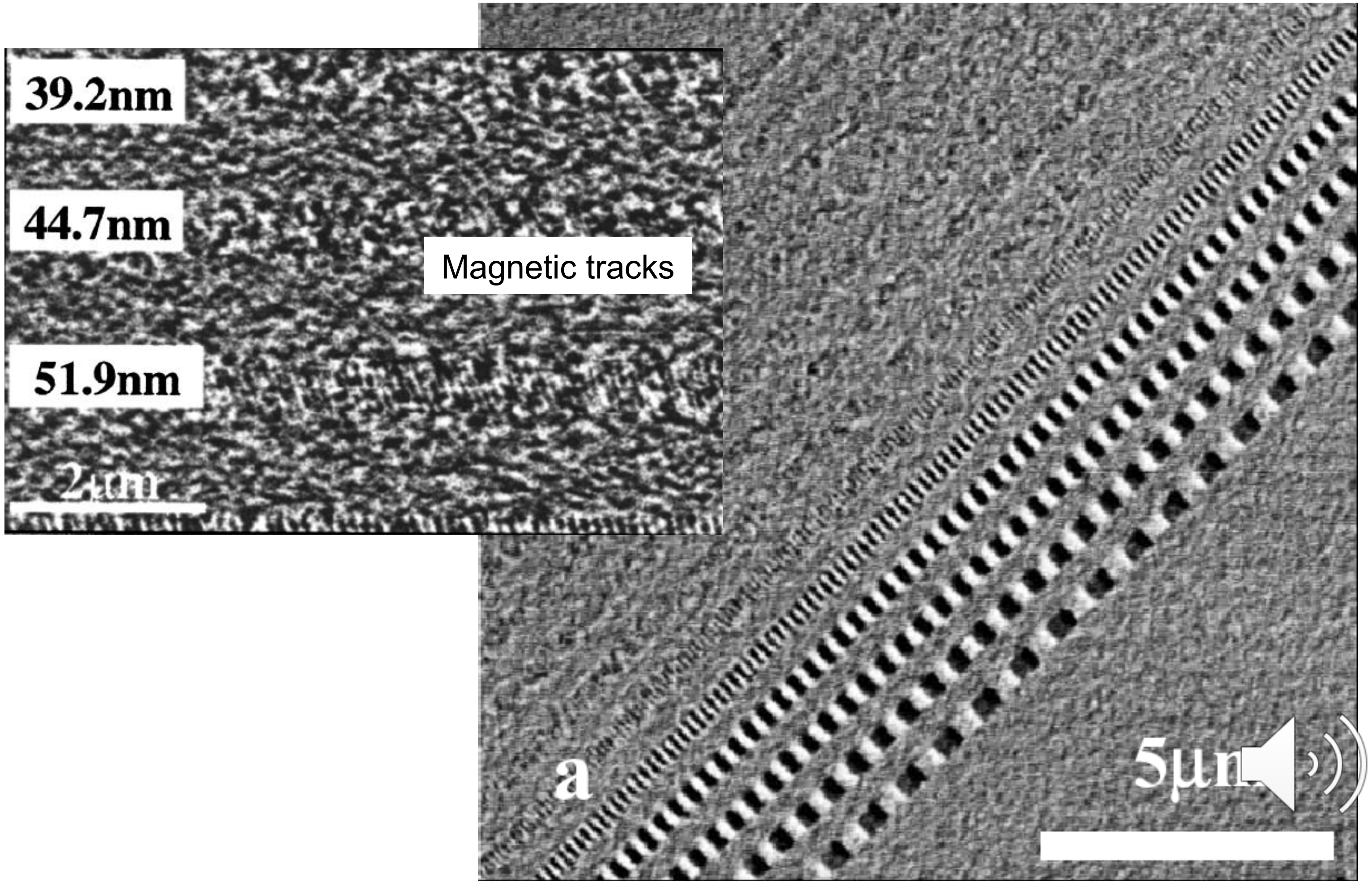


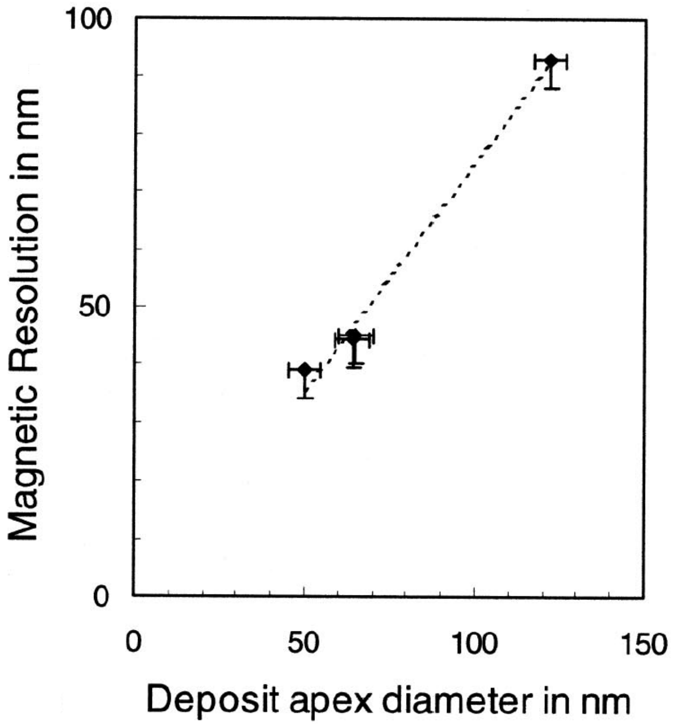
Magnetic Force - MFM

- Uses of MFM:
  - Characterization of magnetic materials and nanostructures, e.g. magnetic semiconductors
  - Hard-disk testing
  - Future magnetic storage



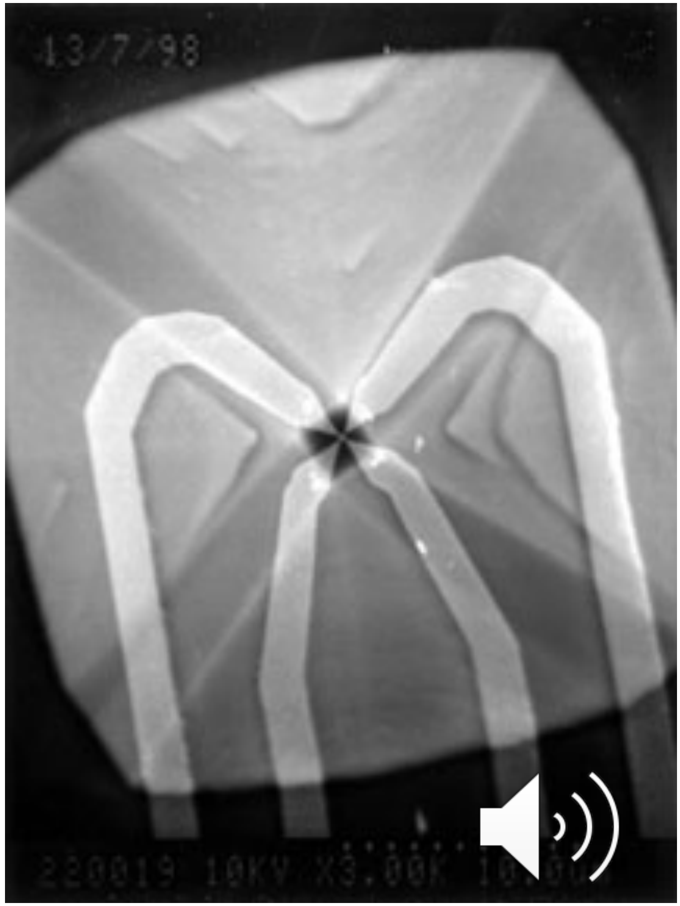
Co magnetic domains





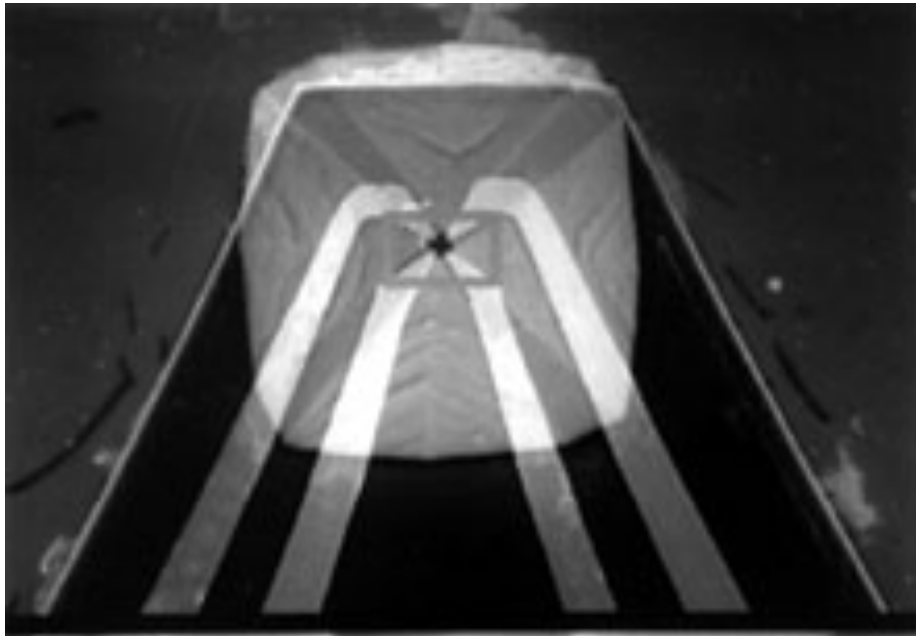
Hall Effect

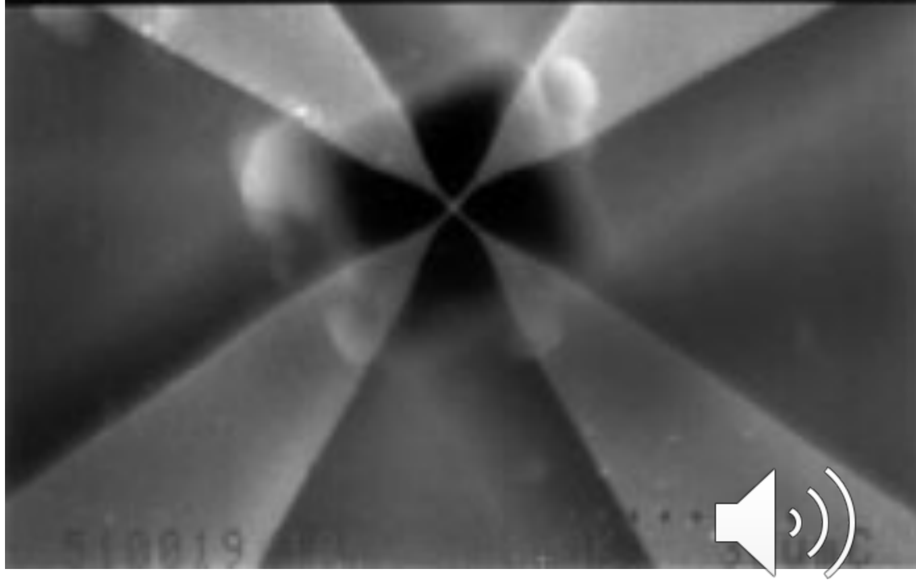
- A miniature Hall cross (0.1 μm) is evaporated on the AFM tip
- Local magnetic fields can be measured with sub-μm resolution
- Resolution is lower than MFM, but sensitivity is higher

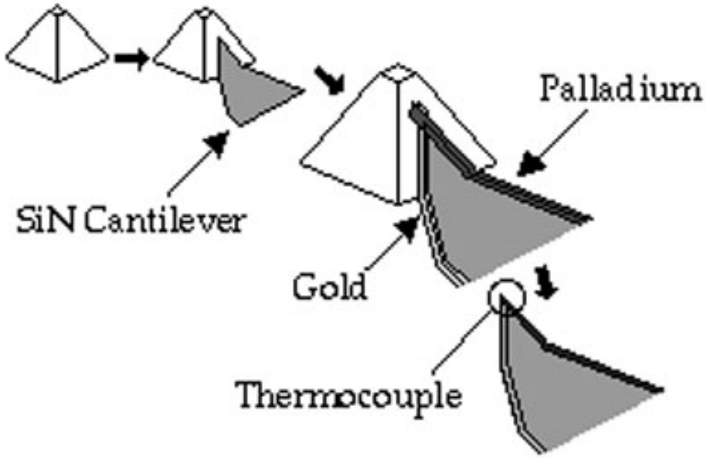


Temperature – SThM

- To sense temperature at the AFM tip, two methods are used:
  - A thermocouple is evaporated on the cantilever, with the junction at the tip
  - The (temperature-sensitive) resistance of the Si cantilever is monitored
- Local defects in circuits can thus be found

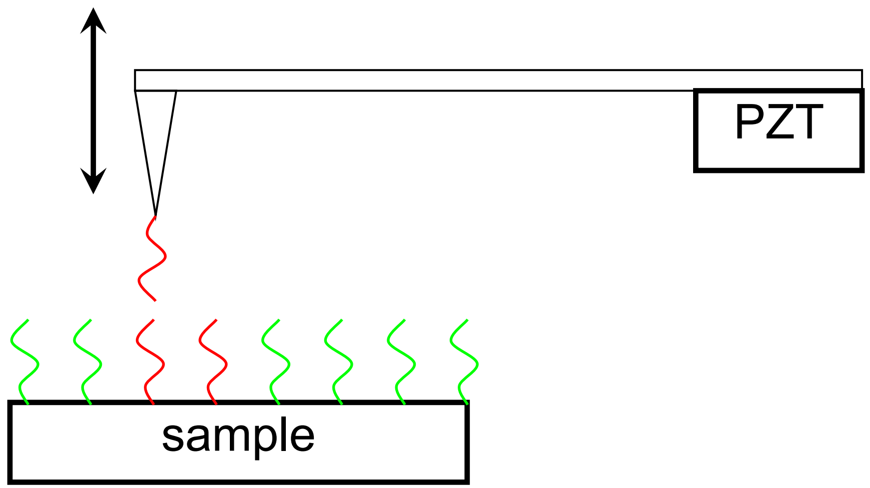


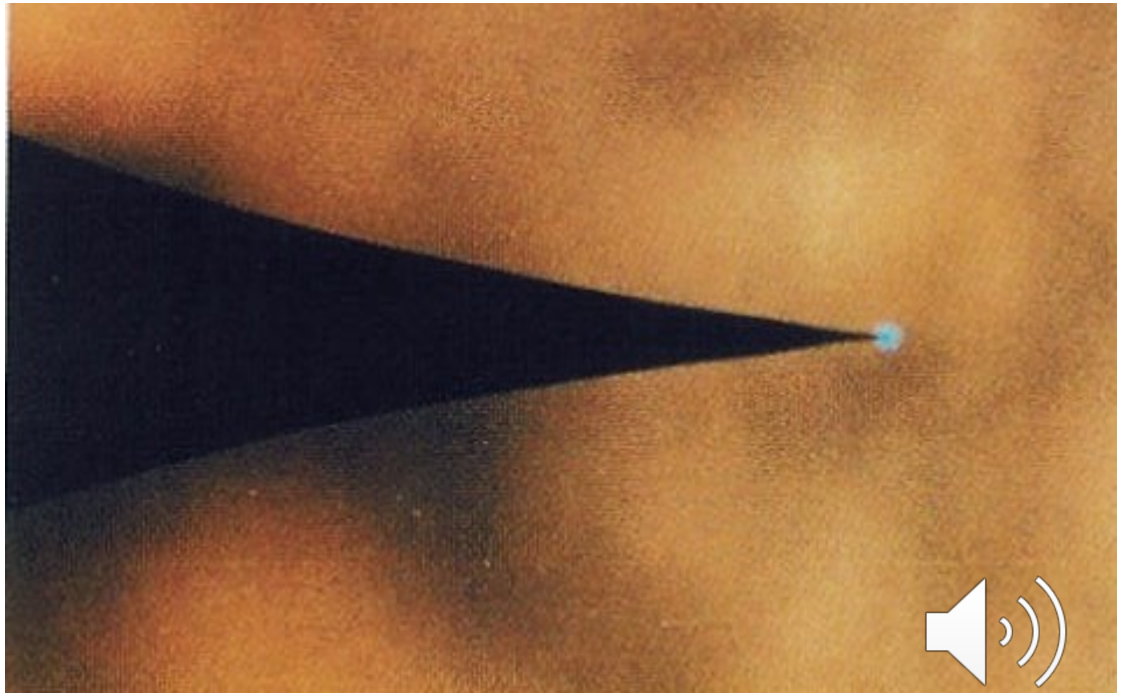




Chemically sensitive AFM

- The high force sensitivity of AFM can be used to measure chemical interactions
- The AFM tip is coated by a chemically active molecule
- This tip is then sensitive to molecules which interact with the tip's coating
- When the right molecule is sensed, chemical interaction causes a change in the force

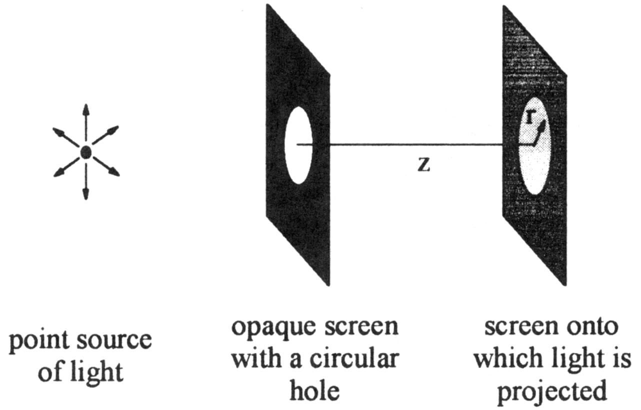


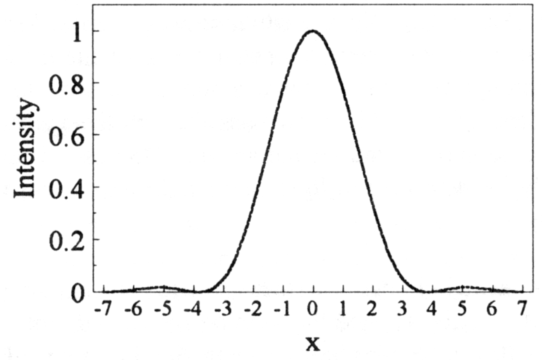


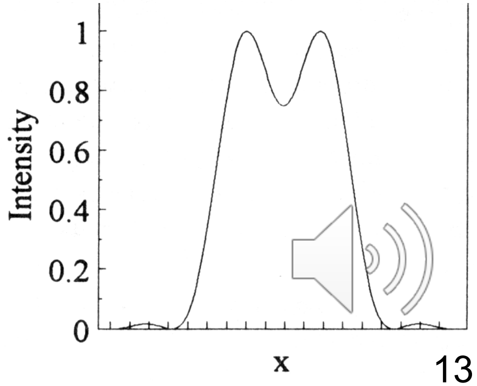
Phosphorescence at the chemically modified tip edge

Scanning Near-field Optical Microscopy – SNOM

- Optical microscopy is normally limited in resolution by the diffraction of light to about 0.5 μm : $I(r) = 4I_0 J_1^2(x)/x^2 \quad x = \pi dr/\lambda z$
  - *d=hole diameter in mask,*
  - *z=distance mask-wafer,*
  - *r=distance from center*
- Close to a sub-wavelength aperture, the optical near field has the extent of the aperture, but it diverges quickly
- The AFM scanning technique can be used to scan a small aperture close to a surface, thus providing sub-wavelength resolution
- Several SNOM techniques exist, mostly using metal-coated optical fibers with a small aperture (< 100 nm) at their end

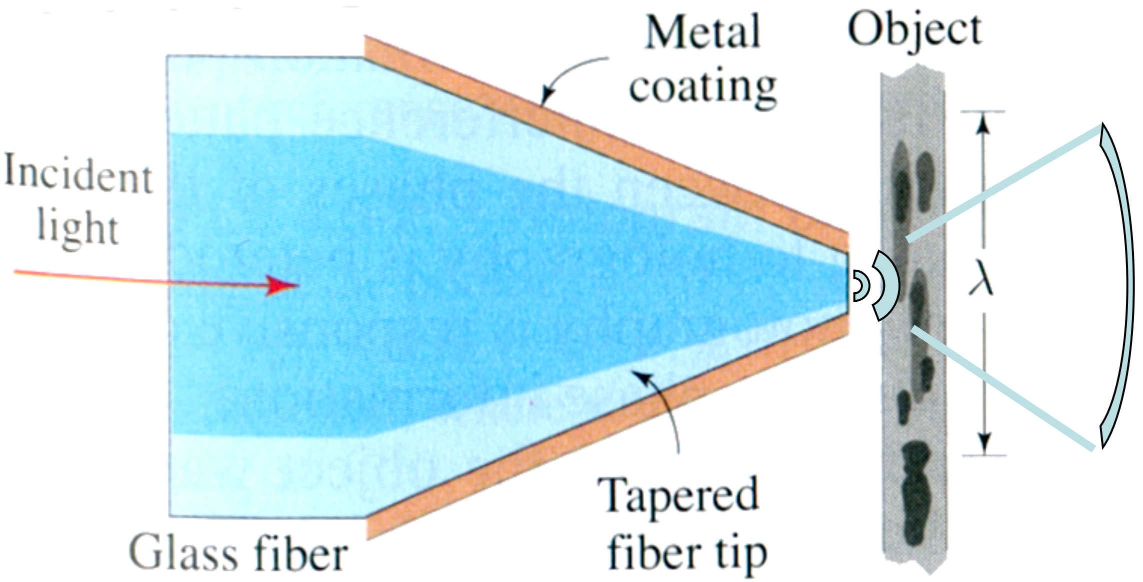




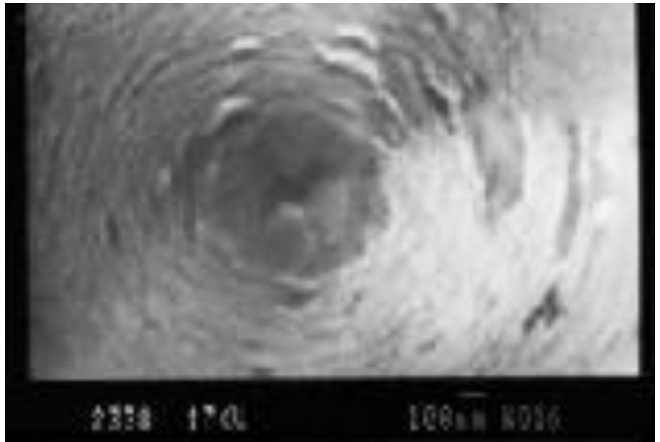


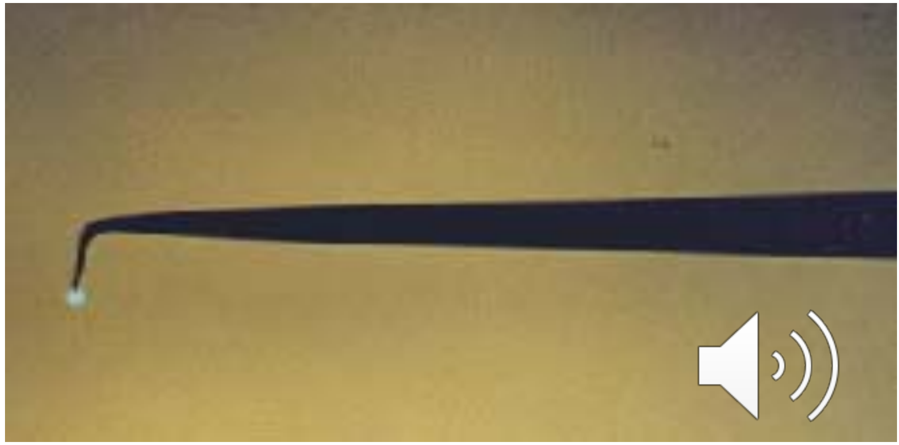
Principle of operation

- A conical-end (drawn or etched) optical fiber is coated by a reflecting metal (Al)
- The conical end of the tip is exposed to let the light come out through a small hole



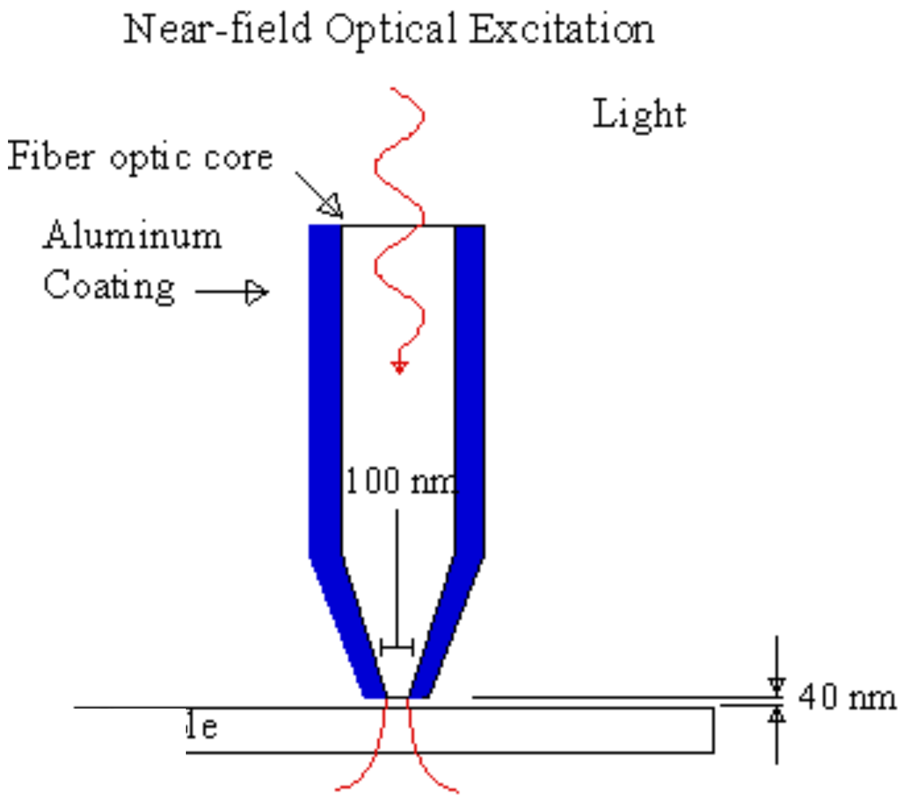
- The tip is scanned close (< 50 nm) to the sample, so that near-field light goes through and can be detected, giving high resolution

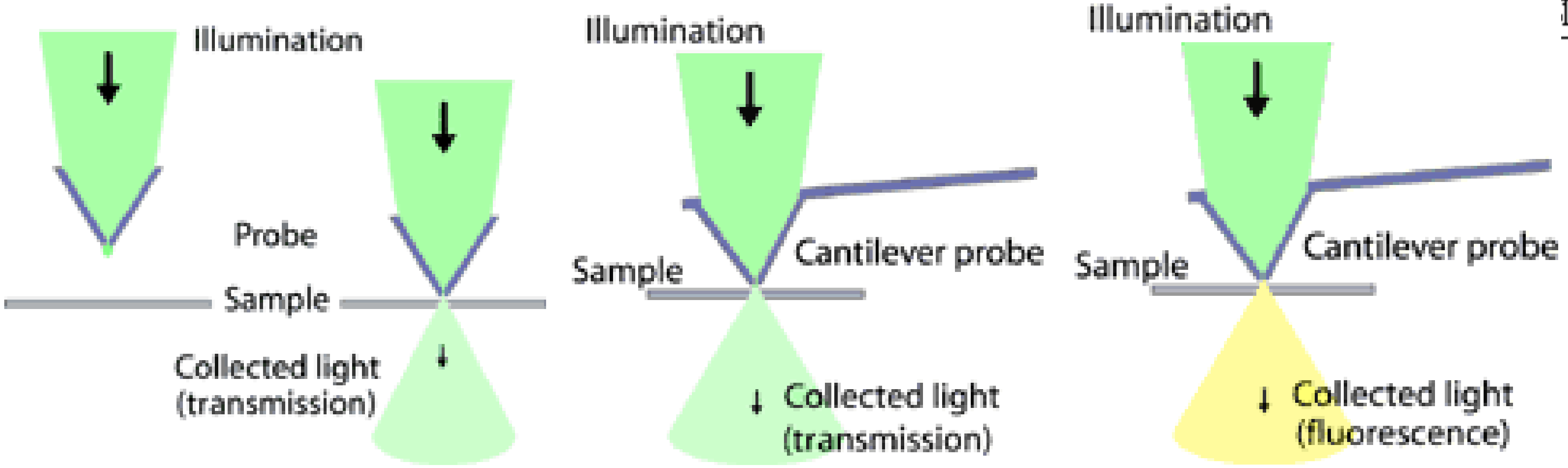




Types of SNOM (1)

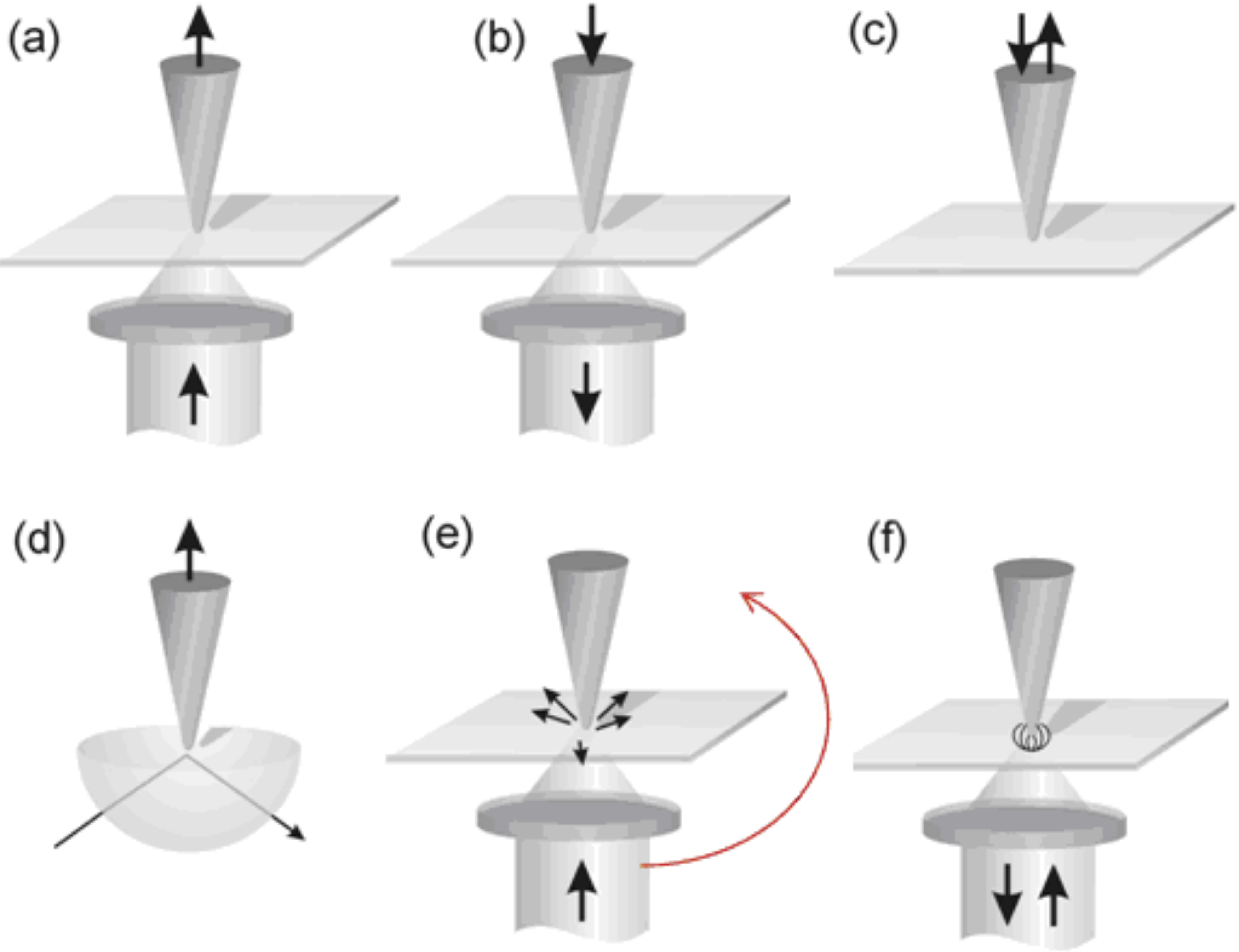
- The illumination is brought to the tip of a fiber, transmitted light is collected through the sample (Transmission)
- The illumination is brought through the AFM tip
- Fluorescence or photoluminescence is collected (PL)
- Light generated by the sample (e.g. laser) is collected

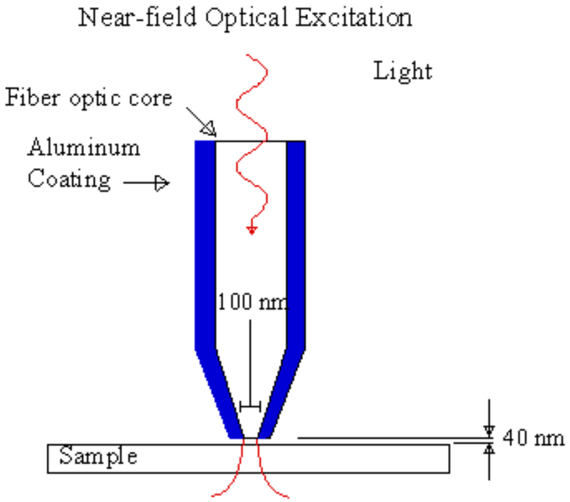


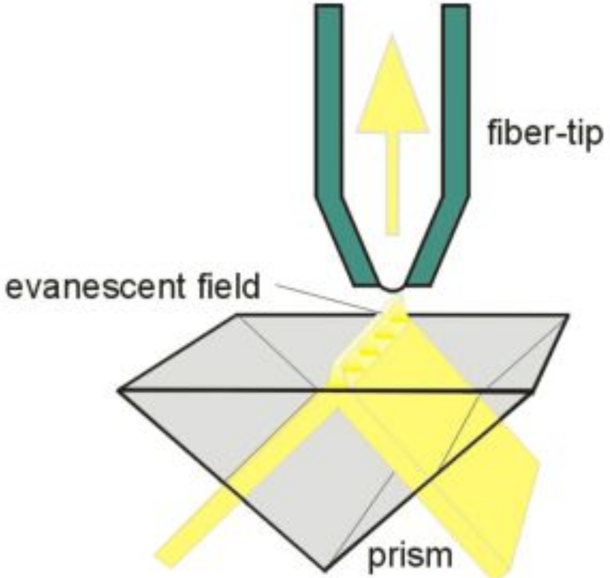


Types of SNOM (2)

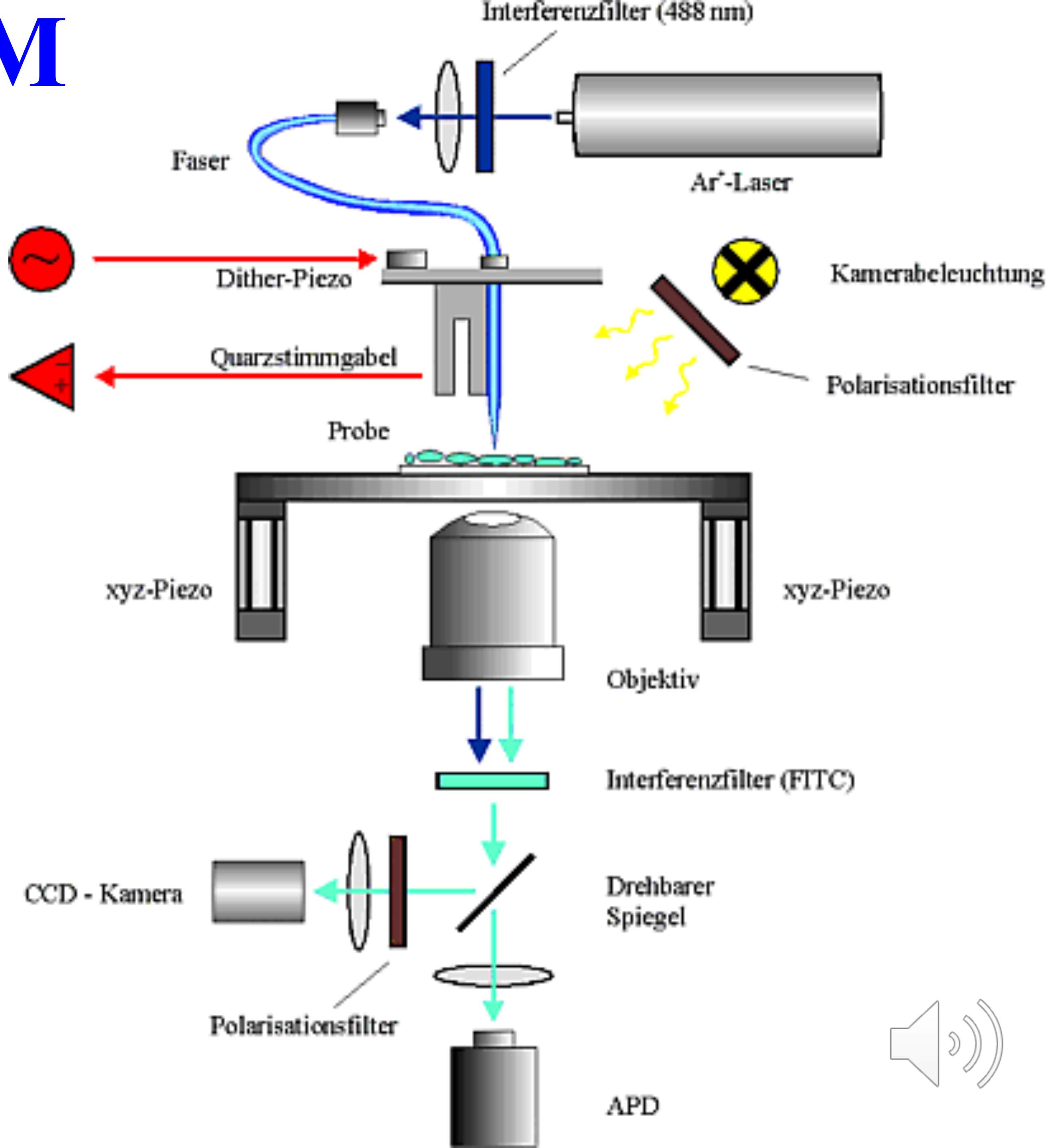
- Different optical schemes can be used: objective lens, prism (evanescent coupling), etc.







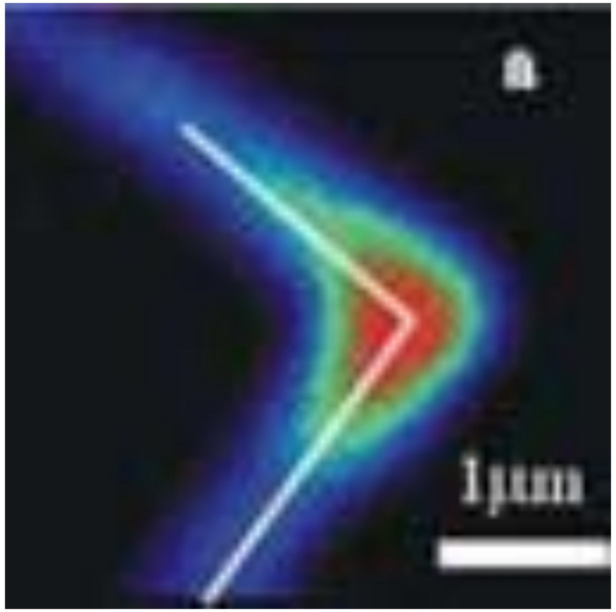
Structure of the SNOM

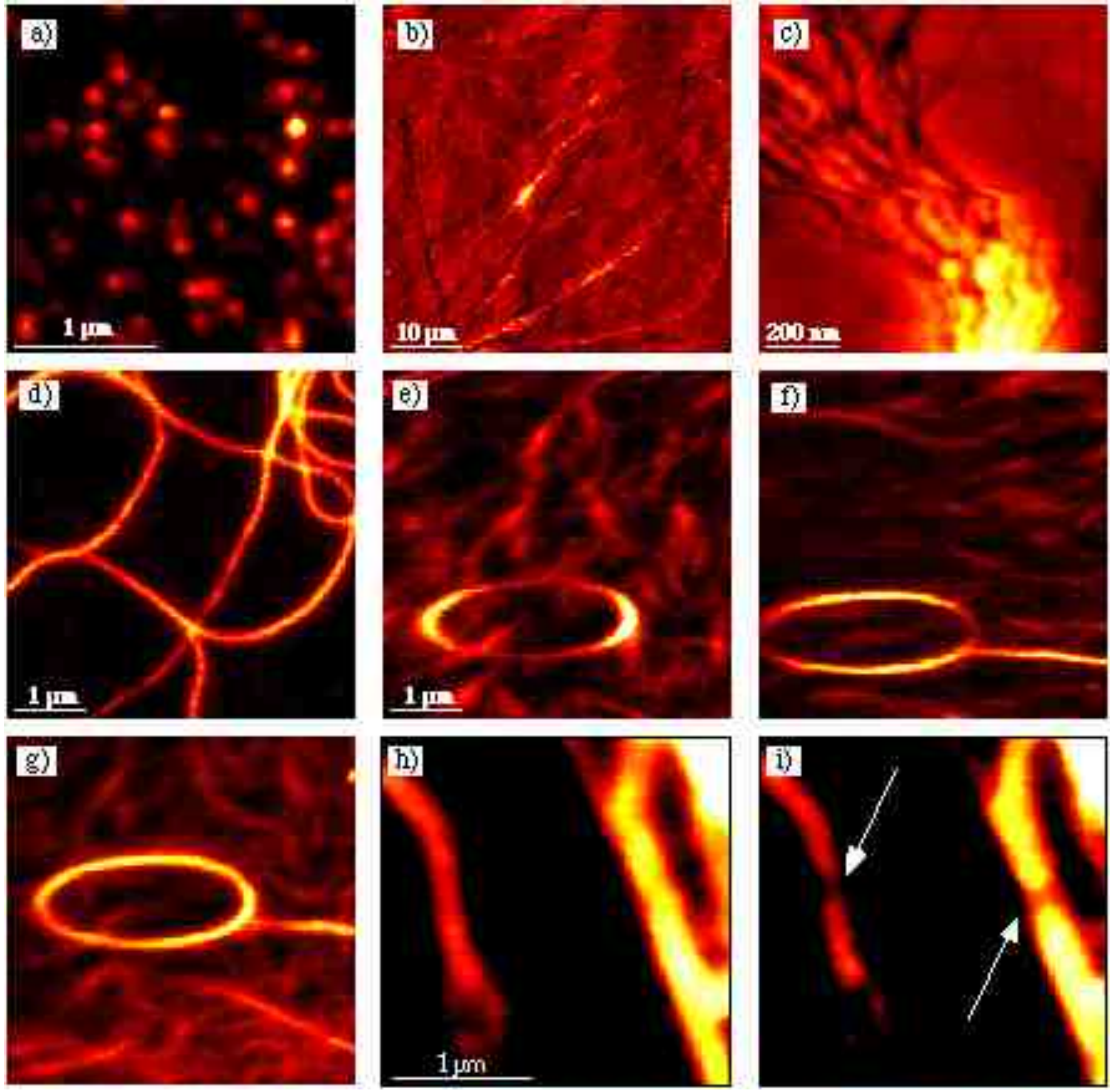


Some SNOM images

- Fluorescent molecules:

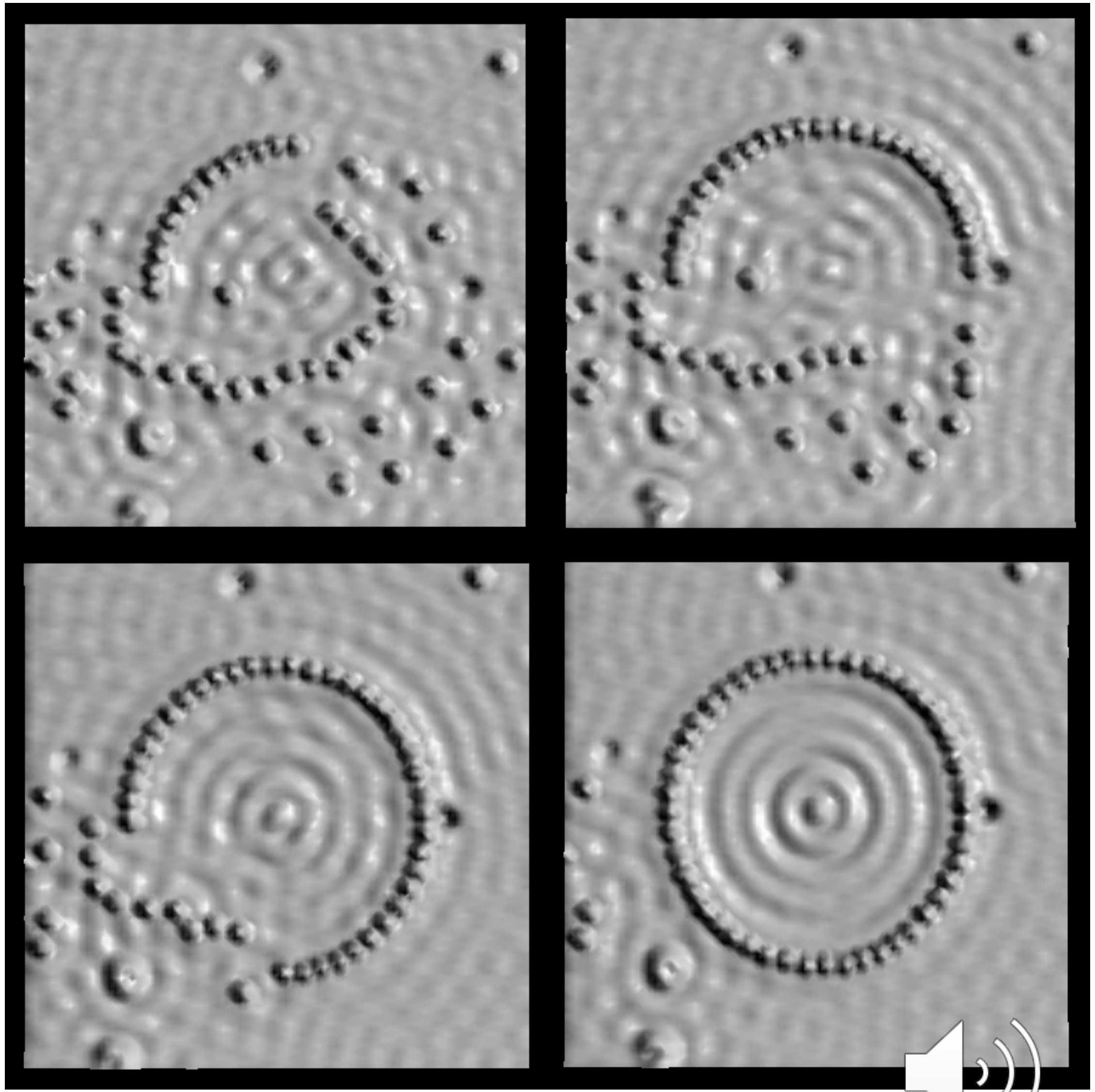
- V-shaped laser (cross-section)





STM and AFM lithography

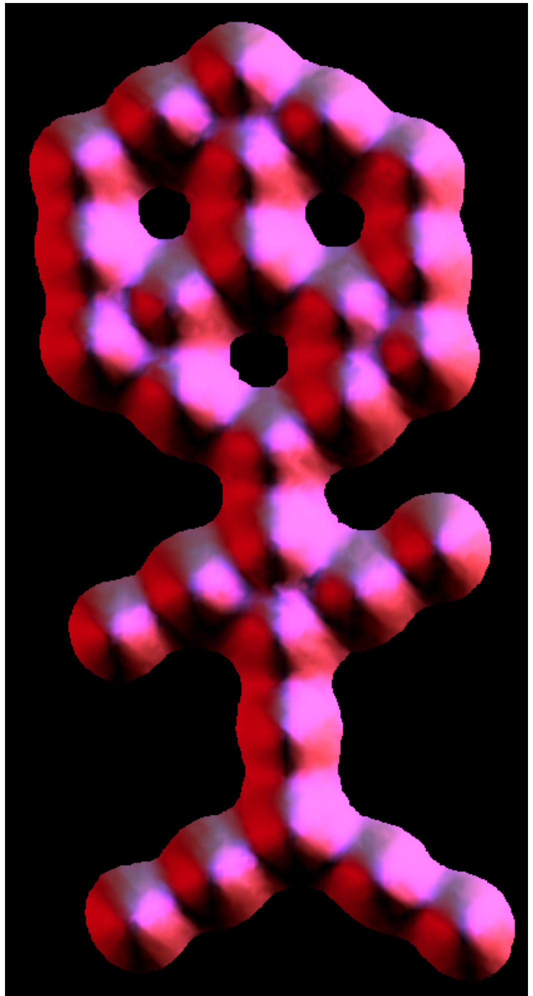
- The small forces between tip and sample can be used to move atoms and molecules
- At low temperatures, Ar or metal atoms can be adsorbed on an atomically flat metallic surface (Ag, Cu) and manipulated by STM
- Artificial structures can be constructed … vary slowly

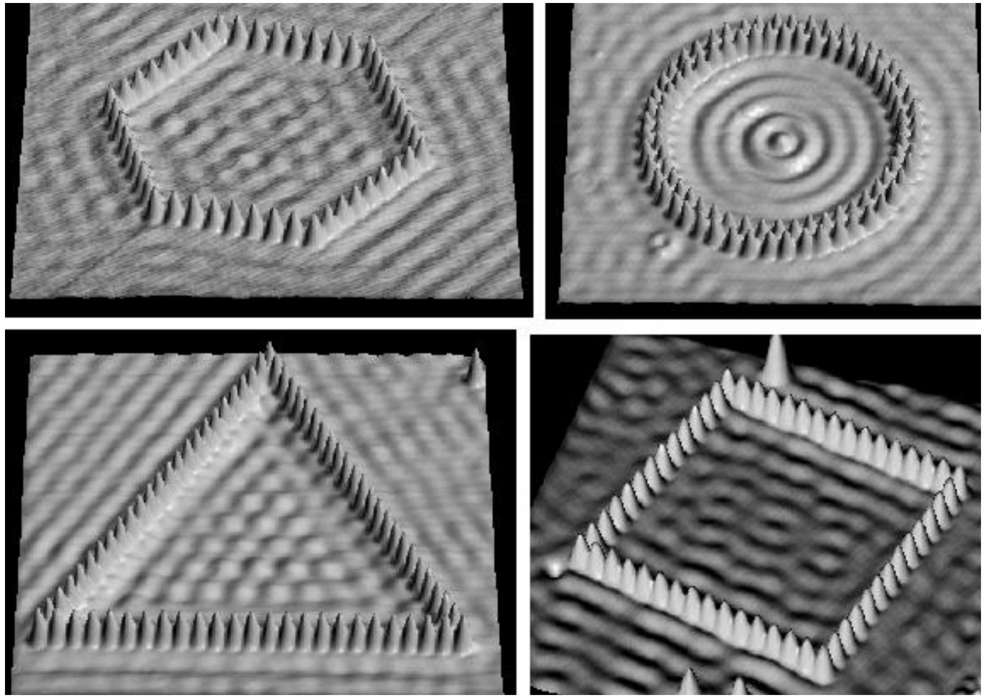


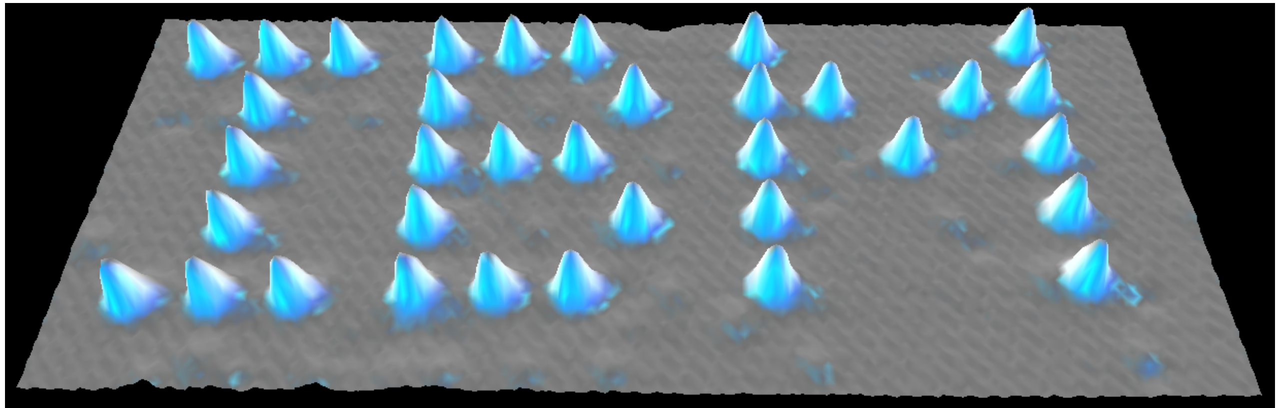
- Note the quantum-mechanical interference !

Examples of STM lithography

- From the labs of you-know-who…

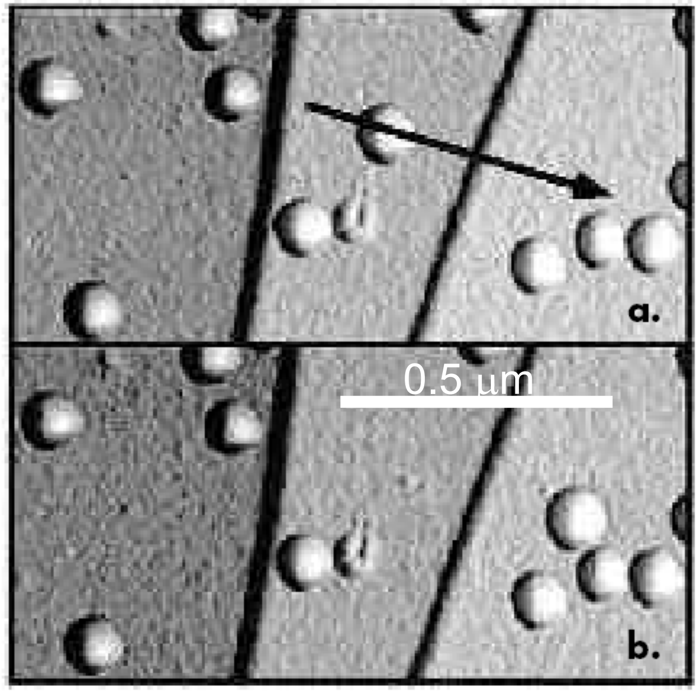


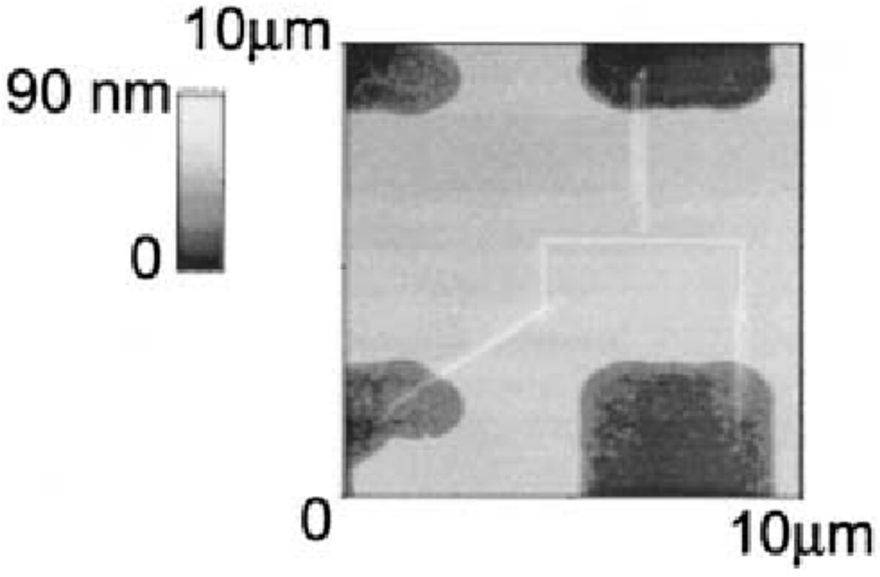


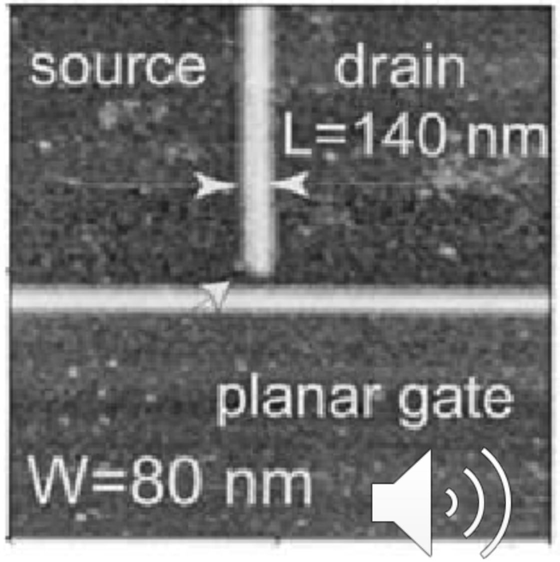


AFM lithography

- AFM can be used for nano-lithography in several ways:
  - The AFM tip can scratch or indent soft surfaces, e.g. a PMMA layer on Si, which is then used as template for etching, deposition, etc.
  - A voltage applied between tip and sample can oxidize a metallic (Ti) layer or the surface of a semiconductor (GaAs), forming isolated regions
  - The AFM tip can directly move molecules, nanoparticles



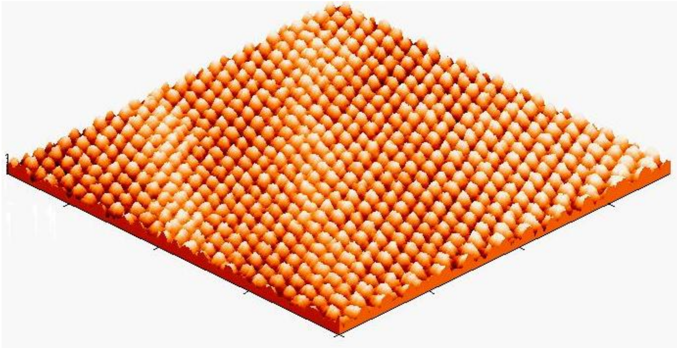




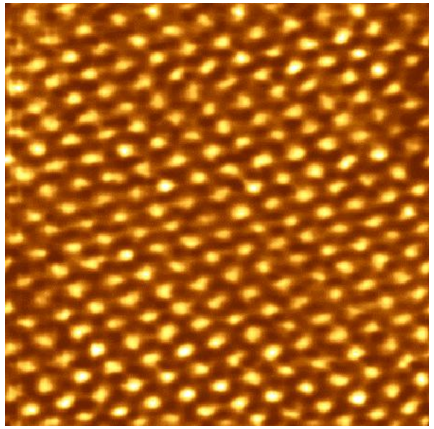
Outline:

- Introduction: What is SPM, history
- STM
- AFM
- Image treatment
- Advanced SPM techniques
- Applications in semiconductor research and industry

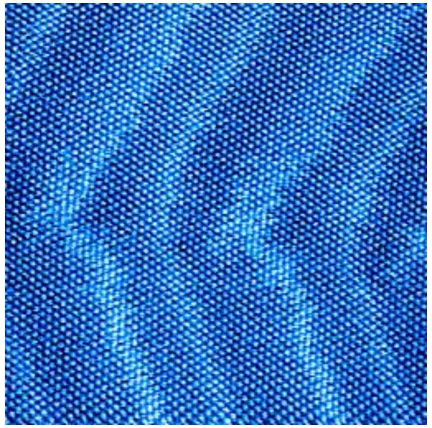
STM Applications



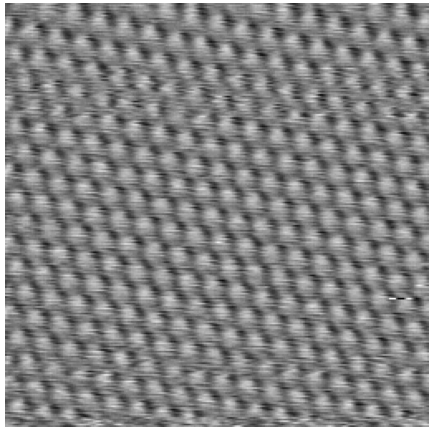
- STM is most useful in vacuum:
  - Naturally forming oxide layer distorts surface states
  - Water layer interferes with tunneling current
- Many MBE growth system have a UHV STM (sometimes low-T STM) coupled to the growth chamber
- STM can show growth morphology, electrical properties, doping on the atomic scale



Au (111) atoms (3x3 nm)

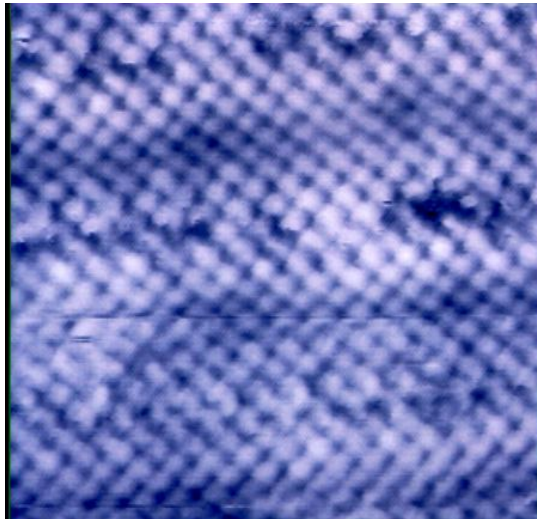


Au (111) atoms (17x17 nm)

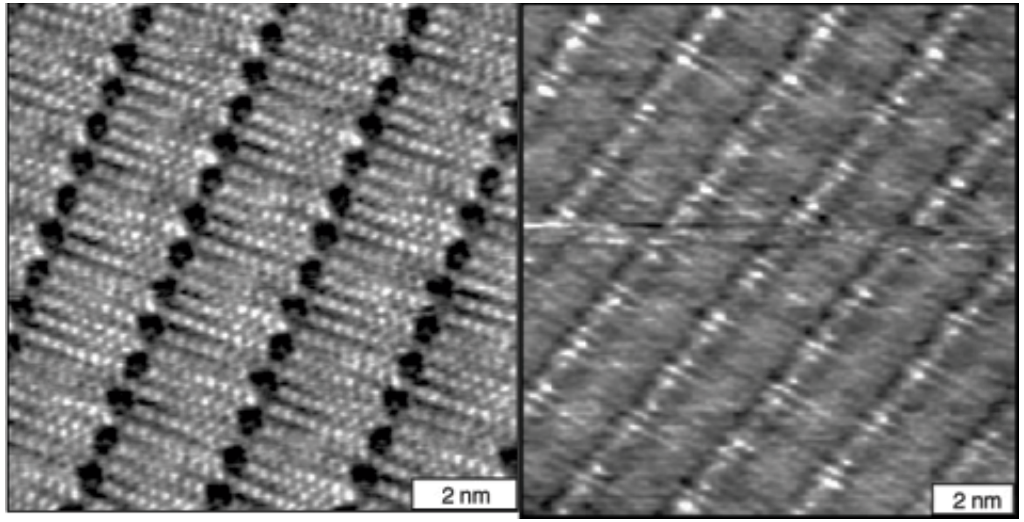


Ag (111) atoms

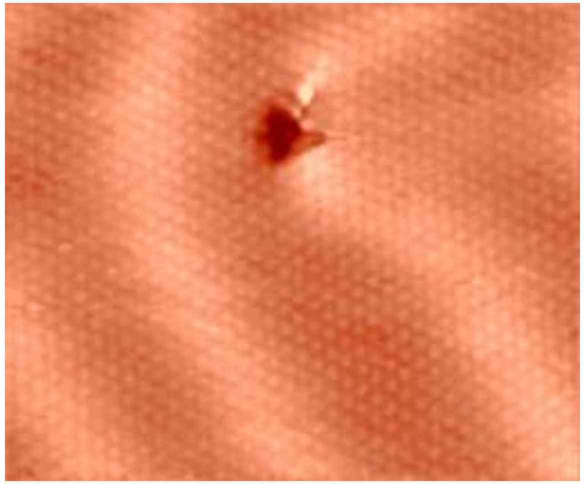
Some STM Images (1)



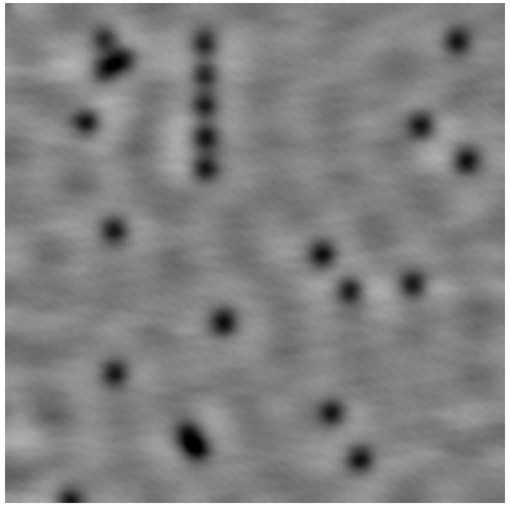
BSCO HTSC
superconductor at 4K



STM Images of molecules. Right – tip is modified to interact with specific part of molecule

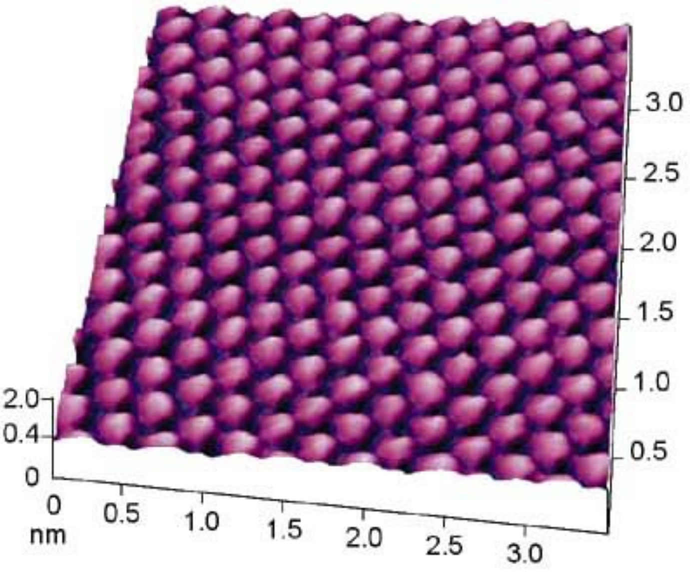


Co atoms (dark) on Au (111) surface

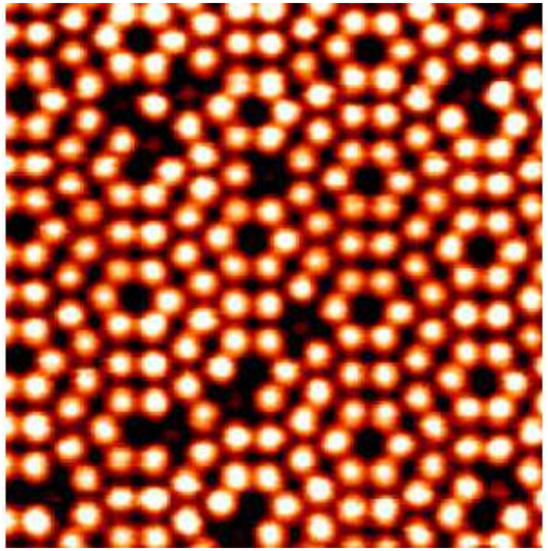


Co atoms (dark) on Ag surface

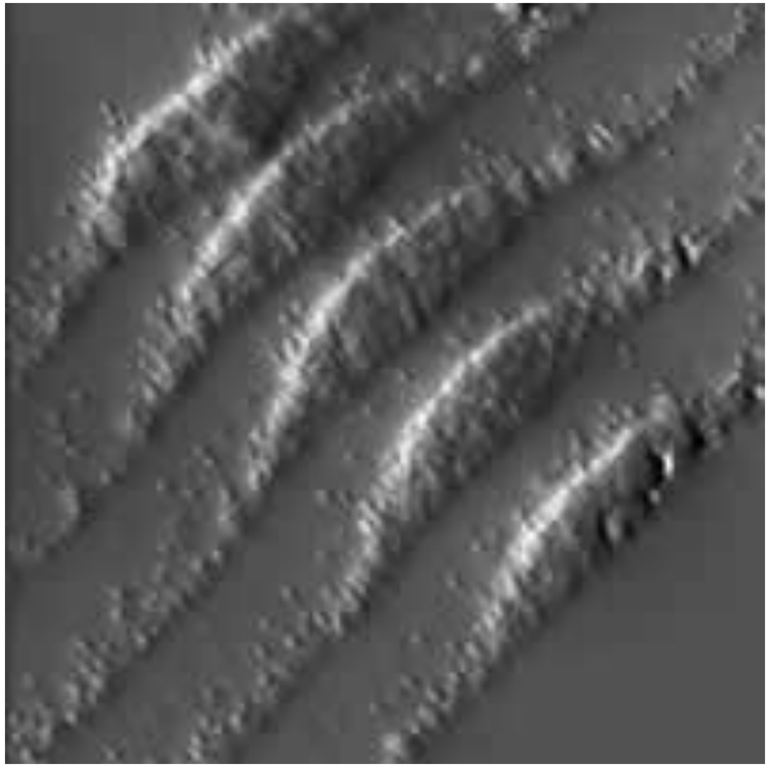
Some STM Images (2)



Graphite atoms

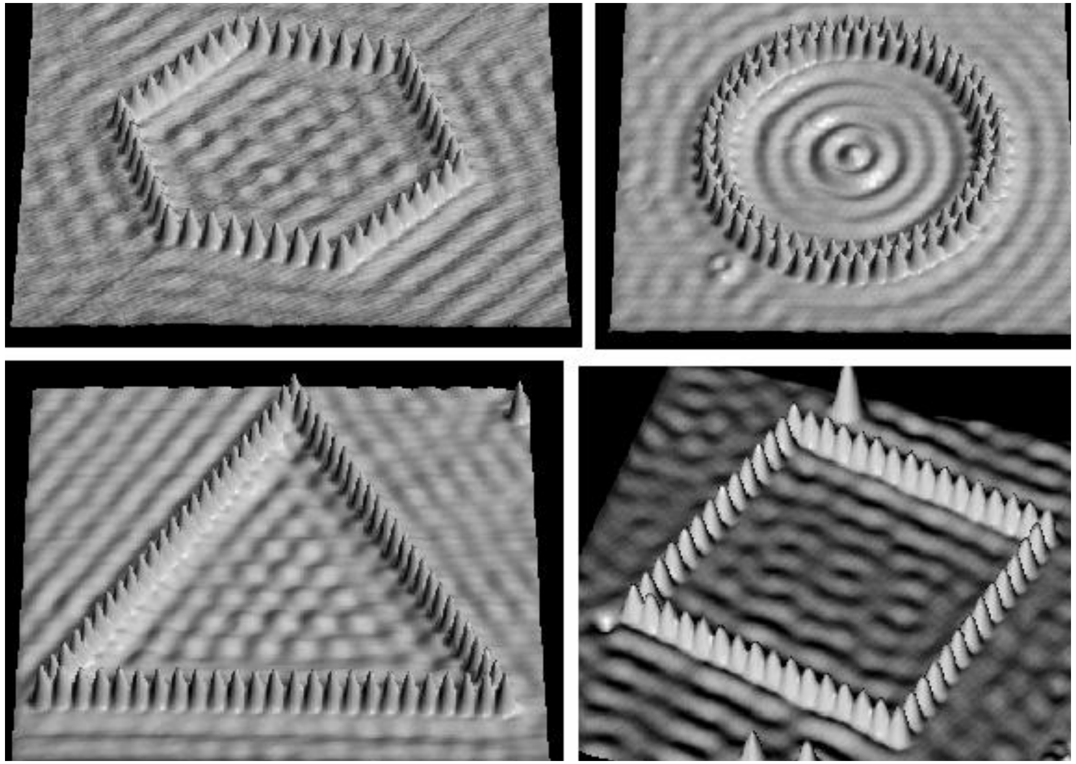


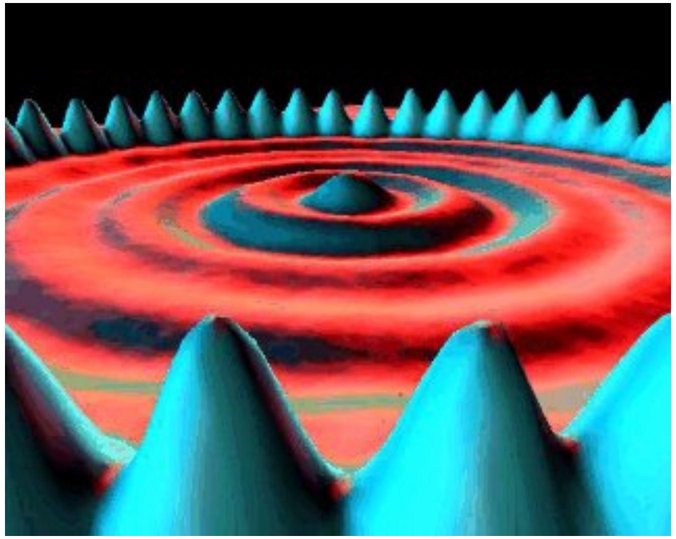
Si atoms

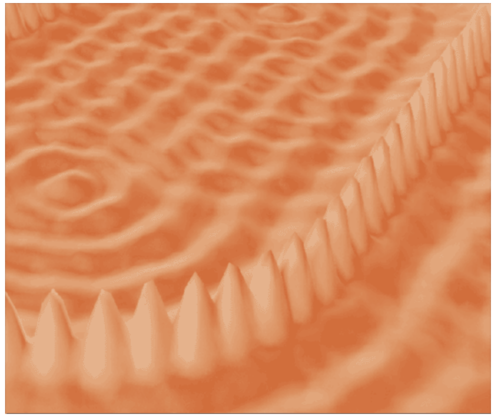


Stacked InGaAs quantum dots

Some STM Images (3)

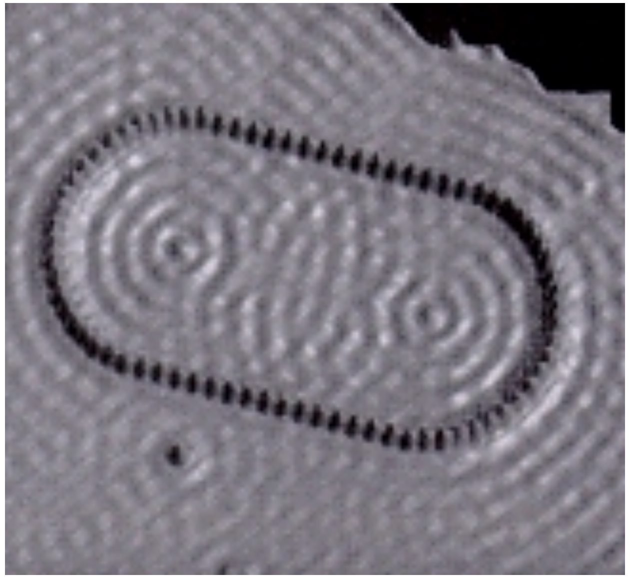






Fe atoms manipulated by STM

Note the quantum interference patterns !



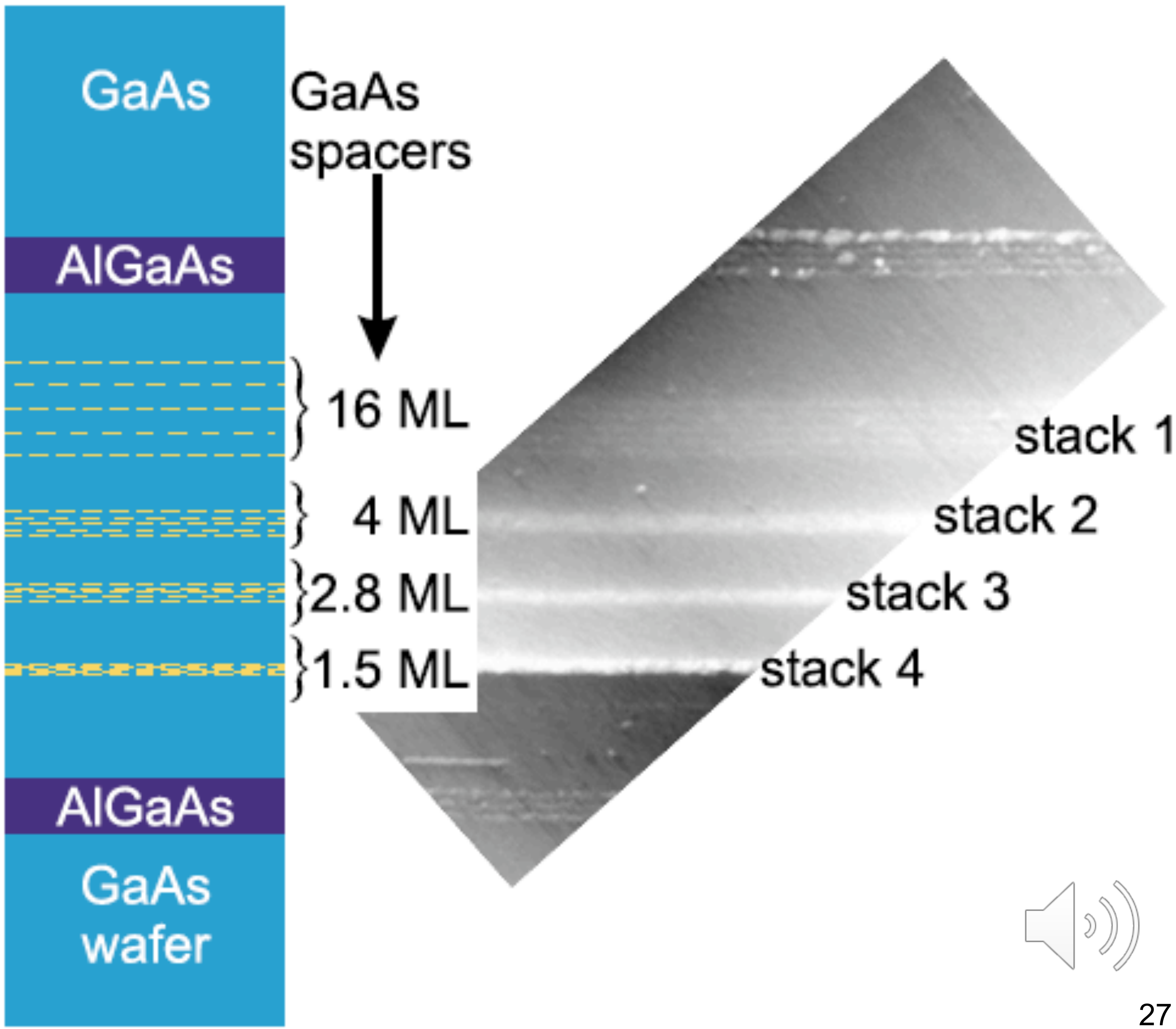
The rat race …

Detailed example of X-STM atomic imaging

Atomic structure and optical properties of InAs submonolayer depositions in GaAs,
A. Lenz, et al.
J. Vac. Sci. Tech. B 29, 04D104 (2011)

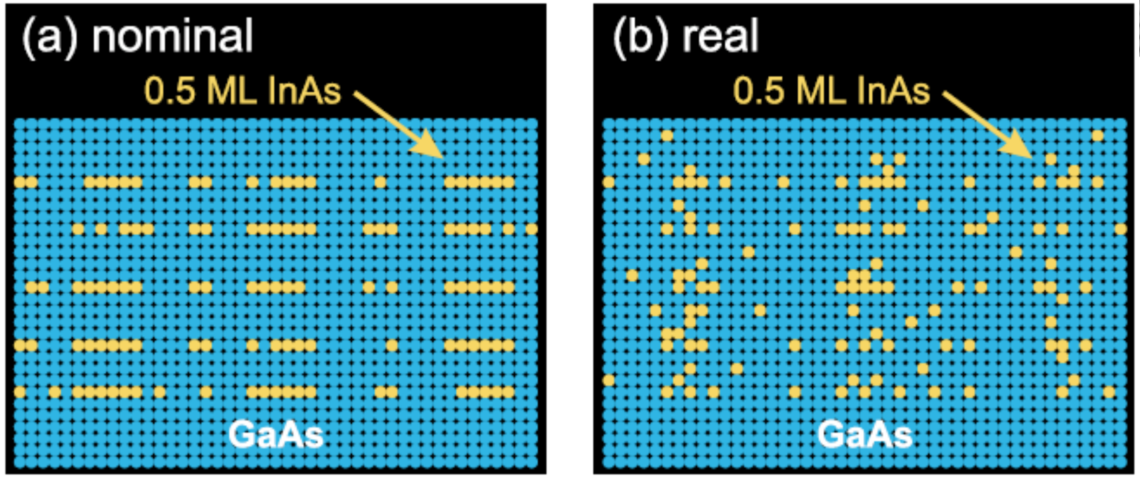
Sample structure:

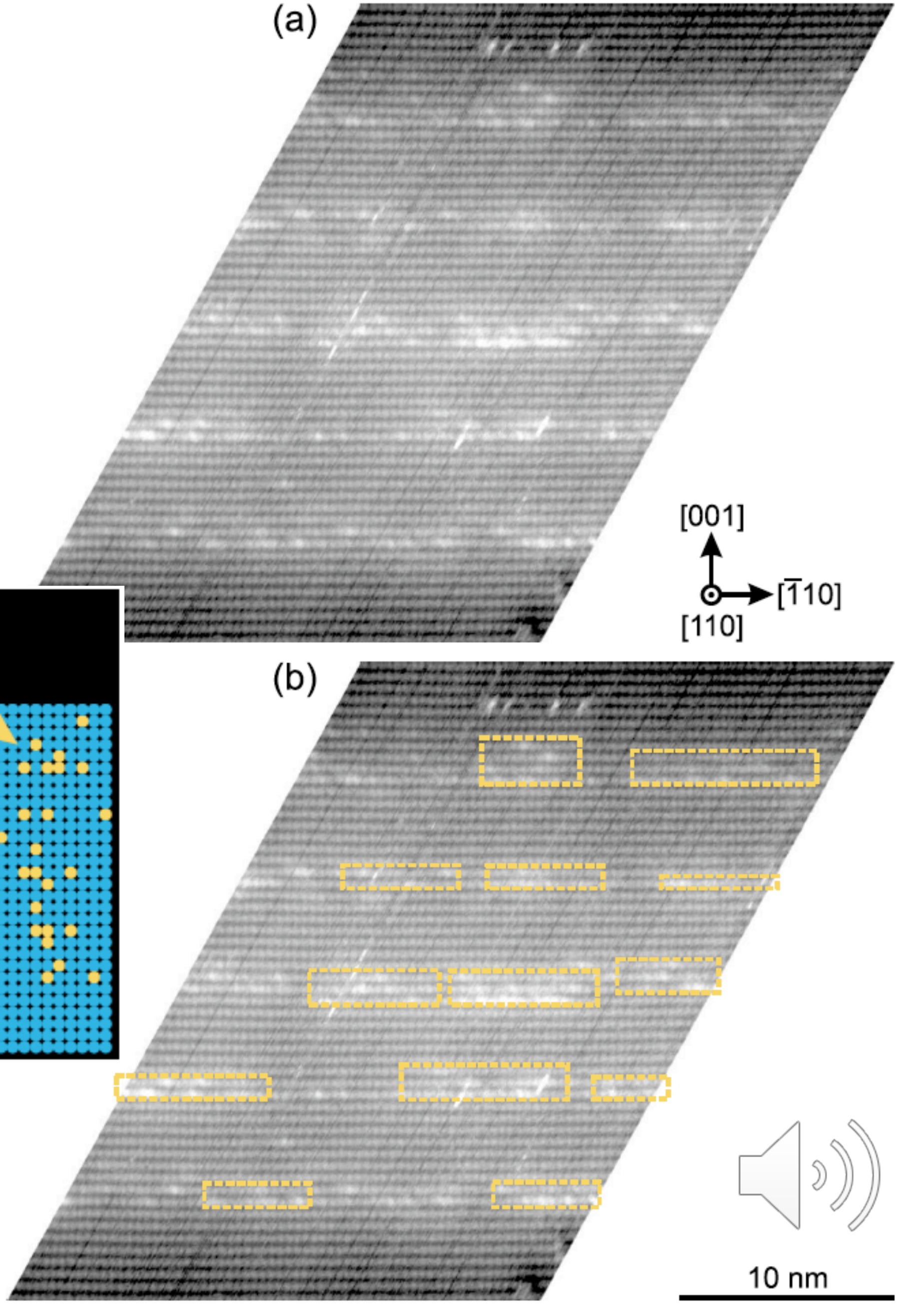
- AlGaAs barriers at extremities ("garbage collection")
- Four "stacks", each of five 0.5 ML InAs layers in GaAs
- Different spacing between InAs layers in stack: 1.5-16 ML.
- Sample cleaved in UHV, STM of cross-section (XSTM)
- InAs brighter than GaAs



XSTM images of one stack

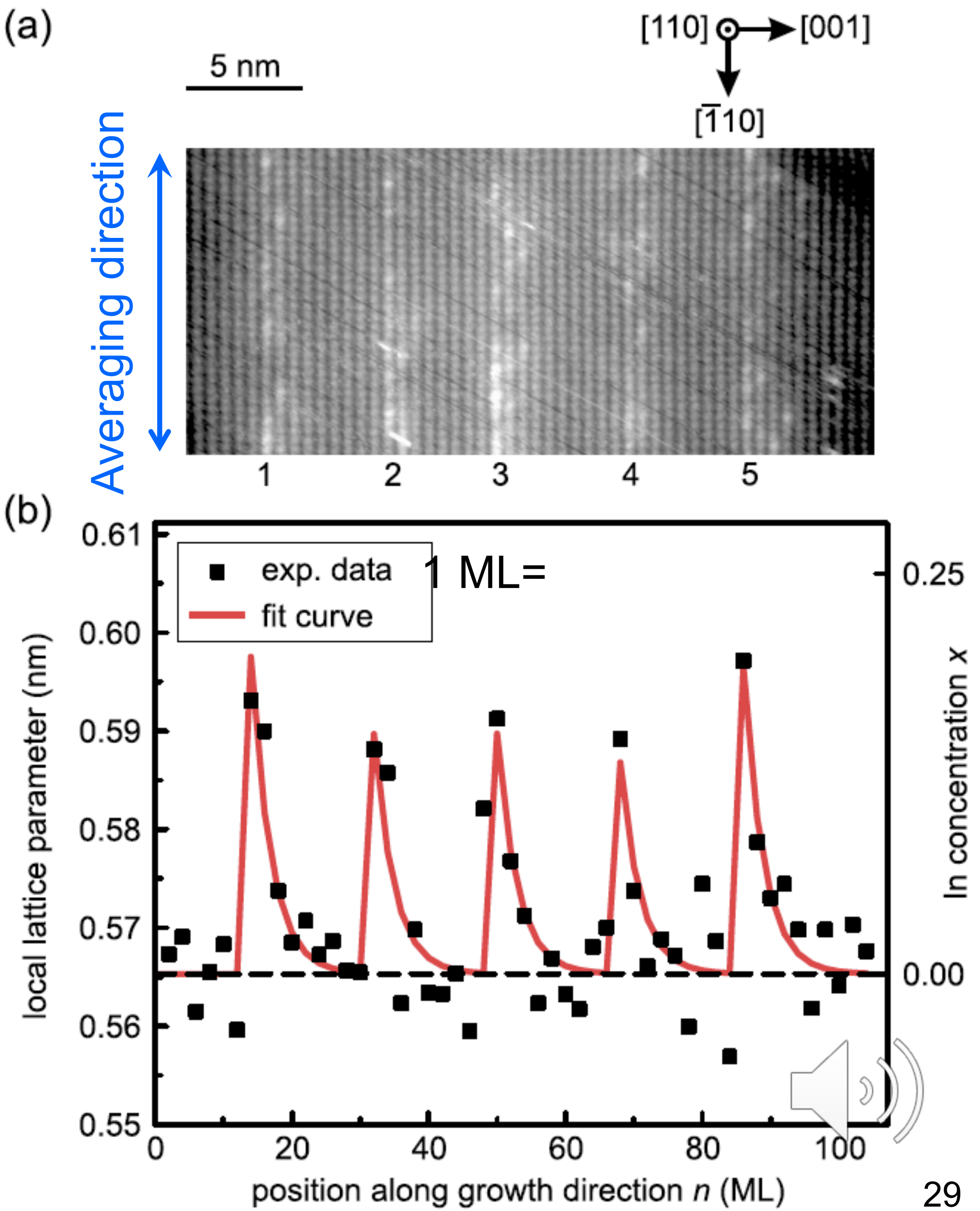
- We can distinguish single atoms
- InAs atoms are brighter than GaAs:
    - Higher topography due to strain release
    - Electron state density higher
- The InAs atoms tend to “cluster” (fig.b) in height





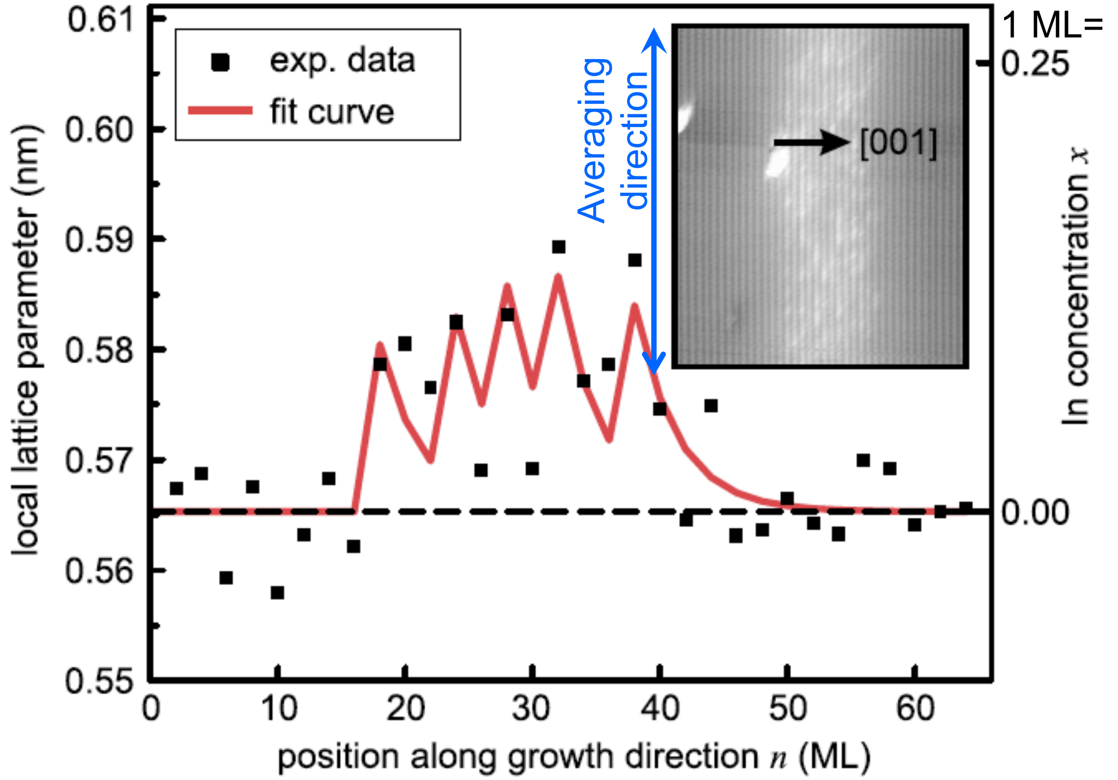
XSTM images of one stack

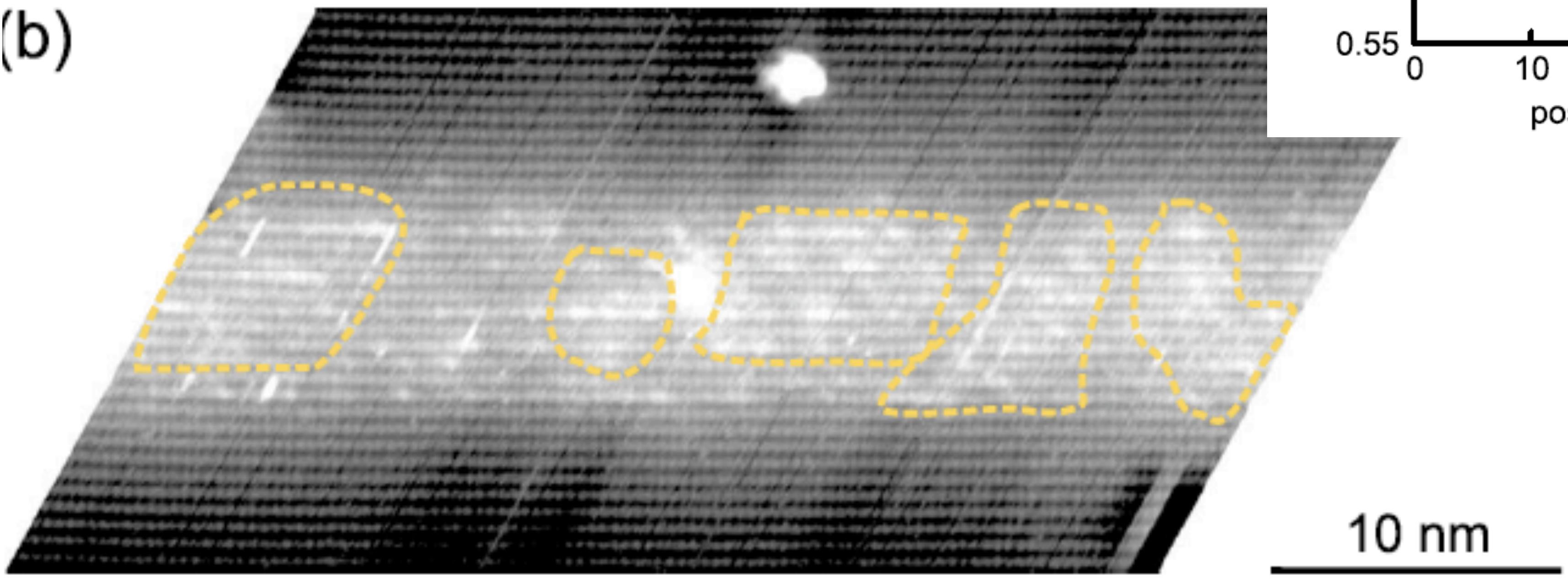
- We can quantify the In contents by measuring local lattice parameter between rows (averaged along the rows)
- Accuracy: ~1 pm!



XSTM images of one stack

- The same can be done on a stack with smaller distance between inAs layers, leading to denser clustering



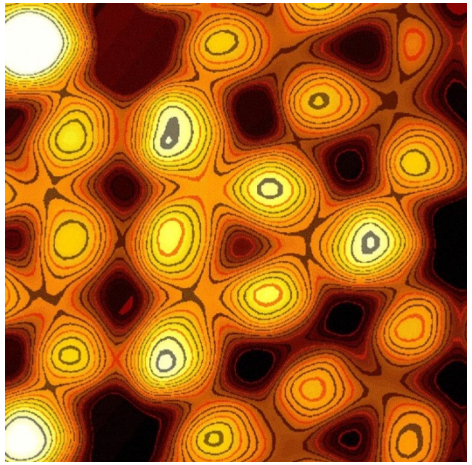


AFM Applications

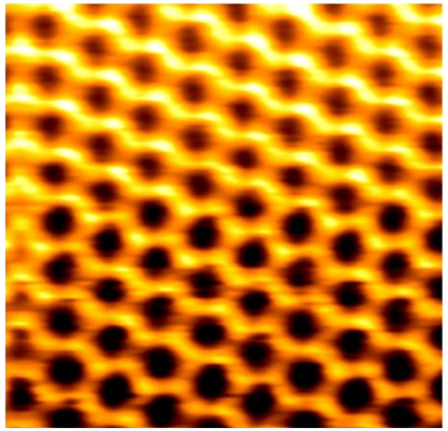
- AFM is more used than STM:
  - Easier to use and to obtain an image
  - Can work at ambient air
- Uses of AFM in characterization:
  - Substrate characterization before growth (especially non-planar substrates)
  - Growth surface characterization (morphology)
  - Cross-sectional imaging (layer structure)
  - Advanced electrical modes (doping)

AFM atomic resolution Images

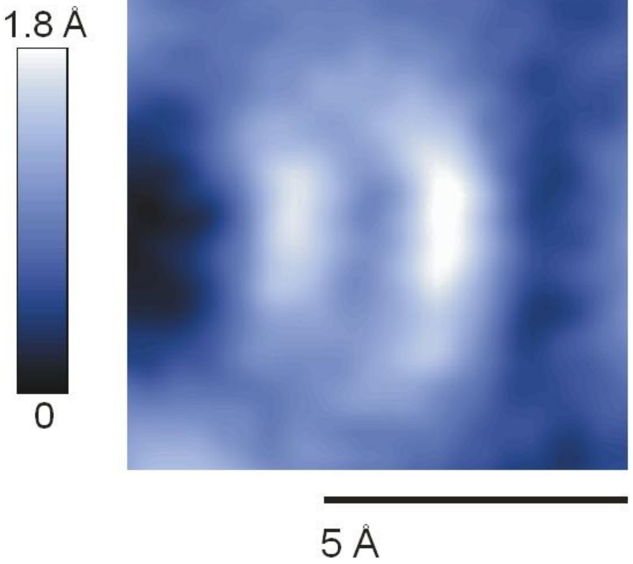
- AFM is also capable to produce atomic resolution images :



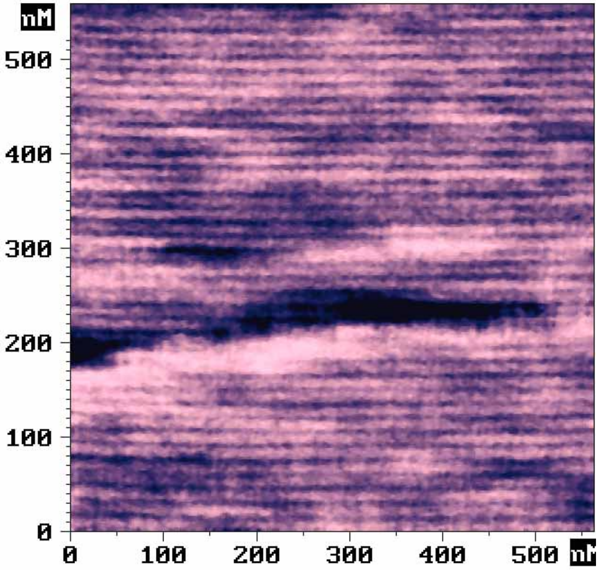
Silicon



Graphite



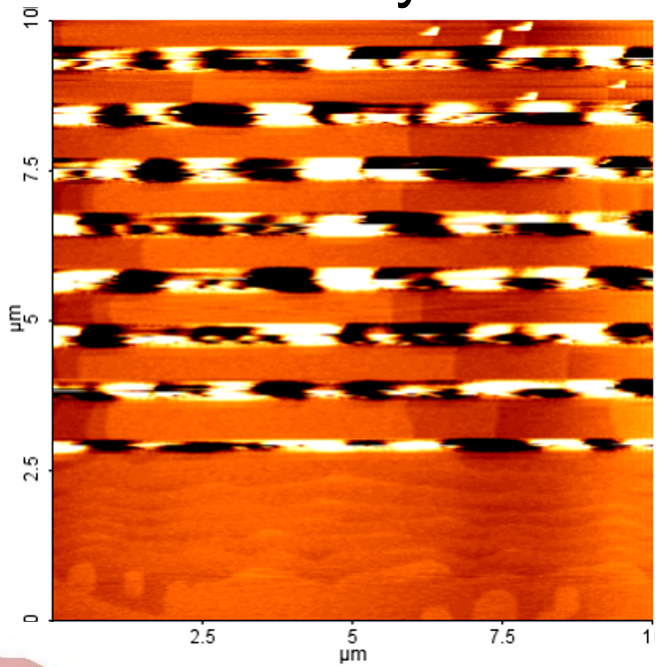
Sub-atomic resolution by AFM

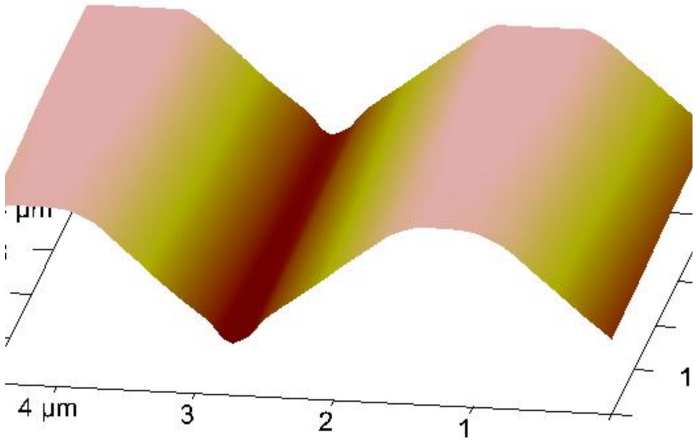


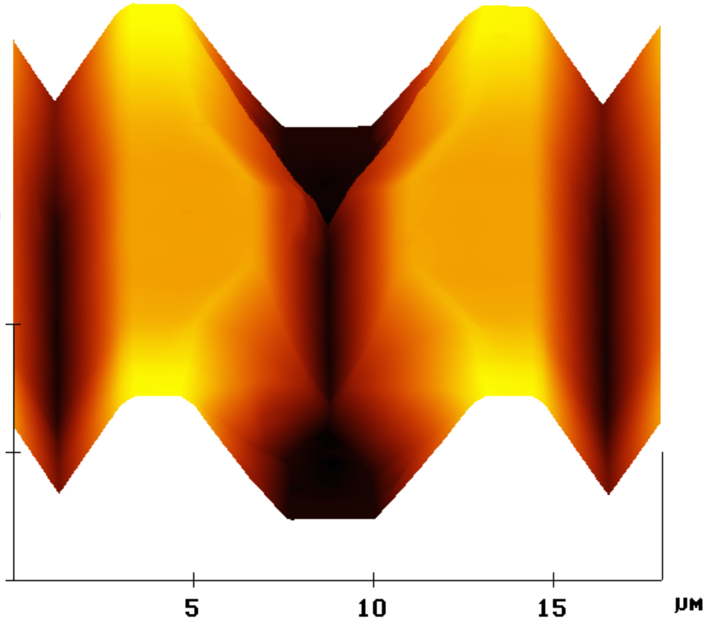
GaAs cross-section

Substrate characterization

- Example: etched V-groove substrate
- The quality of surfaces is easily determined by AFM





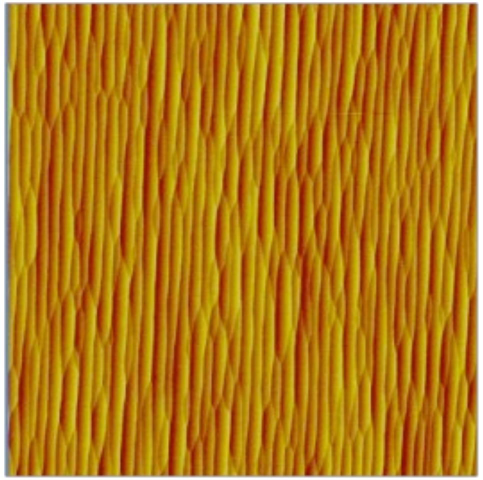


Surface characterization

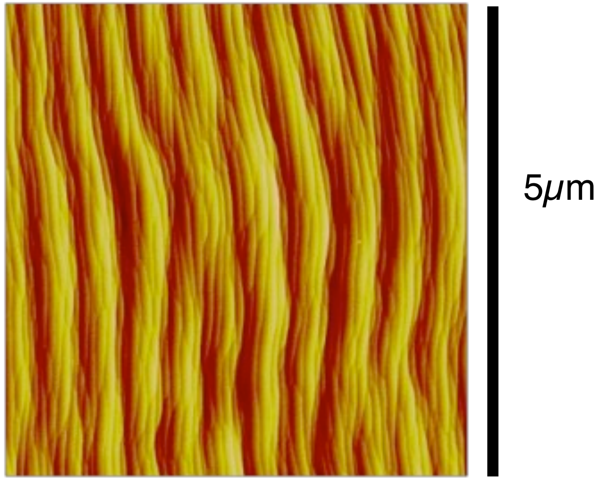
- Example: monolayer steps on GaAs structures
- The substrate misorientation angle determines the growth mode: step-flow, step-bunching, multi-step bunching

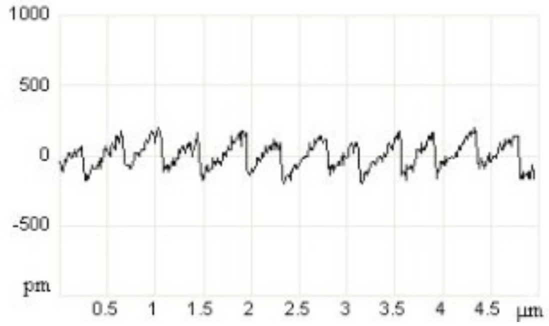
Exact

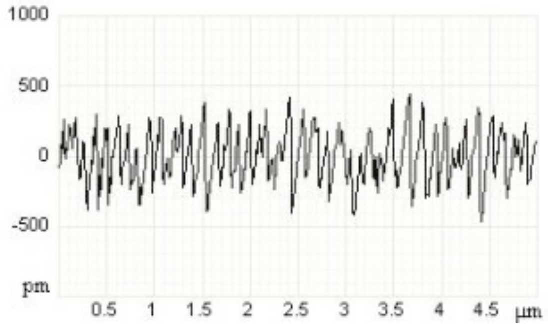
0.3°B

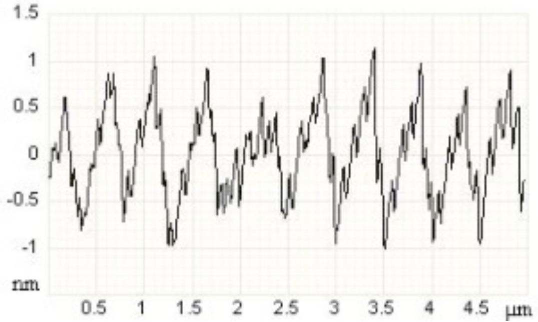


0.6°B



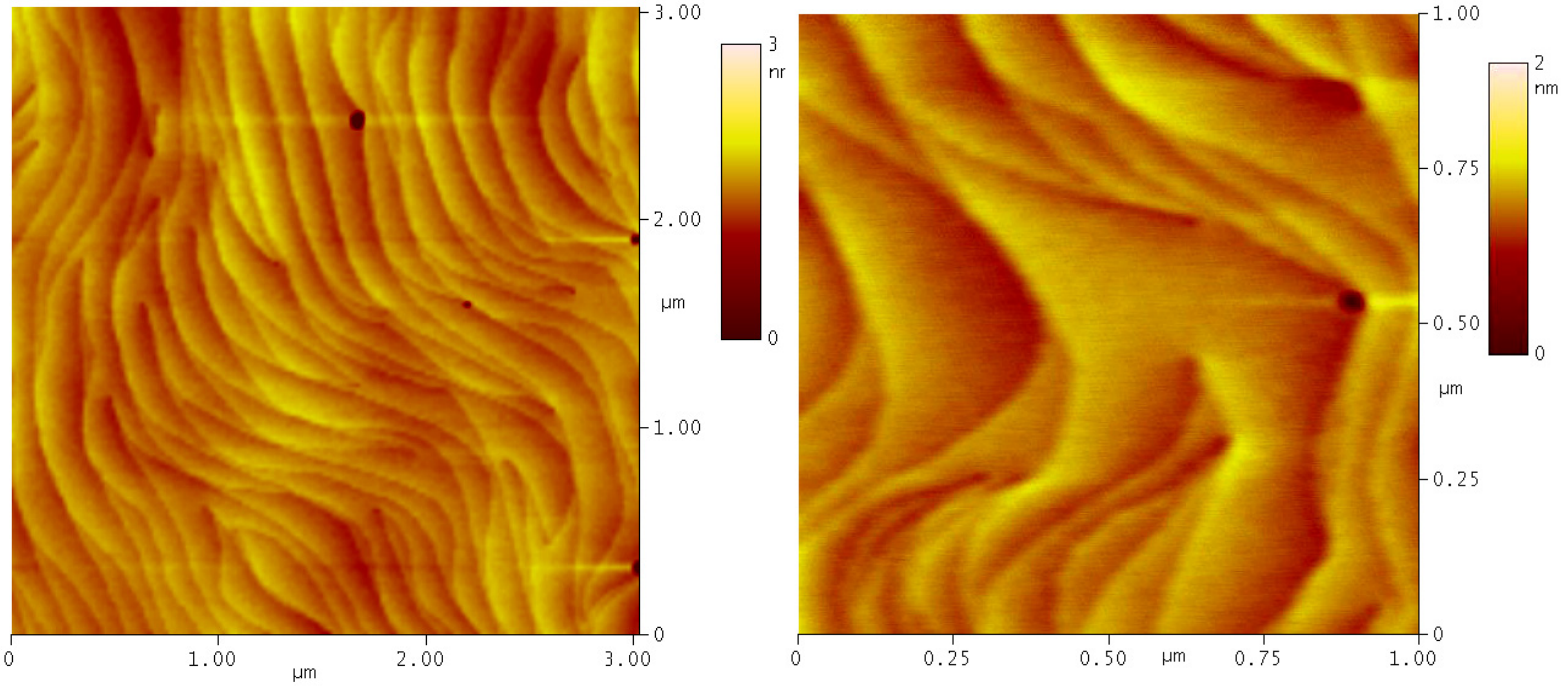






Surface characterization

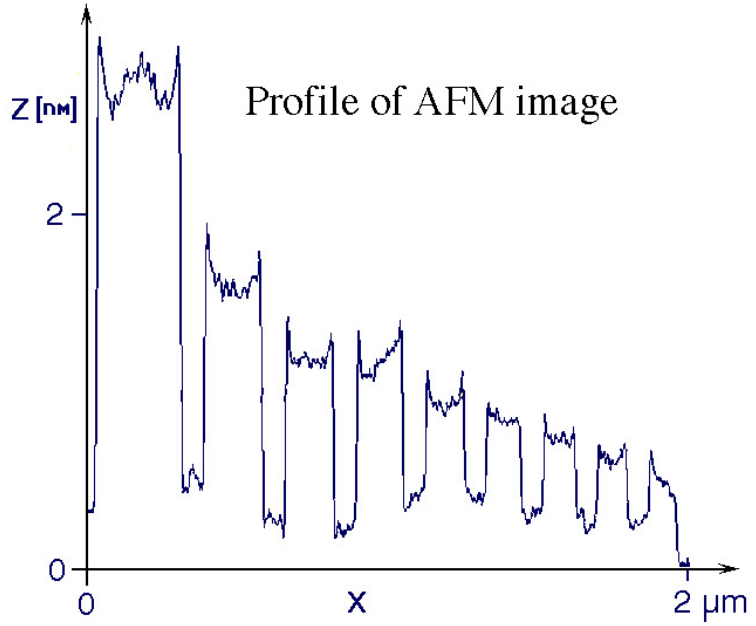
- Example: monolayer steps and dislocations on GaN layers



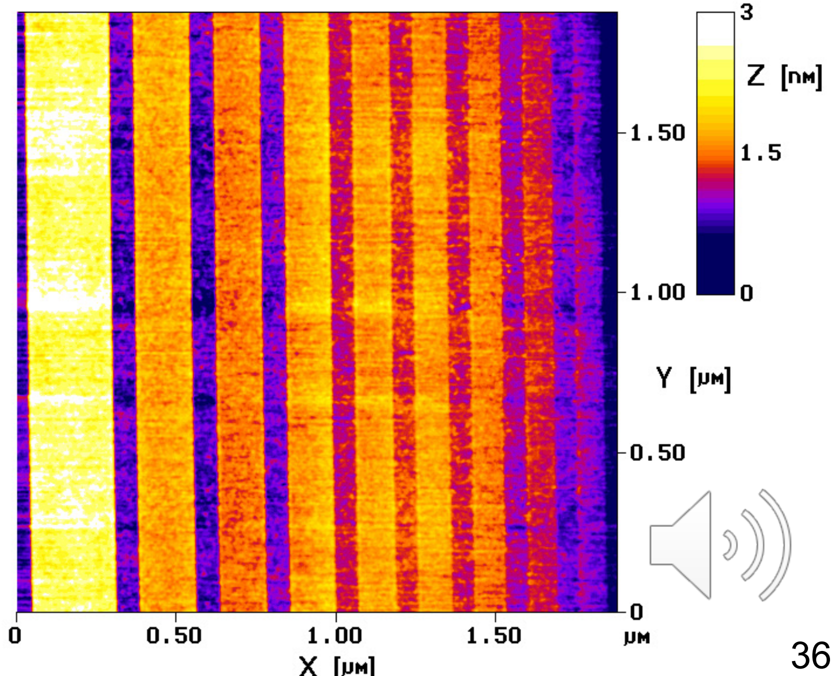
Images of GaN layer on Sapphire by AFM

Cross-sectional characterization

- Oxidation rate in air of GaAs/$Al_xGa_{1-x}As$, depends on Al contents x.
- After 1 hr the oxide reaches finite thickness, depending only on composition
- GaAs is darker than AlAs
- InAs and InP oxidize even less than GaAs



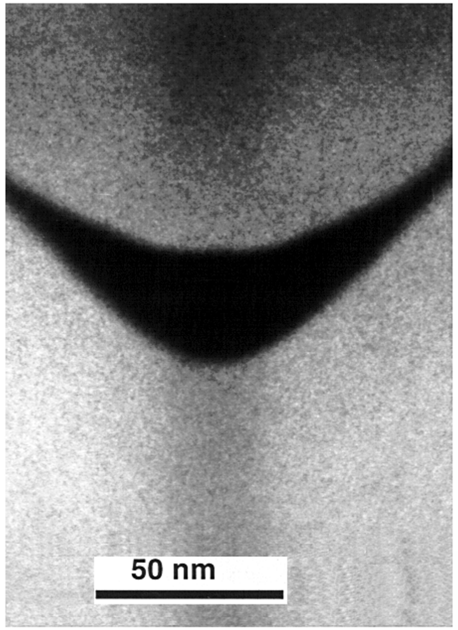
AFM image of multi-layer AlGaAs sample

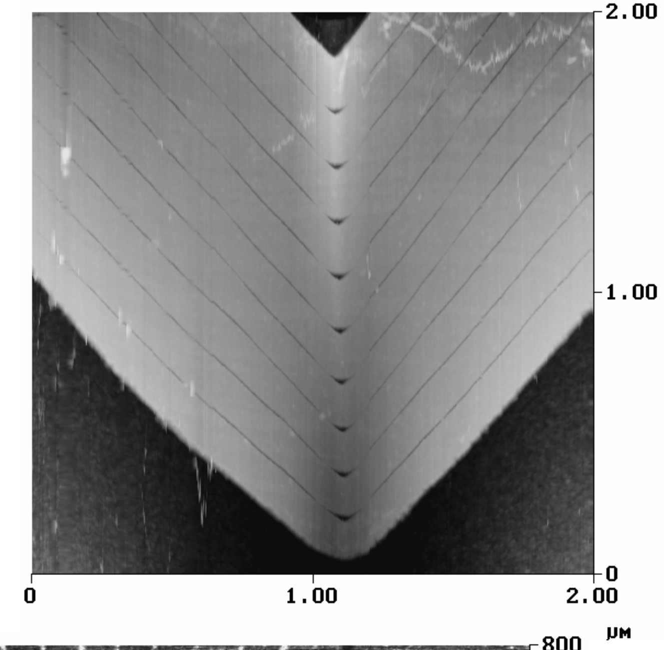


Cross-sectional imaging of QWRs

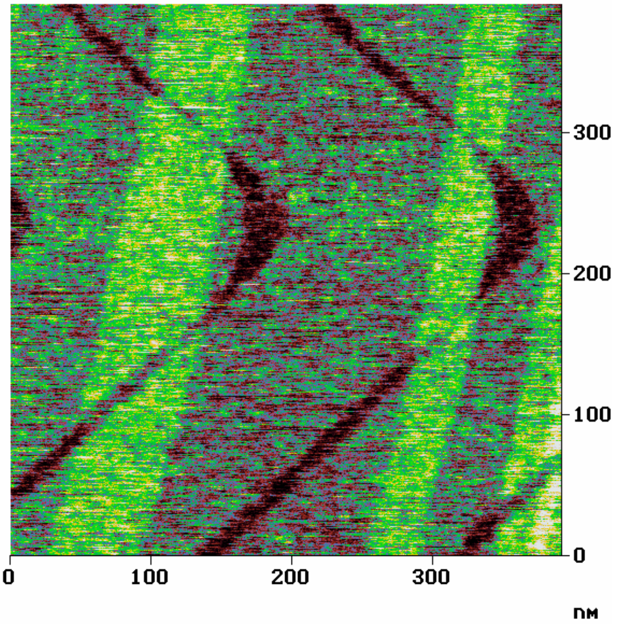
- High-resolution AFM can show small (a few nm) nanostructures like GaAs/AlGaAs QWRs
- Resolution is almost as in TEM, with short sample preparation

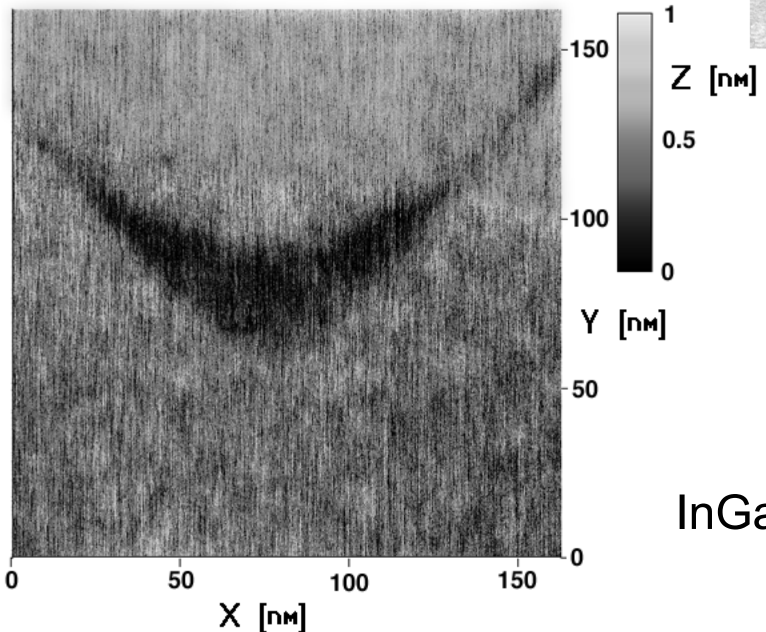
TEM of single QWR



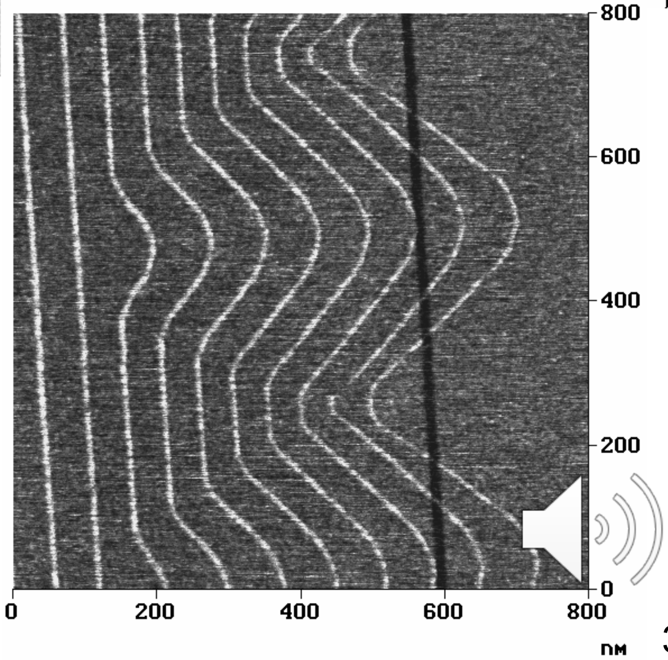


GaAs/AlGaAs QWRs



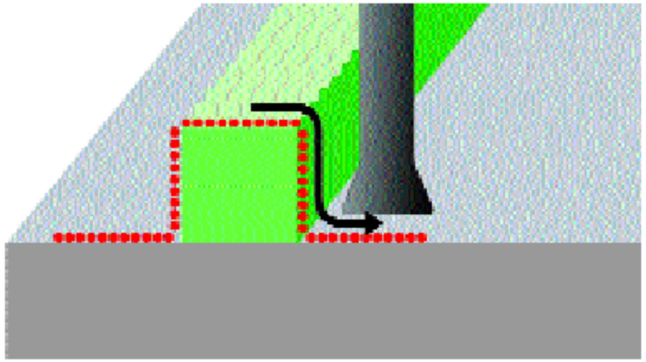


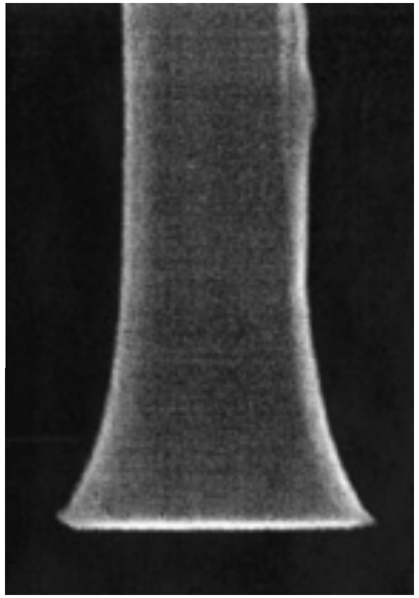
InGaAs grwoth in GaAs



Industrial applications

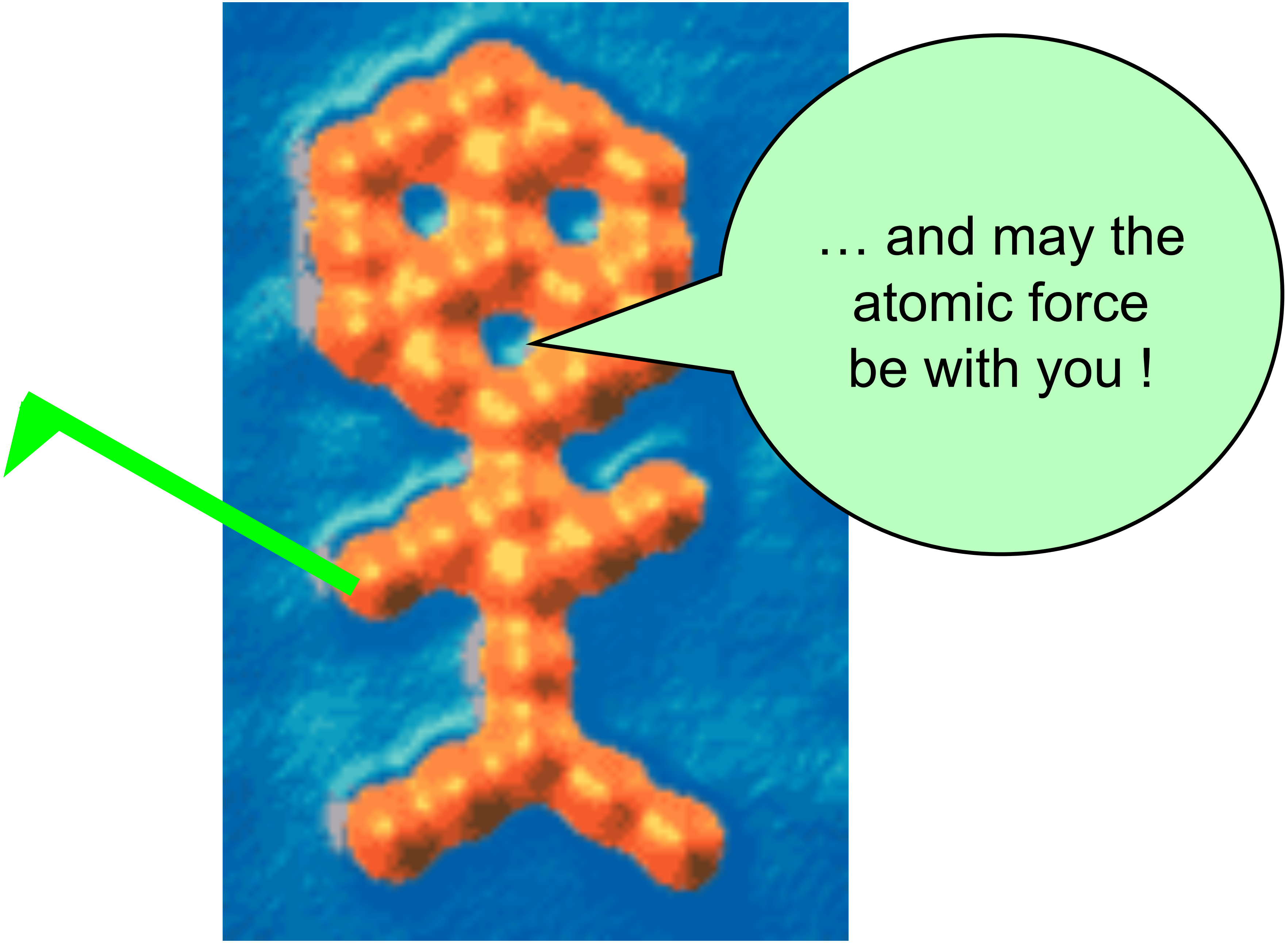
- Metrology : assessment of CDs, calibration
  - Tip characterization is very important
- Measurement of doping concentration
- Detection of defects in structures
  - Structural defects
  - Electrical defects
- The main problem with AFM in industry : Speed !
  - Typical AFM scan : 1-5 min/image, max. size 100 μm
  - To scan a 4" wafer will take 1000 hrs !
  - New high-speed AFM is better (0.1-1s/image)
  - Only surface sampling can be used on production wafers, and no cross-sections!





Summary

- The field of SPM has developed in 20 years into a multitude of surface characterization techniques
- AFM and its derivatives are simple and useful for characterization of semiconductors
- Cross-sectional imaging can reveal the insides of structures
- Industrial applications are growing, limited by AFM speed


… and may the atomic force be with you !

References

- NCSU tutorial : www.ncsu.edu/aif/SPM/AFM%20Tutorial.pdf
- NT-MDT application notes : http://www.ntmdt.com/page/primer
- Pacific Nanotech tutorial : http://www.pacificnanotech.com
- Nanosensors tips : http://www.nanosensors.com
- Nanonics SNOM : http://www.nanonics.co.il/learn-nsom.html
- LPN-SB, EPFL : http://lpn.epfl.ch