Scanning Force Microscopy

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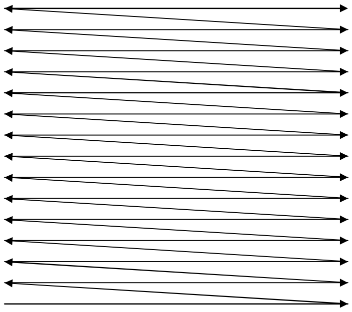
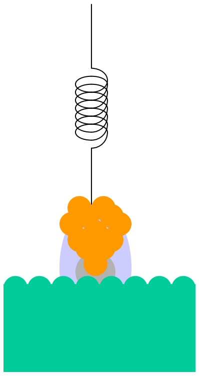
Scanning …

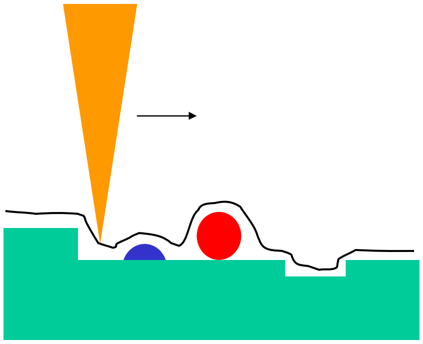
Probe is moved along scan lines over a sample surface



… Force …

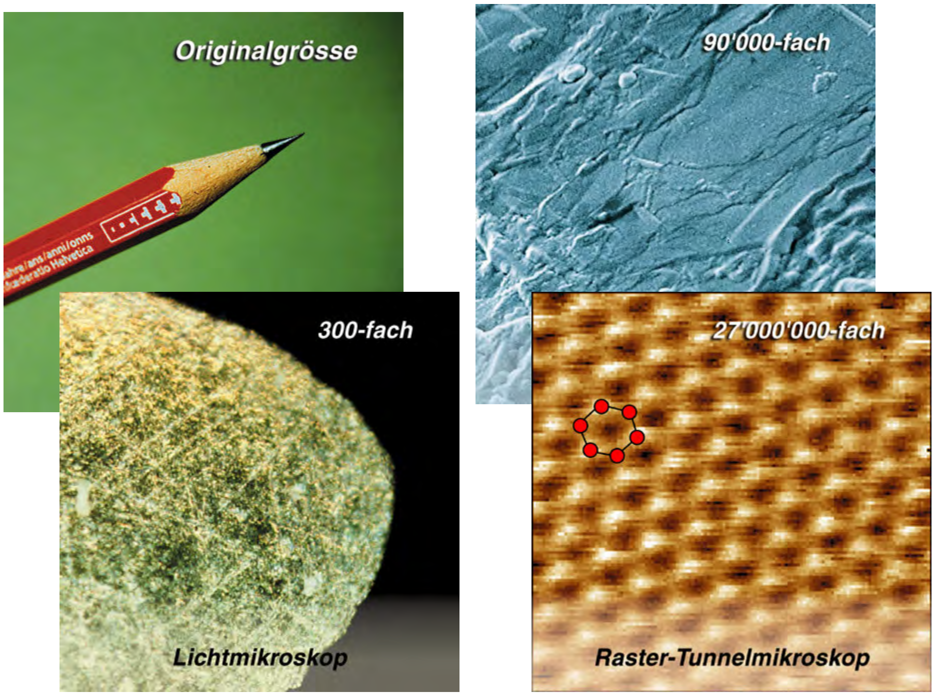


… Microscopy



Data are recorded as a function of lateral position.

Display and analysis with help of computer.

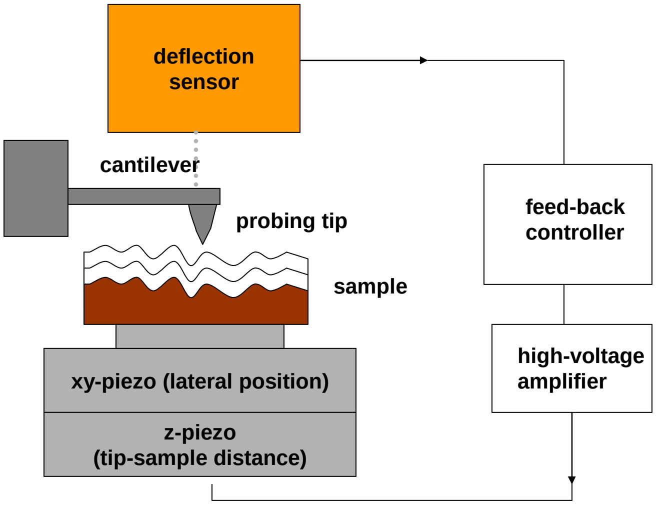

Originalgrösse
90'000-fach
300-fach
27'000'000-fach
Lichtmikroskop
Raster-Tunnelmikroskop


nanoSurf

Parts of a
Scanning Probe Microscope

- sharp tip probing near-field interactions
  (tunneling current, chemical binding forces, optical near-field)
- scanner (positioning actuator) with atomic precision
  (usually piezoelectric)
- coarse approach
  (micrometer screws, optical microscope)
- vibration damping
  (rubber stacks, air-damped tables)
- control electronics
  (pre-amplifier, distance controller, high-voltage amplifier)
- data recording
  (two screen computer, software)

Scanning Force Microscope
(AFM)



deflection sensor

cantilever

probing tip

sample

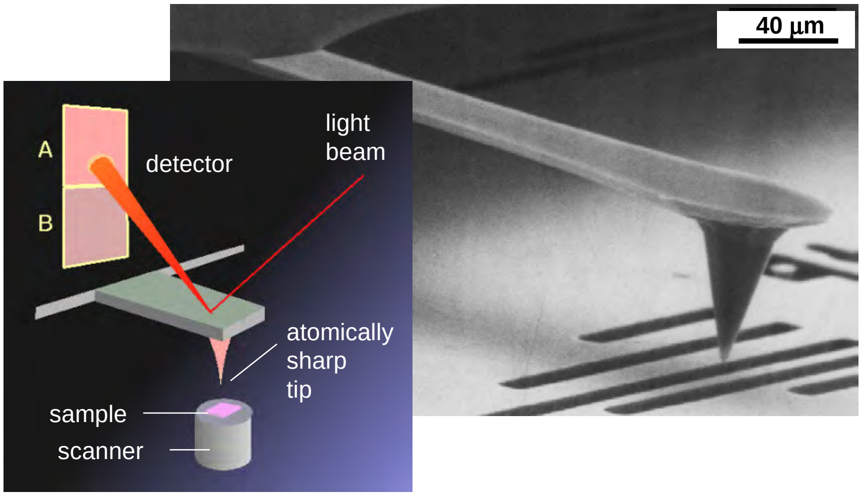
xy-piezo (lateral position)

z-piezo
(tip-sample distance)

feed-back controller

high-voltage amplifier

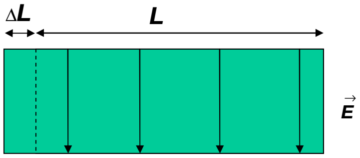
Scanning Force Microscope (AFM)



Piezoelectric effect

Piezoelectric scanners work with the transversal piezoelectric effect. The crystal is elongated perpendicular to the applied electric field.

$$\Delta L = d_{31} \cdot L \cdot \vec{E}$$



$\vec{E}$ electric field, *L* length, ΔL elongation, d_{31} transversal piezoelectric coefficient

Typical material is PZT (Lead Zirkonium Titanat). The relation between Lead and Zirkonium determines the Curie-temerature and the piezoelectric coefficient.

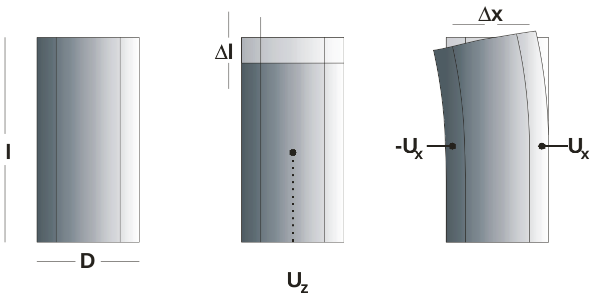
Example: PZT-5H: d_{31}=-2.62Å/V i.e. L=1 cm, ΔL = 1 µm, E=380 V/mm

Piezoelectric tube scanner

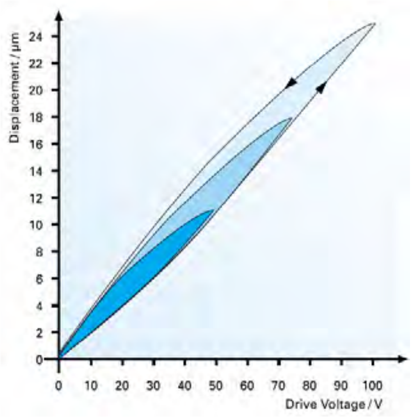
Sensitivity of the tube scanner:

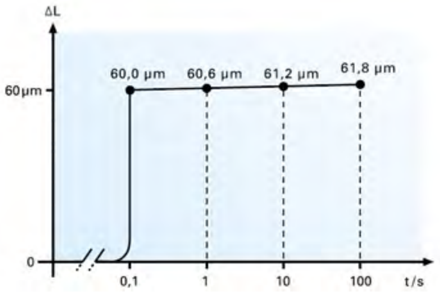
$$\Delta l = d_{31} \cdot U_z \cdot \frac{l}{H} \qquad \Delta x = \cdot \frac{2\sqrt{2}\, d_{31} \cdot l^2 \cdot U_x}{\pi\, D\, H}$$

H **thickness, D diameter, d_{31} transversal piezoelectric coefficient**.



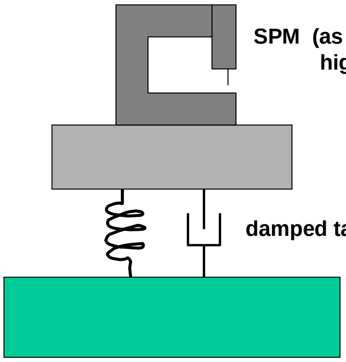
Hysteresis and creep of piezoelectric actuators





http://www.piceramic.com/pdf/PIC_Tutorial.pdf

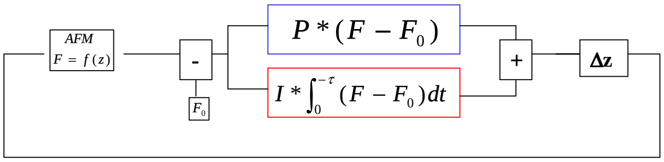
Vibration damping



**SPM (as rigid as possible,
high mechanical resonance frequency)**

damped table (filtering out low acoustic frequencies)

Feed-back controller



Setpoint F_0:	**Force signal which should be maintained**
Error signal:	**Difference between actual force signal and set point**

Proportional feedback:	**Change in tip height proportional to error signal**
Integral feedback:	**Change in tip height proportional to accumulated error signal**

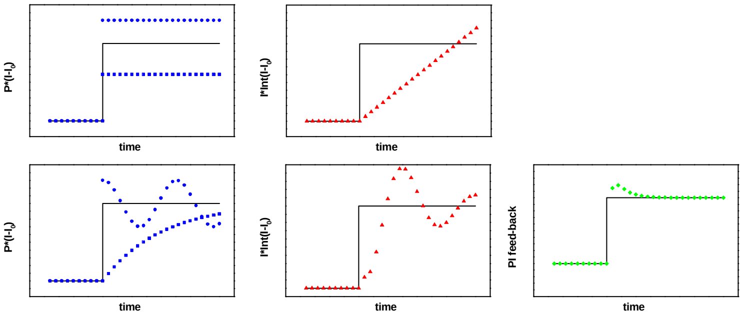
Proportional constant P	**too low – error will never be corrected** **too high – overshooting and oscillations**
Integral constant I	**too low – error will be corrected too slowly** **too high – overshoot will be large**

Feed-back answer to a step

proportional **integral** **combined**

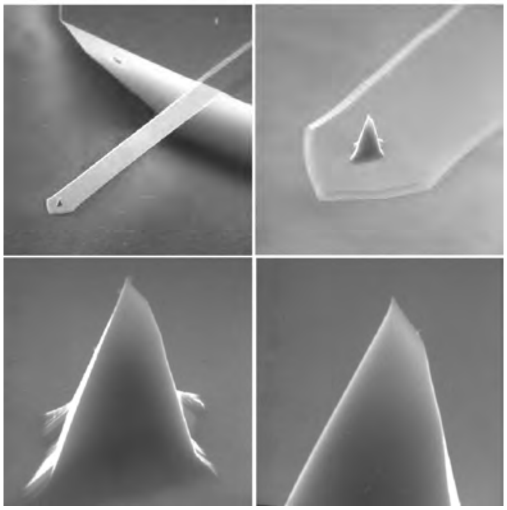
response without feed-back

response with feed-back

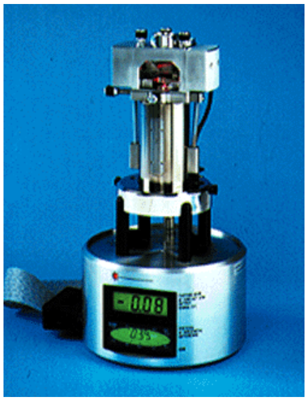


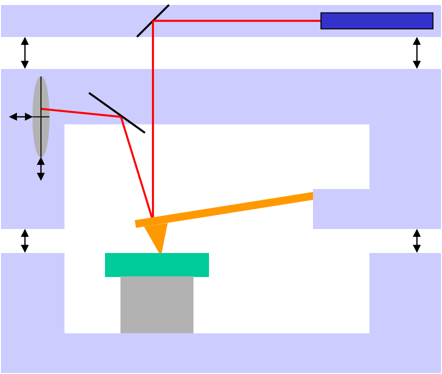
Microfabricated cantilever

Si-Cantilever (1.5x45x450µm)



Example – DI microscope

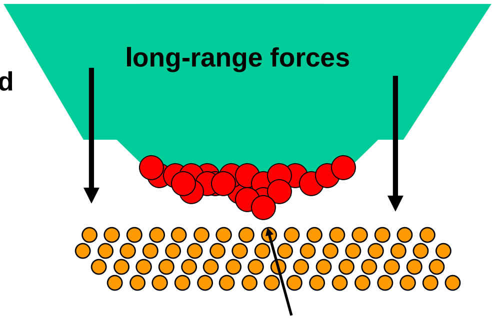




Atomic Force Microscope: Measuring nN forces at surfaces

High resolution by near-field forces between tip apex and surface atoms

Long-range forces between tip body and sample



long-range forces

local chemical binding or repulsive forces

What is a NanoNewton?

What is 1 Newton?
  A chocolate-oriented unit for force.

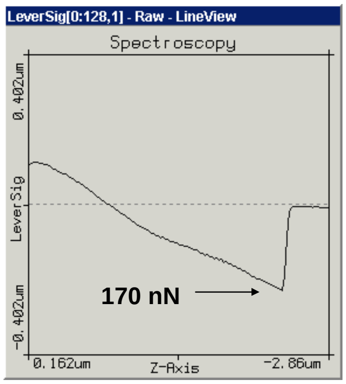
Nanoscience of chocolate?
  1 bar are 100 cm^3 or 10^{23} nm^3
  Weight of 1 nm^3 is 10^{-23} nN (=0)

Binding forces in chocolate
  Cross-section 1 cm^2 or 10^{14} nm^2
  Weight carried 4 kg
  Rupture force 4×10^{-13} N/nm^2

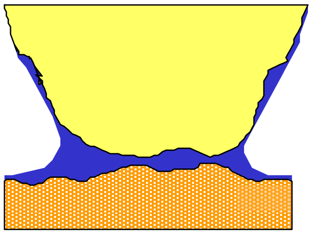
PicoNewton describe molecular forces in softer materials.

NanoNewton describe molecular forces in harder materials

Adhesion - how water disturbes

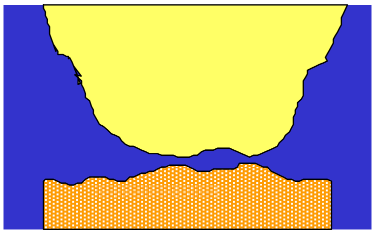


Force vs. distance curve

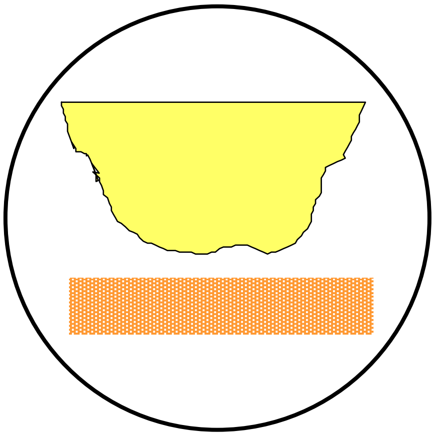


Capillary force

Way out of experimental physics



Measurements in water



... or in vacuum

Relevant forces

- **short-range repulsive forces (Pauli exclusion) or ionic repulsion forces**
- **short-range chemical binding forces**
- **van der Waals forces (always present, retarded beyond 100 nm)**
- **electrostatic forces (long-ranged)**
- **magnetic forces**

- **interaction in liquids**
  - **hydrophobic / hydrophilic forces**
  - **steric forces**
  - **solvation forces**

Literature:
J. Israelachvili
***Intermolecular and Surface Forces with Applications to Colloidal and Biological Systems,* Academic Press (1985)**

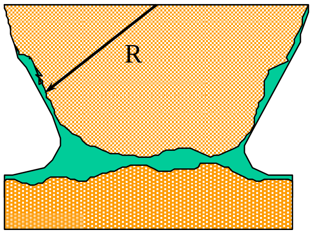
Capillary forces

$F_{max} = 4 \pi R \gamma \cos(\Theta)$

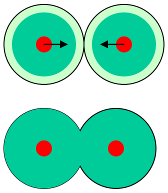
$\gamma (H_2O) = 0.074 N/m$ R=100nm

Contact angle for hydrophilic surfaces $\Theta \approx 0°$

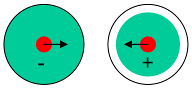
$\Rightarrow F_{max} = 90 nN$



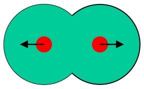
Atomic Forces



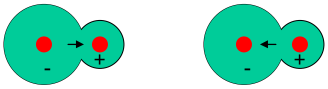
Chemical bond



Ionic attraction

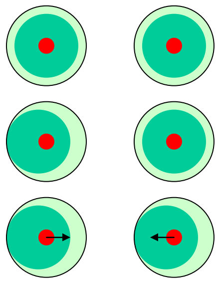


Repulsion upon
overlap of electrons



Dipole attraction

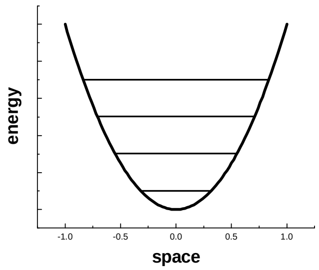
Van der Waals Force



Two neutral atoms

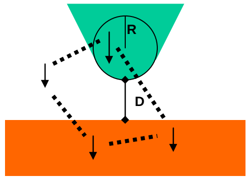
Dipole fluctuation: Unavoidable in quantum mechanics

Induced dipole



Range limited to 10 nm due to retardation effect.

Van der Waals forces between tip and sample



Integration of mutual interactions

Force between the tip and surface can be approximated as force between a ball of radius R and a surface at distance D:

$$F = -\frac{AR}{6D^2}$$

Hamaker constant A is material dependent and of the order of 10^{-19} J.

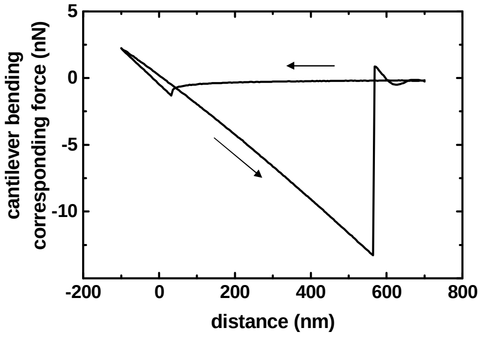
J. Israelachvili, *Intermolecular and surface forces*, chap. 11

Force vs. distance curves

Long-range contributions have force gradients like dF/dz » 1-10 N/m.

Spring constants of k ≈ 0.01-1 N/m provokes "jump-into-contact" when k < dF/dz.

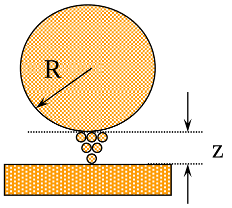
Adhesion causes hysteresis in force vs. distance curves.



Van der Waals forces in vacuum

No capillary forces (no water).

Van der Waals and electrostatic forces dominate.

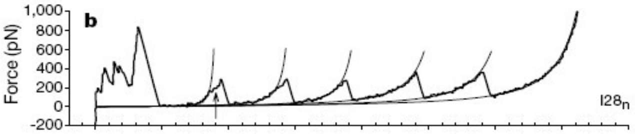


F.O. Goodman and N. Garcia,
***Phys. Rev.* B 43, 4728 (91)**

⇒ R=100nm, z=1nm

graphite-graphite	8nN
diamond-diamond	17nN
metal-graphite	10nN
SiO_2-graphite	1.2nN

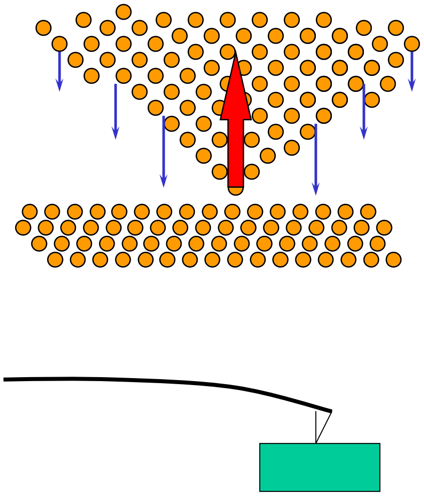
Protein unfolding forces



- **Breaking bonds within DNA and proteins: 60 pN to several hundreds of pN**

Fernandez group, Nature 402 (1999) 100

Estimation of forces

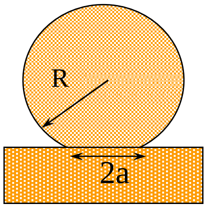


- **Typical long-range forces:**
  - **in air: 10-100nN**
  - **in liquids: 1-100pN**
  - **in ultra-high vacuum: 0.1-10nN**
- **Long-range forces are compensated by short-range repulsion. Bending of the cantilever can reduce the repulsive forces and the contact area.**

Contact area

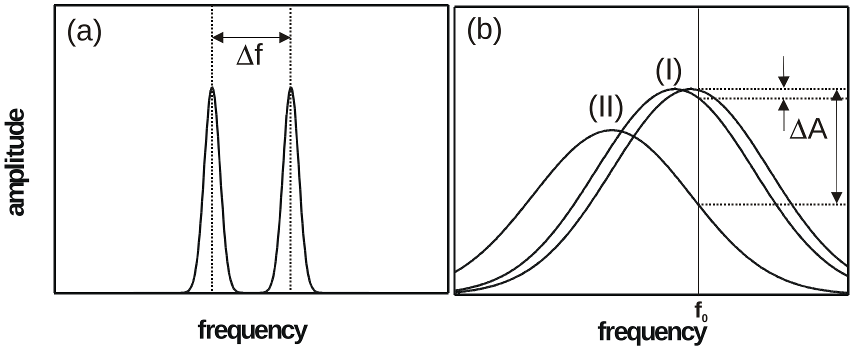
The contact area is given by

$$2a = 2E\sqrt[3]{F \cdot R} \qquad \textbf{(Hertz theory)}$$



- **in air: 5-100nm**
- **in liquids: atomic resolution**
- **in ultra-high vacuum: 1-10 nm**

Dynamic force detection



Cantilever is excited to oscillate, frequency shift and amplitude are measured for force detection
(a) high Q-factor (vacuum)
sharp resonance, detection of frequency shift: non-contact mode, Dynamic Force Microscopy
(b) low Q-factor (air, liquid)
fast amplitude response, detection of amplitude: intermittent contact or tapping mode

Advantages of Dynamic Force Microscopy

Avoid jump into contact.

- Spring constants k > 10 N/m.
- Rather large amplitudes $kA > F_{adh}$ (A=2-60nm).

Reduced damage of the surface due to lateral surfaces.

Atomic resolution in non-contact modes.

Differentiation of force types in force vs. distance curves.

High force sensitivity.

Setup for tapping mode

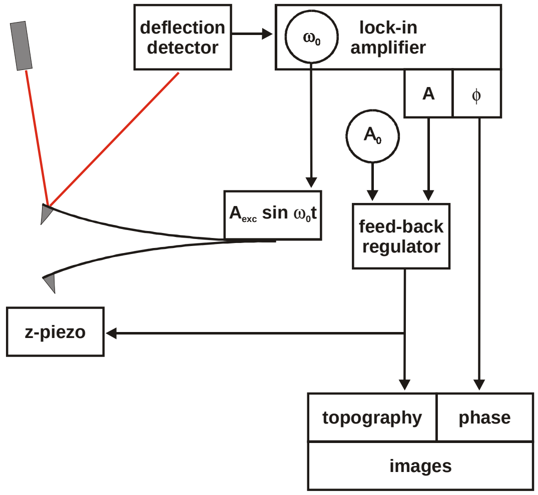
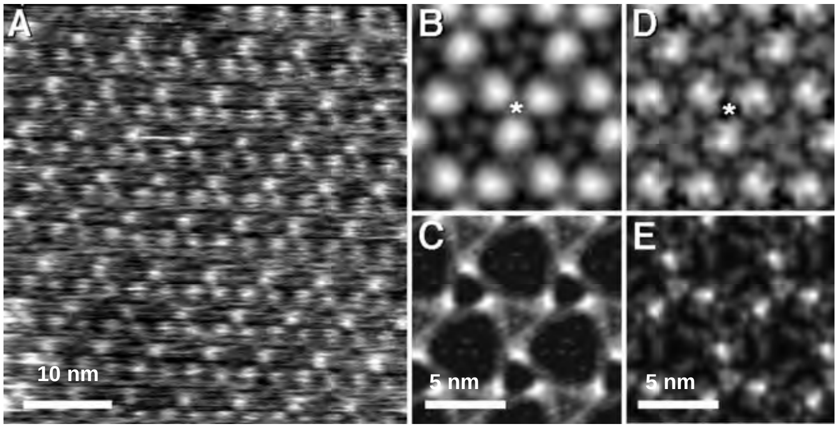


Image of a membrane surface



High-resolution tapping mode images (A). Correlation analysis (B) in comparison with contact mode images (D). C. Möller et al., Biophys. J. 77 (1999) 1150

Modelling of tapping mode

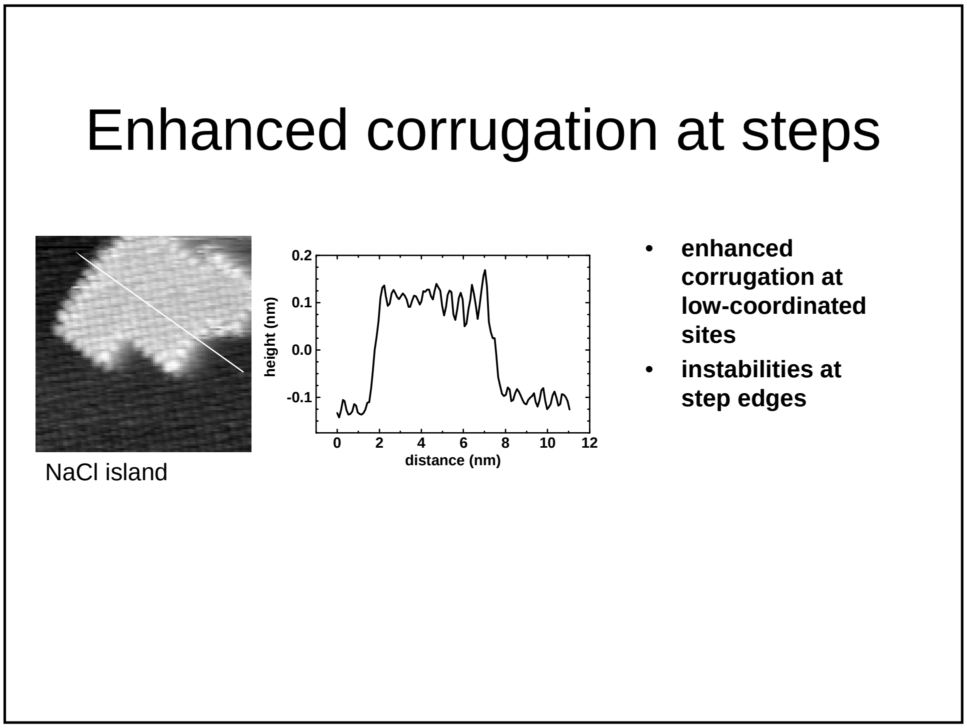
The motion of the tip can approximately be described as a damped harmonic oscillator:

$$m\ddot{z} = -kz - \frac{m\omega_0}{Q}\dot{z} + F_{tip-sample} + F_0\cos(\omega t)$$

The tip-sample and consequently the tip motion is non-linear, particularly in the intermittent contact mode.

Quantitative analysis is difficult due to partly chaotic behaviour.

Garcia and San Paulo, Phys. Rev. B 61 (2000) R13381



Enhanced corrugation at steps

NaCl island

- **enhanced corrugation at low-coordinated sites**
- **instabilities at step edges**