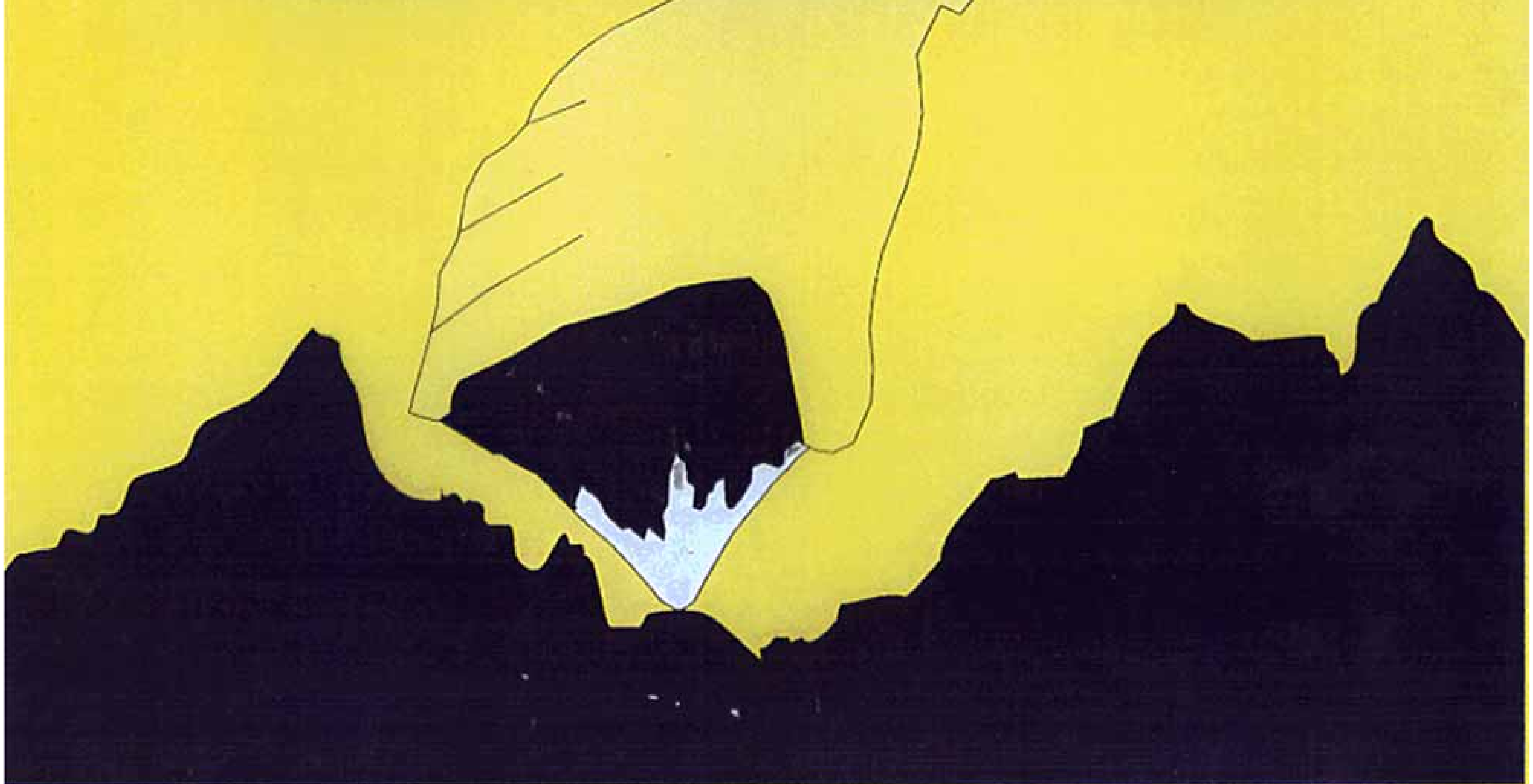
IMAGING / MICROSCOPY
ONE GRAIN OF SAND TOUCHES ANOTHER



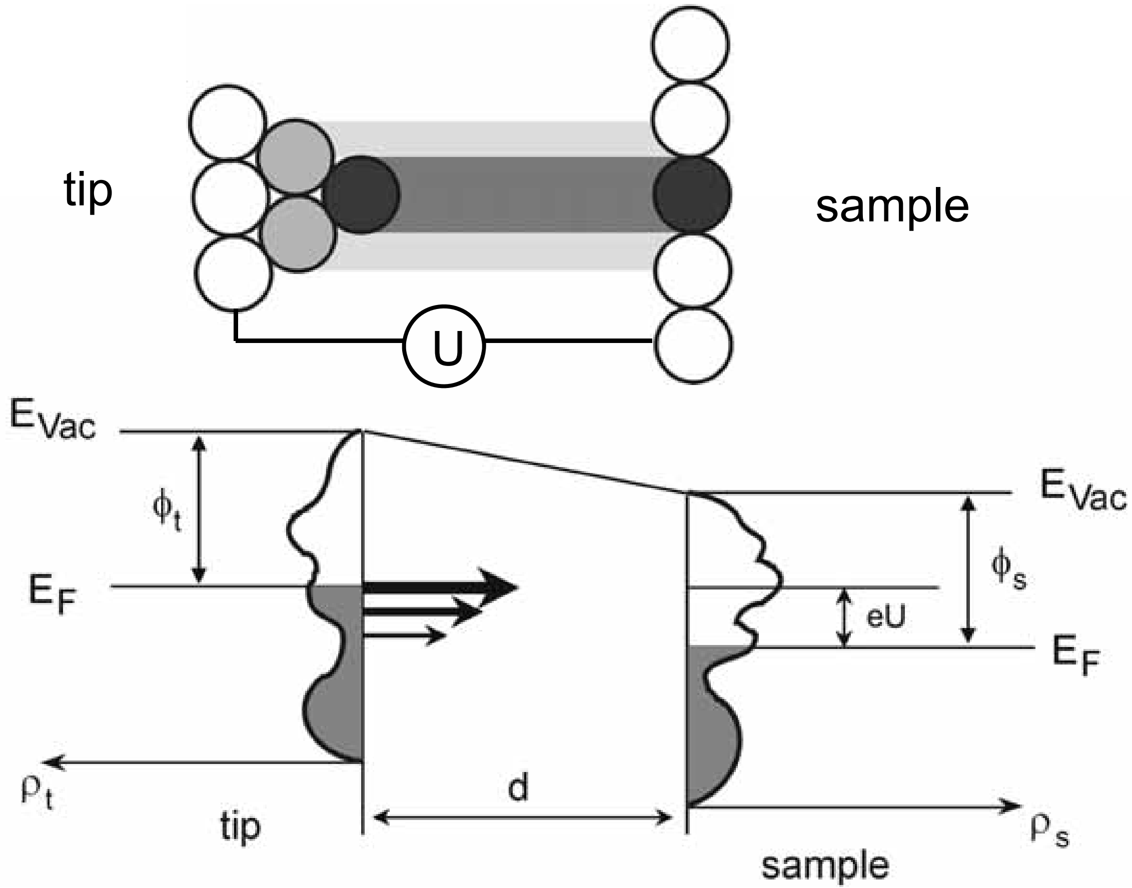
IBM

H. Rohrer
IBM Zurich Research Laboratory, 8803 Rüschlikon, Switzerland

Repetition VII

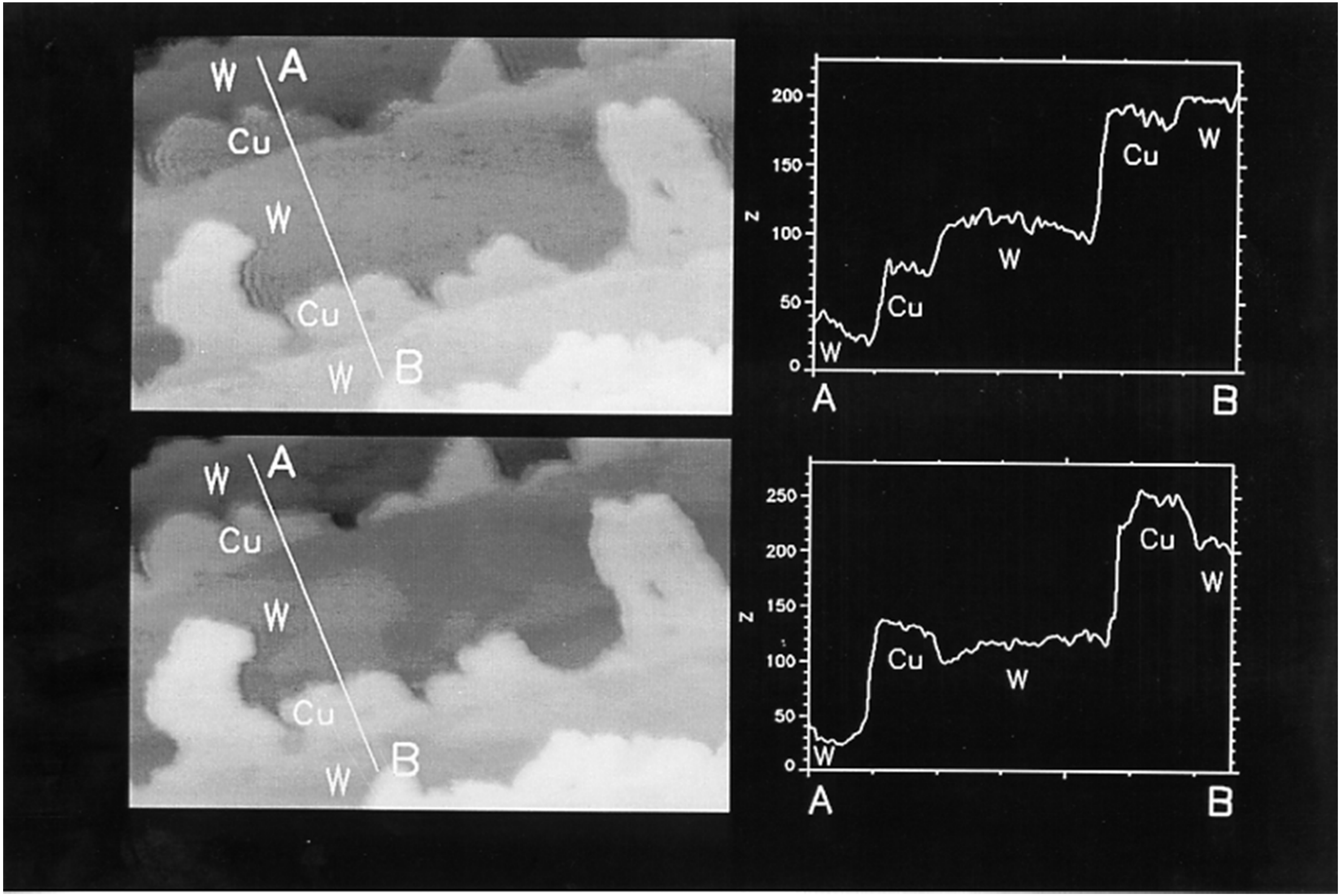
- Scanning Tunneling Microscopy
- Principle, Creep, Non-linearities, Tip Artefacts
  tip preparation
- Beyond Microscopy: Imaging, Mapping, Manipulation
- Quantum mechanical Tunneling: Tip and Surface
  States: Spectroscopy

Scanning Tunneling Microscopy



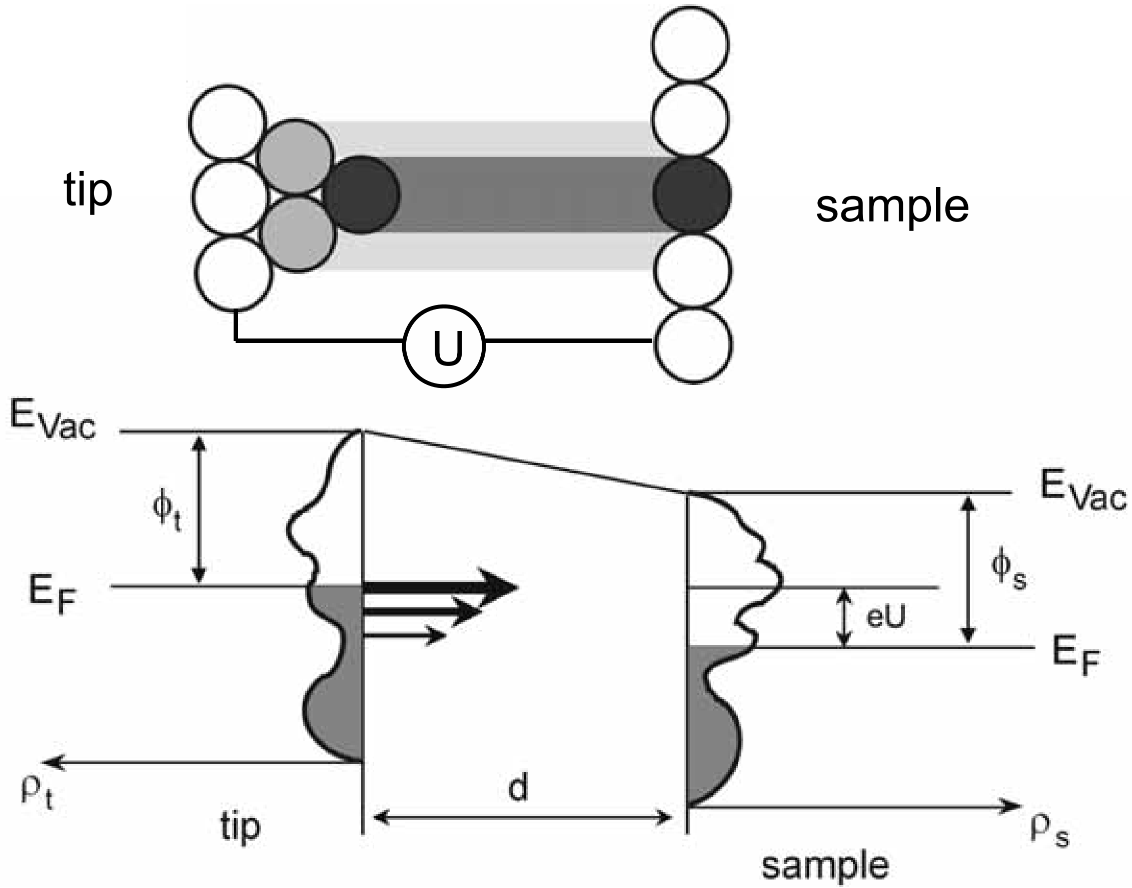
Tunneling current: $I_{tunnel} \sim U \rho_t \rho_{s(x,y)} e^{-const\ d}$ (Tersoff and Hamann)

=> sensitivity to local electronic structure of the sample



W
A
Cu
W
Cu
W
B
200
150
100
50
0
z
Cu
W
W
Cu
W
A
B
W
A
Cu
W
Cu
W
B
250
200
150
100
50
0
z
Cu
W
Cu
W
W
A
B

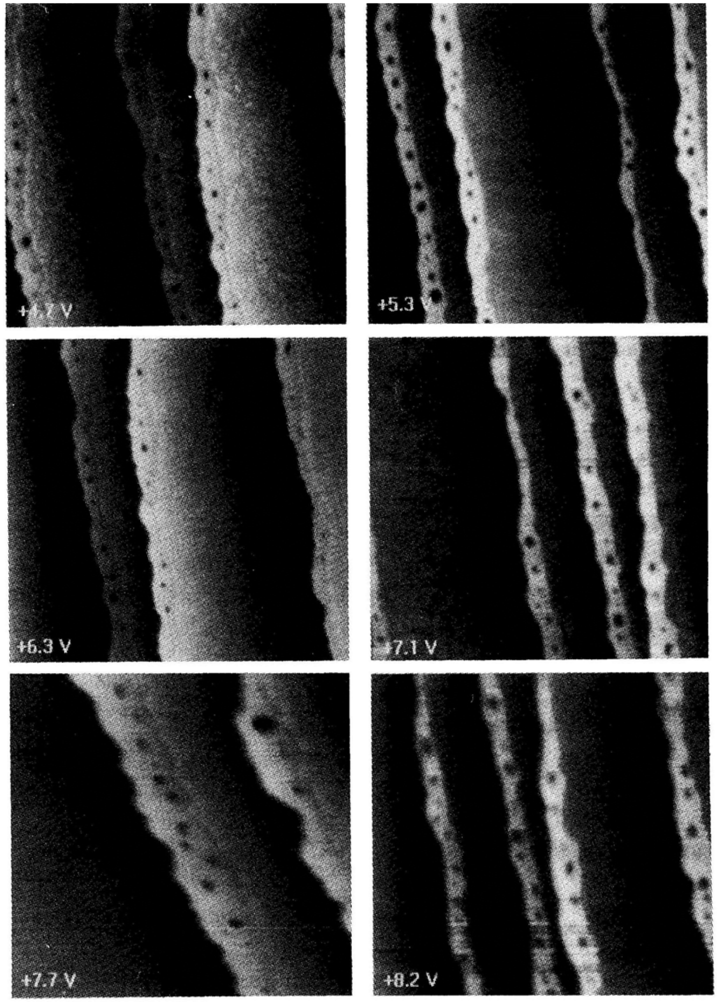
Scanning Tunneling Microscopy

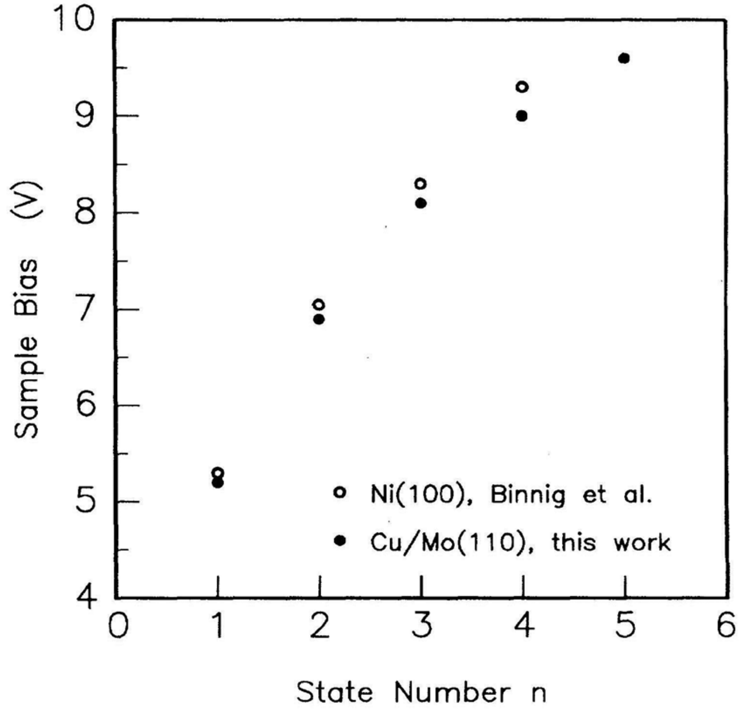


Tunneling current: $I_{tunnel} \sim U \rho_t \rho_{s(x,y)} e^{-const\ d}$ (Tersoff and Hamann)

=> sensitivity to local electronic structure of the sample

Chemical Sensitivity in STM: surface states vs image states

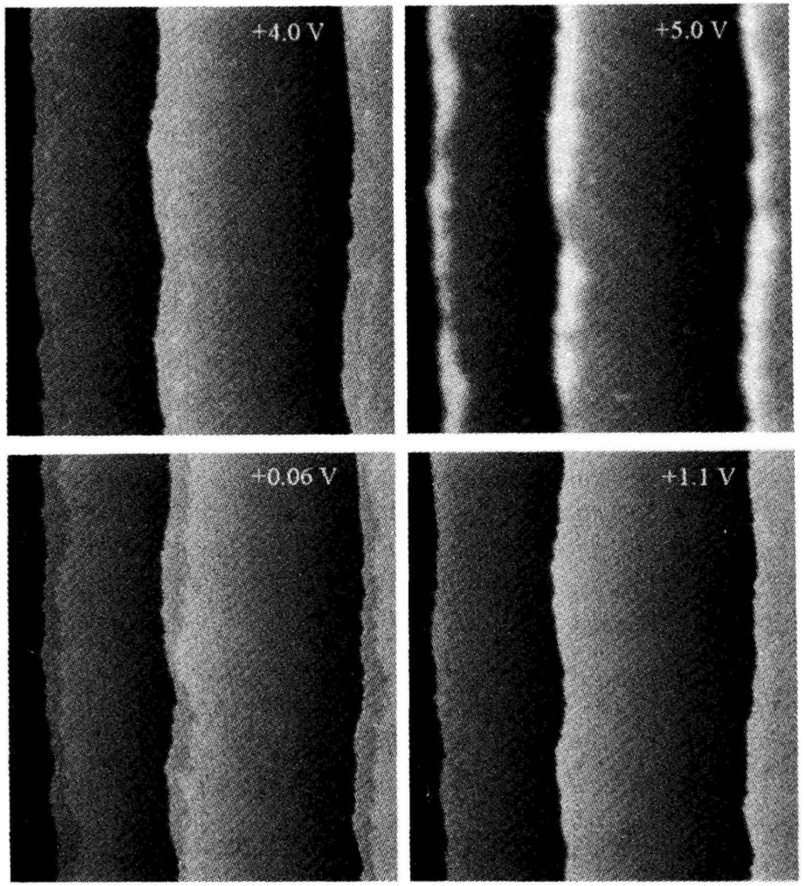




Periodic Contrast Change in U_{gap}: Image Resonant Enhancement !

T. Jung et al. Phys. Rev. Lett. 74, 1641 (1995)

Chemical Sensitivity in STM: surface states vs image states



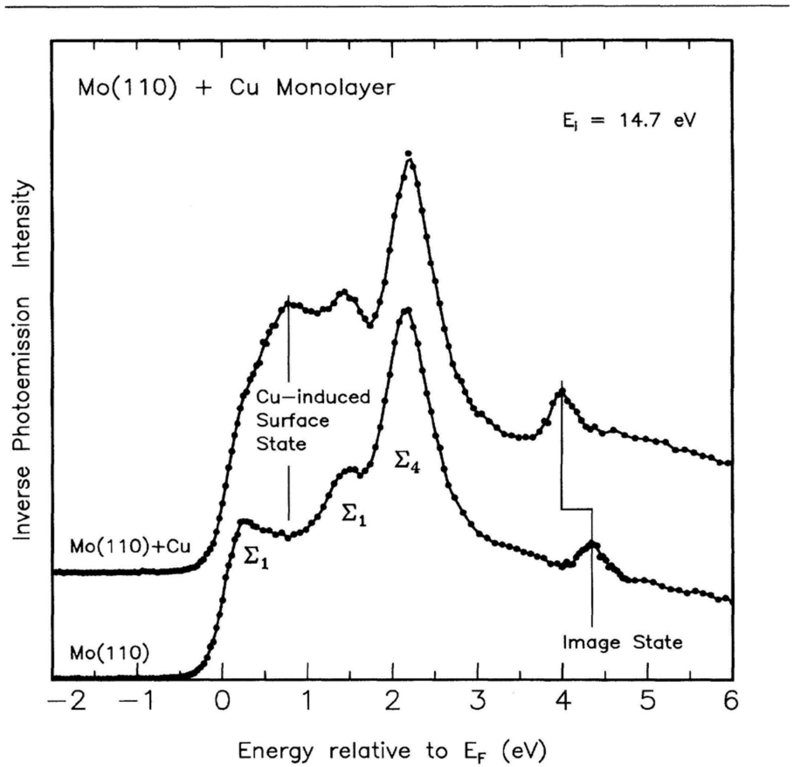
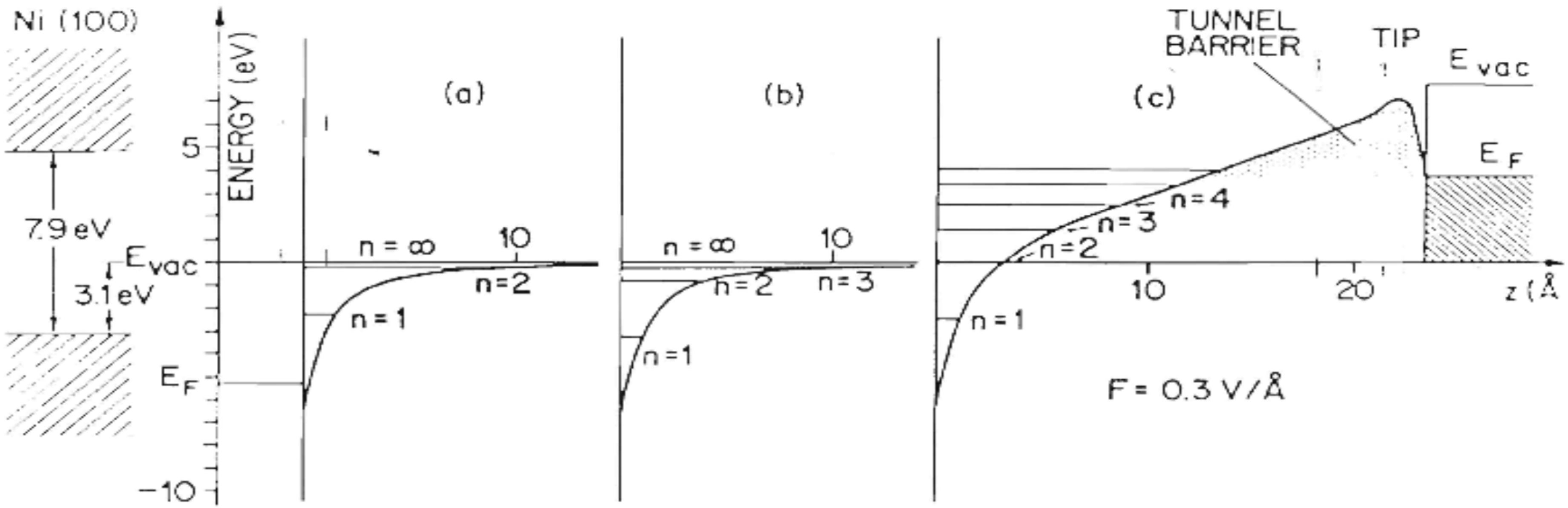


Image State Contrast >>> Surface State Contrast

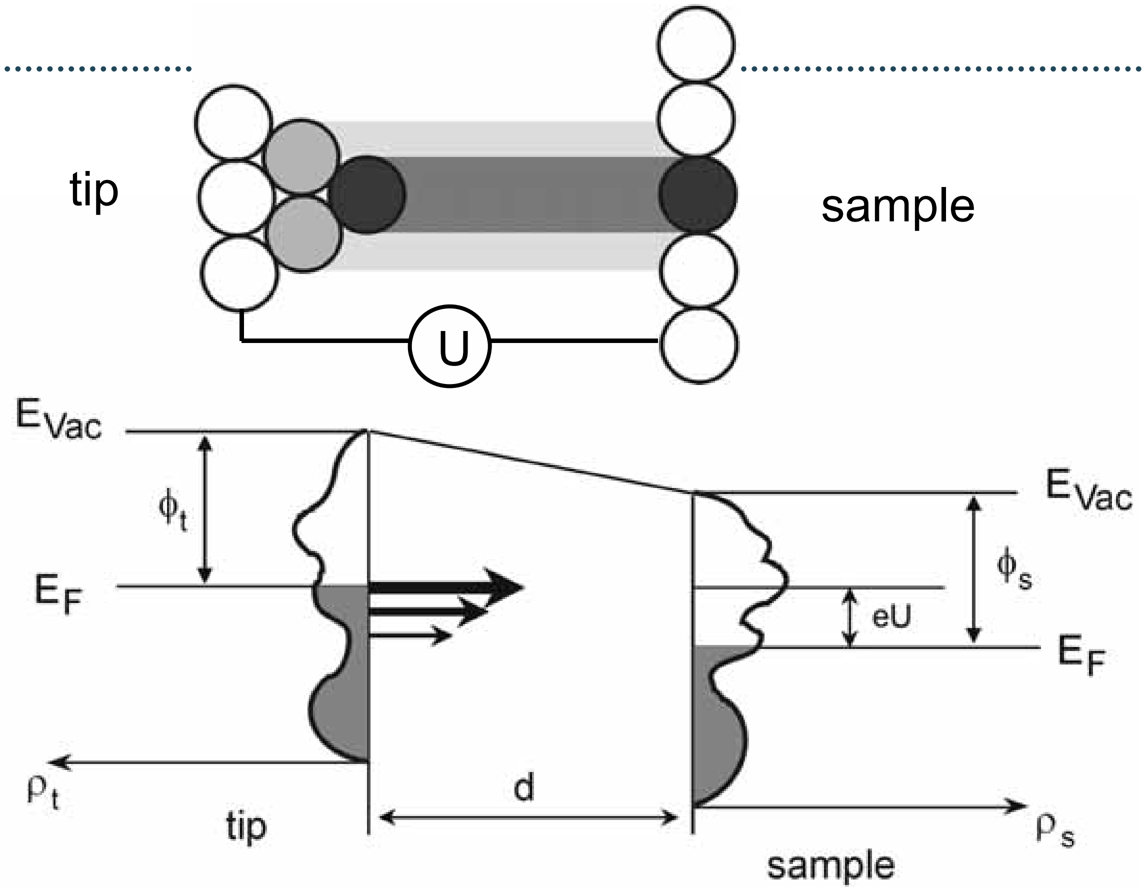
T. Jung et al. Phys. Rev. Lett. 74, 1641 (1995)

Bildladungspotential ueber leitender Oberflaeche



a) idealer Leiter
b) hohe Stufendichte
c) Potentialverschiebung im STM

Scanning Tunneling Microscopy

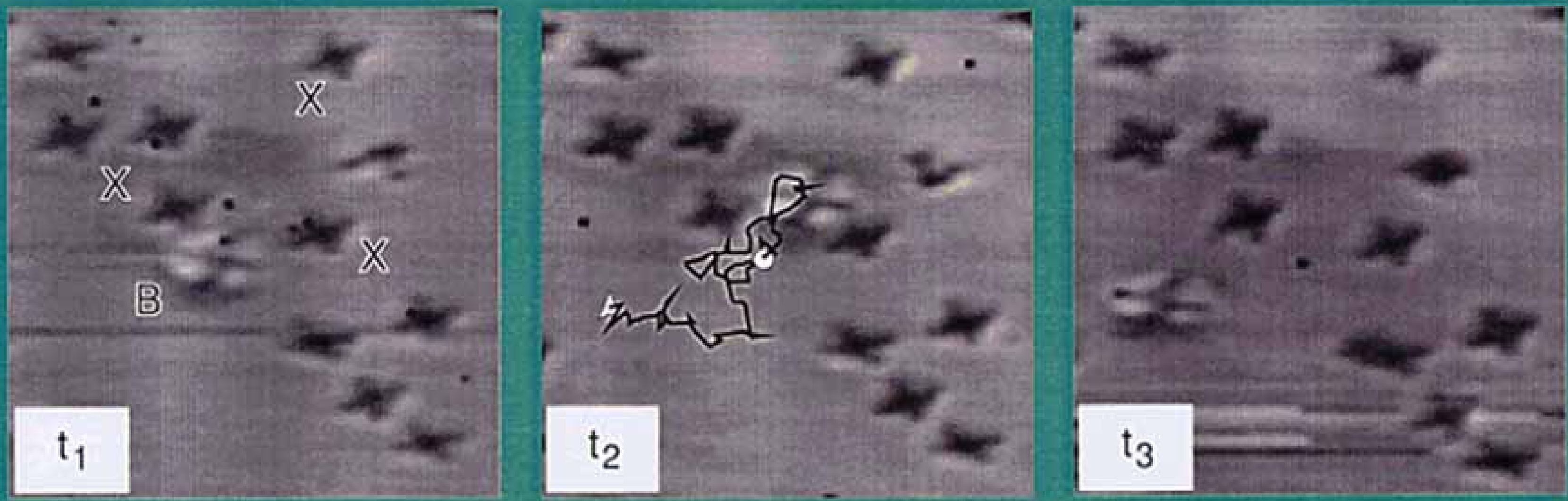


Tunneling current: $I_{tunnel} \sim U \rho_t \rho_{s(x,y)} e^{-const\ d}$ (Tersoff and Hamann)

=> sensitivity to local electronic structure of the sample

Molecular Motion Constrained to Two Dimensions

co-evaporation of Cu-tetraphenyl porphyrin (pins, X) and
Cu-tetra-di-t-butyl-phenyl porphyrin (balls, B)

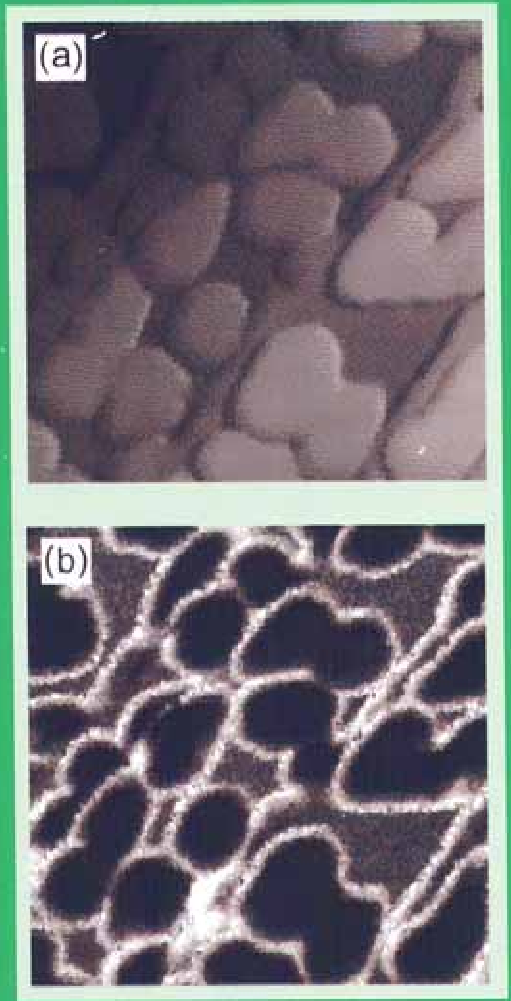


Molecular structure influences: **STM - Contrast**
DE Adsorption
Mobility

IBM
T.A. Jung, R.R. Schlittler and J.K. Gimzewski
IBM Zurich Research Laboratory, 8803 Rüschlikon, Switzerland

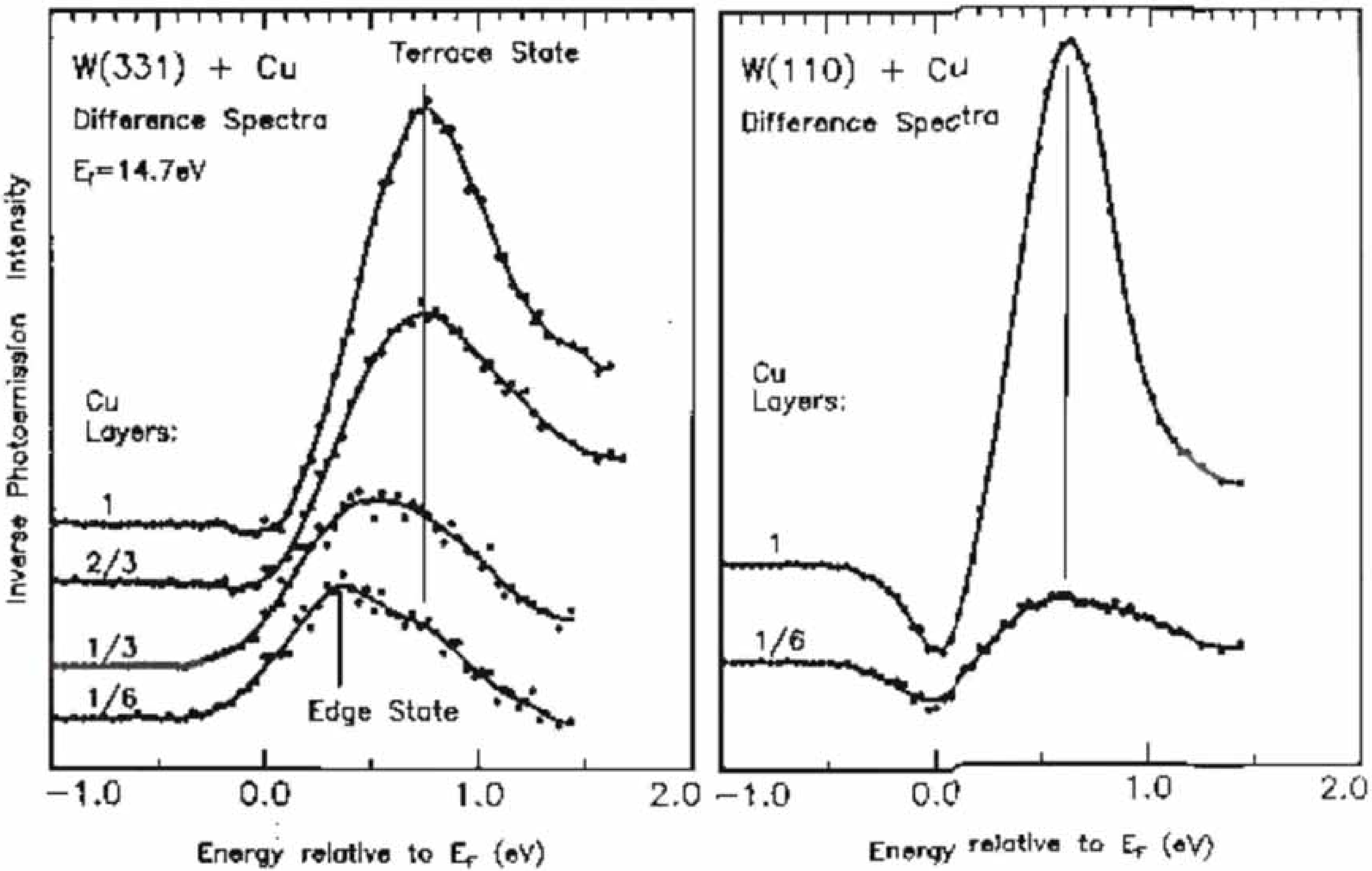
Chemical Information from SPM / Spectroscopy

Spectroscopic Changes at the Edge of Fe Islands on W(110)



(a) From Bode et al., Phys. Rev. B 54, R 8385 (1996);
(b) From Wiesendanger et al., J. Vac. Sci. Technol. A 14, 1161 (1996).

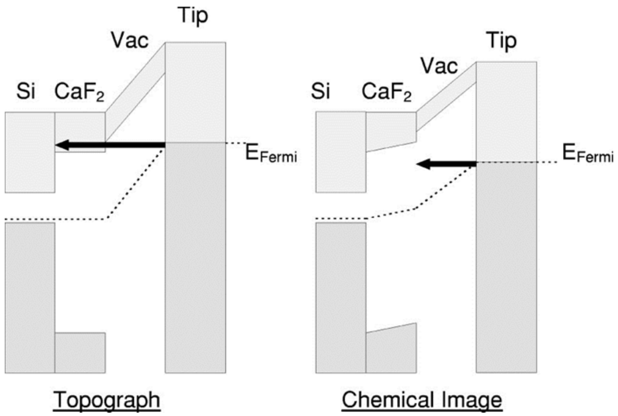
Stufenzustaende und Oberflaechenzustaende auf W(331)

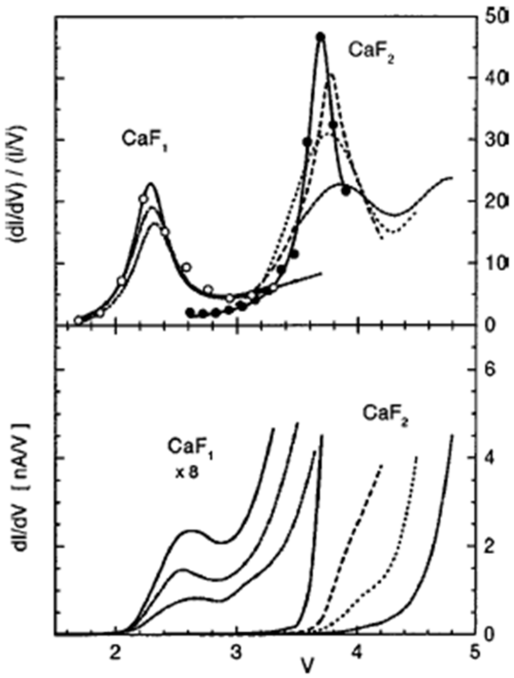


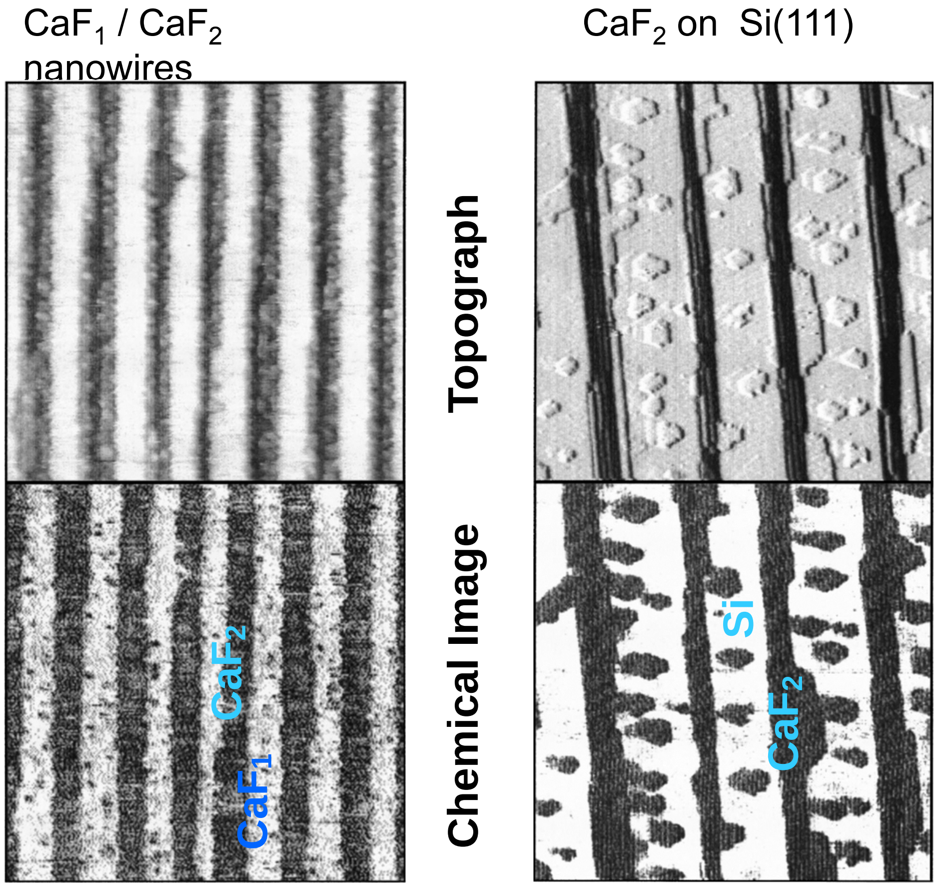
Dimensionalitaet
3D(bulk) – 2D (flaeche) – 1D (draht) – 0D (punkt)

- Wachstumsverhalten
- Elektronische Zustaende
- … andere kooperative Phaenomene

Scientific Background: Chemical Imaging





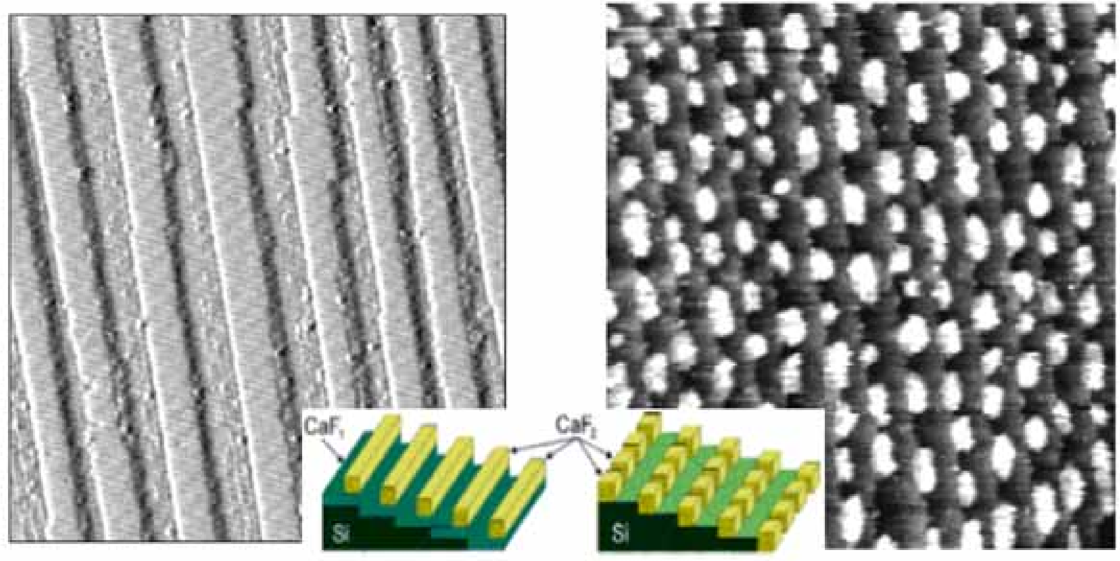


Chemical imaging of insulators by STM

J. Viernow et al., *Phys Rev. B 59 (1999) 10356*

Self- Assembly durch Stufendekoration:
TD Gleichgewicht und eingefroren im kinetischen Grenzfall

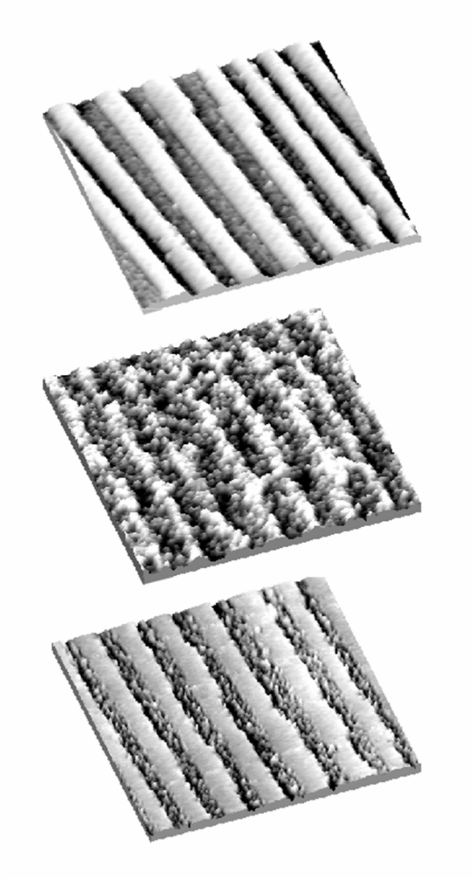
CaF_2 nanowires' and 'dots' can be produced by combination of:
- step decoration
- submonolayer precision of deposition
- controlled growth kinetics and annealing



Self organised Growth of CaF_2 on Si(111)

J. Viernow et al., *Appl.Phys.Lett.* ***72*** *(1998) 948*
J.-L. Lin et al., *J.Appl.Phys.* ***84*** *(1998) 255*

One-dimensional confinement of molecules via selective adsorption



CaF_2 / CaF_1 wires

After deposition of
DPP molecules

After subsequent
annealing

H. Rauscher et al., *Chem. Phys. Lett.* ***303*** *(1999) 363*

One-dimensional confinement of molecules via selective adsorption

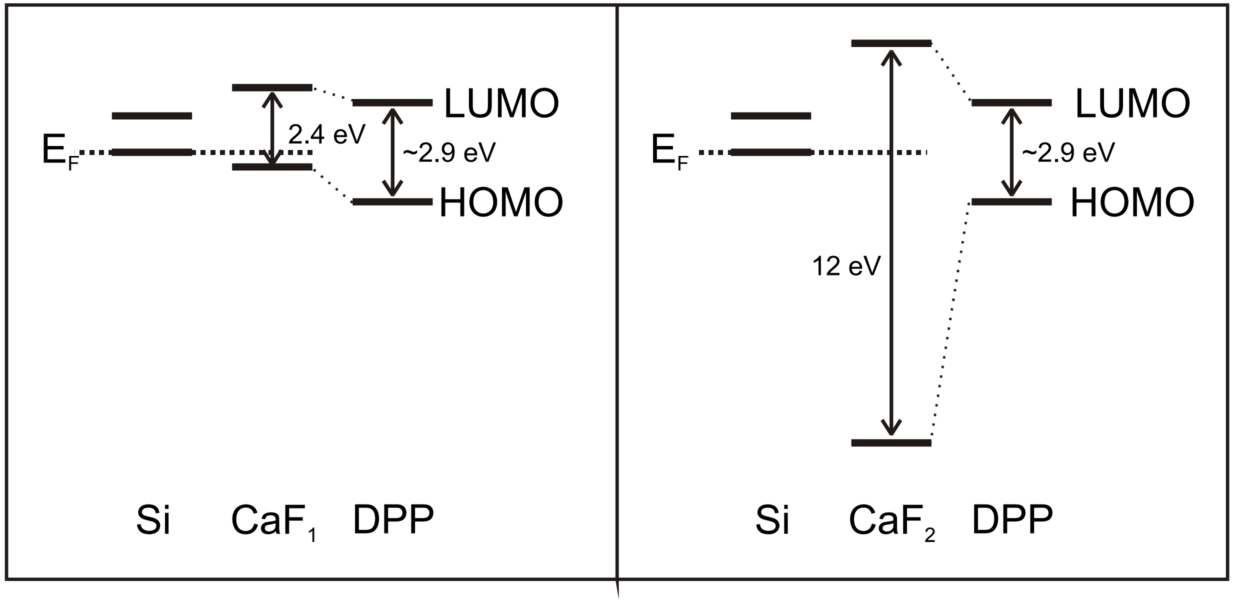


Fig. 4

H. Rauscher et al., *Chem. Phys. Lett.* ***303*** *(1999) 363*

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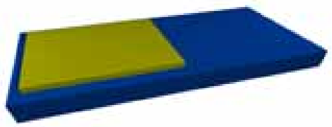
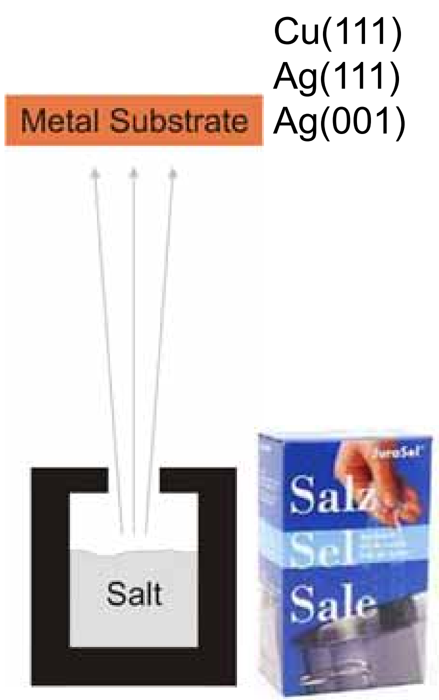
Growth of ultrathin insulator layers



NaCl

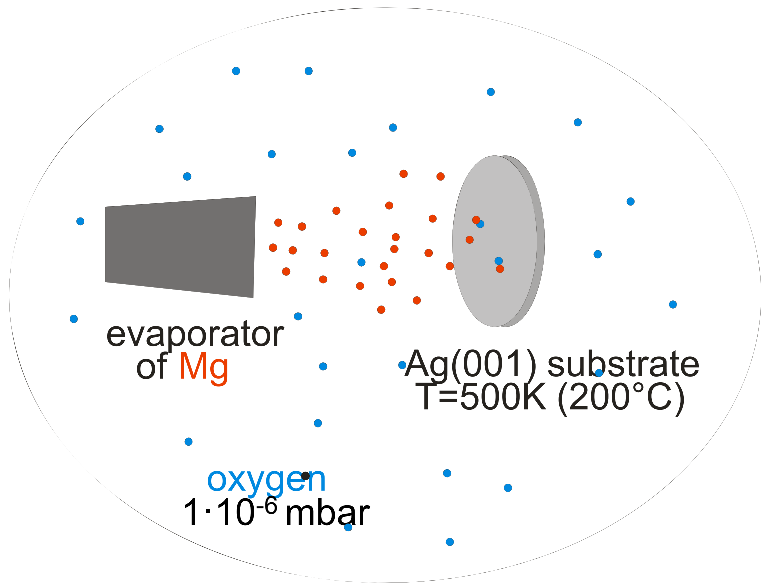


sublimation of NaCl

- Evaporator rate ~ 1 Å / min
- Substrate temperature ~ 400 K

NaCl dimer formation upon sublimation
Rothberg *et al.* Journal of Chemical Physics **30**, 517 (1959)

MgO



sublimation of Mg in oxygen background

- Evaporator rate ~ 1 Å / min
- Substrate temperature ~ 500 K
- oxygen $1 \cdot 10^{-6}$ mbar

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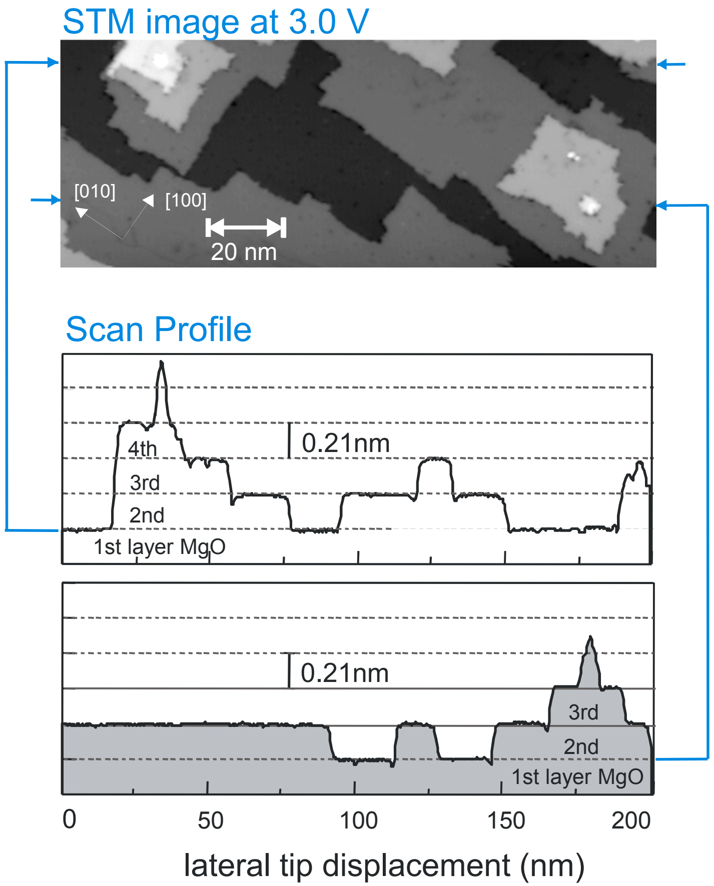
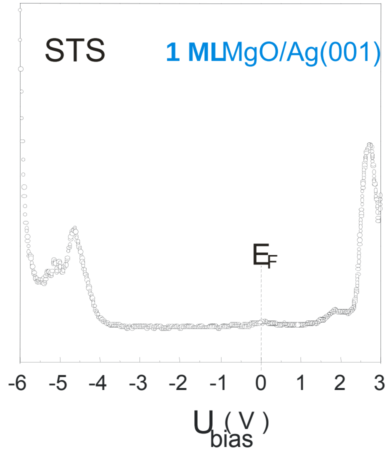
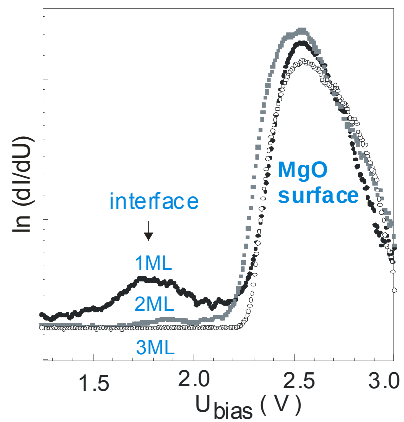
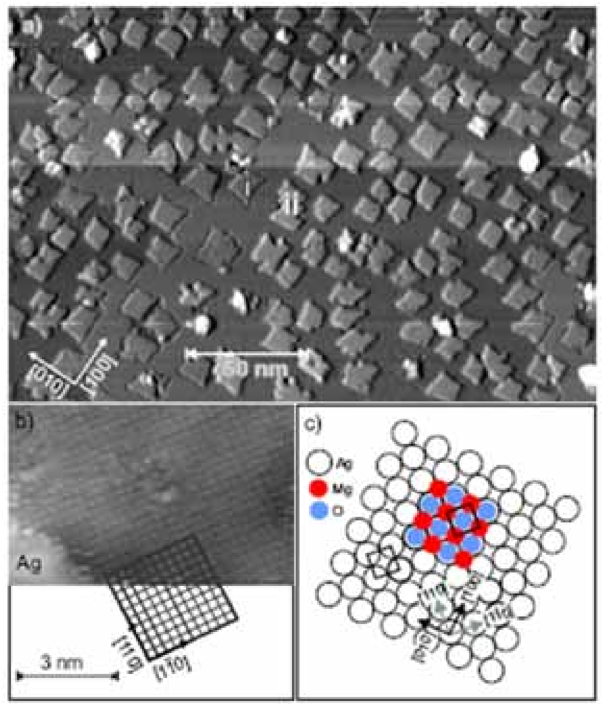
MgO/Ag(001): Insulator at the limit





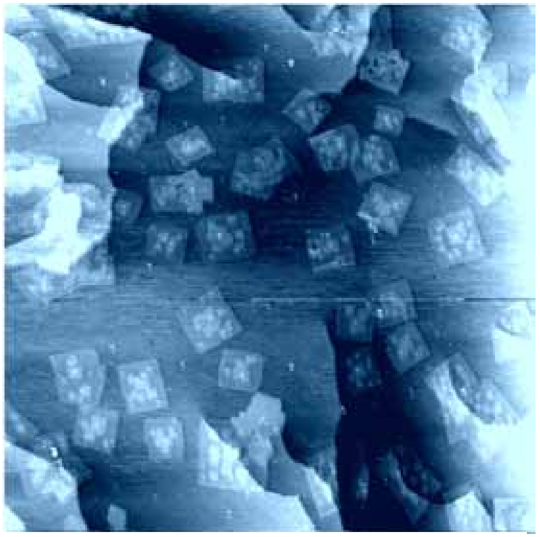




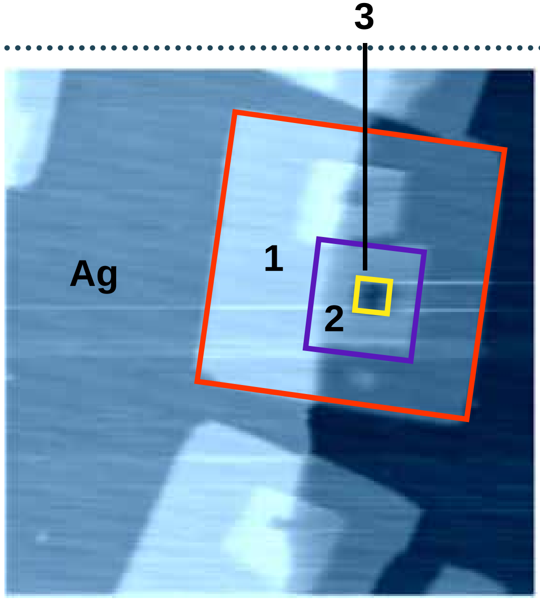
S. Schintke et al., *Insulator at the ultrathin limit: MgO on Ag(001)*, Phys. Rev. Lett. **87**, 276801 (2001)

S. Schintke and W.-D. Schneider, *Insulators at the Ultrathin Limit: Electronic Structure studied by Scanning Tunneling Microscopy and Scanning Tunneling Spectroscopy*, J. Phys.: Condens. Matter **16**, R49-R81 (2004)

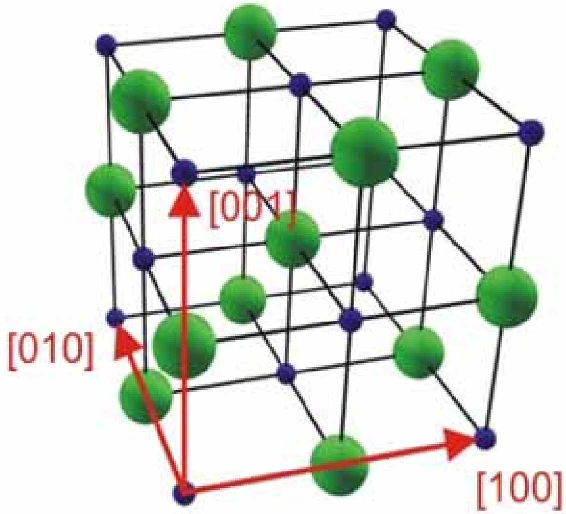
NaCl layers

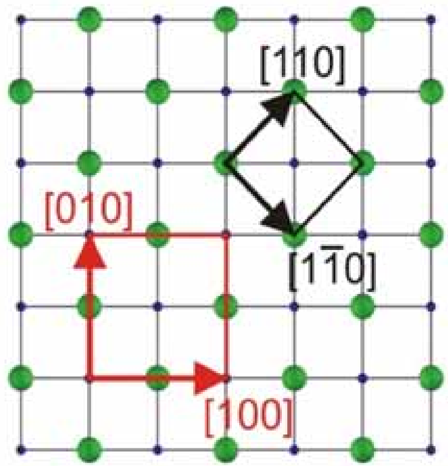


NaCl on Ag(111)
1.25 μm x 1.25 μm



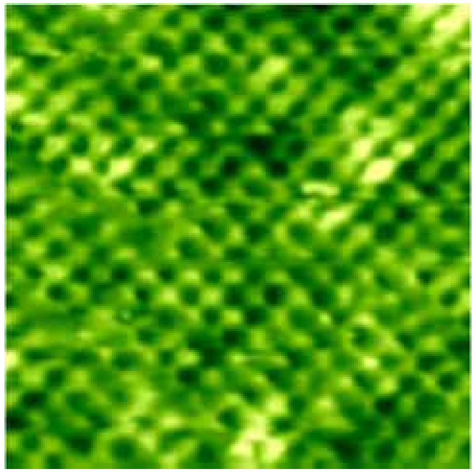
NaCl on Ag(111)   200 nm x 200 nm
U = 4.0 V, I = 15 pA





a_0 = 5.65 Å

atomic resolution: <u>one</u> type of the ions is imaged



NaCl on Cu(111)
5 nm × 5 nm
U = -1.5 V, 50 pA

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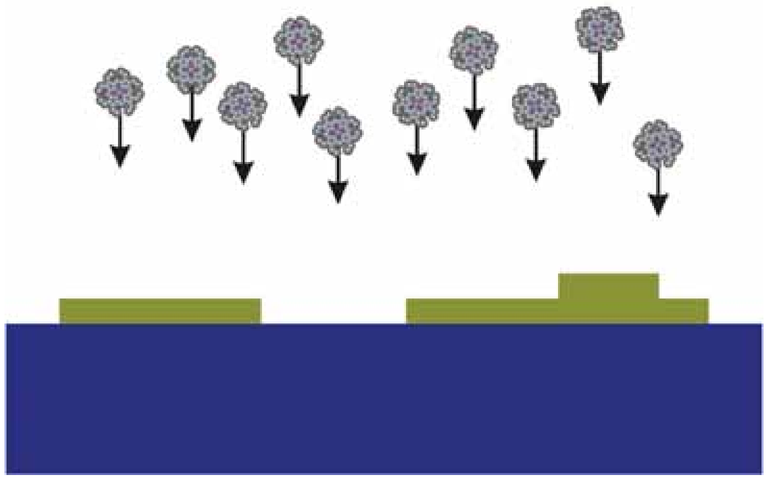
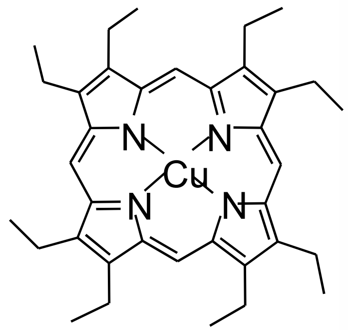
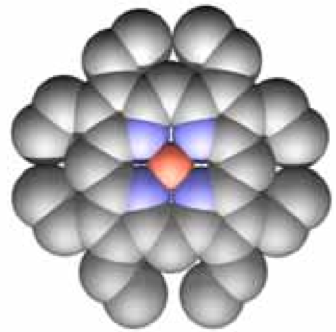
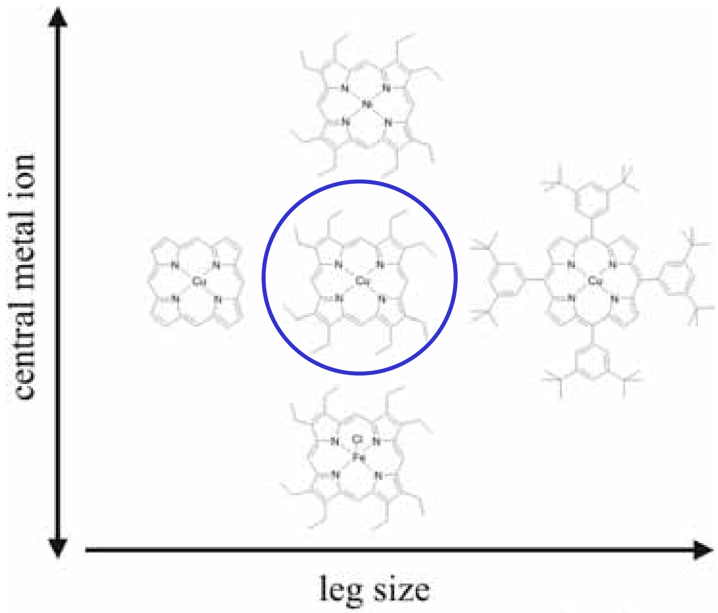
CuOEP on NaCl/Metal



copper(II) octaethyl-porphyrin (CuOEP)



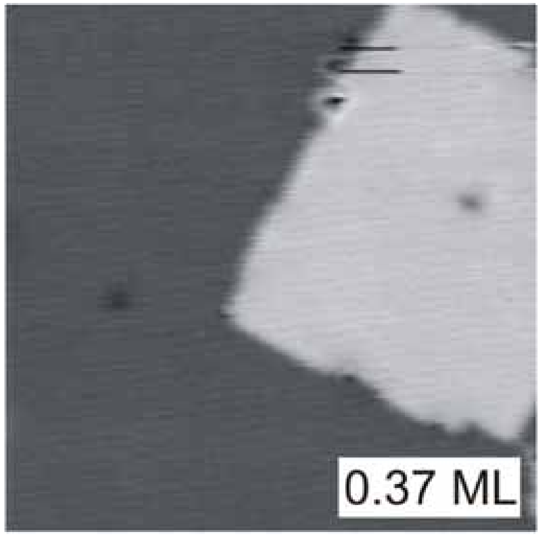




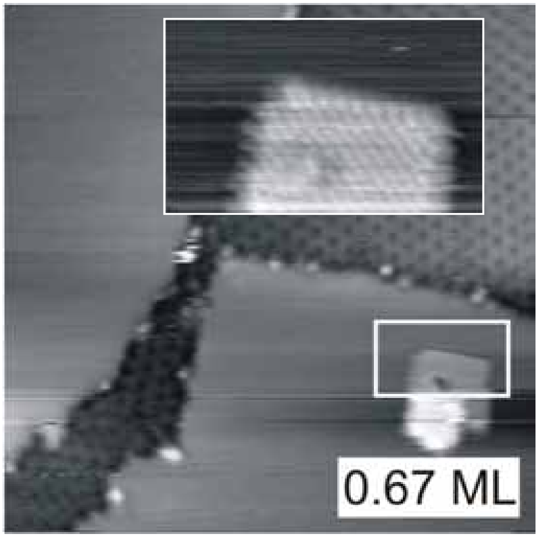
Substrate
- Metal with 0.3-0.7 ML NaCl
- NaCl structures: 0 to 3 atomic layers thick

Molecule deposition: sublimation
- Evaporation rate ~ 1-2 Å / min
- Substrate temperature ~ 300 K

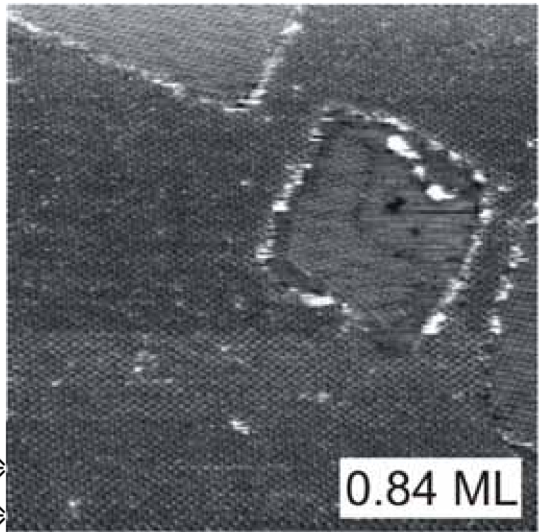
Layer selective adsorption



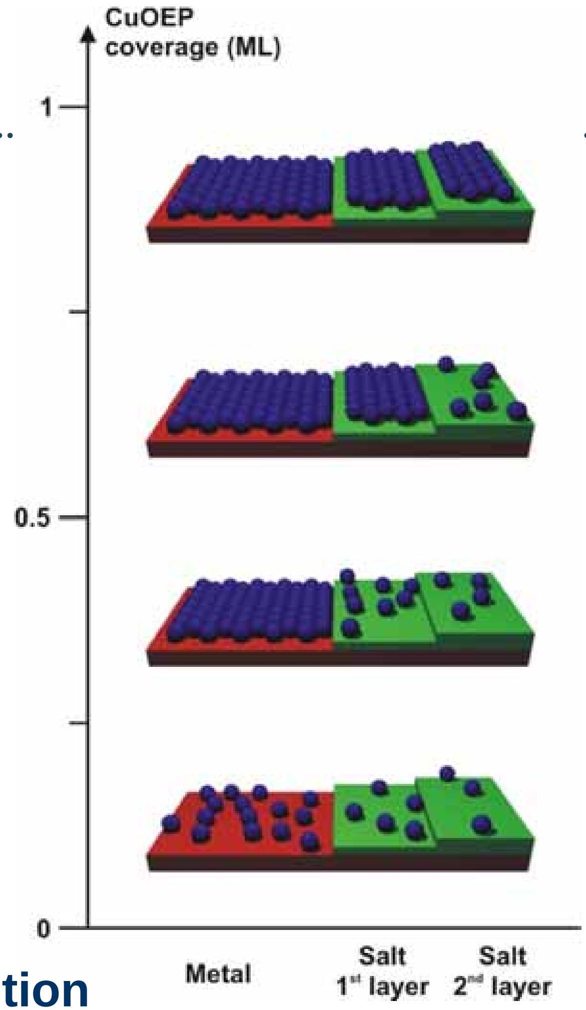
25 × 25 nm, 1.0 V, 24 pA



40 × 40 nm, -2.9 V, 45 pA
inset 10 nm × 6 nm



100 × 100 nm, -1.6 V, 24 pA



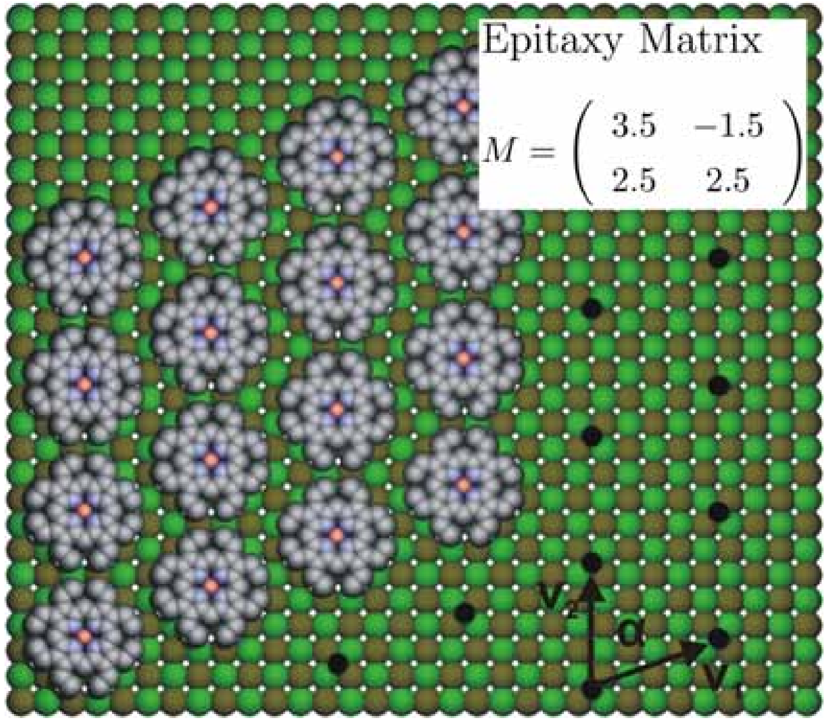
⇒ **layer-selective adsorption**

adsorption energy depends on NaCl layer thickness:

$$E_{ads}^{(metal)} > E_{ads}^{(1^{st}\ layer\ NaCl)} > E_{ads}^{(2^{nd}\ layer\ NaCl)}$$

L. Ramoino, M. von Arx, S. Schintke, A. Baratoff, H.-J. Güntherodt, T.A. Jung
Chem. Phys. Lett. **417**, 22 (2006)

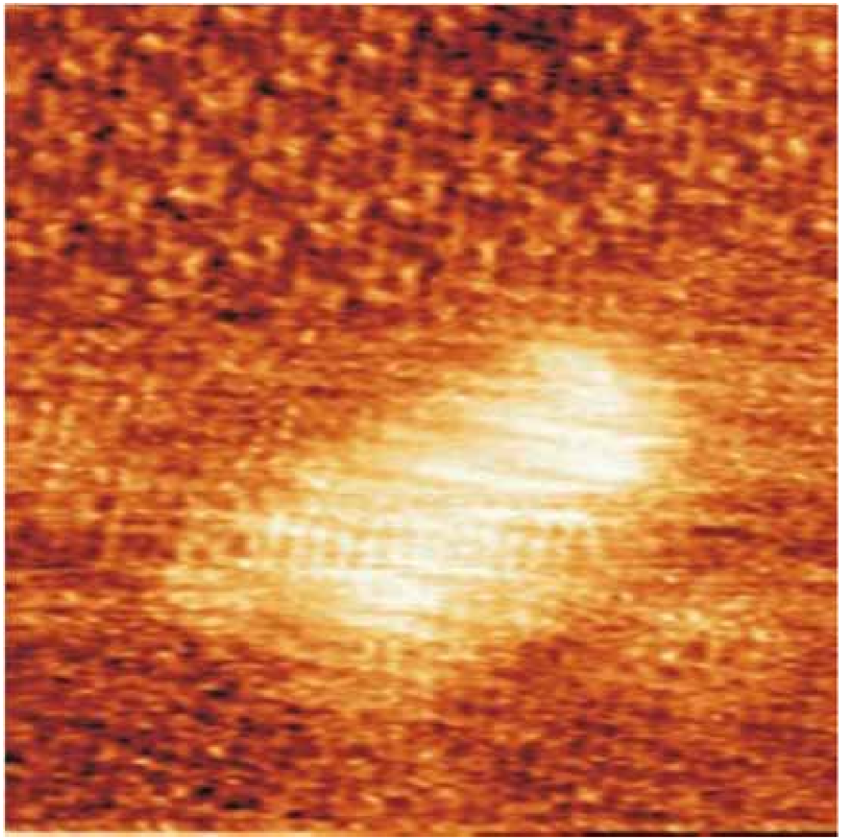
CuOEP Self-Assembly on Salt



	model	experiment
v_1	14.6 Å	14.3 ± 0.3 Å
v_2	13.5 Å	13.5 ± 0.3 Å
α	68.2°	69.0 ± 1°

L. Ramoino, M. von Arx, S. Schintke et al.
Chem. Phys. Lett. **417**, 22 (2006)

CuOEP on NaCl/Ag(111)



15 × 15 nm, U = -0.25 V, I = 81 pA

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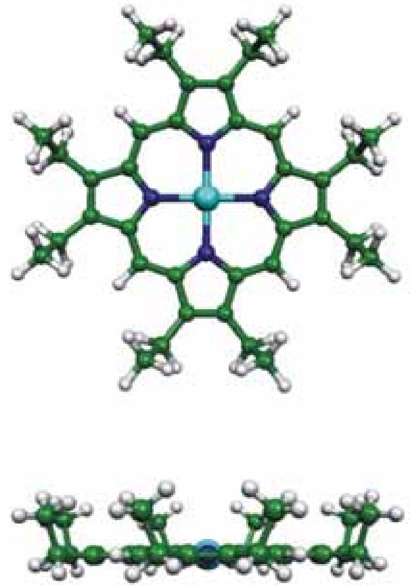
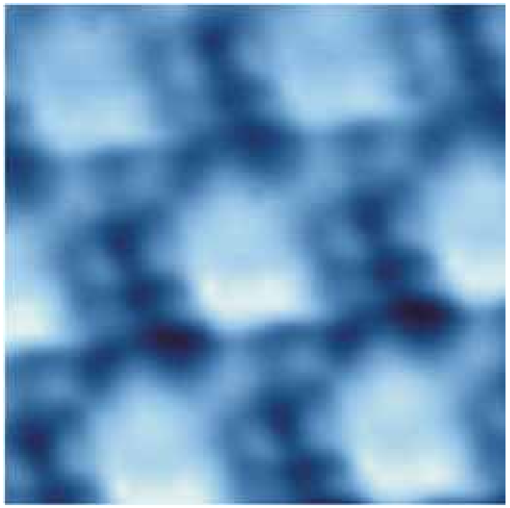
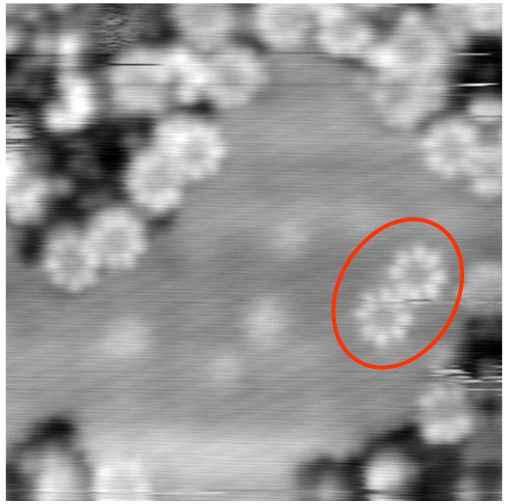
CuOEP molecules on metal and NaCl/metal





CuOEP on Cu(111)
(averaged image)
3.0 nm × 3.0 nm, U = -0.55 V, I = 24 pA



CuOEP on
Pd(111) and on NaCl/Pd(111)
15.0 nm × 15.0 nm, U = -1.9 V

- on Pd(111) no assembly of CuOEP
  => stronger molecule-metal substrate interaction than on Cu(111)
- stable adsorption of individual molecules on NaCl

- smaller broadening of electronic states on NaCl than on metal
  => reduced molecule-substrate interaction !

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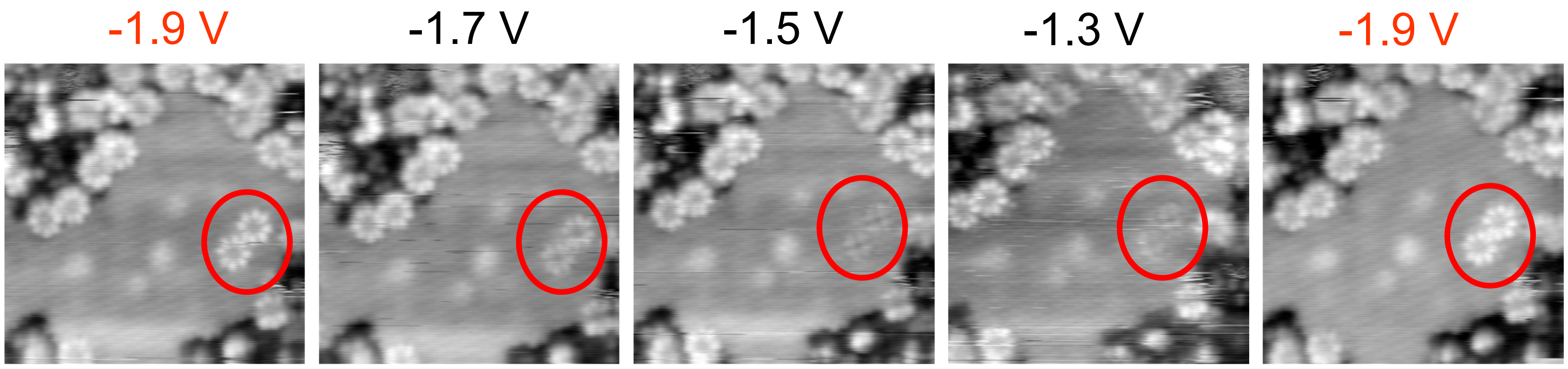
Bias dependence: CuOEP on NaCl/Pd(111)

S. Schintke et al. submitted (2007)



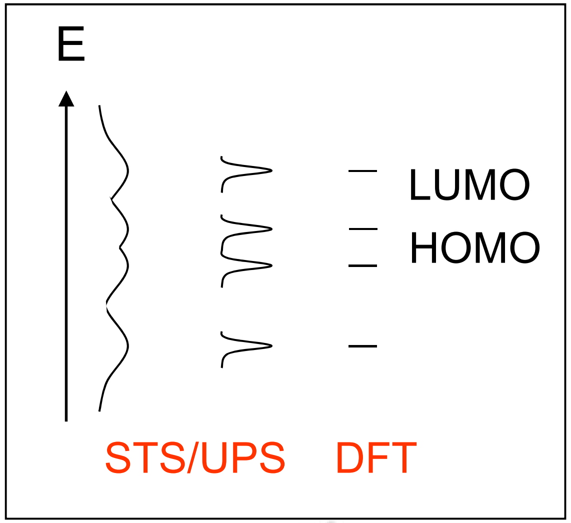
15 x 15 nm

- Small broadening of the HOMO on NaCl

  => confirming decoupling from metal

- CuOEP on Pd(111): eight lobe structure

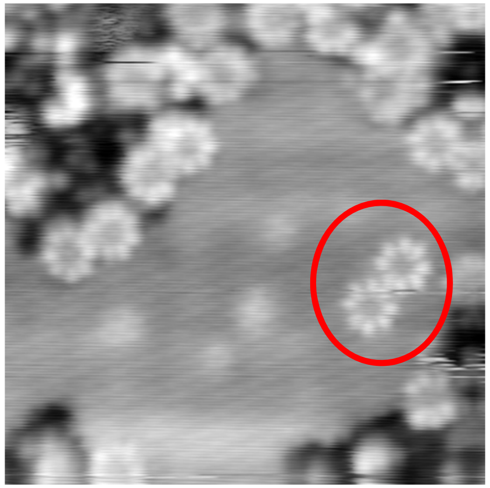
  => HOMO level broadening



Isolated molecule on ultrathin insulator

CuOEP on NaCl/Pd(111)

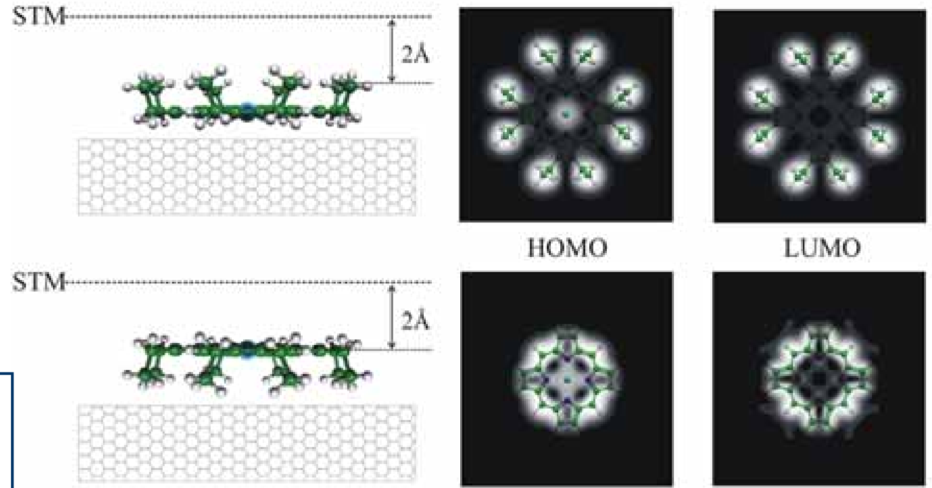
S. Schintke et al. submitted (2007)



-1.9 V
(HOMO)

Resonant tunneling via HOMO states
⇒ eight lobe structure

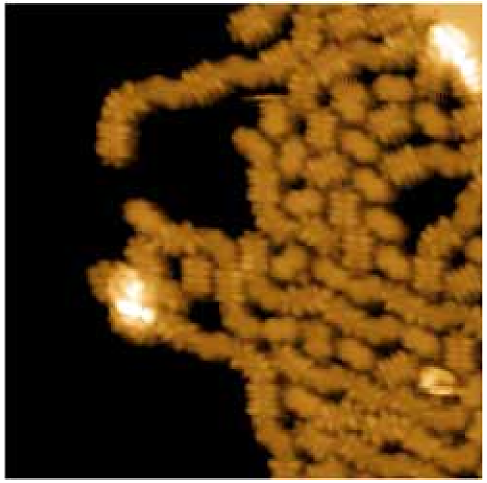
side groups imaged in STM although
HOMO belongs to the porphine ring!

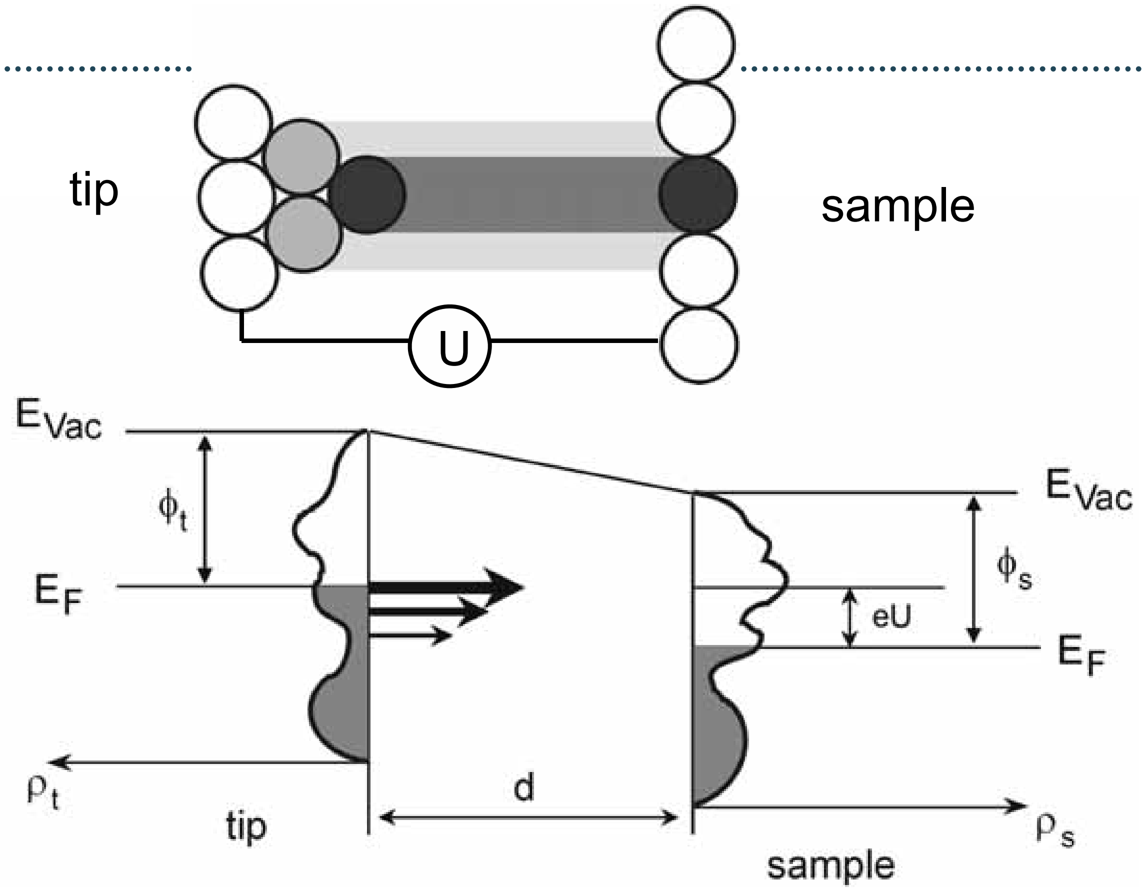


Compare: simulated STM images

=> adsorption geometry:
porphine ring towards substrate

Scanning Tunneling Microscopy



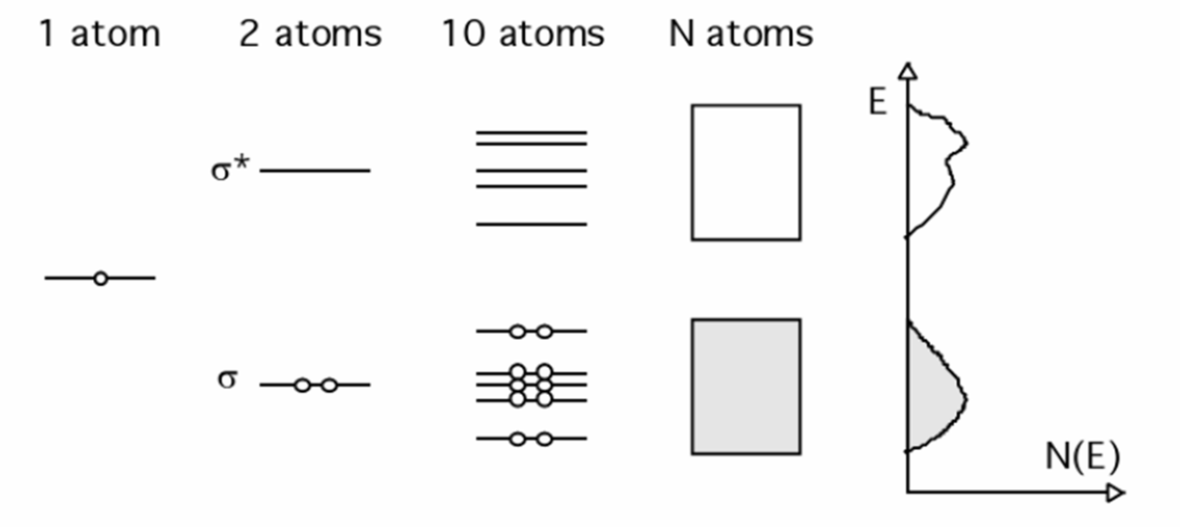


Tunneling current: $I_{tunnel} \sim U \rho_t \rho_{s(x,y)} e^{-const\ d}$ (Tersoff and Hamann)

=> sensitivity to local electronic structure of the sample

STS (scanning tunneling spectroscopy)

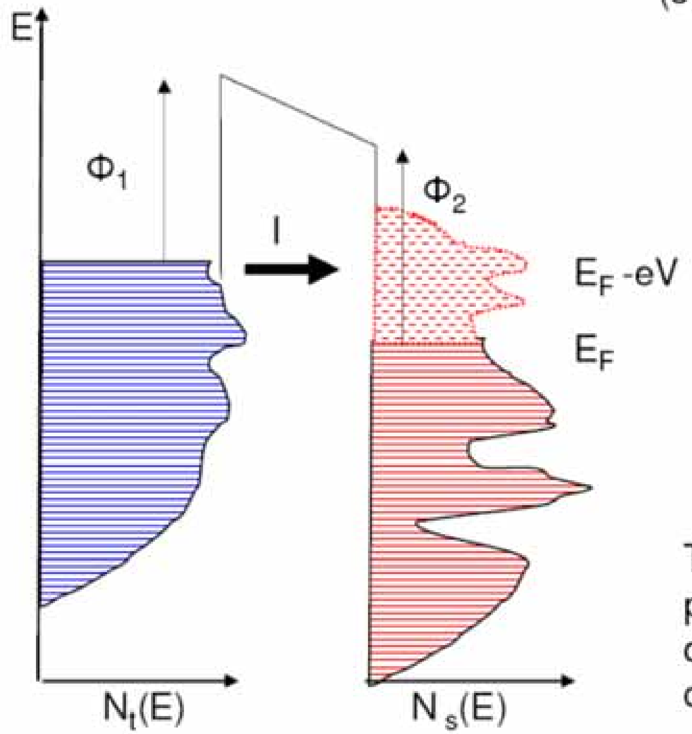
Density of States (DOS)



Density of States (DOS), N(E) is the number of energy levels bewteen E and E+dE (states per eV)

States can have s,p,d,f or mixed (hybrid) character
Bands may be separated by band-gaps E_g

Voltage dependence of tunneling current



By changing the voltage, the density of states can be recorded as function of the voltage (e.g., band structure of semiconductors)

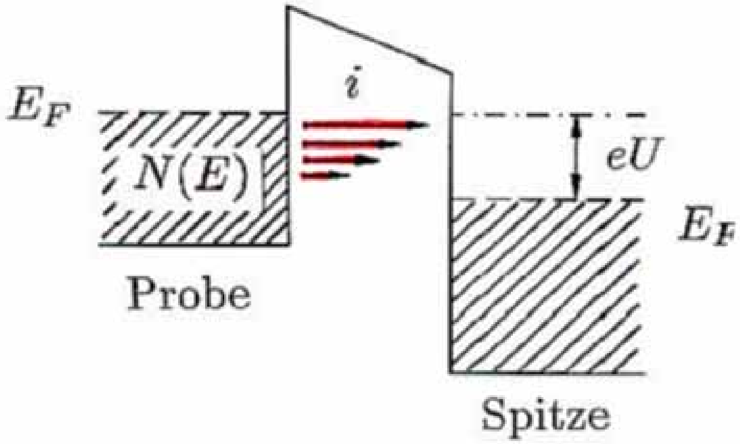
$$I \propto \int_0^{eV} N_1(E) N_2(E-eV) T(E,V) dE$$

where N_1 N_2 are the densities of states at the Fermi niveau and T(E,V) the transmission probability.

$$T(E,V) = \exp\left\{-2s\left[\phi - E + \frac{eV}{2}\right]^{1/2}\right\}$$

The contribution of the states to the tunneling process decays exponentially with their energetic distance to the Fermi niveau. Core levels do not contribute at all.

Spektroskopie



Spektroskopie

Lokale Messung der I/U-Charakteristik bei $x, y, z = const$ (R.J. Hamers, R.M. Tromp and J.E. Demuth, Phys. Rev. Lett. **56**, 1972 (1986))

Information über lokale elektronische Zustandsdichten N(E) enthalten in

$$I/U$$

$$dI/dU$$

$$\frac{dI}{dU}/\frac{I}{U} = \frac{d\ln I}{d\ln U}$$

CCT's mit $+U$ und $-U$

Stabilisierungsspannung U_0 und U sind Parameter

Zustandsdichte der Wolframdichte im Bereich der Fermienergie ändert Sich wenig, d.h. es wird primär die Zustandsdichte der Probe beobachtet (+; unbesetzte Zustände, -, besetzte Zustände)

[redacted]

2. STM beyond imaging

- STM a tool for nanofabrication:

Adsorbate manipulation

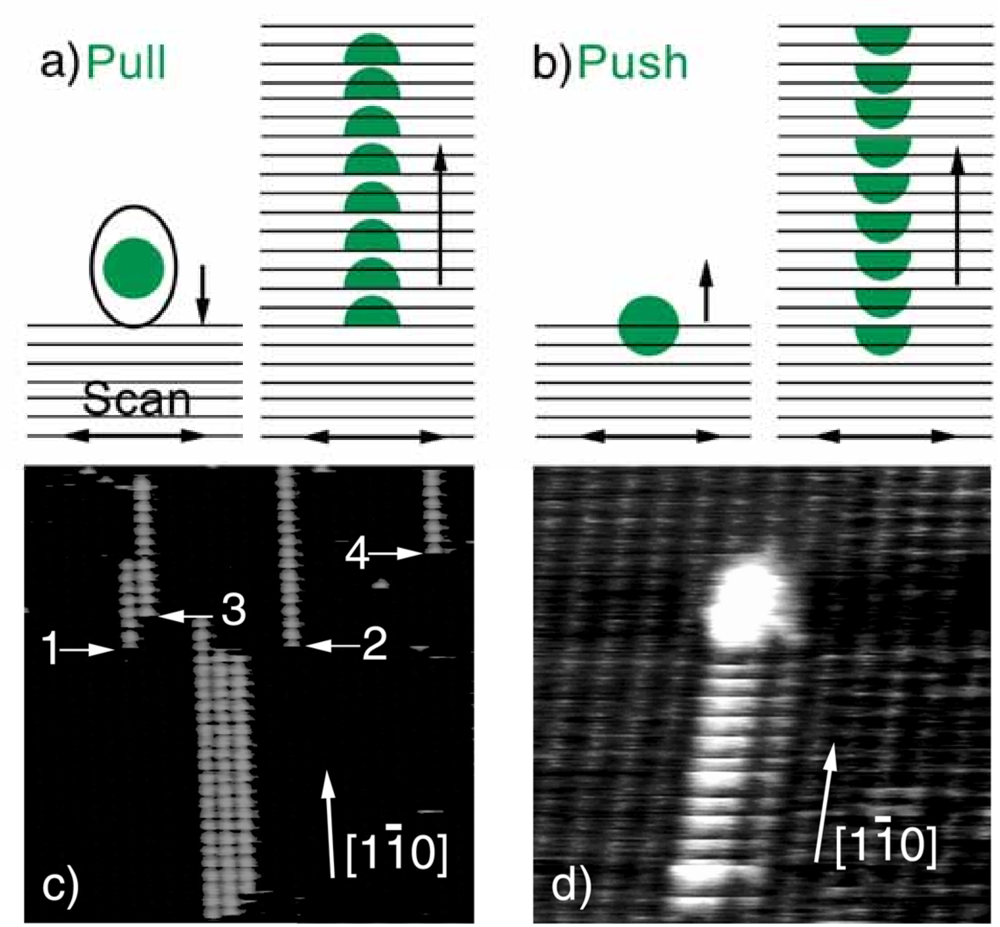
- STM a local spectroscopy tool:

Scanning Tunneling Spectroscopy (STS)

Inelastic Tunneling Spectroscopy (IETS)

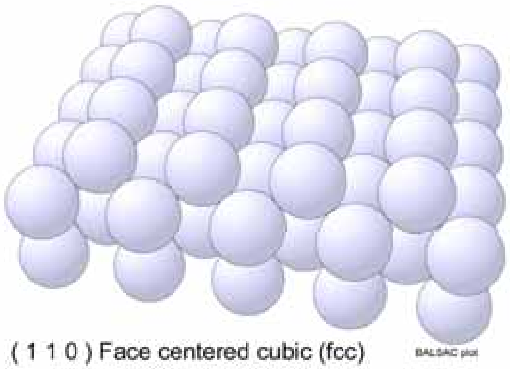
Local Photonemission spectroscopy

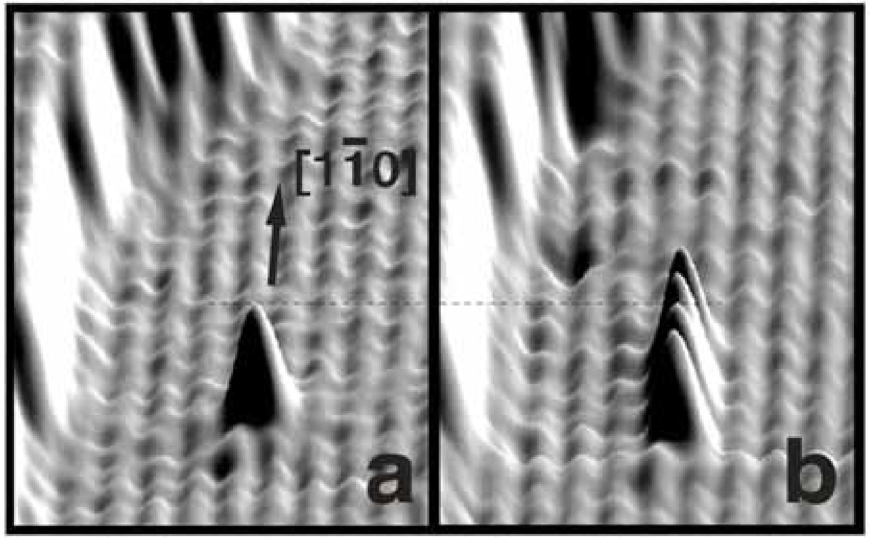
Tip-sample interaction



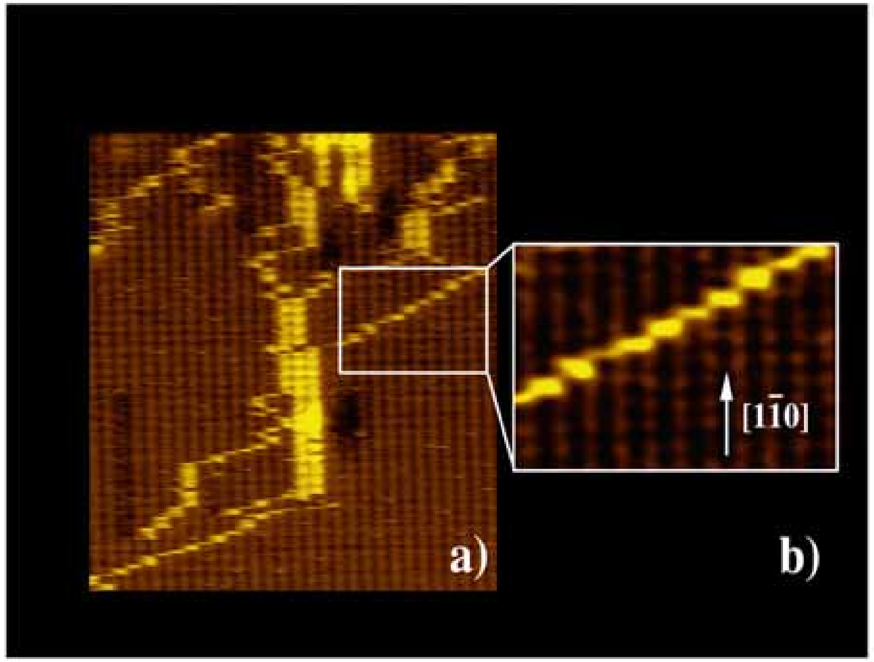
Low-temperature manipulation of Ag atoms and clusters on a Ag(110) surface,
J.T. Li, W.-D.Schneider, and R. Berndt, *Appl. Phys. A*, 66, 575 (1998).

Tip-sample interaction



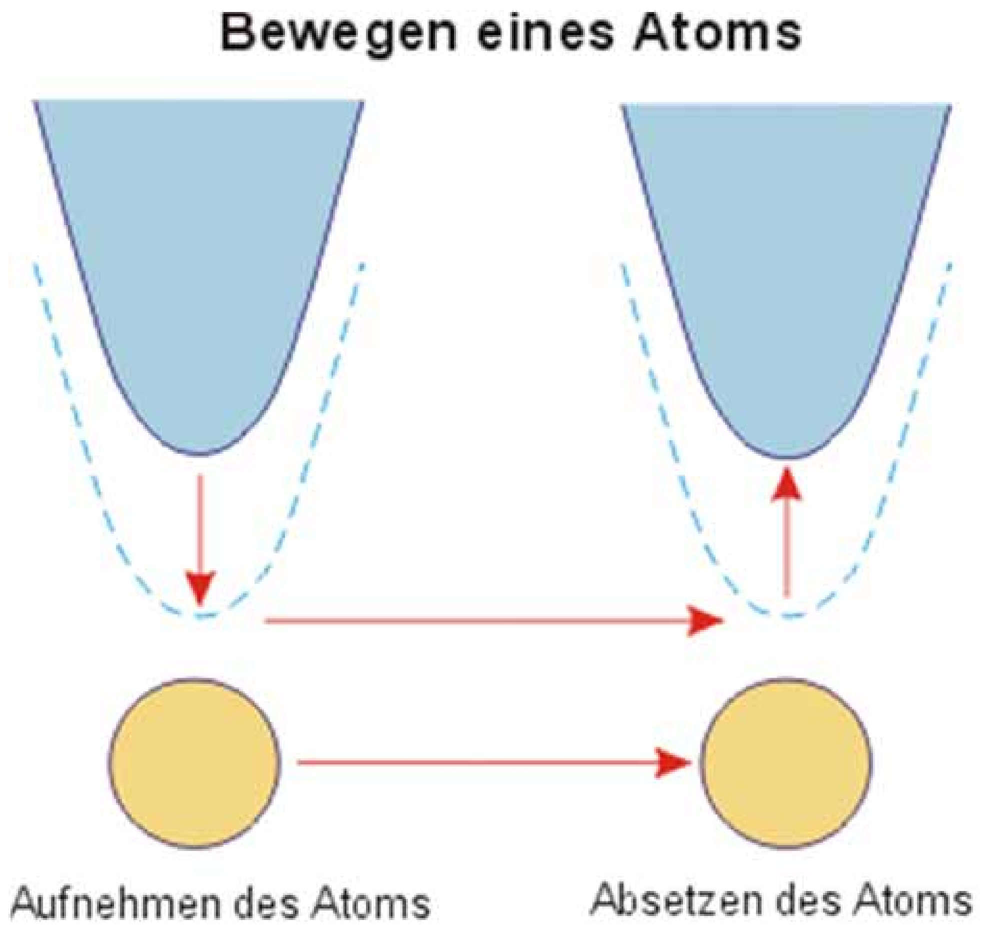


Diagonal Ag adatom motion along [1-11] direction (atom exchange)

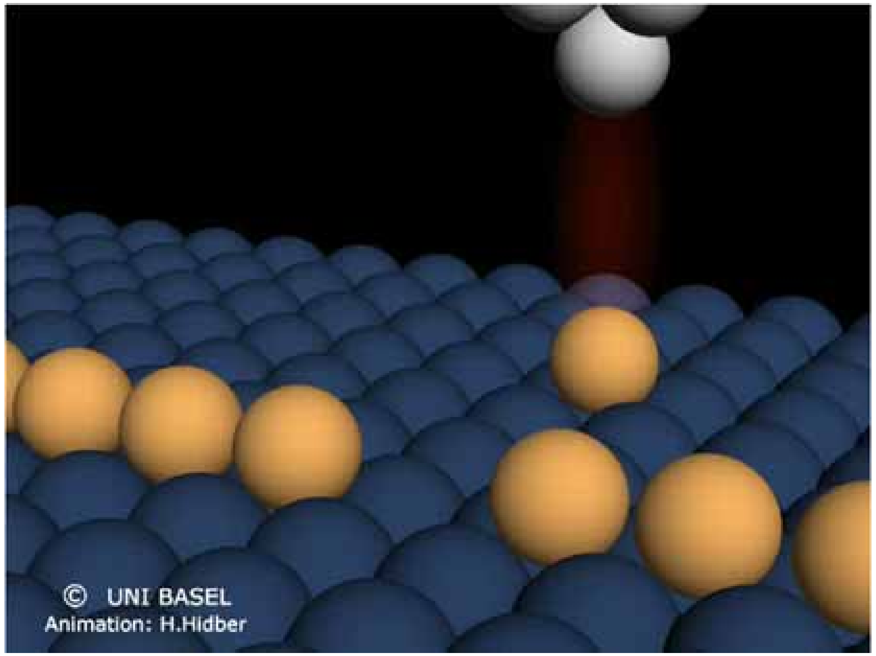


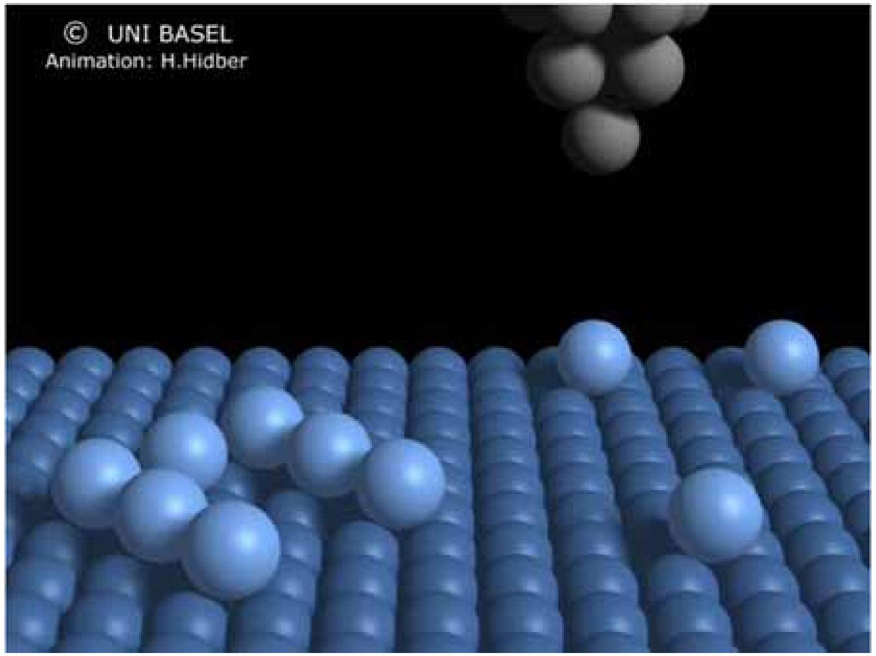
Low-temperature manipulation of Ag atoms and clusters on a Ag(110) surface,
J.T. Li, W.-D.Schneider, and R. Berndt, *Appl. Phys. A*, 66, 575 (1998).

Adsorbate manipulation by STM



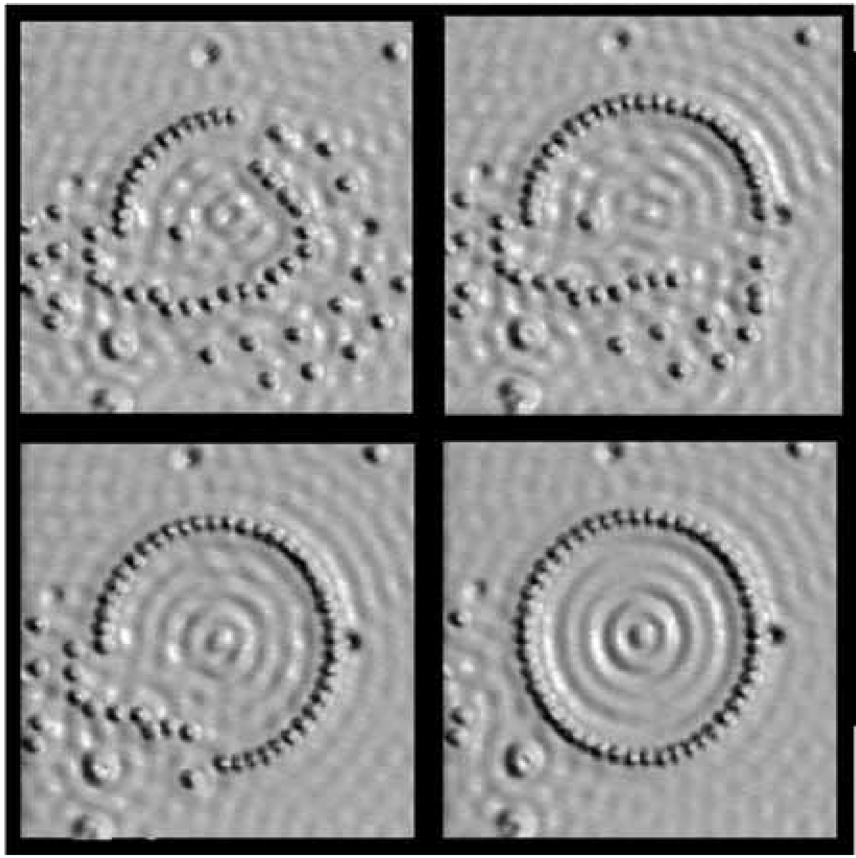
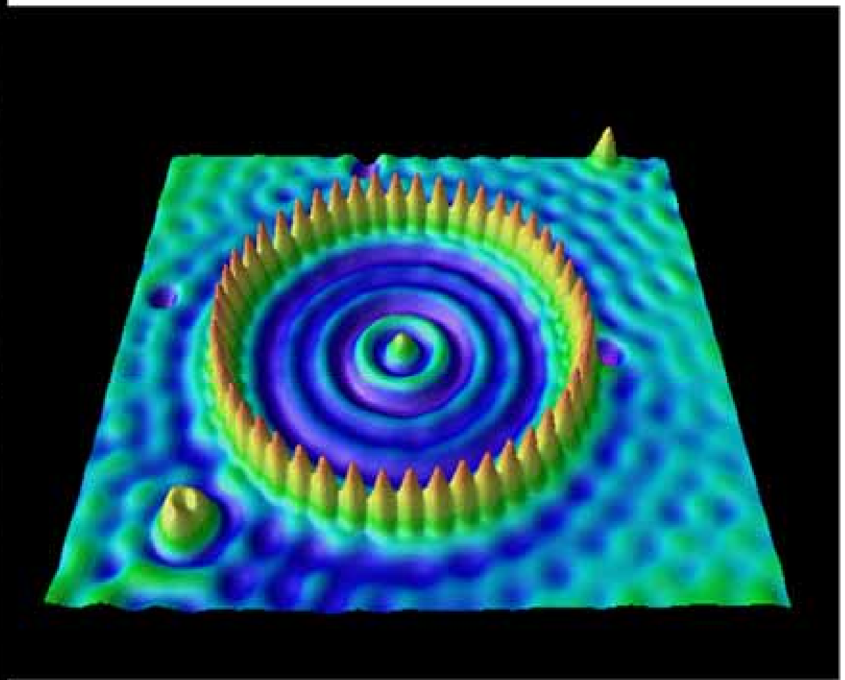
Déplacer des atomes ou molécules





Animations: H. Hidber, Université de Bâle

Quantum Corral

IBM

Oberflächenzustände auf Cu(111)

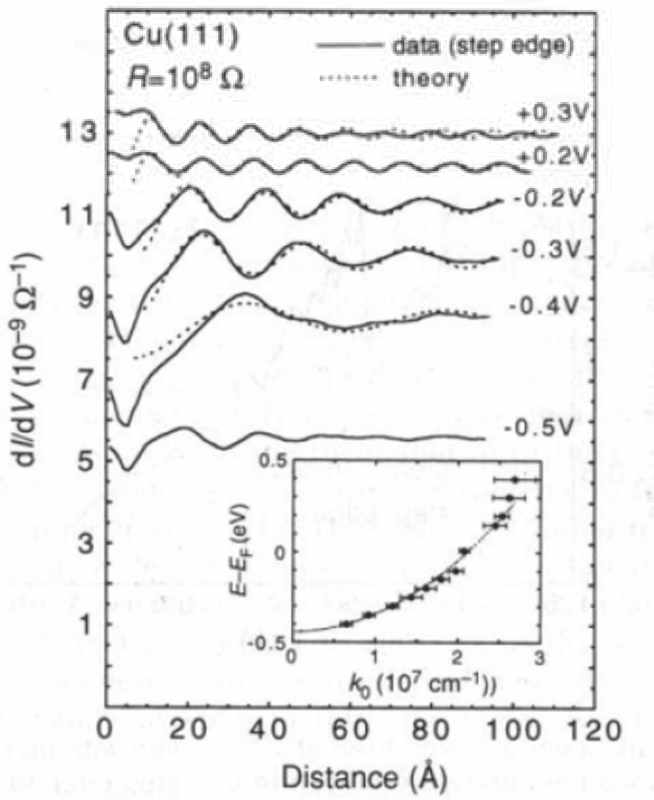


Fig. 2.16. Spatial dependence of dI/dV across a step edge on Cu(111) at 4K. For details see text. From [80].

„Confined electrons“

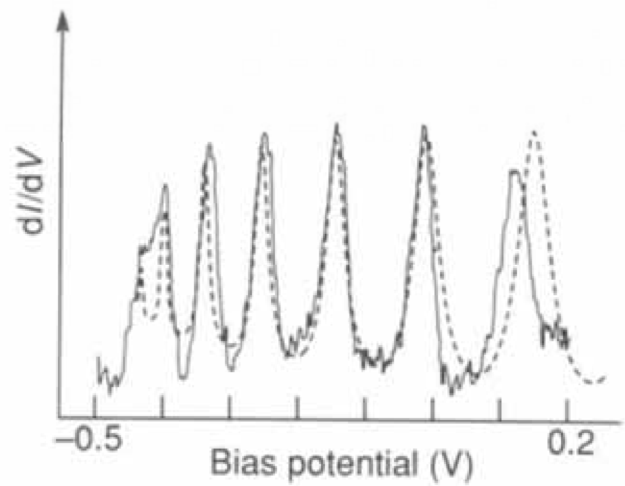
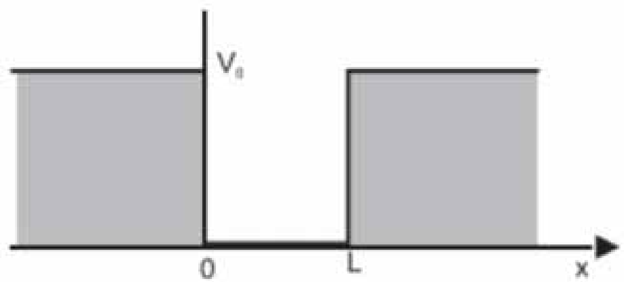


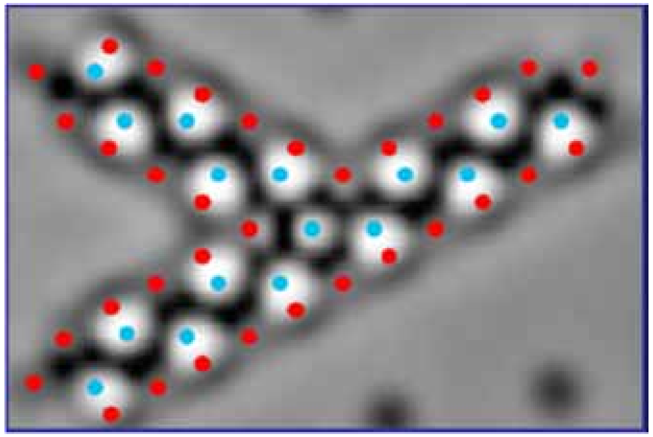
Fig. 2.18. The experimental (solid line) and theoretical (dashed line) voltage dependence of dI/dV, with the top of a STM located at the center of a 88.7Å diameter, 60-atom circle of Fe atoms on a Cu(111) surface. From [84].

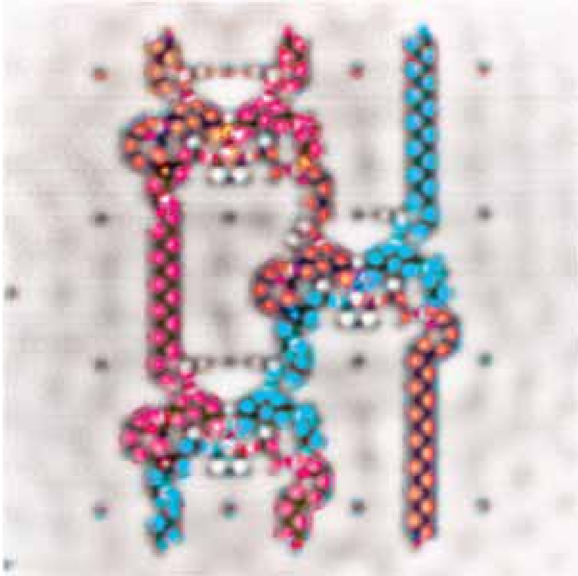


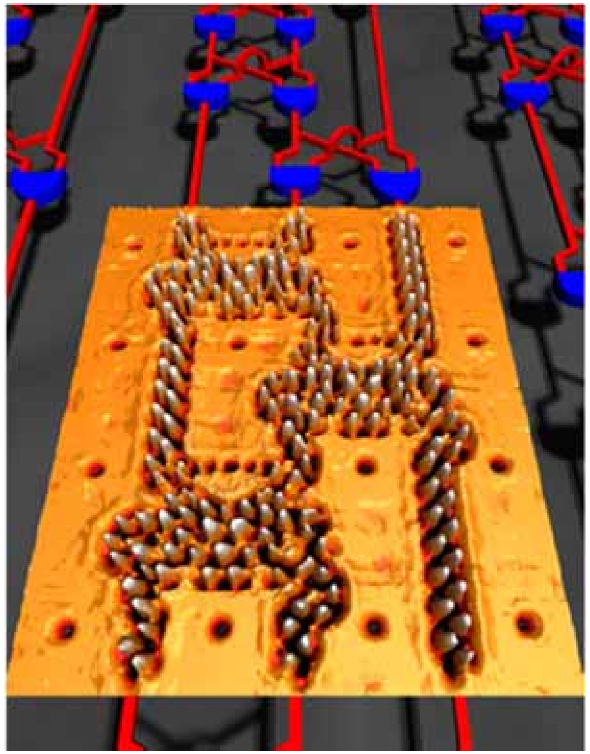
$$E_n = \frac{h^2}{8mL^2} n^2$$

E.Heller,M.Crommie,C.Lutz,D.Eigler:Nature 369, 464 (1994)

Construction of exciting molecular cascades at IBM Almaden







•**3-input sorter cascade with electrical schematic**
•**AND Gate**

Atomic Scale Memory at a Silicon Surface

R. Bennewitz*, J. N. Crain, A. Kirakosian, J.-L. Lin, J. L. McChesney, D. Y. Petrovykh, and F. J. Himpsel

Nanotechnology Aug. 2002; 13(4): 499-502

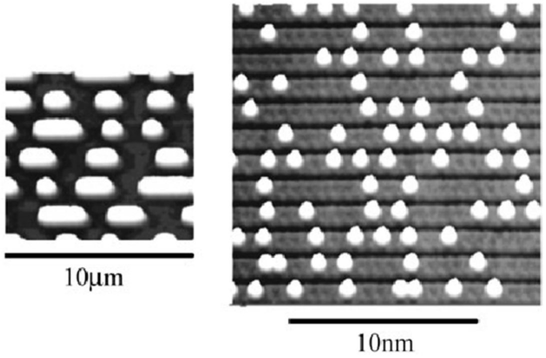


Figure 1. Comparison of the atomic memory on silicon with a CD-ROM [5]. Extra silicon atoms occupy lattice sites on top of tracks that are five atom rows wide (1.7 nm). The scale is reduced from μm to nm, which leads to a 10^6 times higher density.

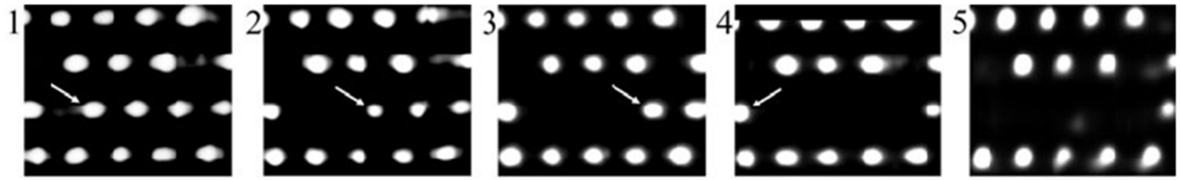


Figure 3. Writing a sequence of four zeros. Silicon atoms are transferred to the STM tip one by one (arrows).

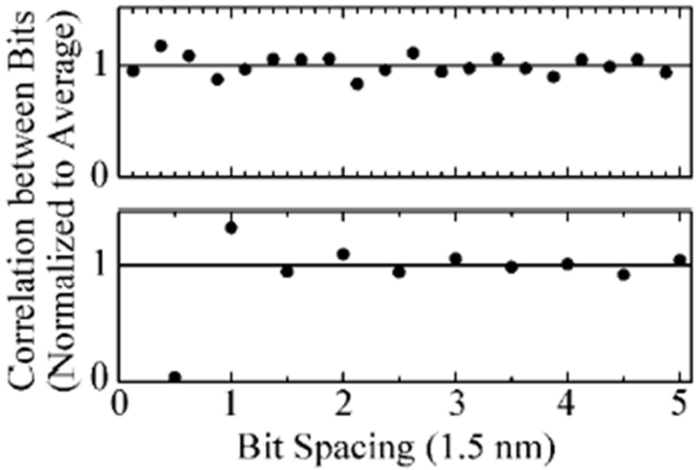


Figure 4. The autocorrelation between neighbouring Si atoms as a test of interactions between adjacent bits. The closest 5 × 2 site along a track is nearly excluded (bottom), showing that 5 × 4 atoms form the minimum viable cell. Neighbouring tracks are not correlated (top).

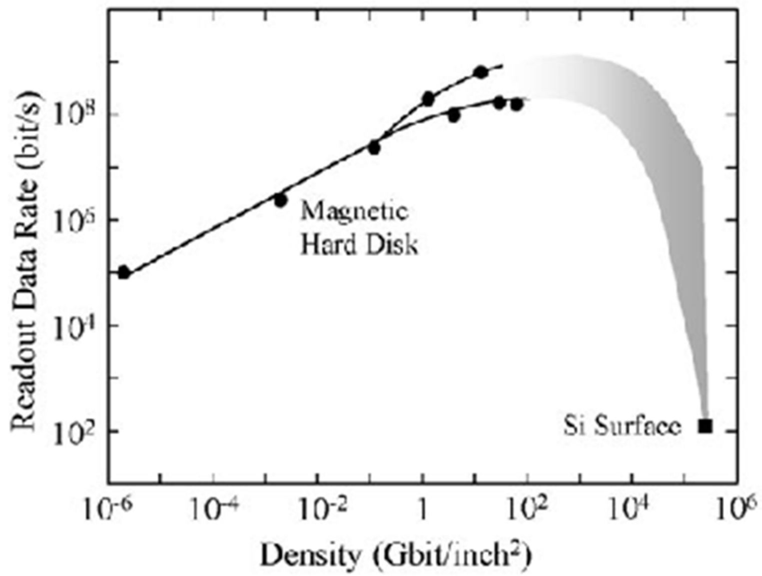
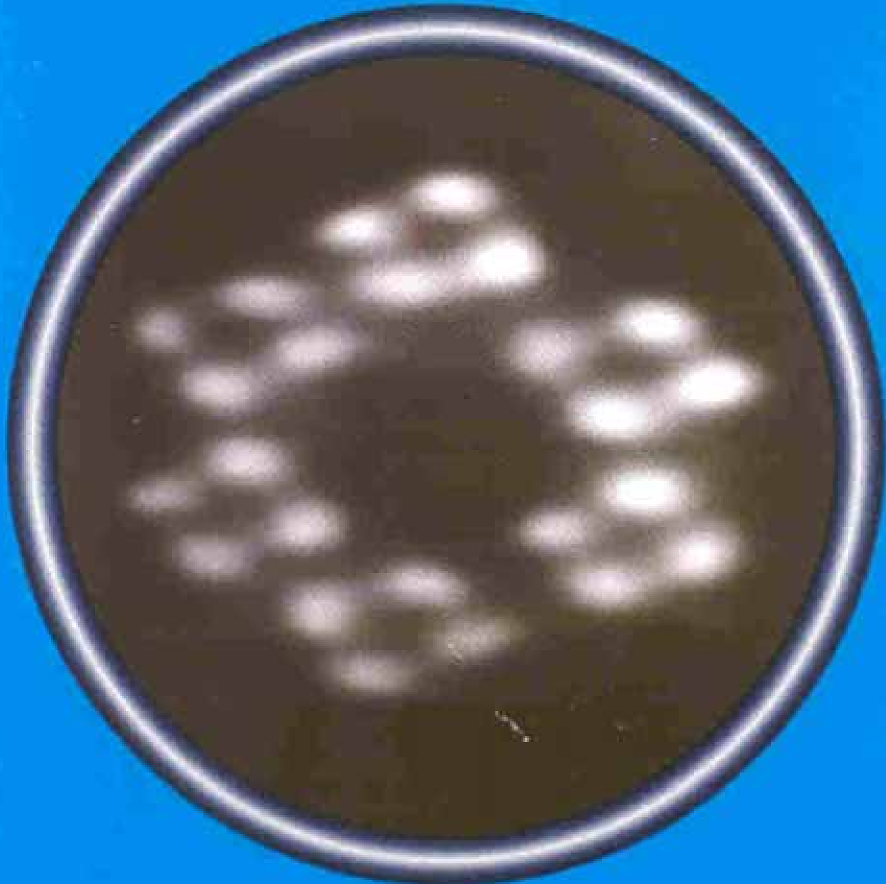


Figure 5. Trade-off between readout speed and storage density at the atomic limit.

Molecular Positioning

T.A. Jung, R.R. Schlittler and J.K. Gimzewski
IBM Zurich Research Laboratory, 8803 Rüschlikon, Switzerland



IBM

Science 271, 181-184 (1996)

Manipulation mit dem STM

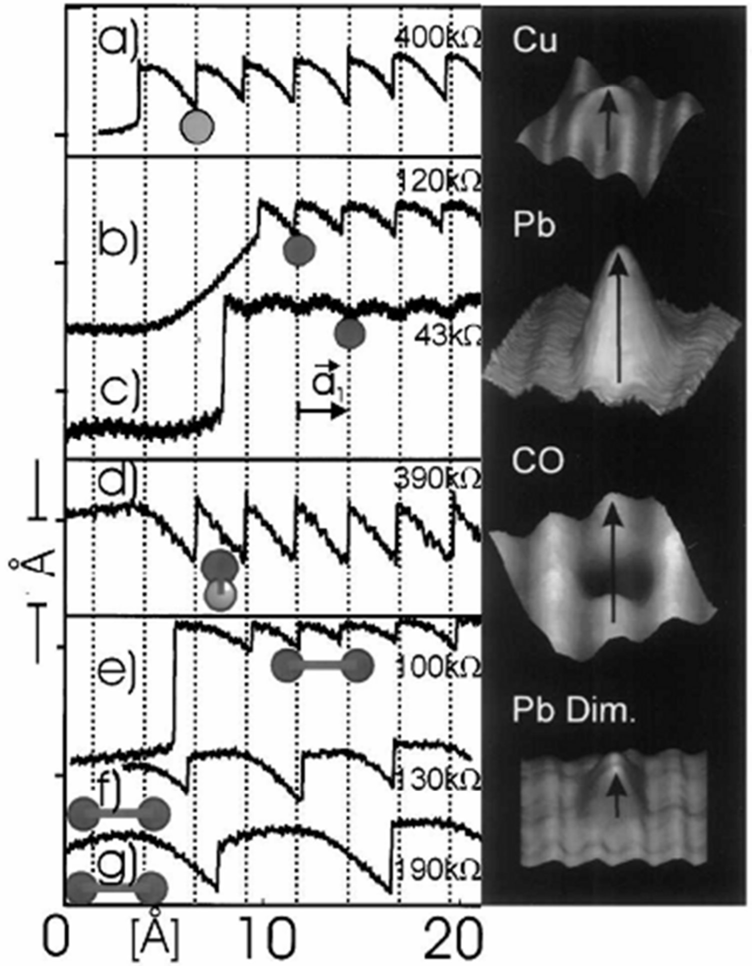
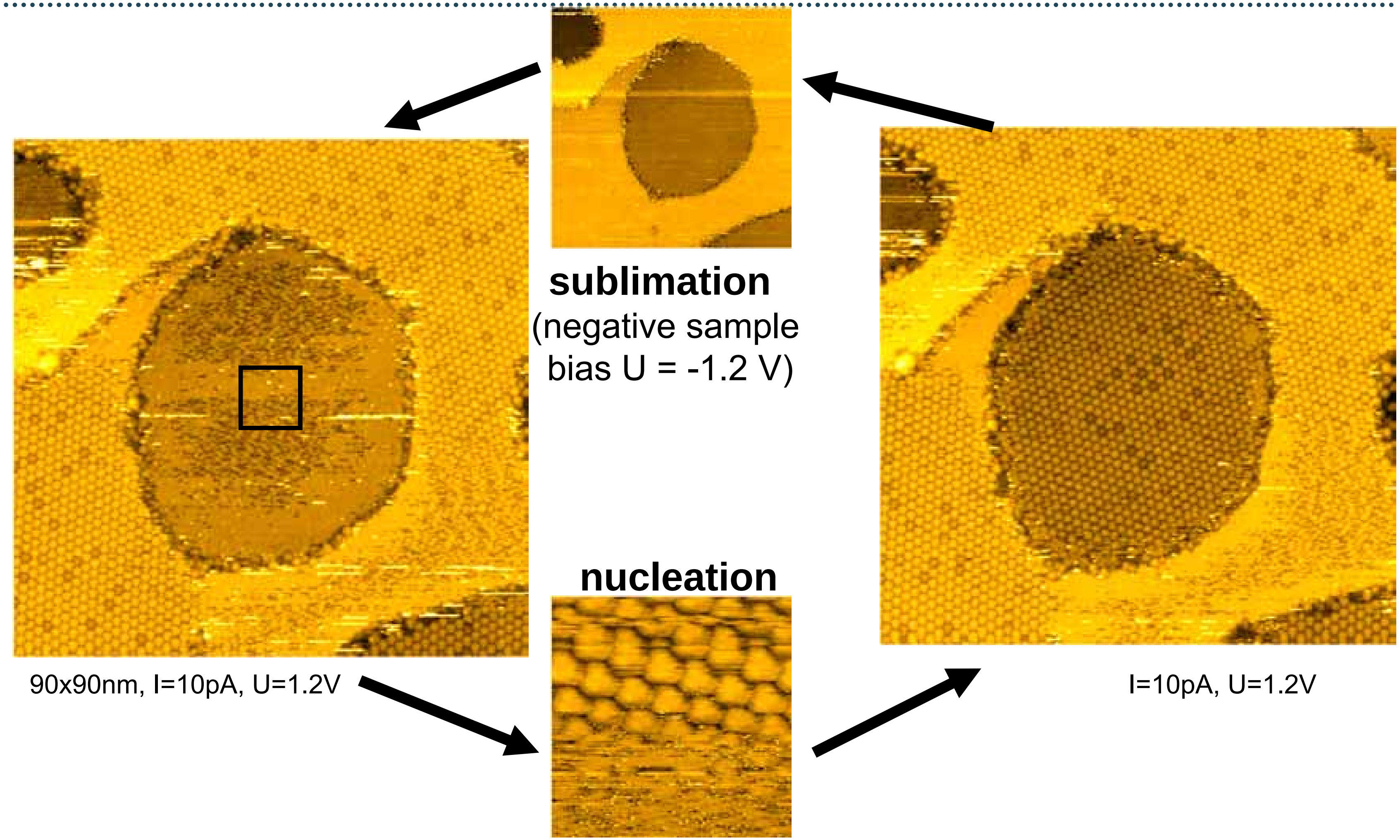


Fig. 2.10. Tip height curves are shown during manipulation of a Cu atom (a), a Pb atom (b,c), a CO molecule (d), and a Pb dimer (e)-(g) along the $[1\bar{1}0]$ of the Cu(211) surface. The tip movement is from the left to the right, and the tunneling resistances are indicated. The vertical dotted lines correspond to fcc sites next to the step edge. The initial sites of the manipulated species are indicated by small sphere models. On the right part STM images of the different adparticles are shown. The arrows indicate the direction of tip movement. From [43].

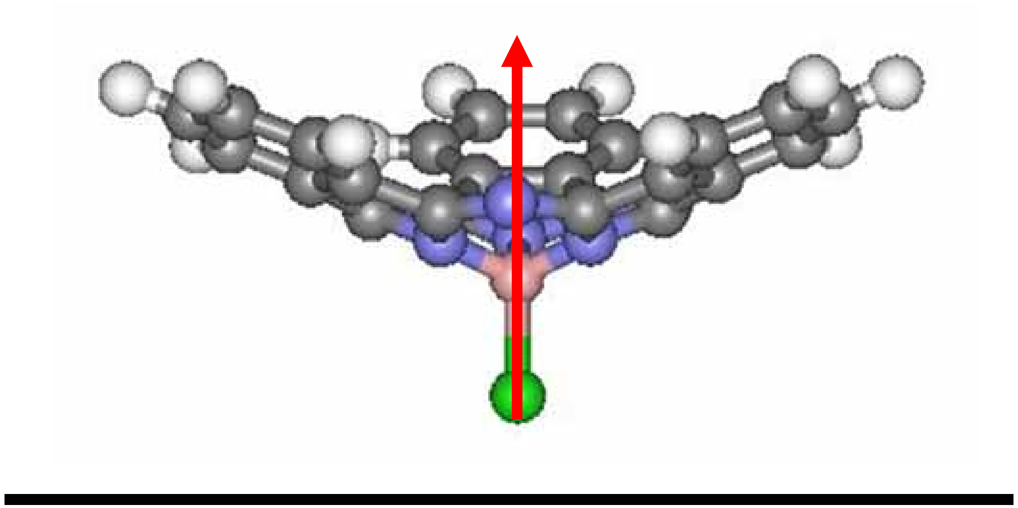
.L.Bartels,G.Meyer,K.H.Rieder:Phys.Rev.Lett. 79(4),697(1997)

Reversible 2D Phase Transition controlled by the STM tip



Controlled phase transition 2D fluid <=> 2D solid

SubPc Adsorption Geometry



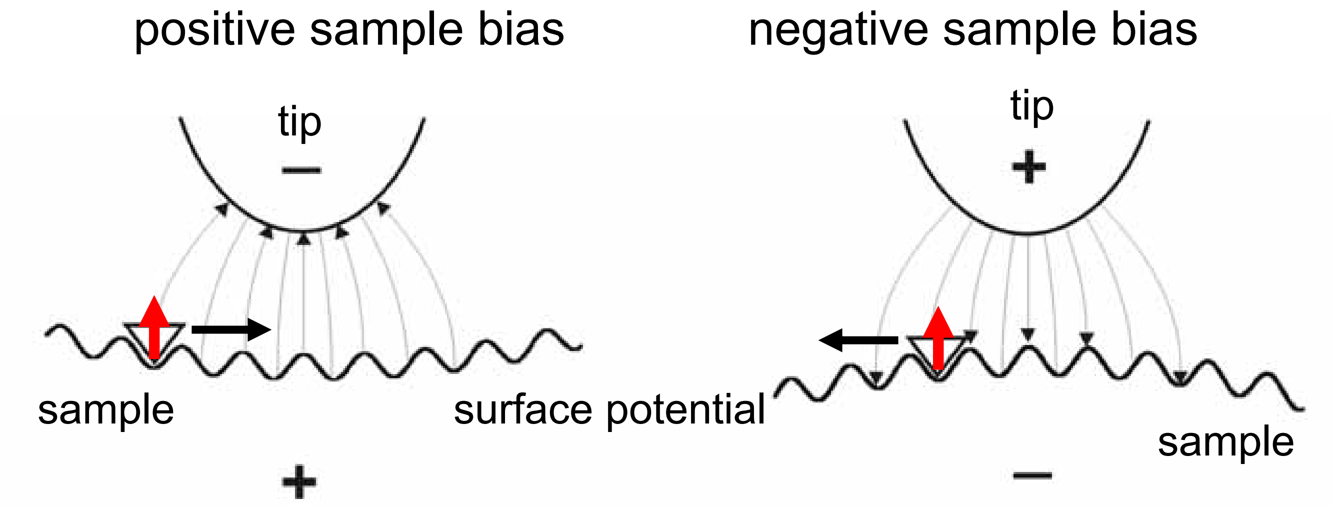
Ag(111)

Adsorption with the Cl toward the Ag
=> dipole moment is pointing away from the surface

Microscopic Model

Model Tip Induced Diffusion

SubPc dipole moment and inhomogeneity of the electric field of the tip lead to induced diffusion



pos. sample bias: diffusion towards the tip
neg. sample bias: diffusion away from the tip

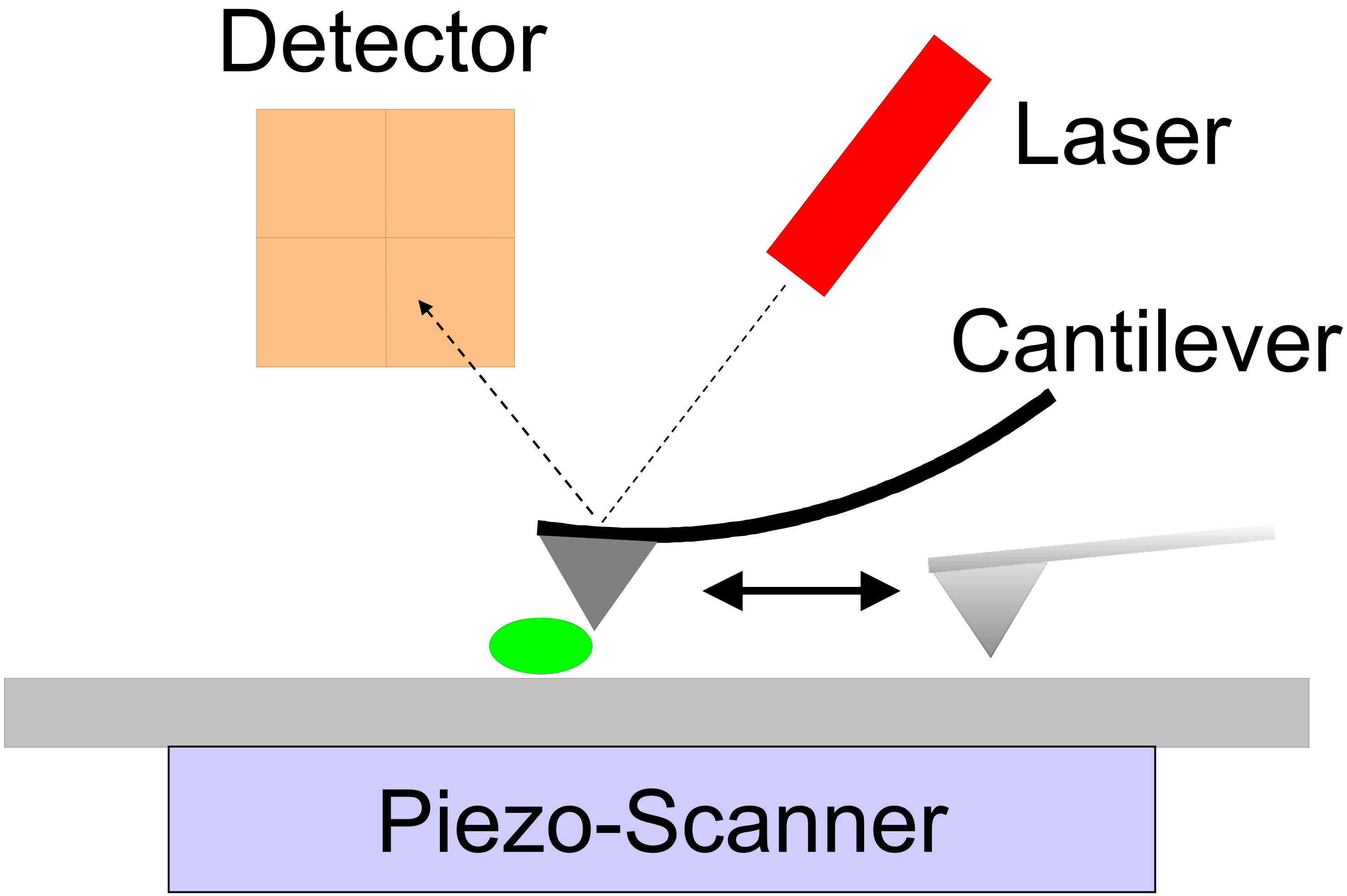
Induced diffusion due to electric field:

Stroscio & Eigler, Science **254** (1991) 1319

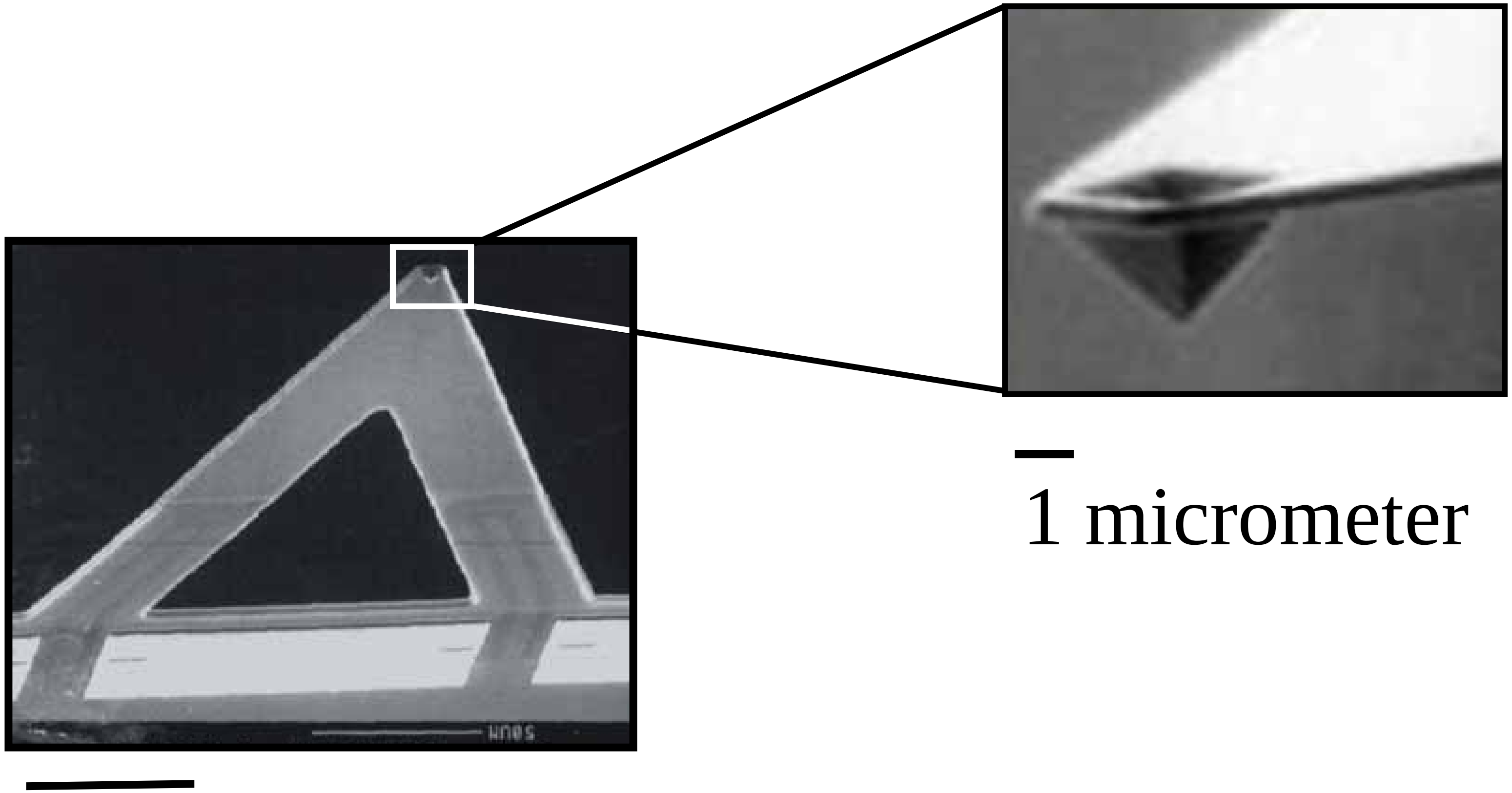
Mingo & Flores, Surf. Sci. **395** (1998) 342

[redacted]

AFM - “Hands & Eyes“



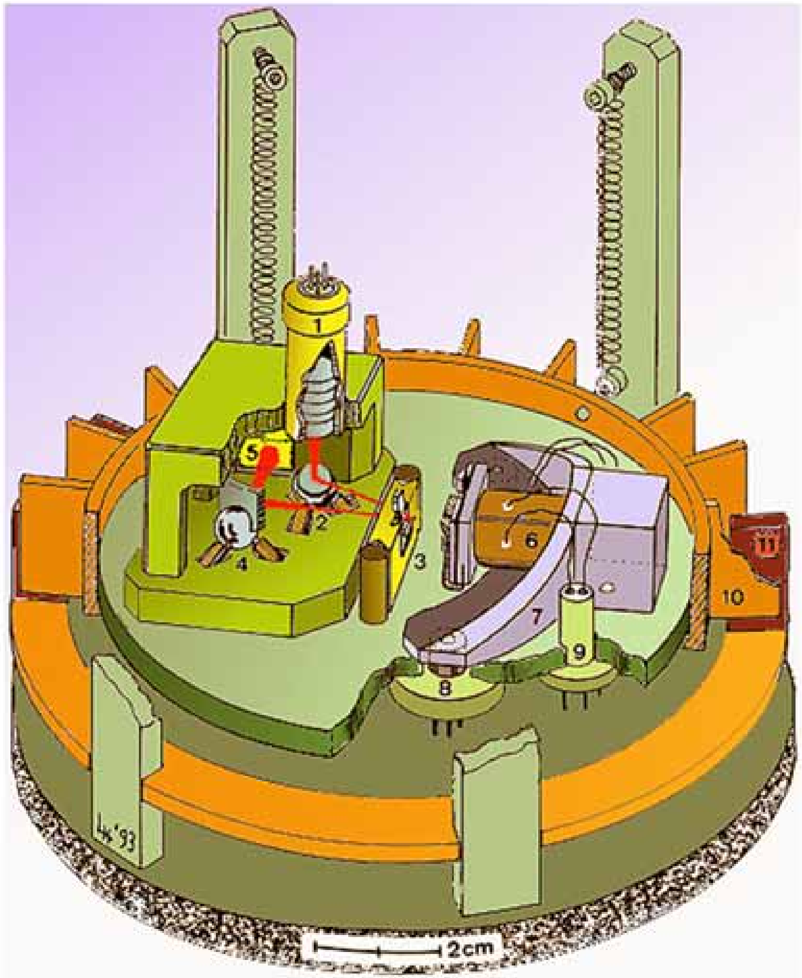
Cantilever with integrated Tip



1 micrometer

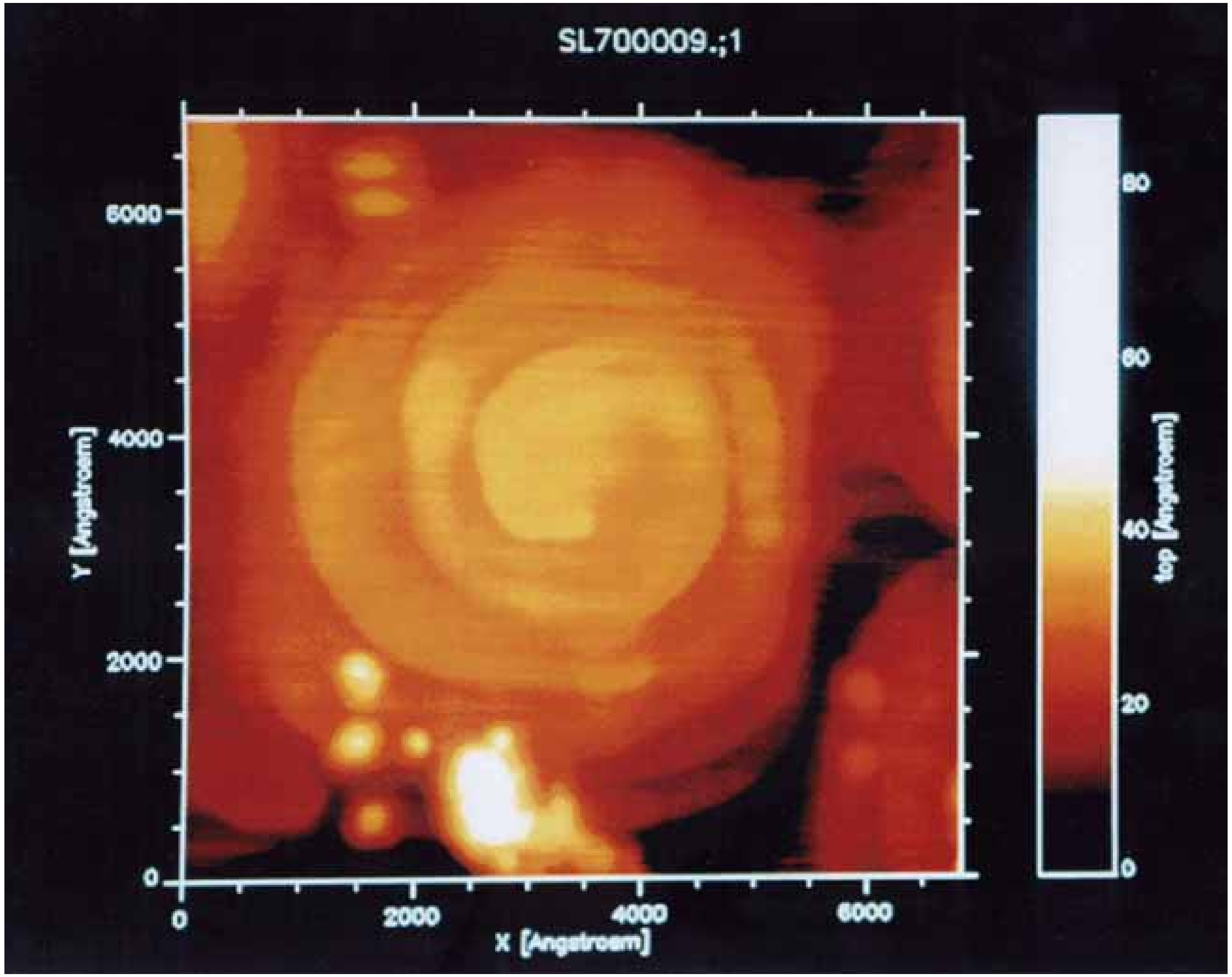
50 micrometers

Examples

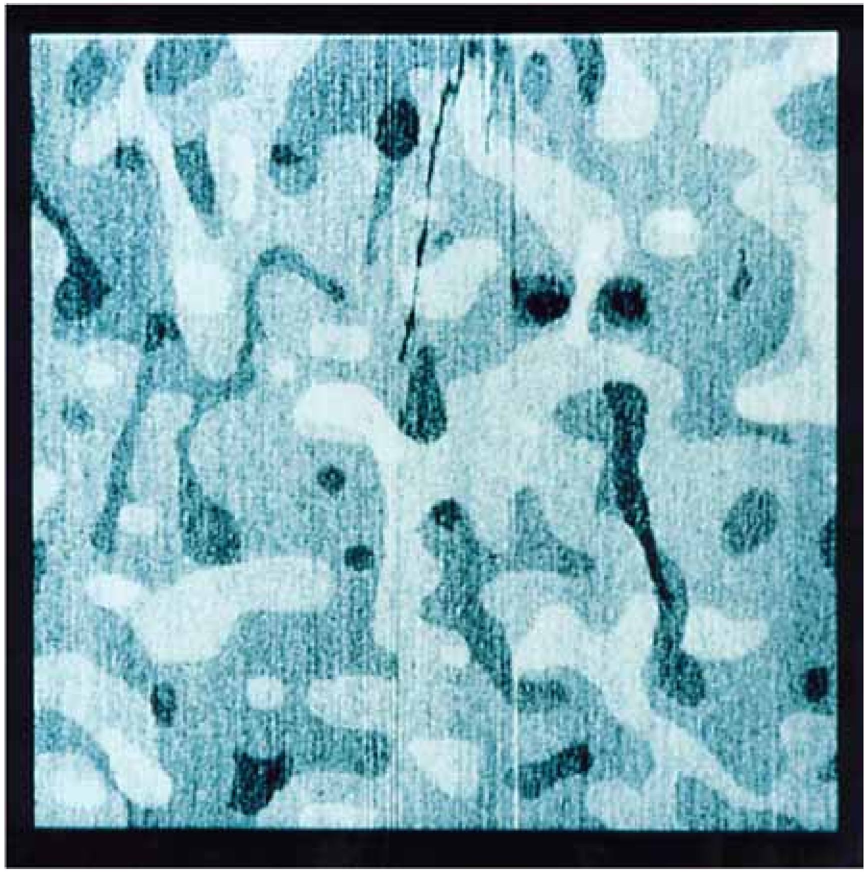


„Screw Dislocation“ on High Tc YBCO

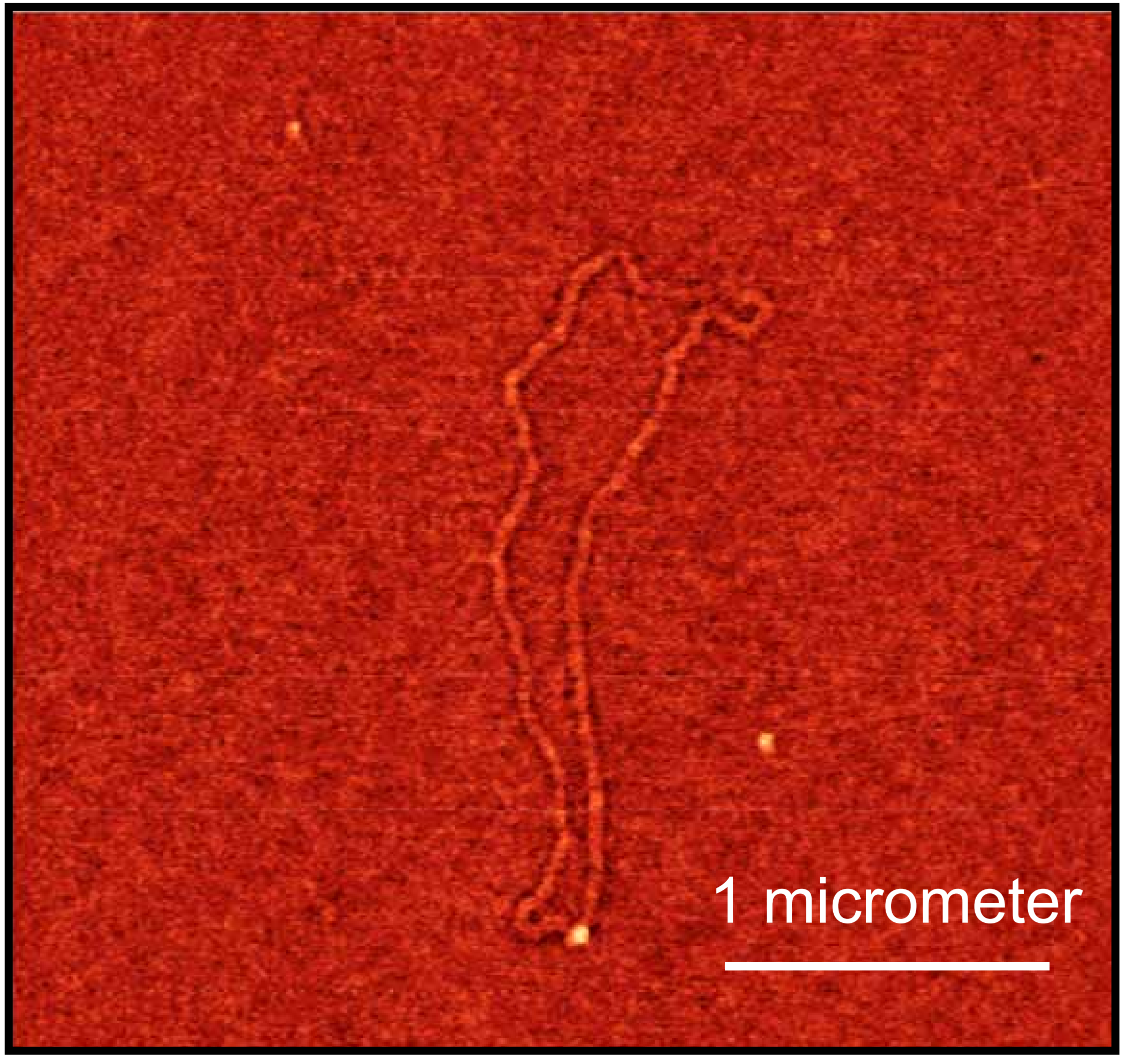
~ 400 nm diameter



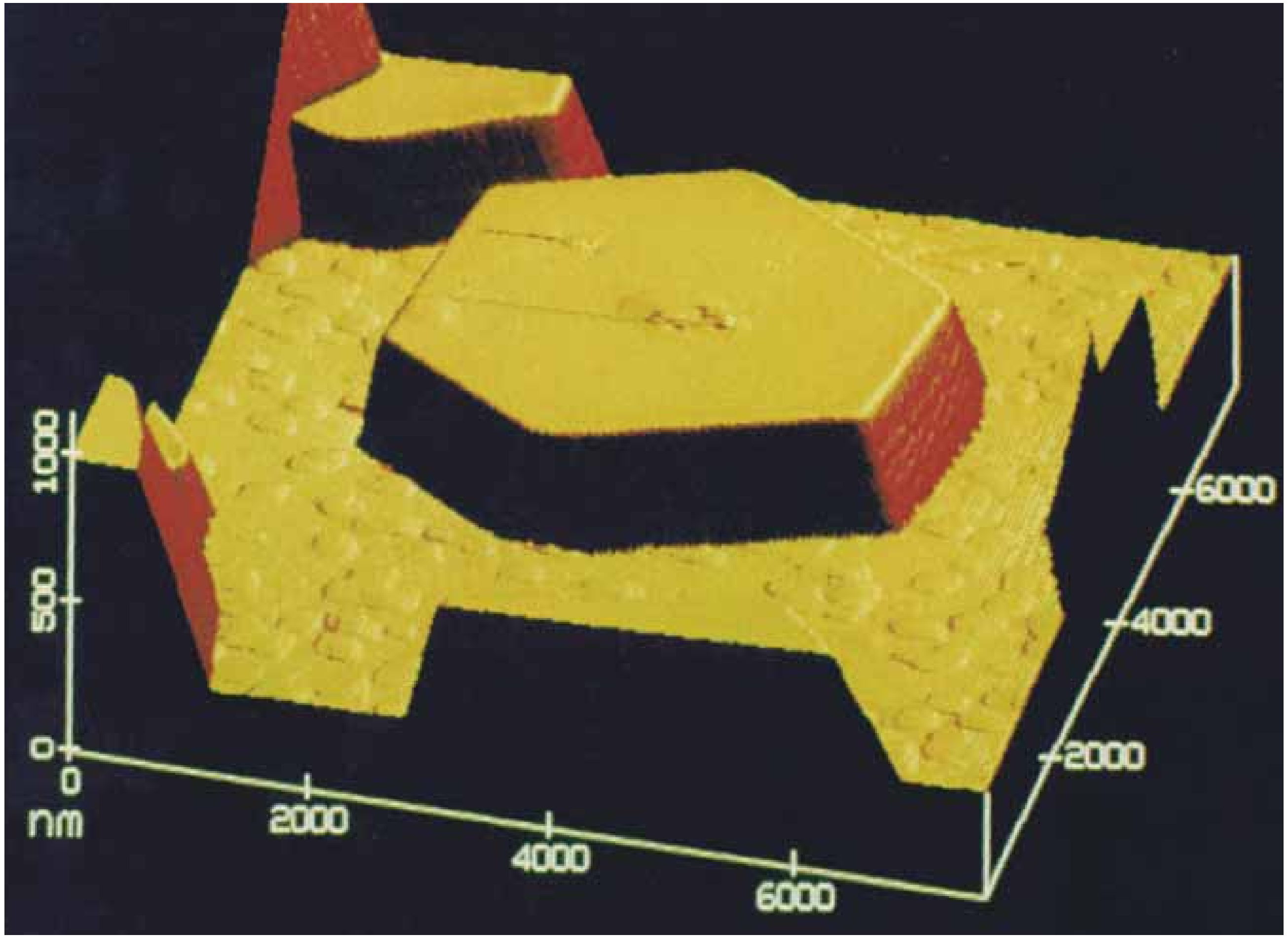
T. /



DNA-Molecule

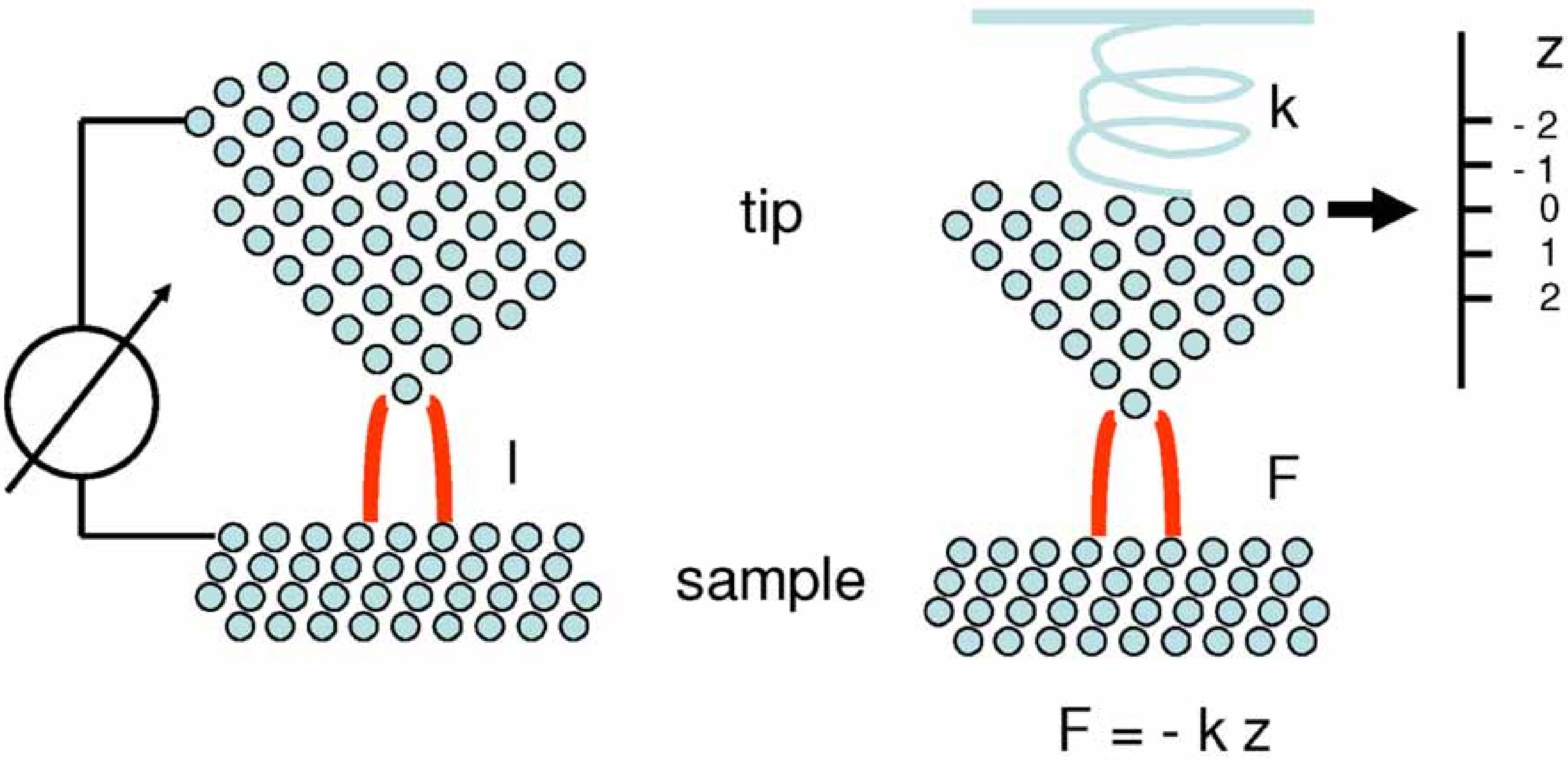


T-(tabular) AgBr grain of a photographic emulsion (Ilford)

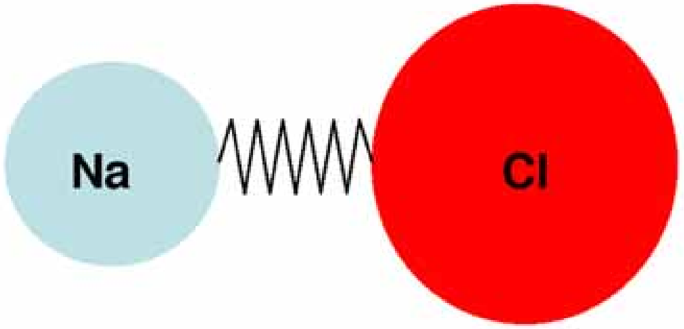


Scanning X Microscopy

S Tunneling **M** | **S F**orce **M**



Force between two atoms

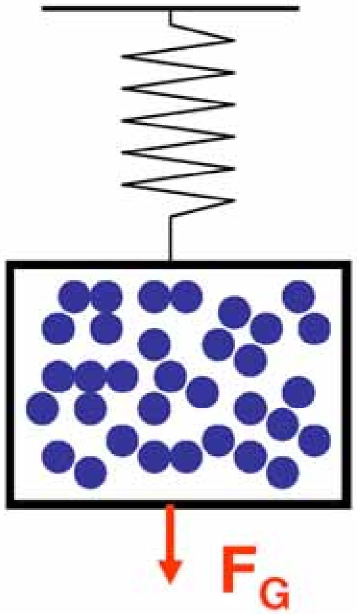


Chemical bond

F_{chem} = 1eV/ 0.1 nm

1.6 nN

Sensing Forces



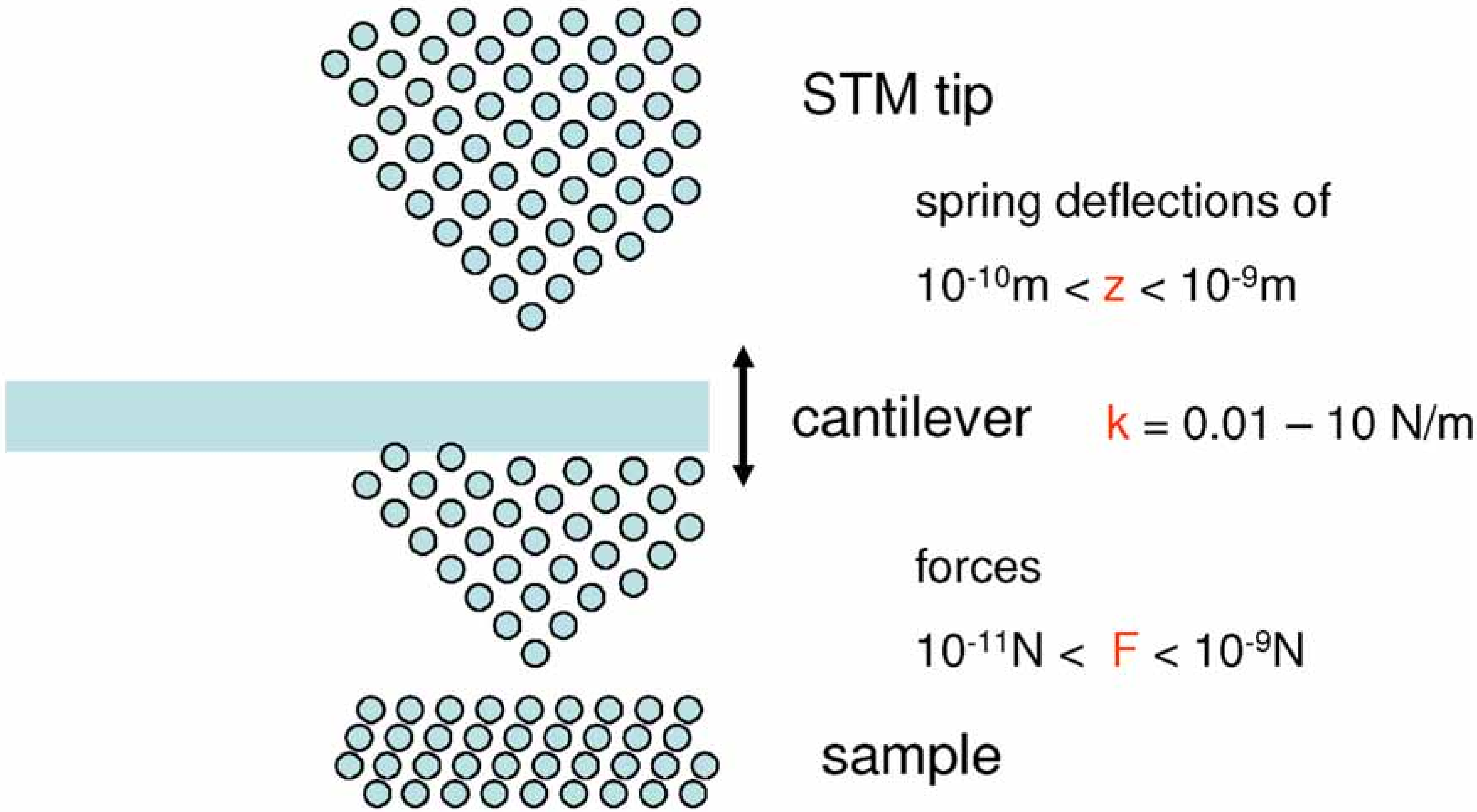
1 nm^3 water (33 molecules)

$F_G = 10^{-23}$ N = 10^{-14} nN

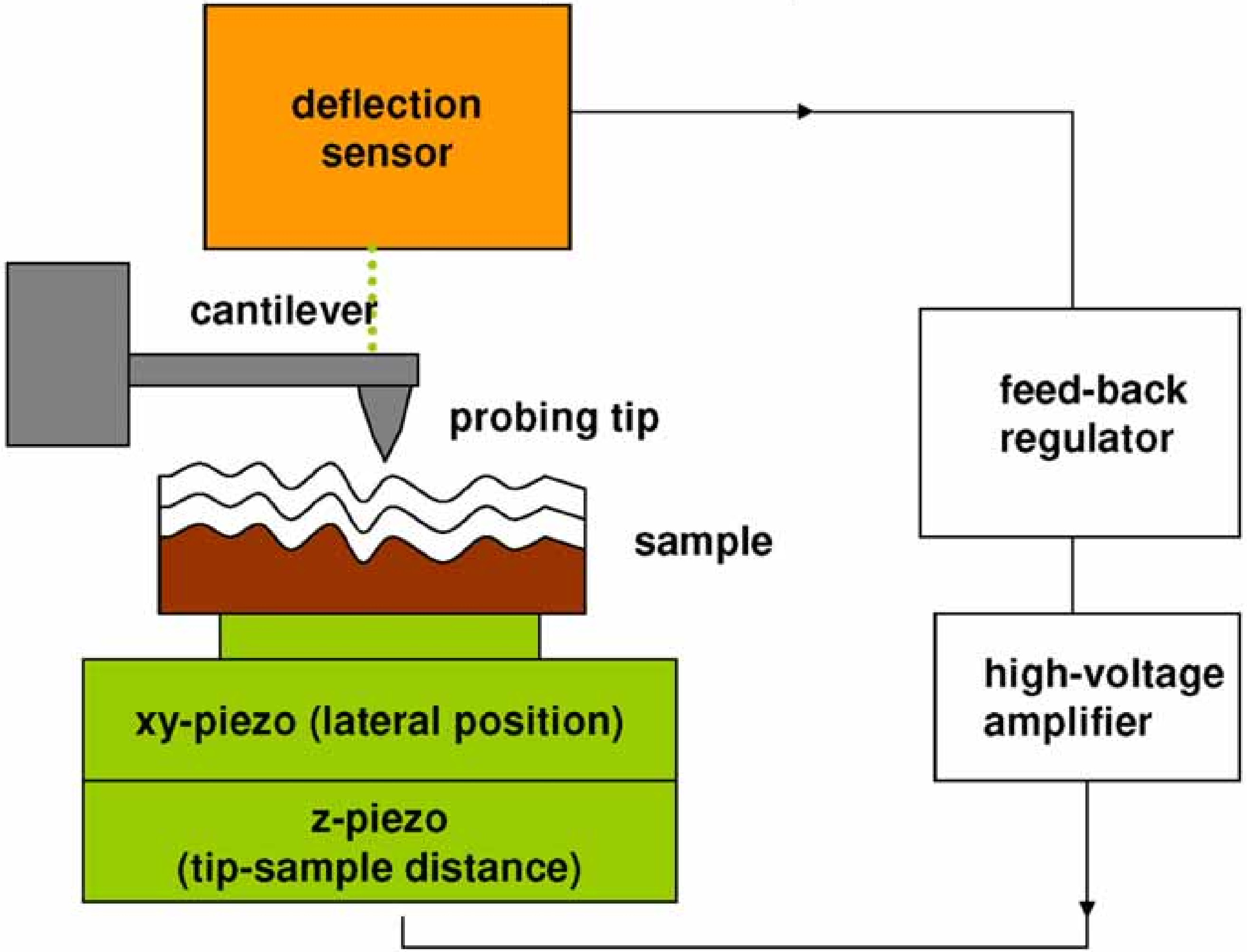
0.01 g

F= 0.1 mN = 10^5 nN

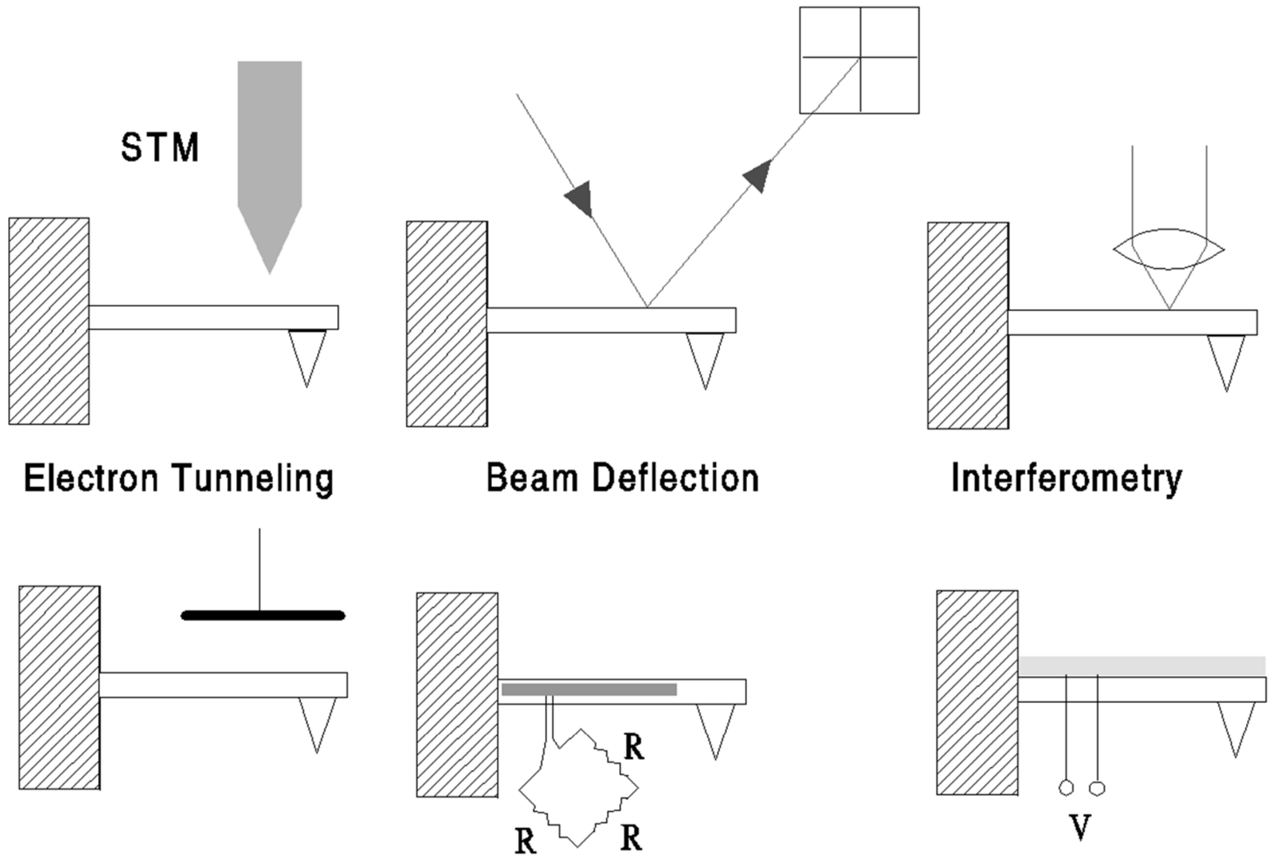
Principle of First Atomic Force Microscope



Scanning Force Microscope (AFM)



Deflection sensors



Electron Tunneling | Beam Deflection | Interferometry

Capacitance | Piezoresistance | Piezoelectricity

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)
D. Tabor
Gases, liquids and solids, Cambridge University Press (1979)

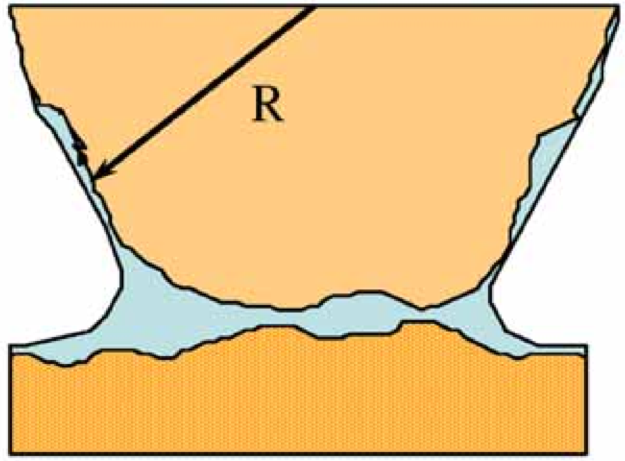
Capillary forces

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

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

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

$\Rightarrow$ F_{max} = 90nN



Van der Waals forces in vacuum

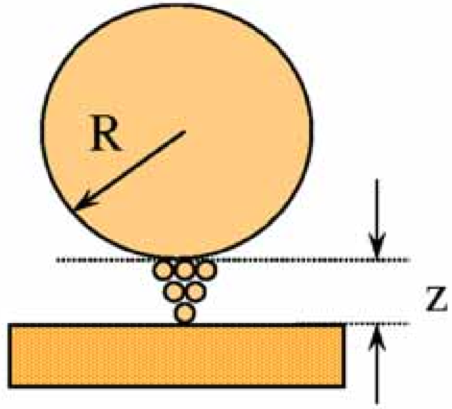
- No capillary forces (no water)
- Van der Waals and electrostatic forces dominate

$F_{vdW} = - B\ R/z^2 * 1/(1+z/2\ R)^2$

$B=3K/4\ (\varepsilon_s-1)(\ \varepsilon_t-1)/\ [(\varepsilon_t+1)(\ \varepsilon_t+2)]$
K=1.41eV

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

$\Rightarrow$ R=100nm, z=1nm



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

Van der Waals forces in liquids

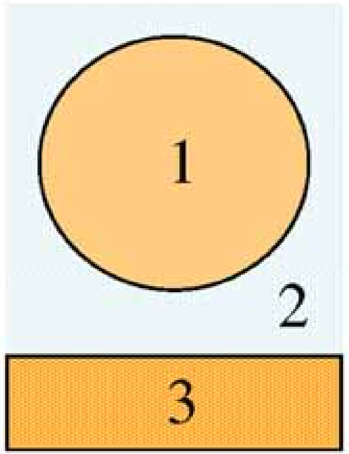
- capillary forces are eliminated
- Van der Waals can be repulsive:

  $U \approx (n_1^2 - n_3^2)(n_2^2 - n_3^2)$

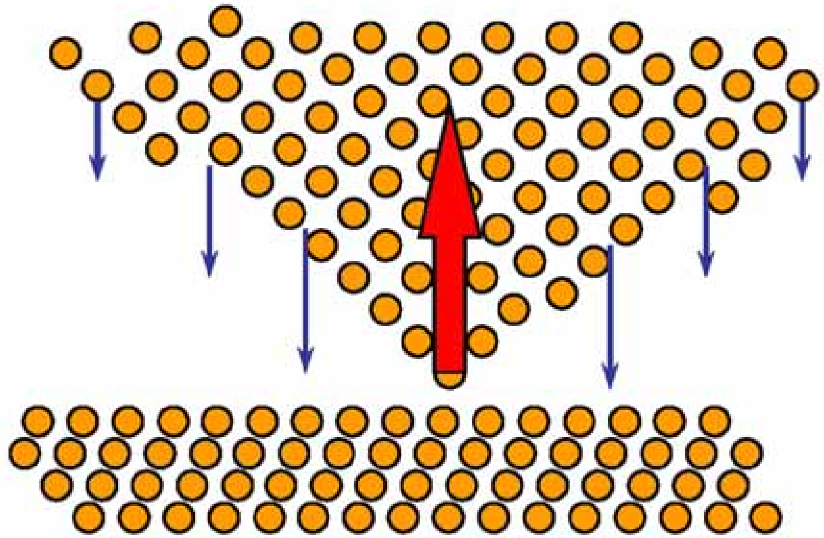
  For $n_1 < n_2 < n_3$ result negative van der Waals forces.

  Mc Lachlan, *Proc. Roy. Soc.* A 271, 38 (1963)
- Observation of very weak forces (10pN) by Ohnesorge und Binnig. Atomic resolution of a calcite surface.

  F. Ohnesorge and G. Binnig, *Science* 260, 1451 (1993)
- For hydrophobic surfaces entrpoy effects can increase the net forces.



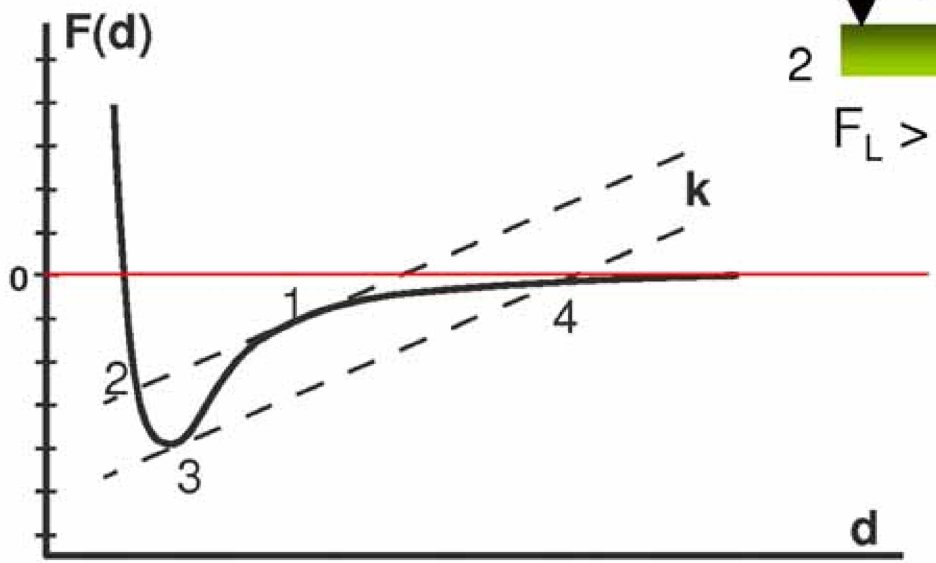
Estimation of forces

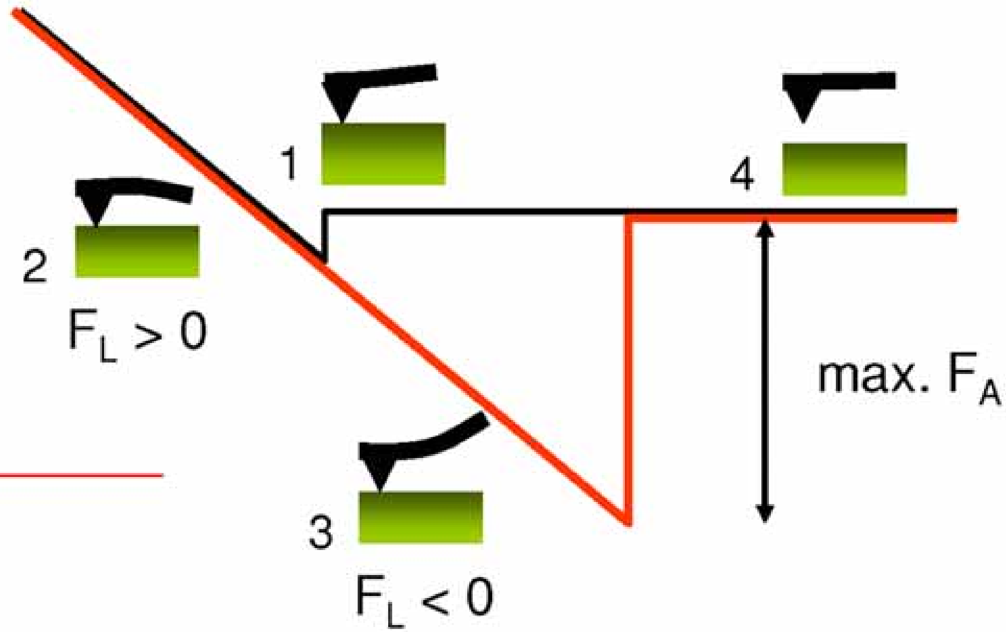


- **Typical long-range forces:**
  - **in air: 10-100nN**
  - **in liquids: 1-100pN**
  - **in ultra-high vacuum: 0.1-10nN**

- **Long-range forces are compensated by short-range repulsion. Bending of the cantilever can reduce the repulsive forces.**

Force vs. distance curves



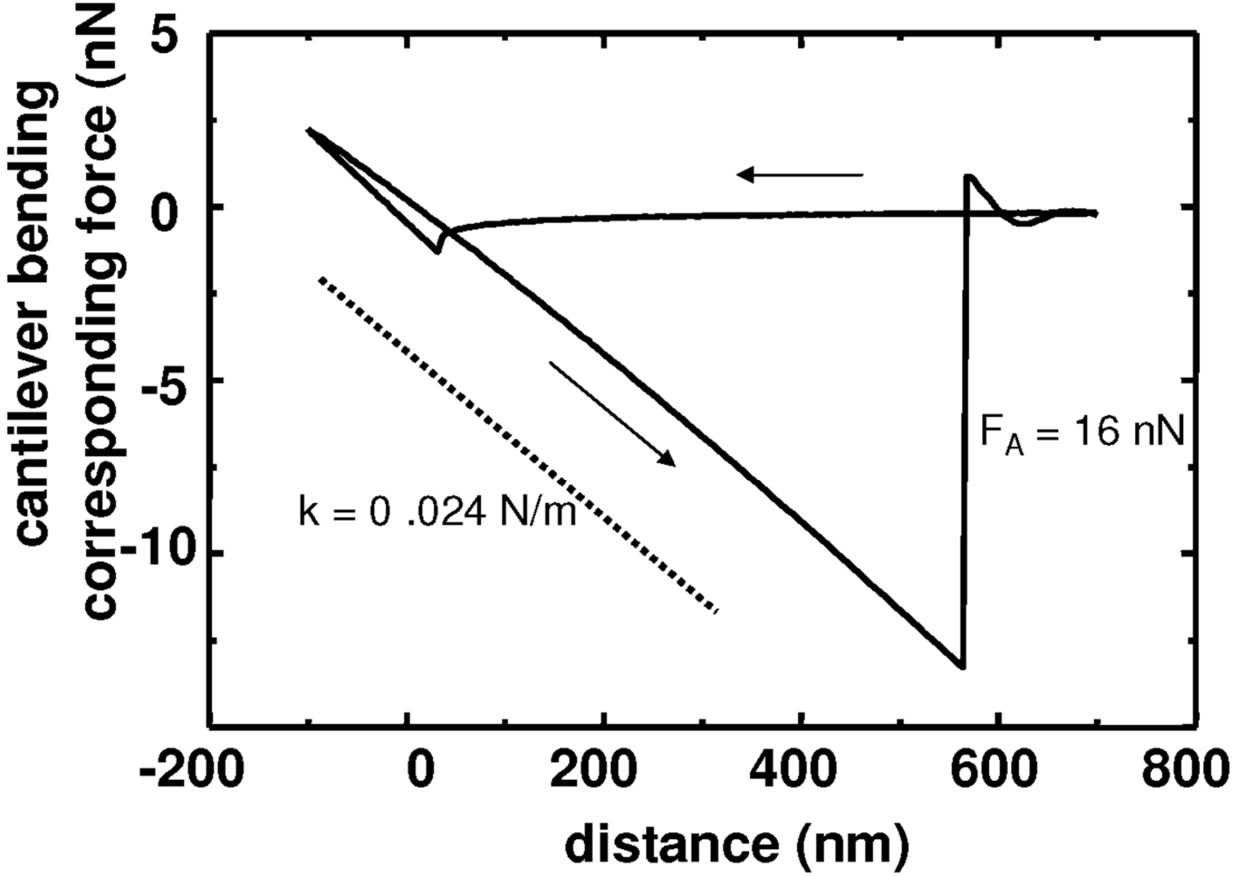


F(d): Interaction force between tip and sample

d: tip sample distance

k: spring constant of cantilever

Force vs. distance curves



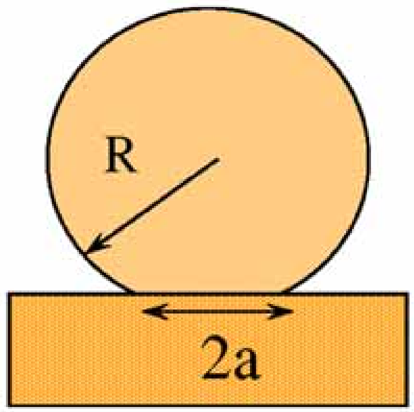
Contact area

The contact area is given by

$2a = 2\,E^*(F\,R)^{1/3}$ (Hertz theory)

- in air: 5-100nm
- in liqiuds: atomic resolution
  F. Ohnesorge and G. Binnig, Science 260, 1451 (1993)
- in ultra-high vacuum: 1-10 nm

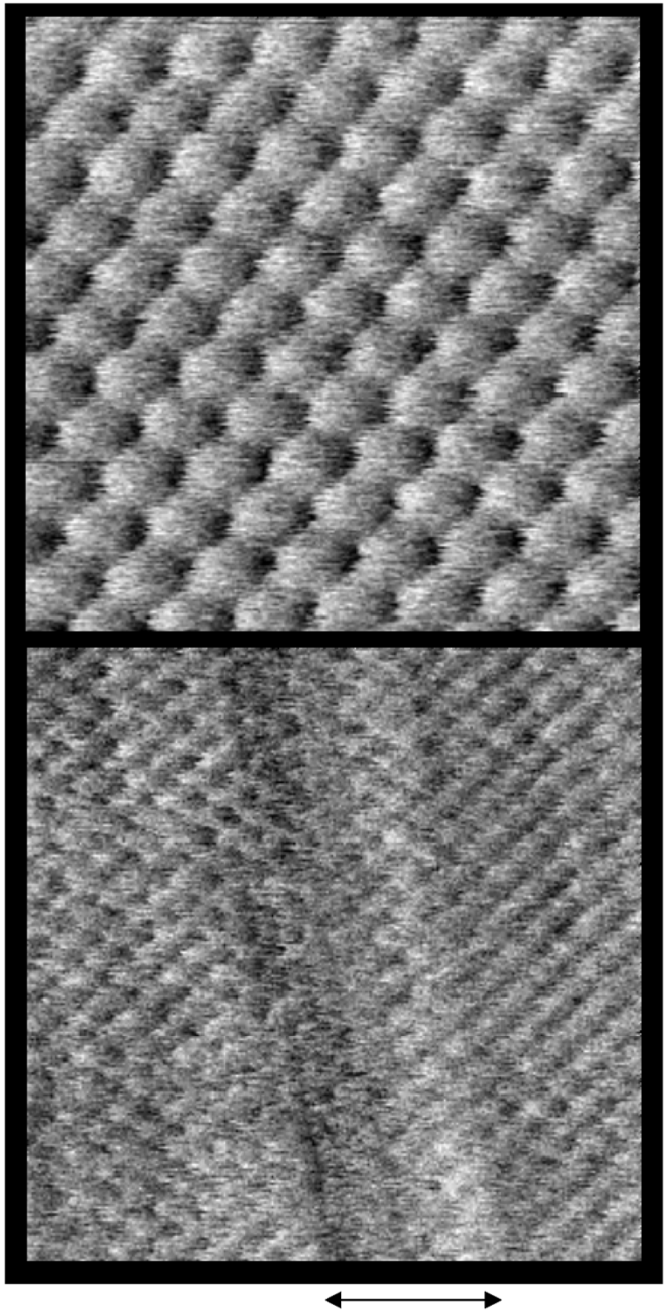
Best resolution in ultra-high vacuum:



Steps on NaCl: L. Howald et al., *Phys. Rev. B* 49, 5651 (1995)

Si(111)7x7 unit cell: L. Howald et al. *Phys. Rev. B* 51, 5484 (1995)
(chemically modified tip)

C_{60}-molecules: R. Lüthi et al., *Z.f. Phys. B* 95, 1 (1994)

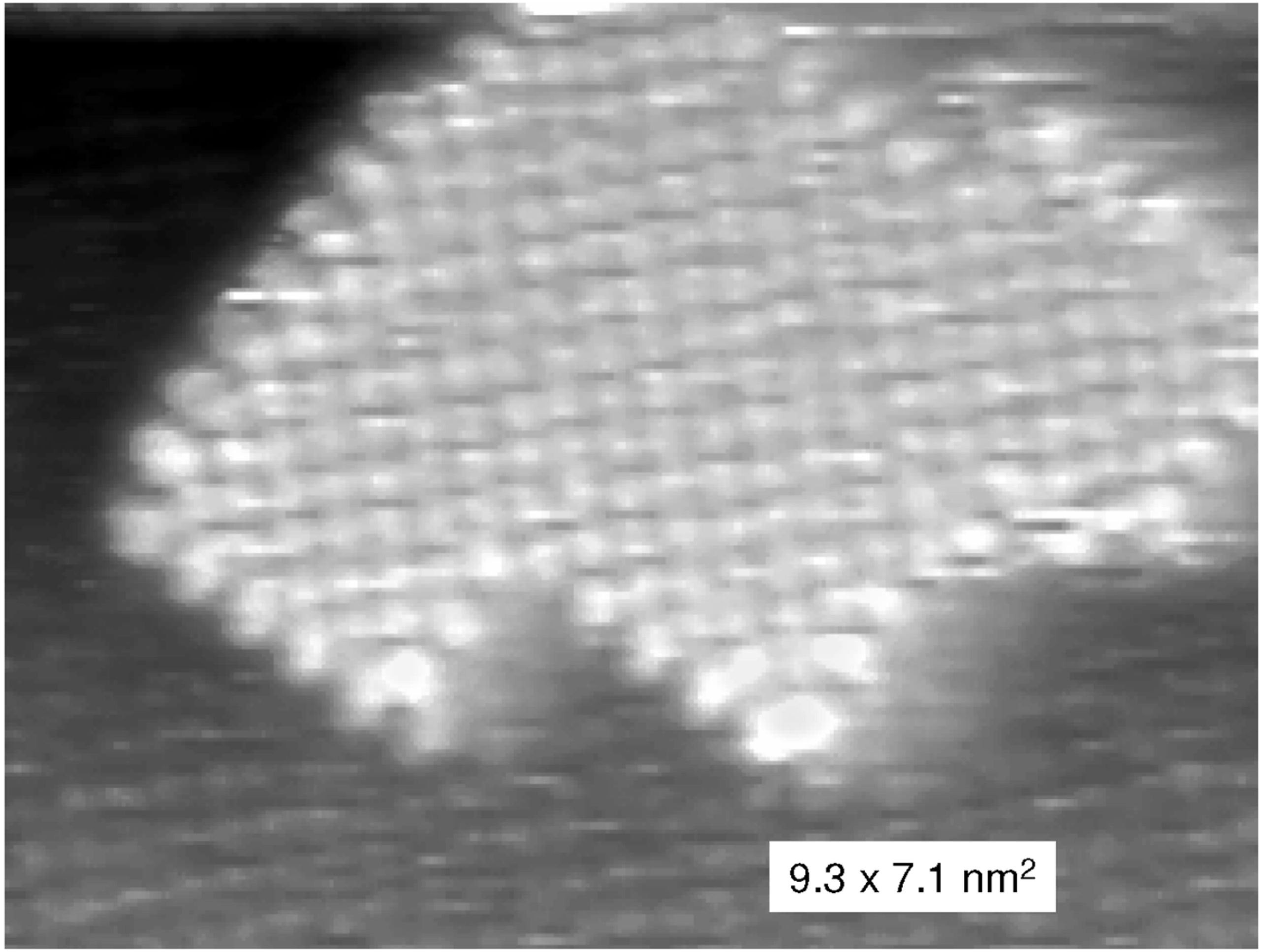


AFM on NaF(001)

- **contact mode imaging on NaF(001)**
- **observation of the atomic periodicity**
- **steps area distorted in a range of 1 nm**

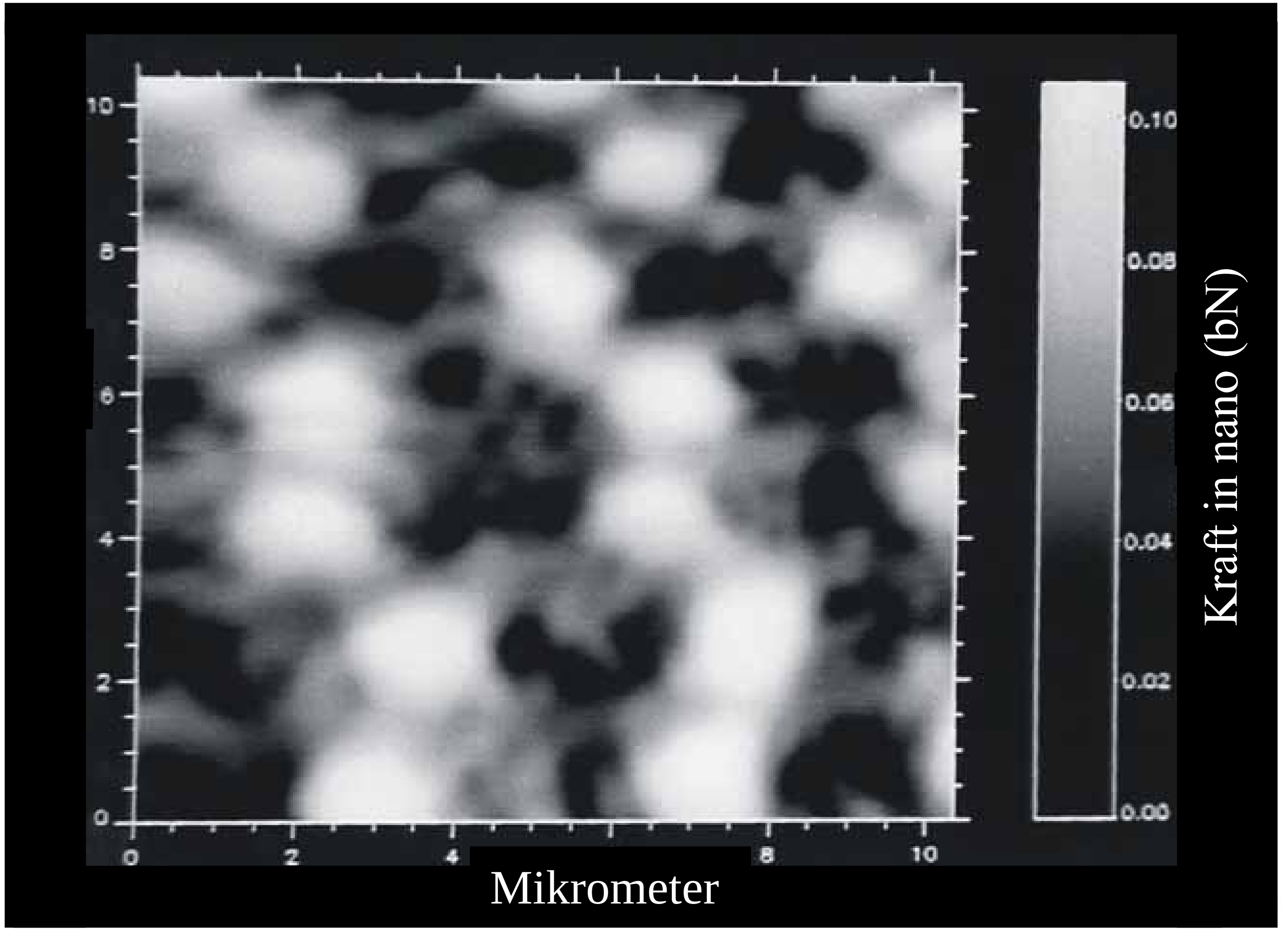
⇒ 1 nm contact radius

True atomic resolution on insulators



NaCl-island imaged by nc-AFM

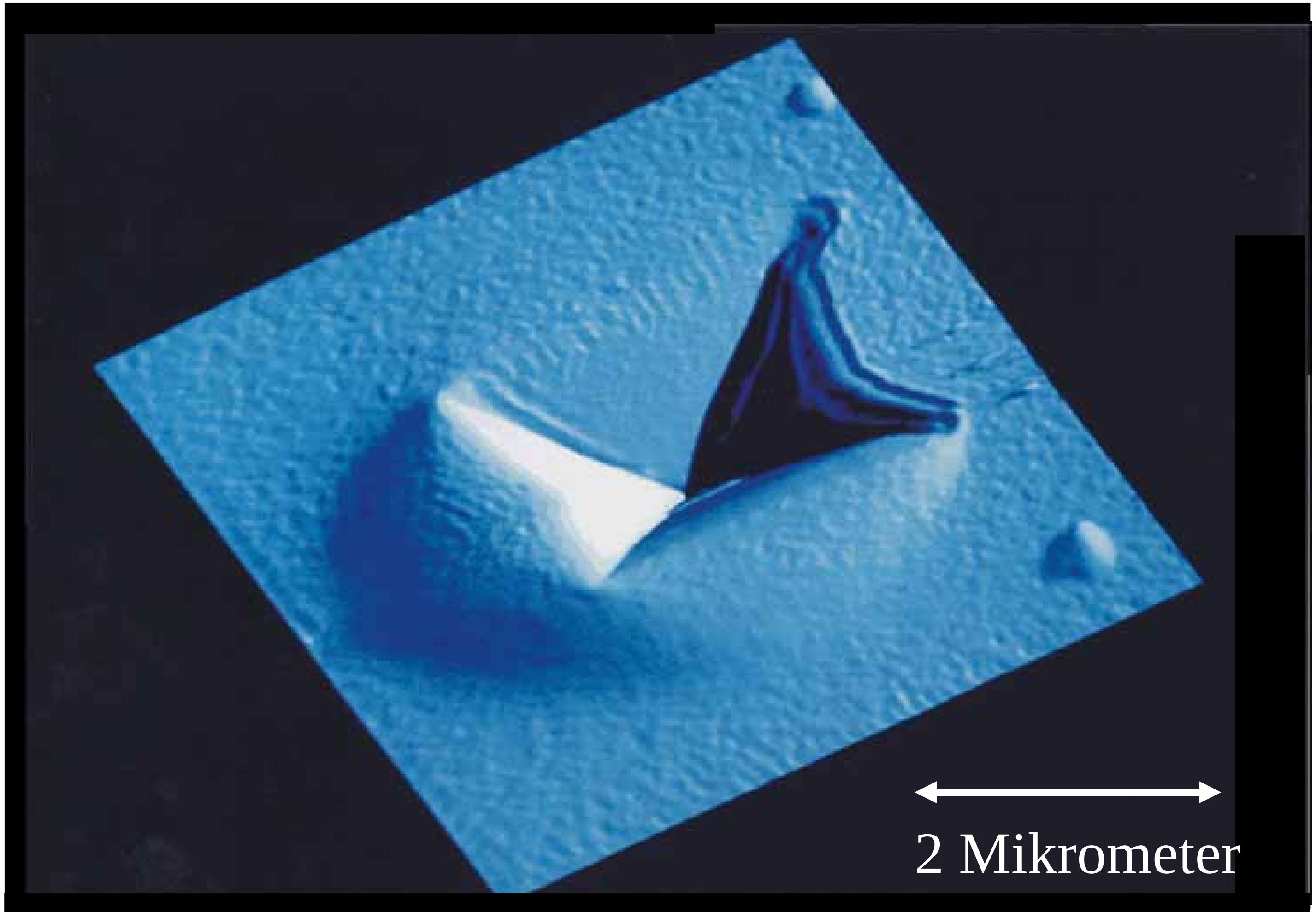
Magnetic domains on Computer HD



T. A. Jung SPM Tutorial

Indentation Hardness

tip-tools – materials testing and data storage



„HEUREKA“

— writing in between the lines of a CD

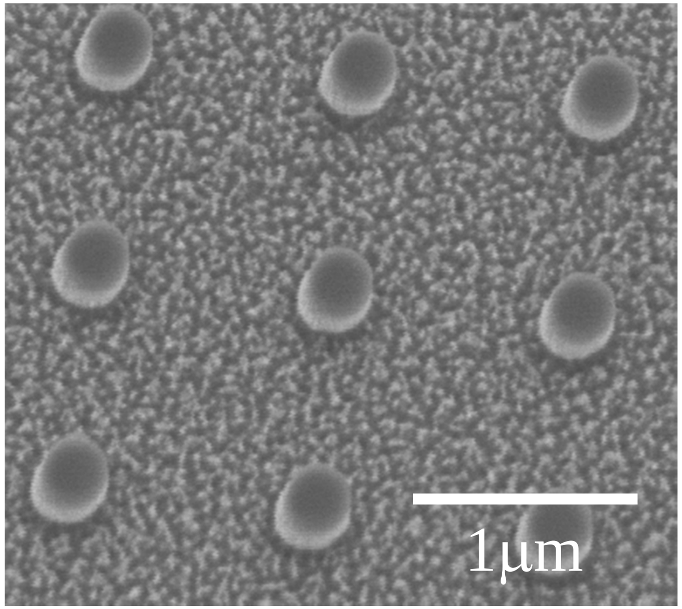
Nano-Fracture / Nano-Wear

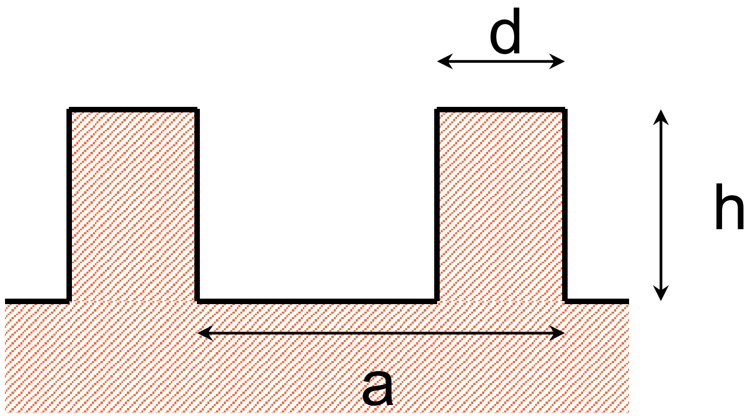
Fracture is a macroscopic phenomenon which crucially depends on microscopic properties

- Crystal structure
- Dislocation lines
- Interfaces
- Crack initiation
- Crack propagation

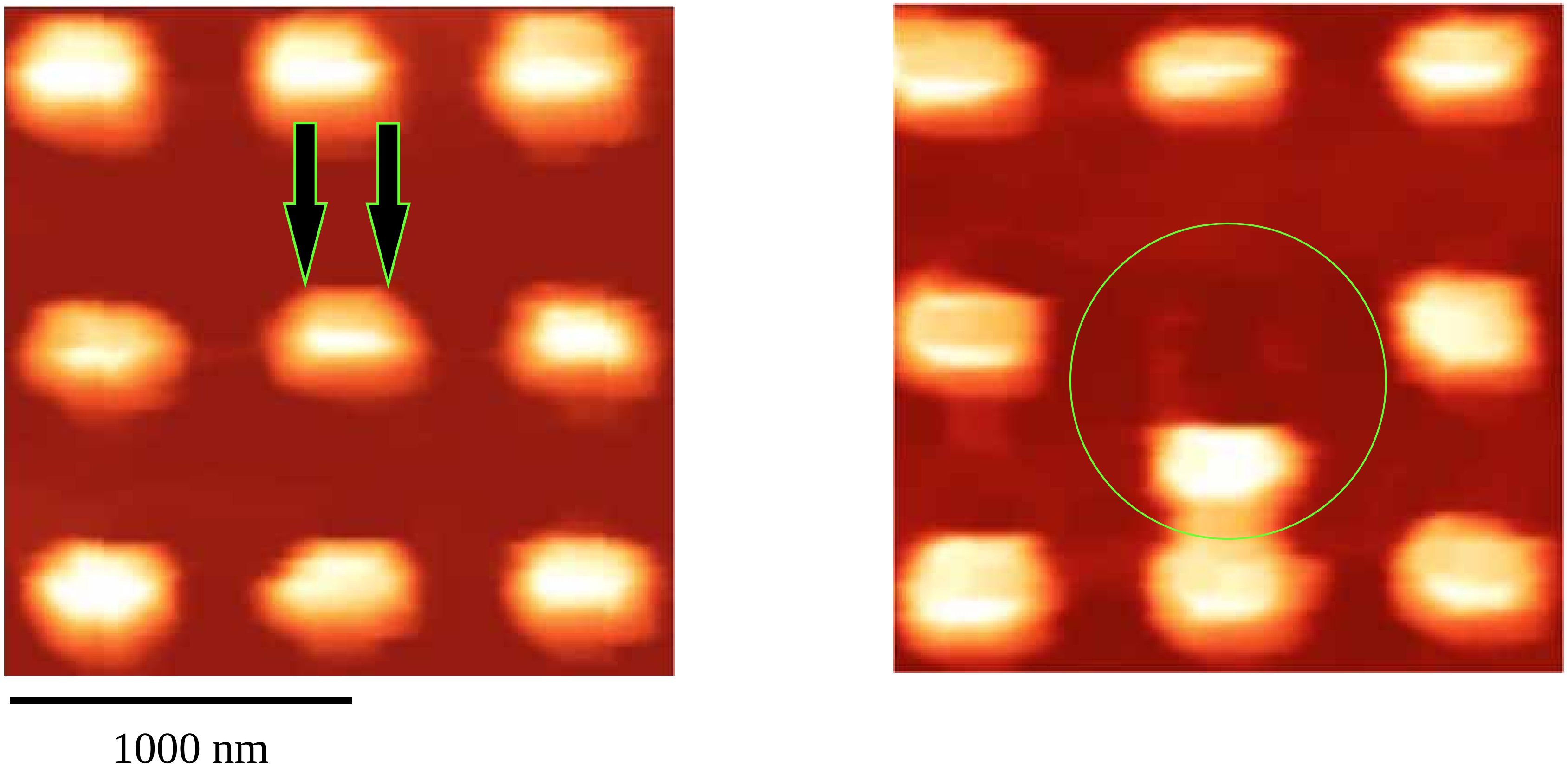
Well defined model system

- Nanotower arrays produced by lithography technique



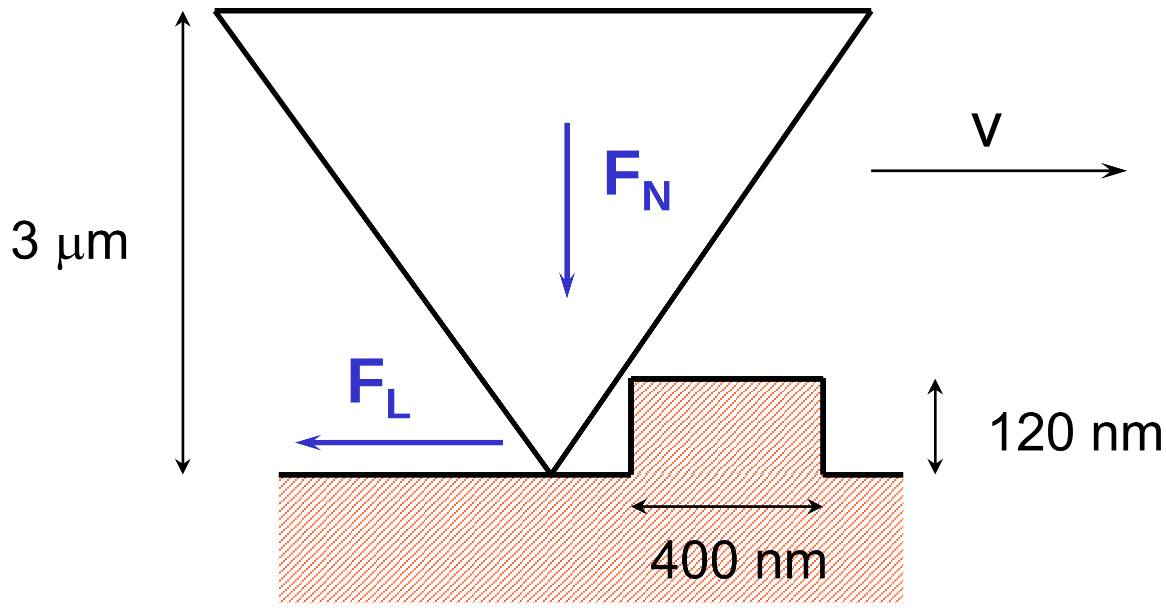


Nanotower Fracture Experiments

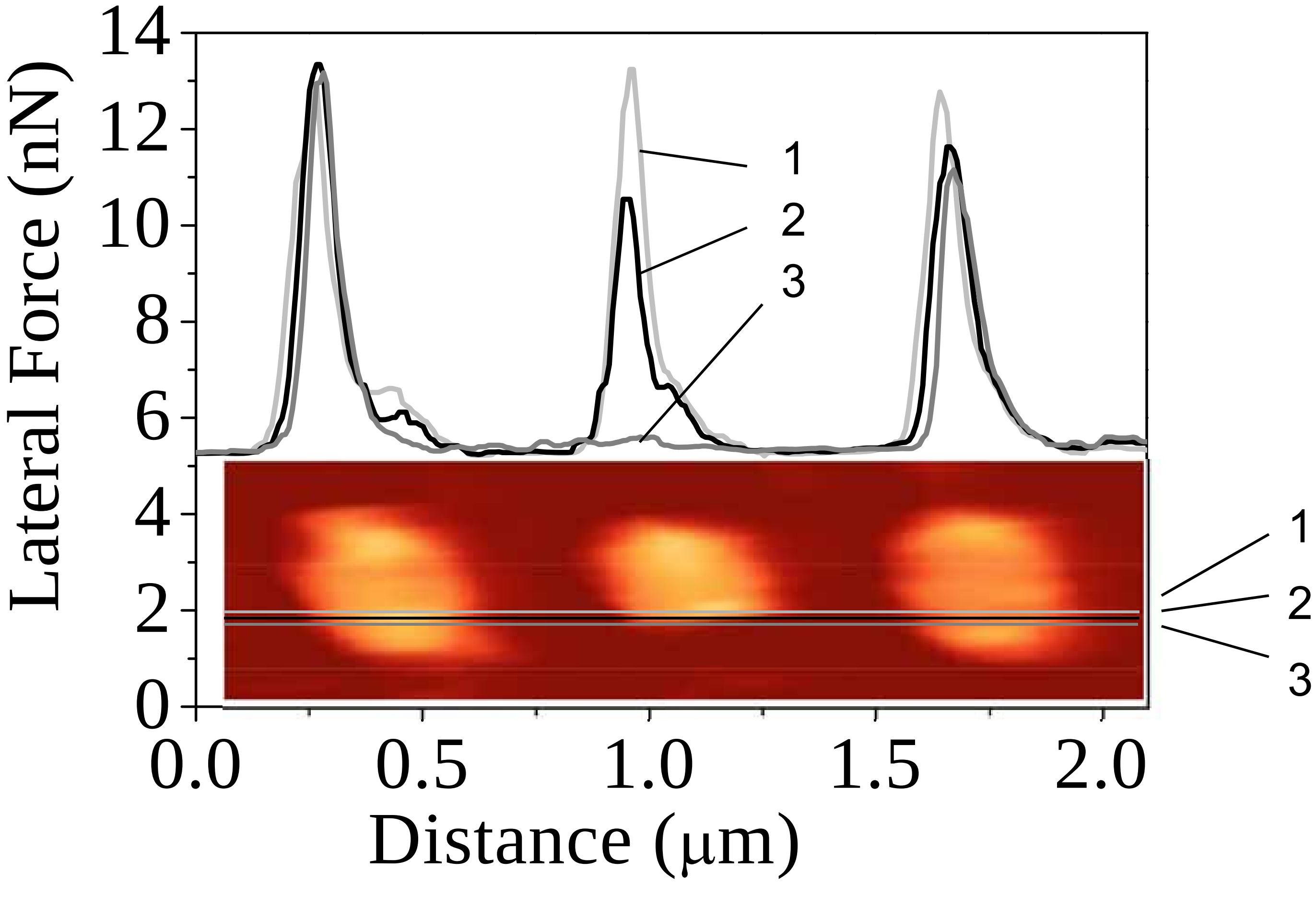


breaking off and removing nanotowers

Lateral force measurement

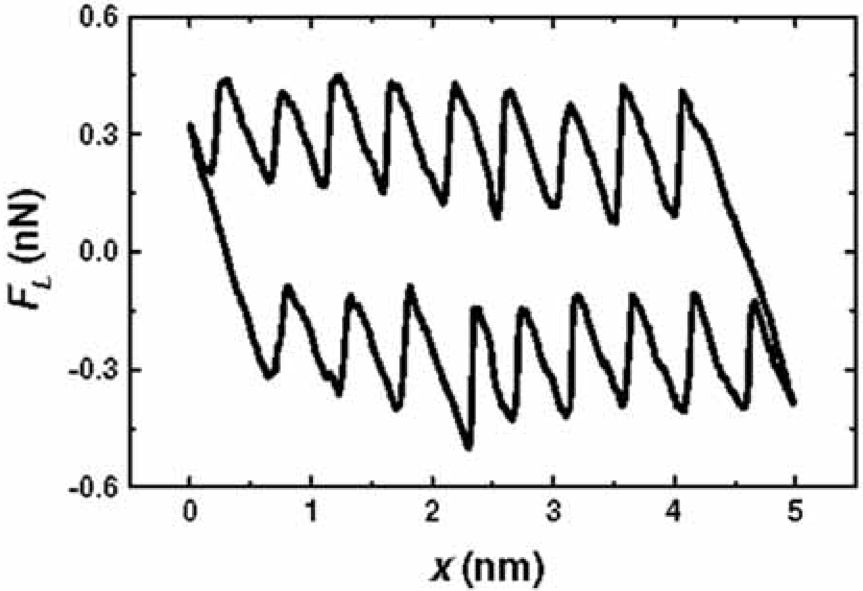


Lateral forces during fracture



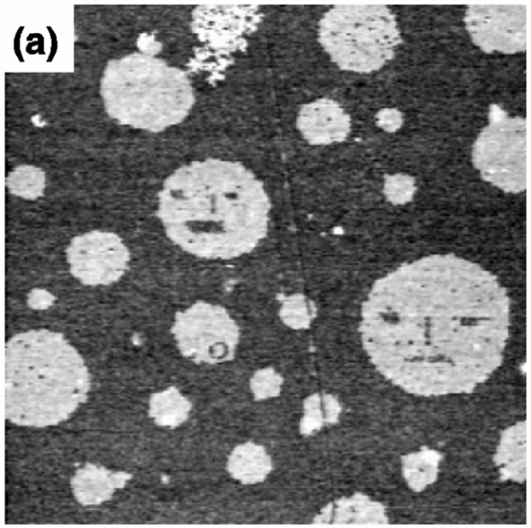
Atomic-scale stick-slip

NaCl(100)

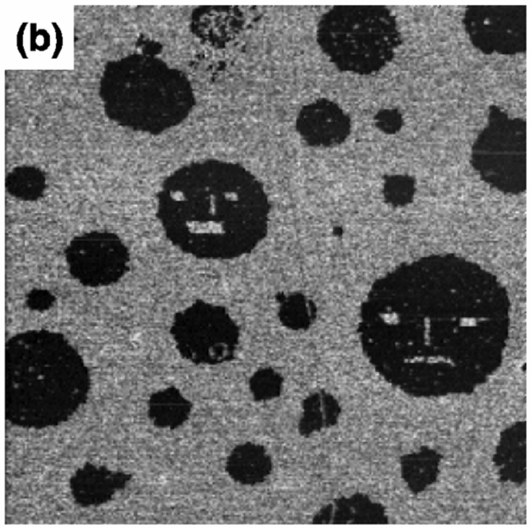


⇒See part II

Friction contrast



Topography



Lateral Force

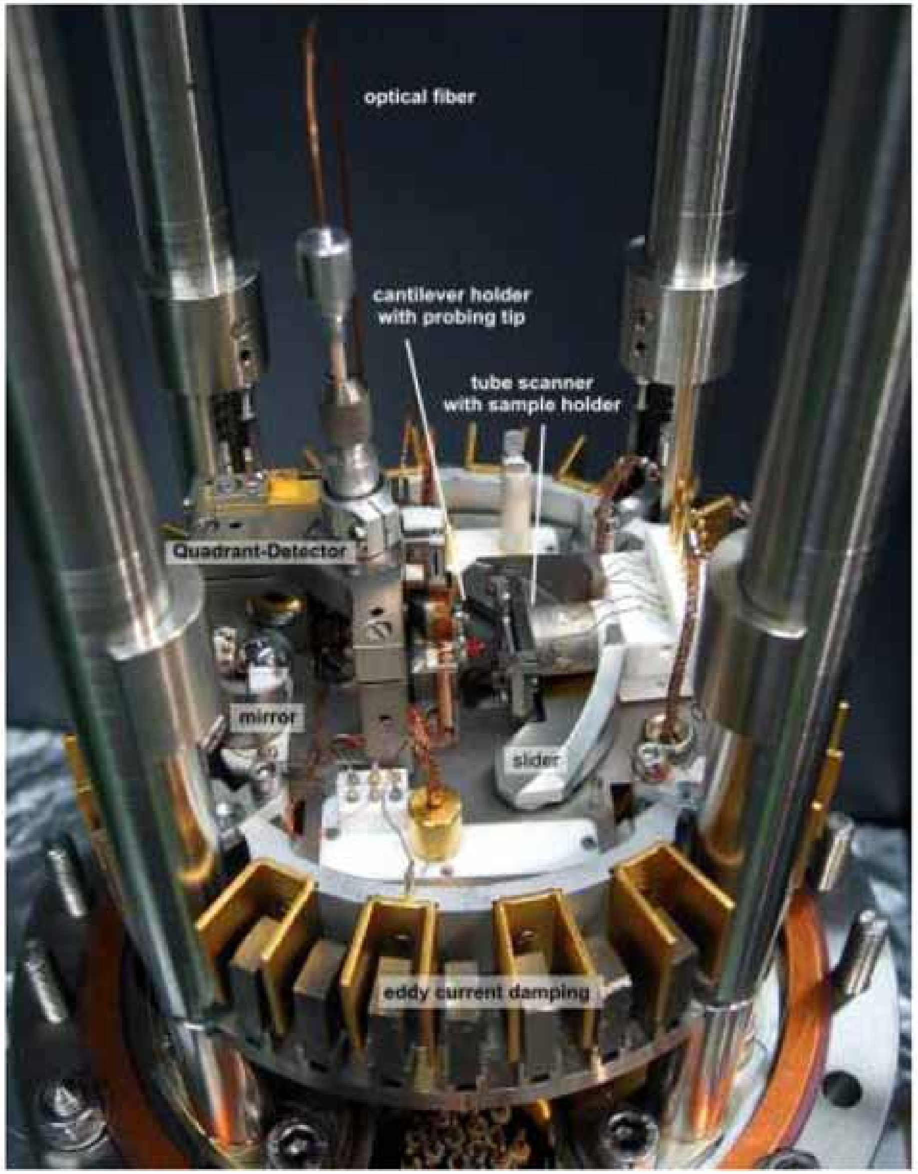
2.8x2.8μm^2

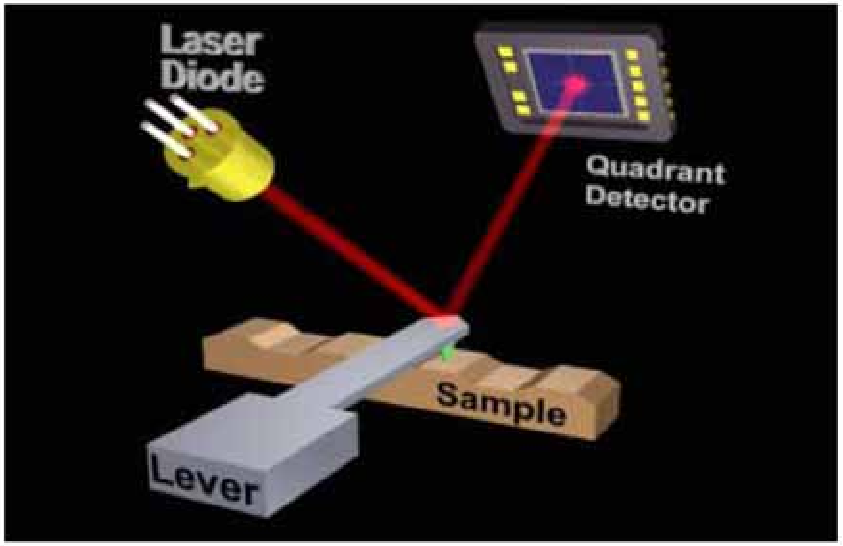
Mixed Langmuir-Blodgett films
($C_{21}H_{43}COO^-$/$C_9F_{19}C_2H_4OCC_2H_4COO^-$)

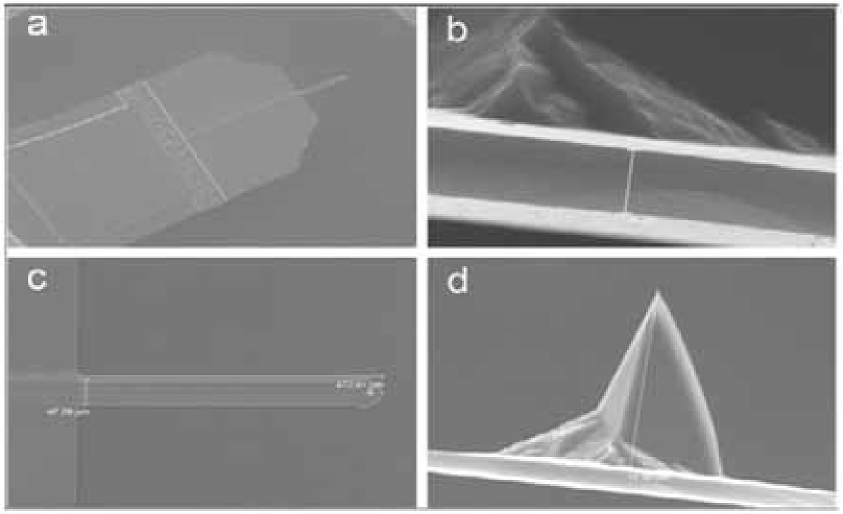
E. Meyer et al.
Thin Solid Films **220**, 132 (1992)

[redacted]

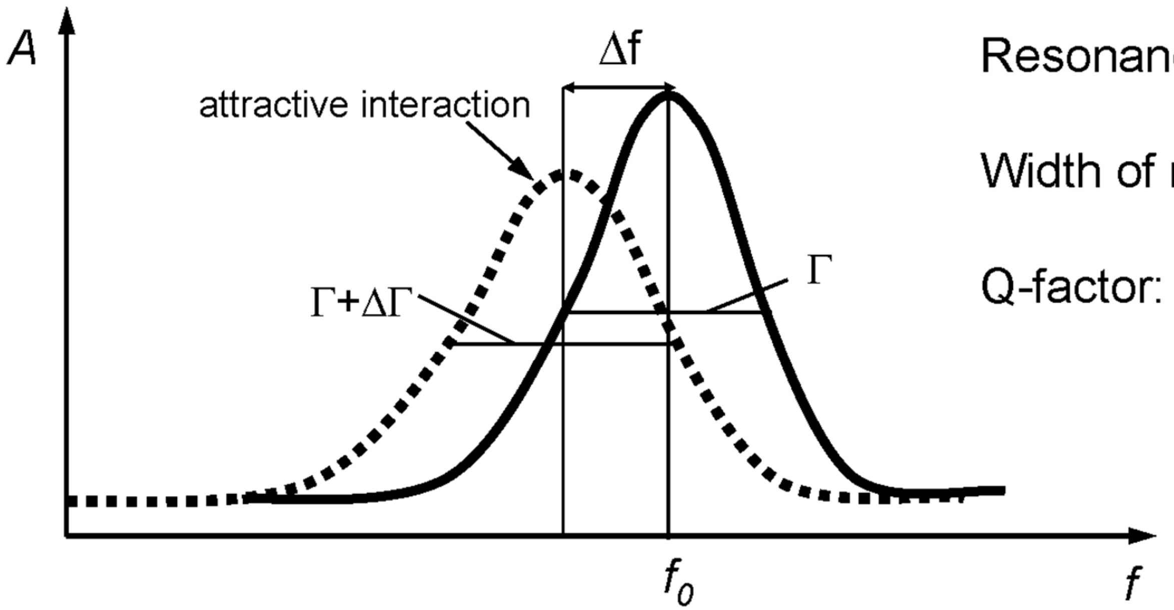
Noncontact-AFM (nc-AFM)







Quantitative understanding of nc-AFM



Resonance frequency: f_0

Width of resonance curve (FWHM): Γ

Q-factor: $Q = \frac{2\pi \cdot f_0}{\Gamma}$

Conservative forces $\Rightarrow$ shift of resonance curve Δf
Dissipative forces $\Rightarrow$ broadening of curve $\Delta\Gamma$

Forces in nc-AFM

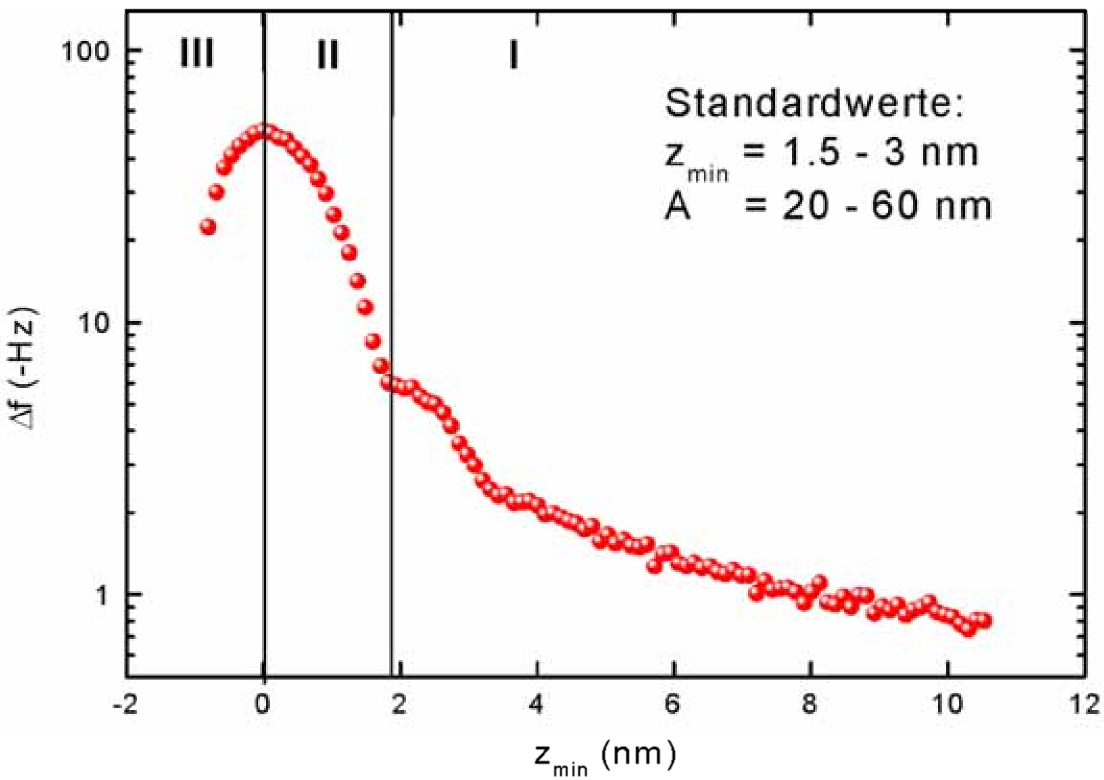
Frequency modulation: $f_0 = \frac{1}{2\pi}\sqrt{\frac{k}{m^*}}$ $\Delta f = -\frac{f_0}{2k}\frac{\partial F_{tot}}{\partial z}$

$\Rightarrow$ measured topography = surface of constant $\frac{\partial F}{\partial z}$

$$F_{tot} = F_{chem} + F_{mag} + F_{el} + F_{vdW}$$

- F_{chem}: bonding between tip and sample atoms (only for d < 5 Å)
- F_{mag}: only for magnetically sensitive tips
- $F_{el} = -\frac{1}{2}\frac{\partial C}{\partial z}V^2$
- $F_{vdW} = -\frac{HR}{6d^2}$

Dynamic Mode, non-contact

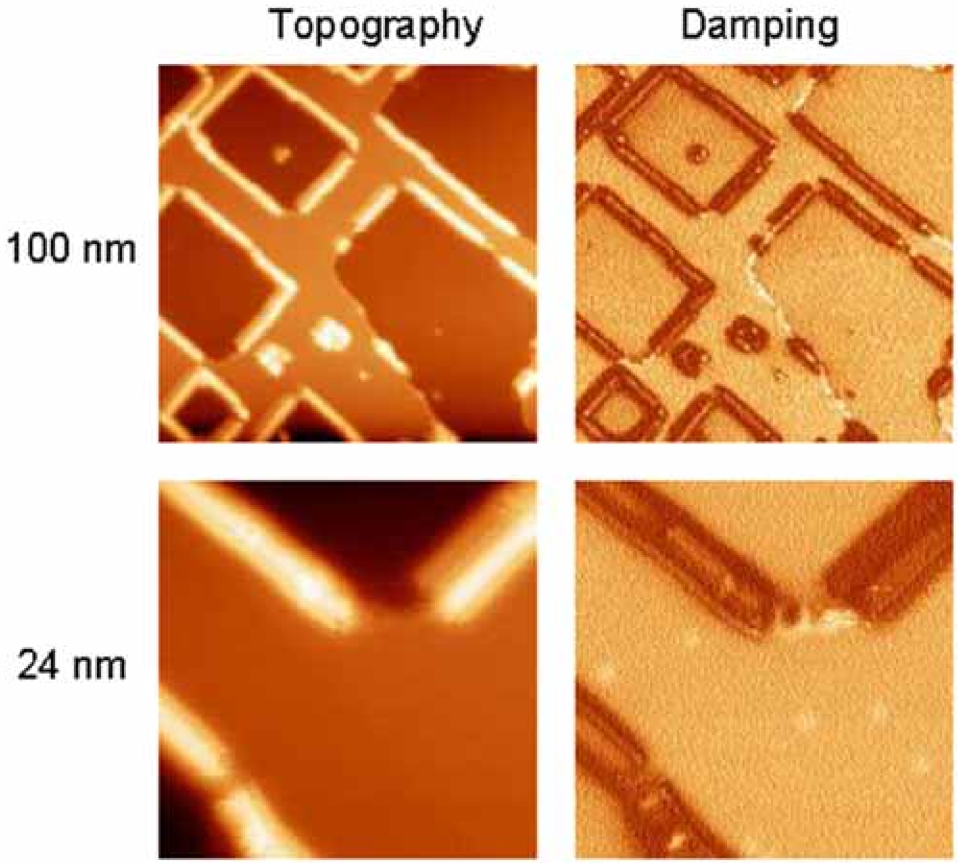


region I:
- attractive forces
- non-contact mode

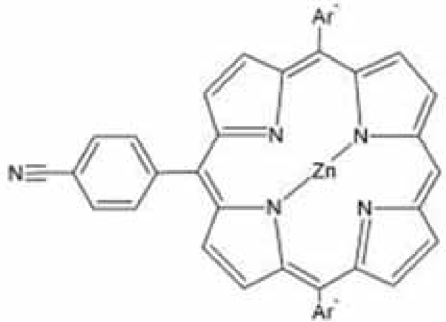
region II:
- attractive forces
- atomic resolution

region III:
- repulsive forces
- tapping mode

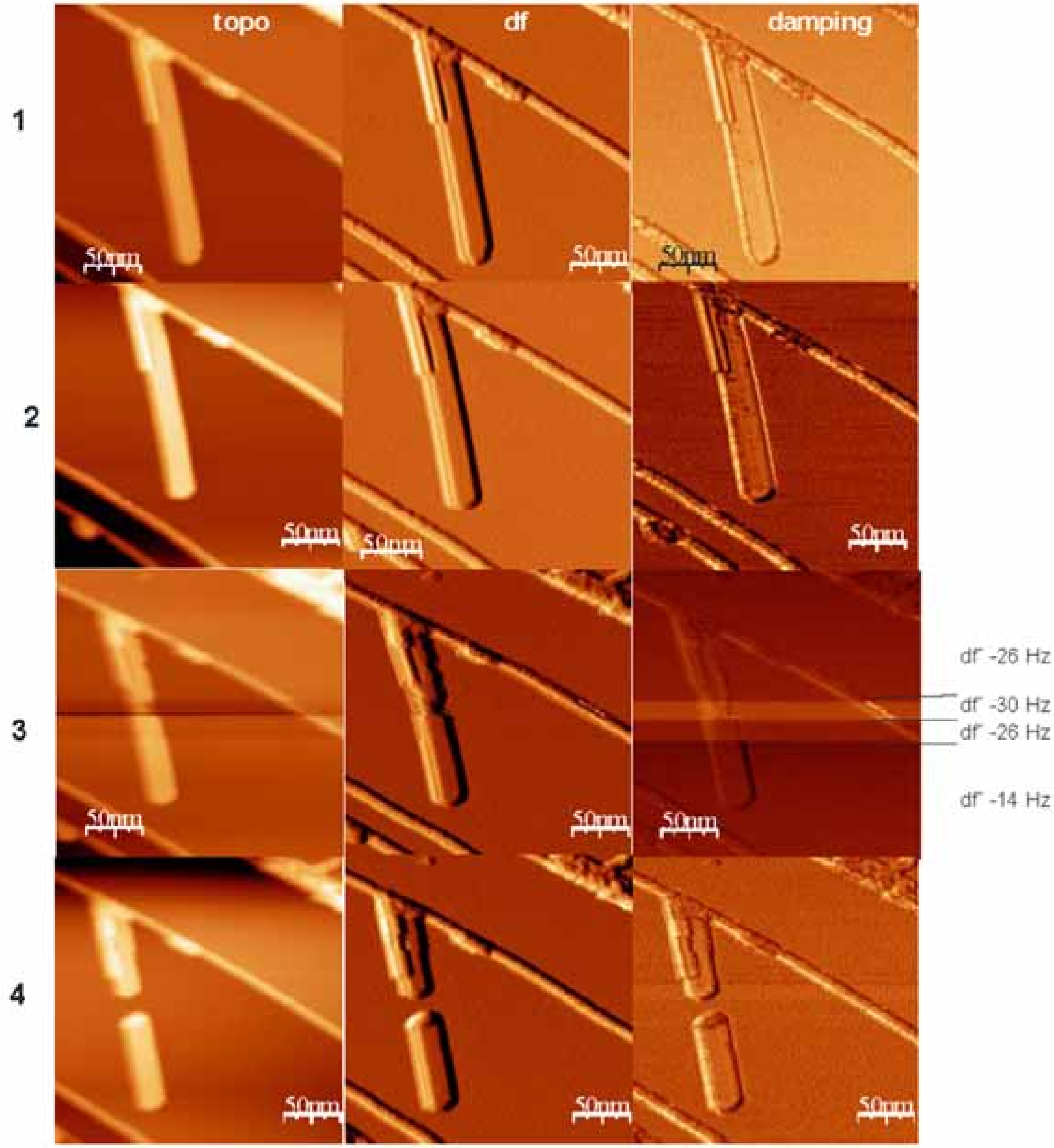
Molecular nanowires on KBr



- "Asymmetric" porphyrins on KBr with pits
- Straight edges are decorated
- Image height approx 1nm, Single molecules ?

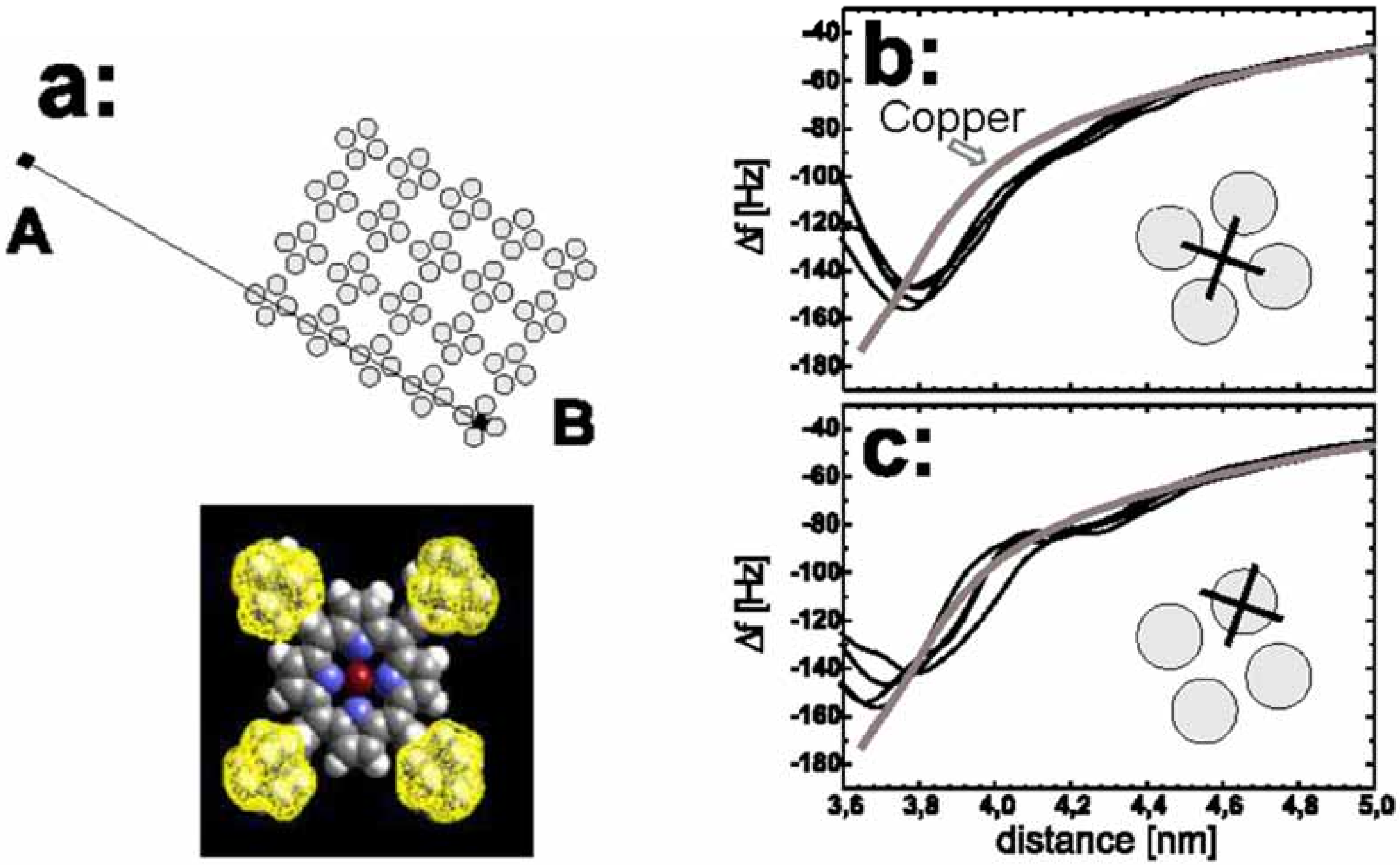


Cutting a molecular wire



Wieviel Kraft braucht man für einen molekularen Schalter?

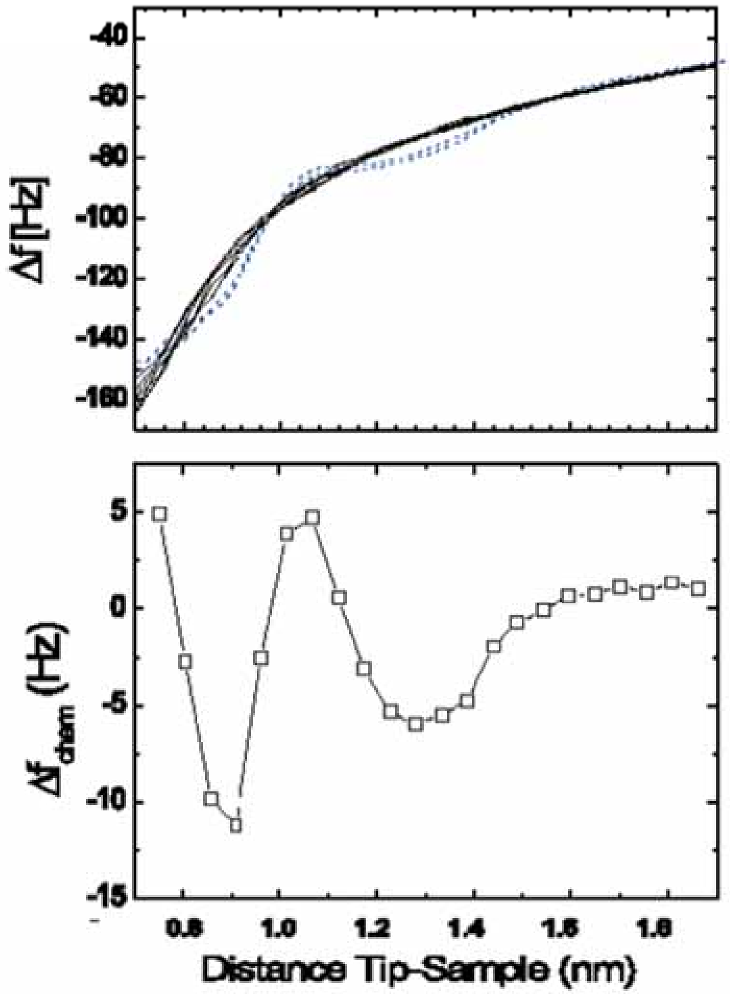
Force spectroscopy of Cu-TBPP molecules on Cu(100)



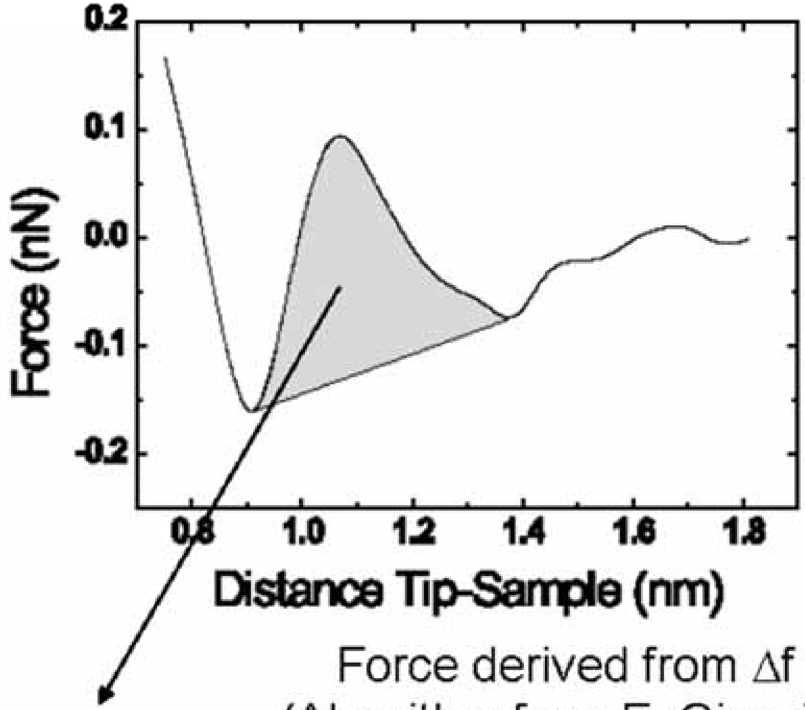
20 Curves on 4x5 Cu-TBPP island; thermal drift 5nm/h

Ch. Loppacher et al., PRL **90**, 066107 (2003)

Force spectroscopy above a leg of Cu-TBPP



Difference ($\Delta f_{leg} - \Delta f_{Cu}$)

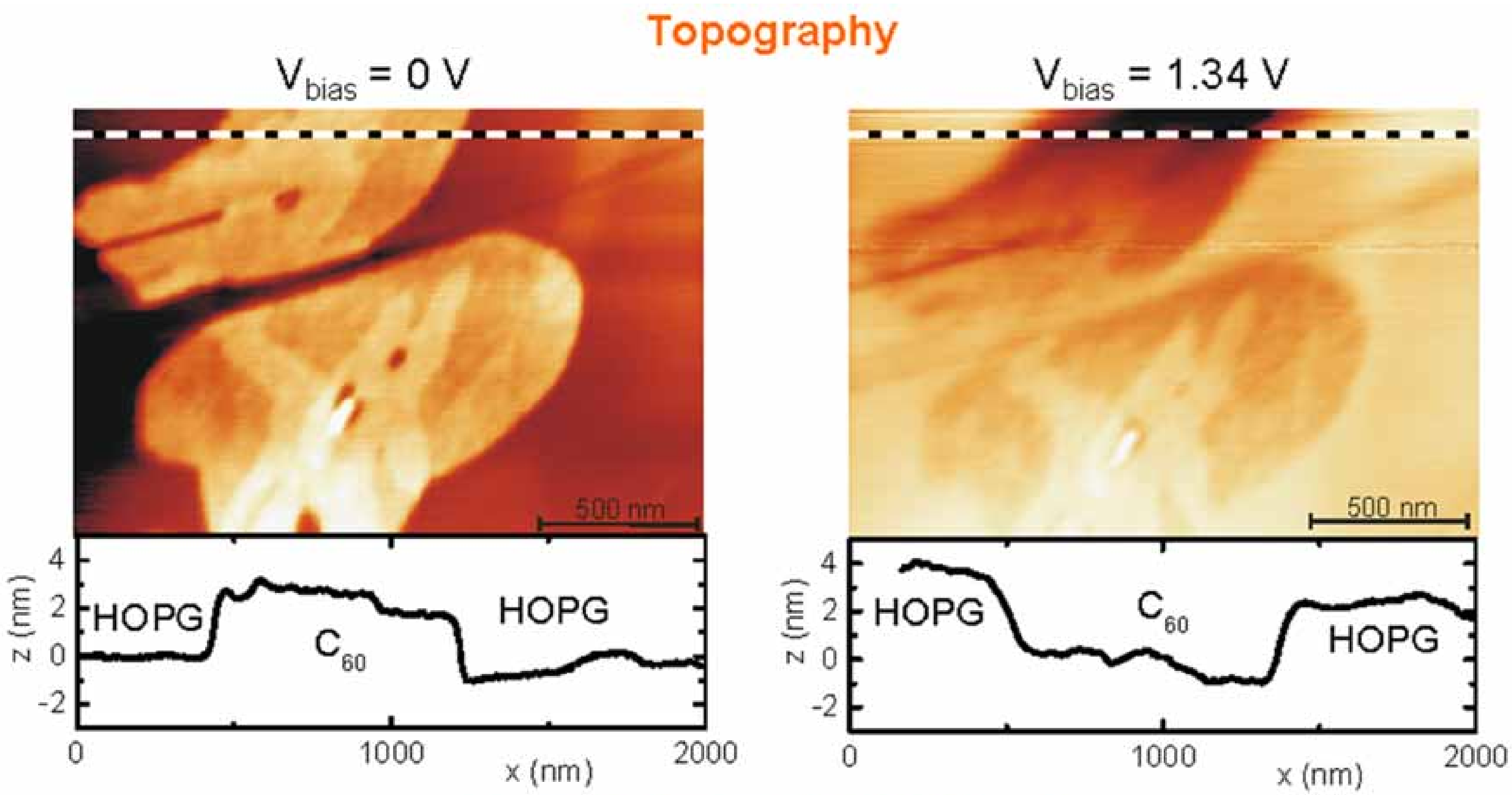


Force derived from Δf
(Algorithm from F. Giessibl)

47×10^{-21} J P<7fW

10^{-4} switching energy
of a state-of-the-art transistor

inhomogeneous sample: HOPG + ½ monolayer C60

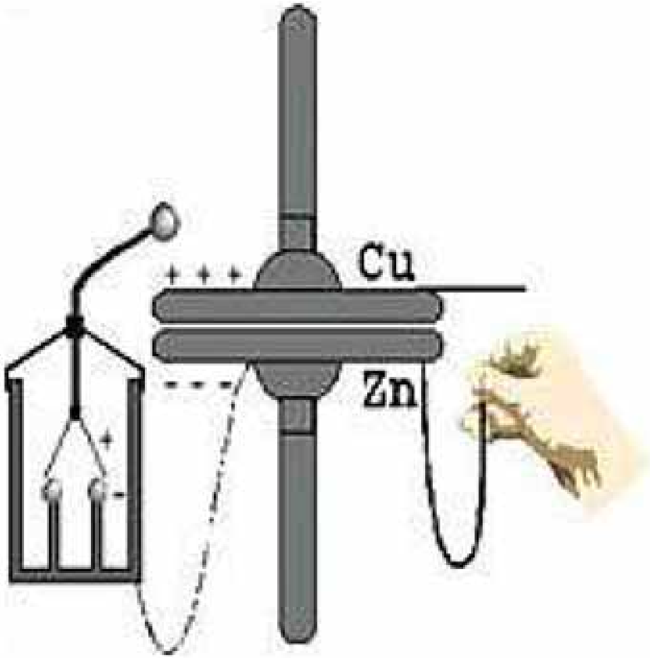


→ contrast inversal: HOPG ↔ C_{60}

S. Sadewasser et al., PRL 91 266101 (2003)

Makroskopische Kelvin-Sonde

Lord Kelvin 1861



Verschiebestrom

$I(t) = (U_{dc} - U_{CPD})\, f\ \Delta C \cos \omega t.$

Kelvin Principle