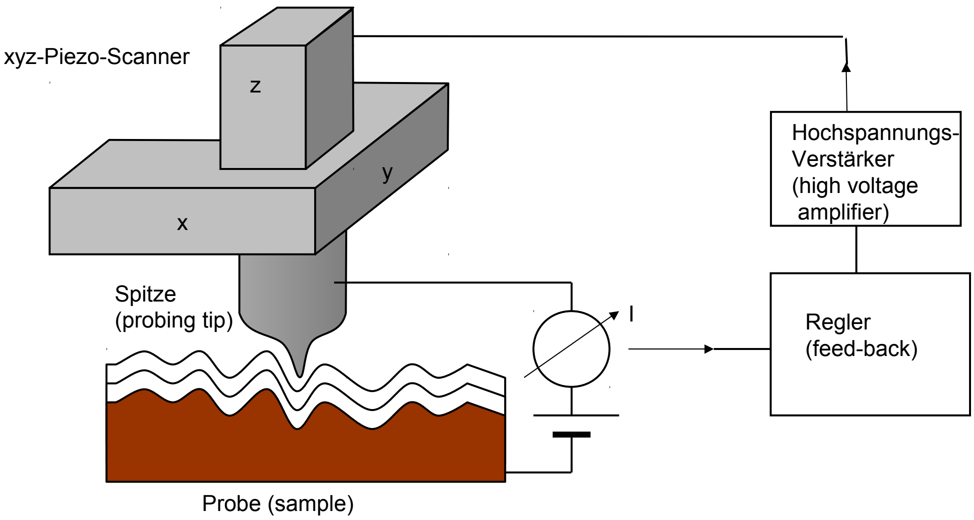
Nanostrukturen-Analysemethoden

Scanning Probe Microscopy

- **Scanning Tunneling Microscopy**
- Tunneleffekt
- G. Binnig and H. Rohrer, Nobelpreis 1986
- Experimenteller Aufbau
- **Friction Force Microscopy**
- Force Calibration
- Atomic Stick Slip
- Tomlinson Model
- Nano-manipulation
- **Atomic Force Microscopy**
- Short- and Long-Range Forces
- Kelvin Probe Force Microscopy
- Measurements on Semiconducting Devices
- Molecules on Insulating Surfaces
- Manipulation

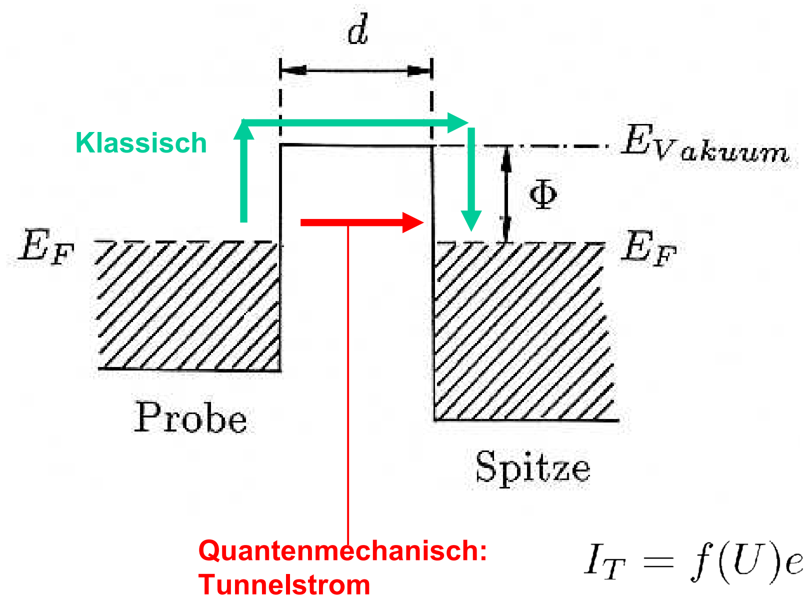
Thilo Glatzel, thilo.glatzel@unibas.ch
NANOlino Lab

Rastertunnelmikroskop (STM)



Ein Regler hält den Tunnelstrom (≈pA-nA) zwischen Spitze und Probe konstant. Es werden Kontouren konstanten Tunnelstroms abgerastert.

Tunneleffekt



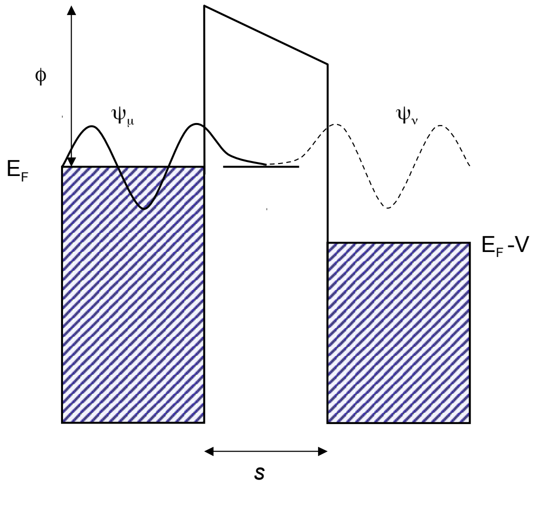
$$I_T = f(U)e^{-A\sqrt{\phi s}}$$

$$I_T \approx 1nA$$

J. Frenkel, *Phys. Rev.* **B 36**, 1604 (1930)

Tunneleffekt

Schon zu Beginn der Quantenmechanik wurde der Tunneleffekt vorausgesagt. Der Überlapp der Wellenfunktionen führt zu einer Transmission von Elektronen durch ein klassisch verbotenenes Gebiet. Zwischen zwei Metallen, die durch Vakuum oder ein Oxid getrennt sind, fliesst ein Tunnelstrom.

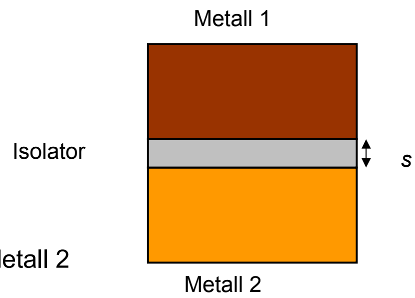


J. Frenkel, *Phys. Rev.* **B 36**, 1604 (1930)

Tunneleffekt

$$I_T = f(U)e^{-A\sqrt{\phi s}}$$

I_T: Tunnelstrom
U: Extern angelegte Spannung
s: Distanz zwischen Probe und Spitze
ϕ: Barrierenhöhe



$$\phi \approx \frac{\phi_1 + \phi_2}{2}$$ ϕ_1, ϕ_2 Austrittsarbeiten von Metall 1 und Metall 2

$$A = 2\sqrt{\frac{2m}{\hbar^2}} = 1.025 Å^{-1} eV^{-1/2}$$

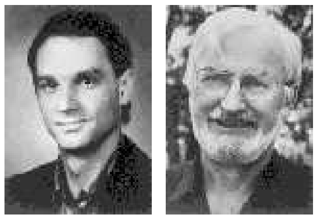
f (U) : Funktion der elektronischen Struktur von Probe und Spitze
Für freie Elektronen *f* (U) ~ U

er Tunnelstrom hängt exponentiell vom Abstand *s* ab. Für typische Austrittsarbeiten von =4.5eV ändert sich der Strom etwa um eine Grössenordung, wenn die Distanz um 1Å verändert wird. istorisch wurde zuerst das Oxidtunneln realisiert. Erst mit dem STM konnte Vakuumtunneln beobacht erden.

J. Frenkel, *Phys. Rev.* **B 36**, 1604 (1930)

Scanning Tunneling Microscope (STM)


Source: IBM

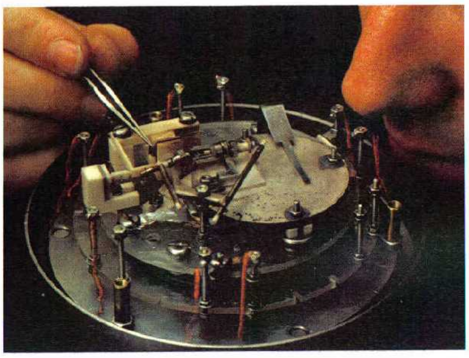


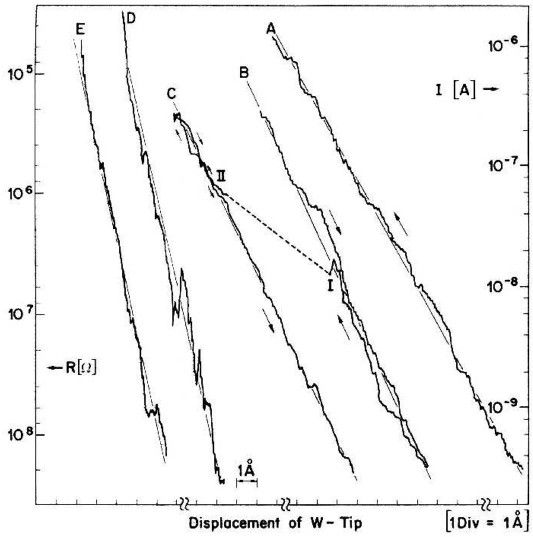
G. Binnig and H. Rohrer
Nobelpreis 1986

IBM Rüschlikon
Switzerland

G. Binnig, H. Rohrer, Ch. Gerber, and E. Weibel, Phys. Rev. Lett. 50, 120 - 123 (1983)
G. Binnig, H. Rohrer, Ch. Gerber, and E. Weibel, Phys. Rev. Lett. 49, 57 - 61 (1982)
G. Binnig, H. Rohrer, Ch. Gerber, and E. Weibel, Appl. Phys. Lett., Vol. 40, Issue 2, pp. 178-180 (1982)

Scanning Tunneling Microscopy (STM)

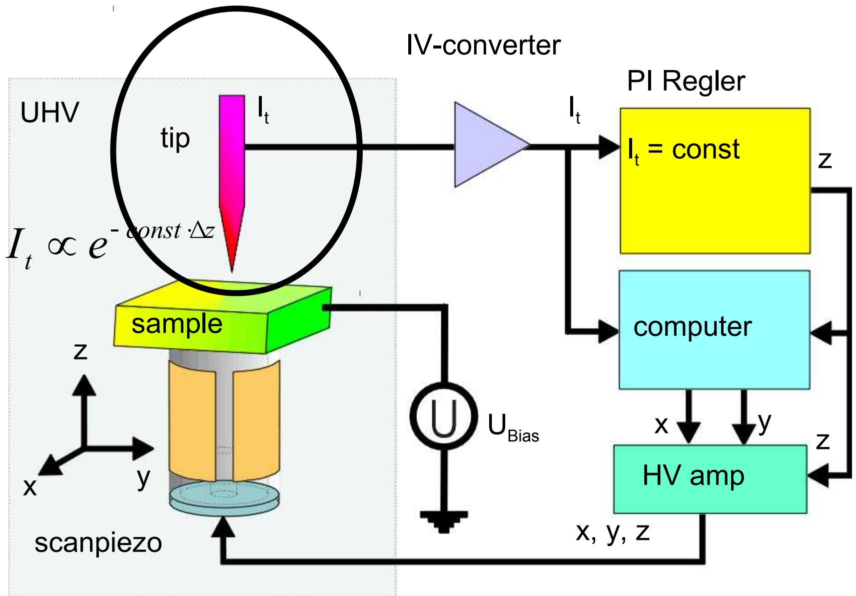




Exponentieller Abfall des Tunnelstromes mit dem Abstand

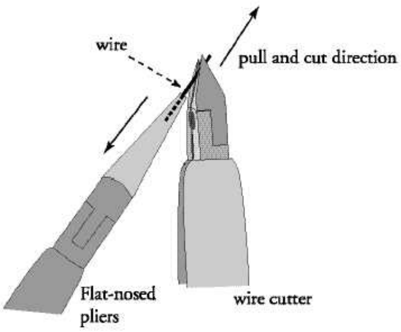
G. Binnig, H. Rohrer, Ch. Gerber, and E. Weibel, Appl. Phys. Lett., Vol. 40, Issue 2, pp. 178-180 (1982)

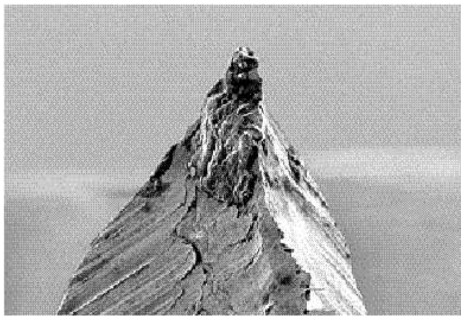
Blockschaltbild STM



Spitzen

1. Abgerissener PtIr Draht

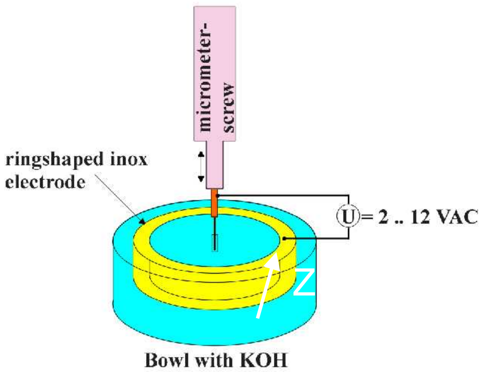


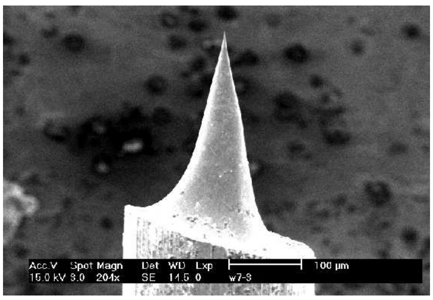


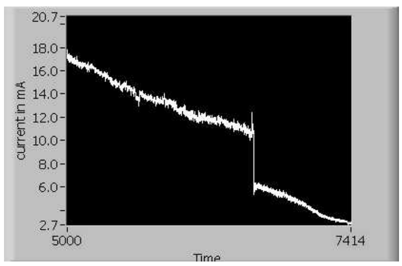
Oder...

Spitzen

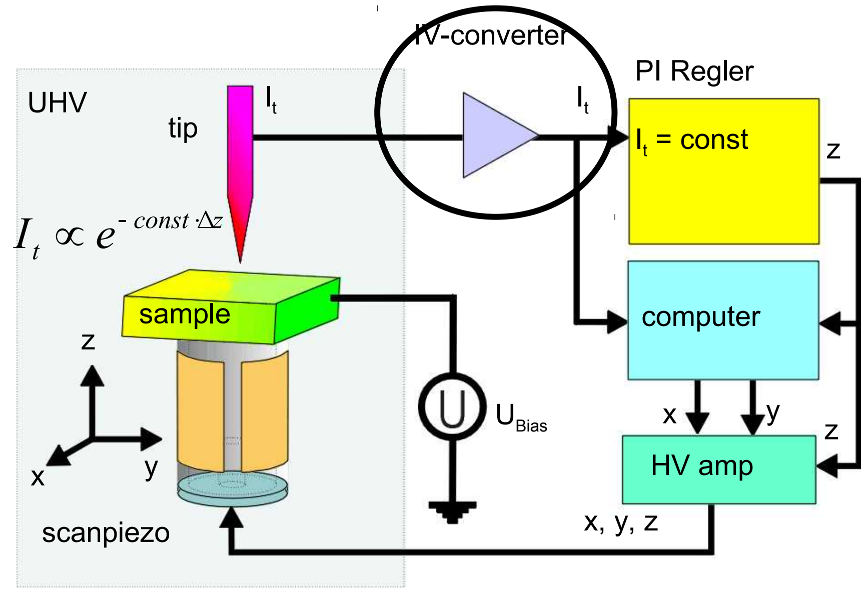
2. Elektrochemisch geätzte Wolframspitzen:



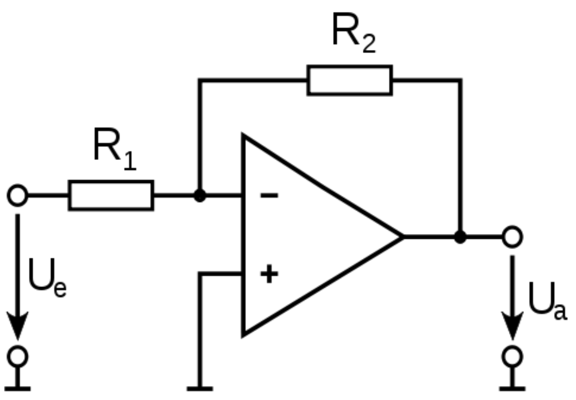




Blockschaltbild STM



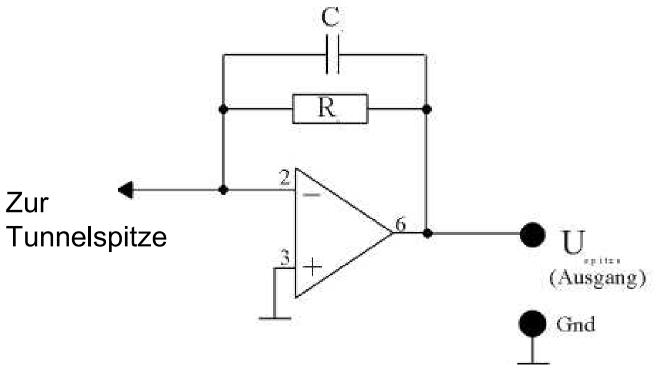
Invertierender Verstärker



$$U_a = -\frac{R_2}{R_1} U_e$$

http://de.wikipedia.org/wiki/Operationsverst%C3%A4rker

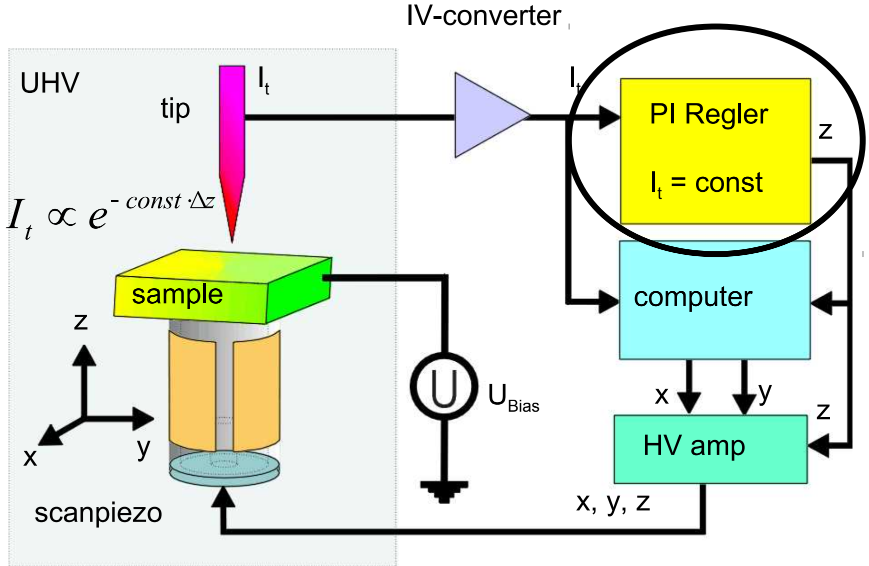
Strom-Spannungswandler



$$U_A = - R \cdot I_t$$

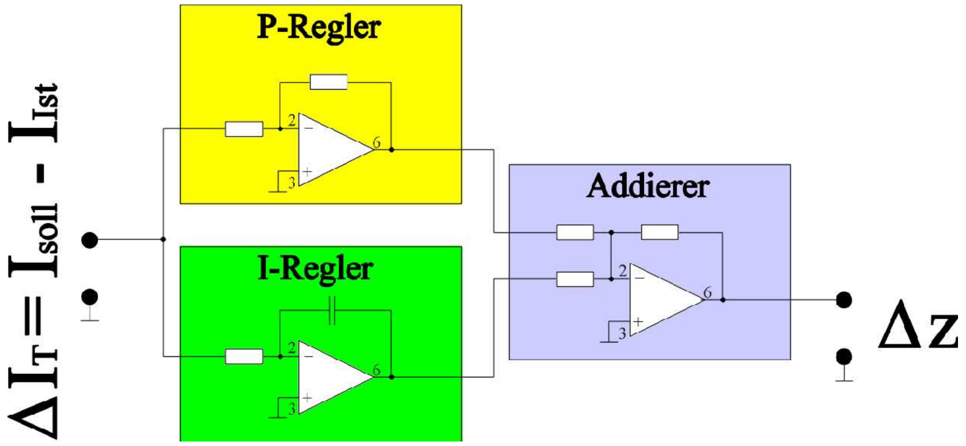
Bei R = 100MΩ entspricht U_A = 1V
einem Tunnelstrom von 10nA

Blockschaltbild STM

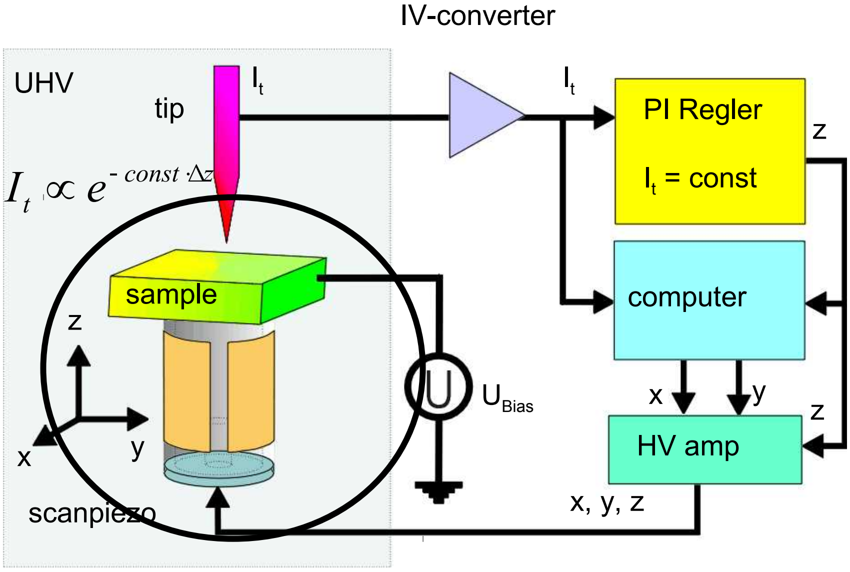


PI Regler

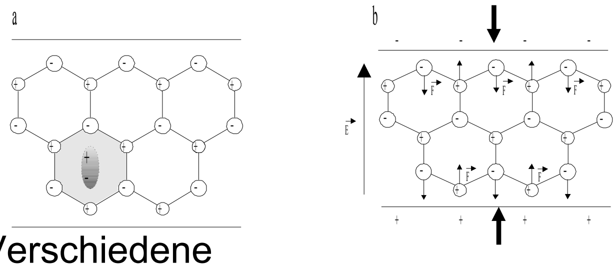
Regelt den Abstand Spitze-Probe so, dass der Tunnelstrom konstant bleibt



Blockschaltbild STM



Piezos



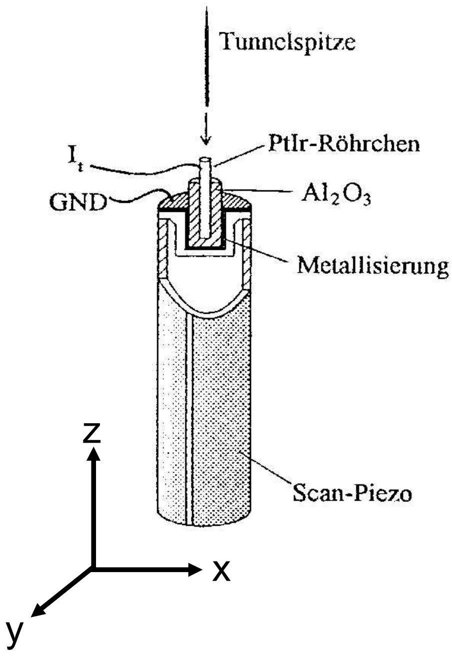
Verschiedene Ladungsschwerpunkte

Verformung durch Anlegen einer elektrischen Spannung

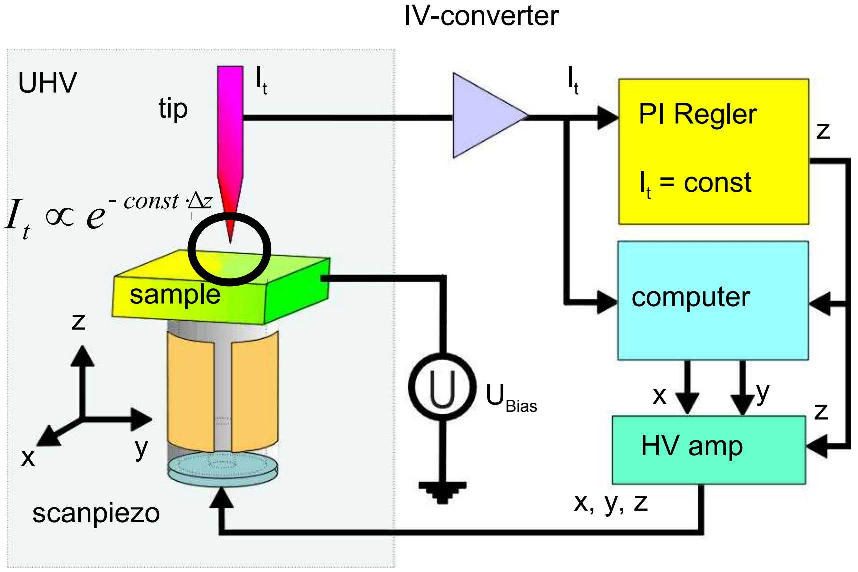
Typische Piezoelektrische Materialien:
•Quarz
•Bariumtitanat
•Bleizirkontitanat (PZT)
•Etc.

Piezotubes

XYZ-Stellglieder



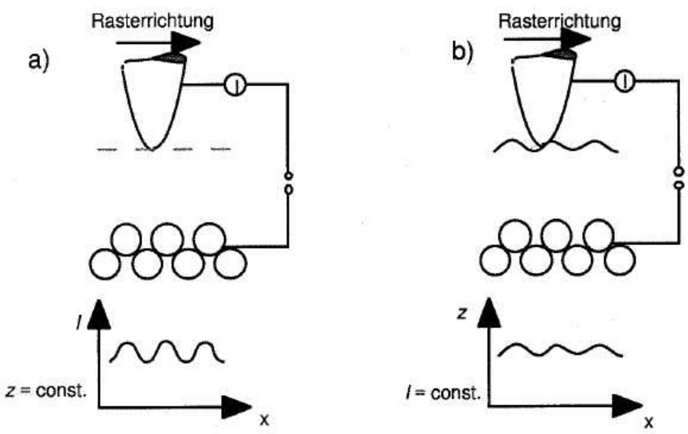
Blockschaltbild STM

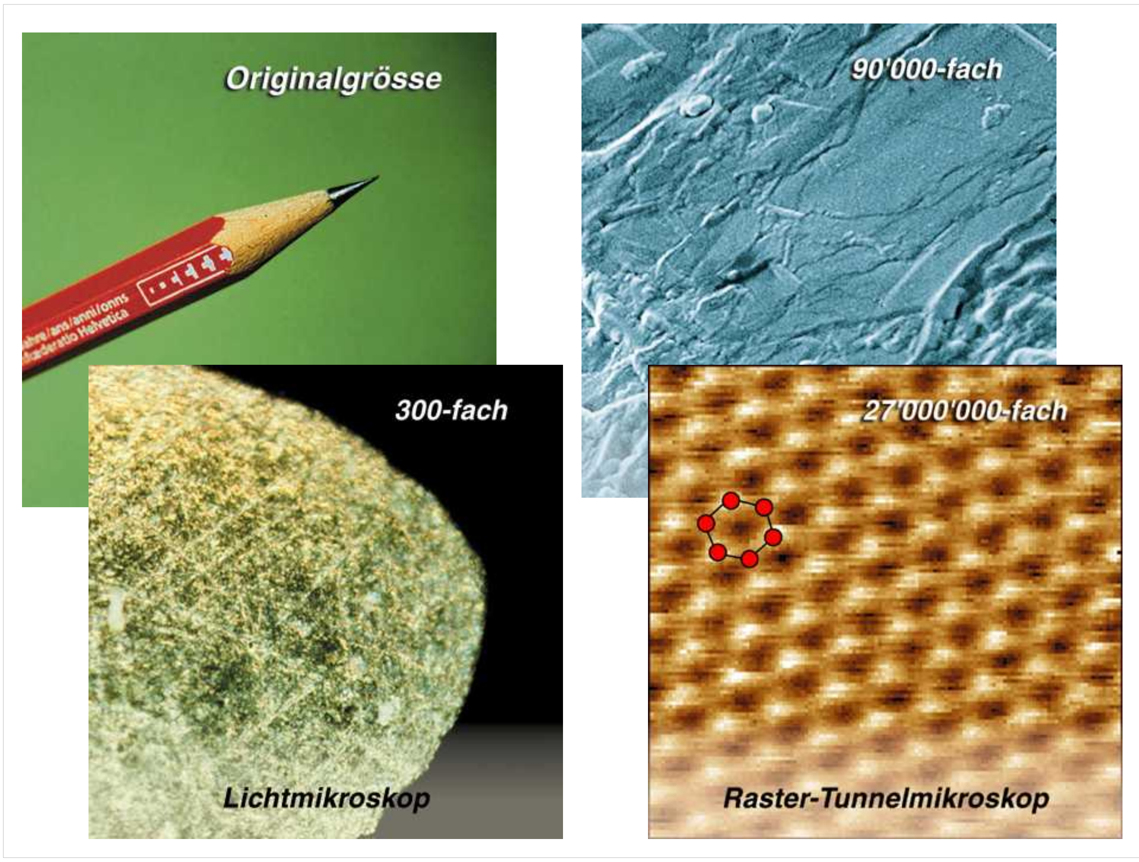


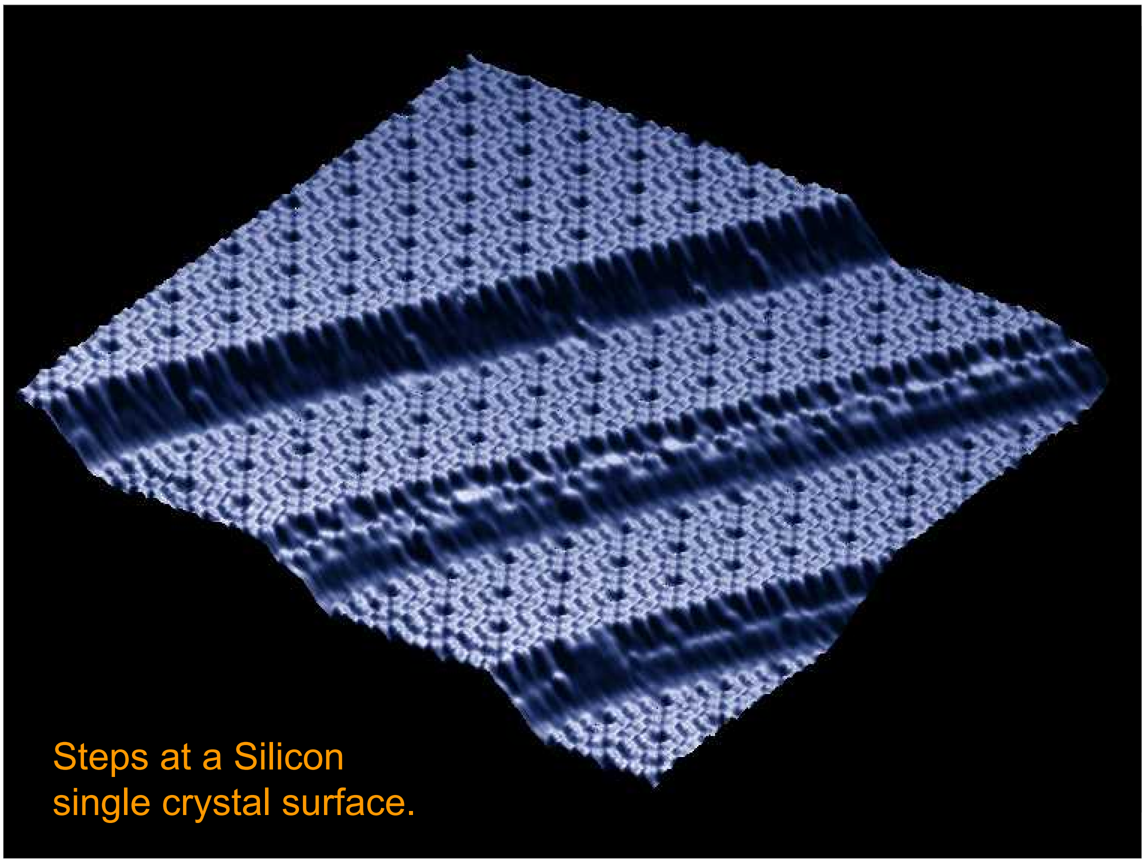
Messmodi

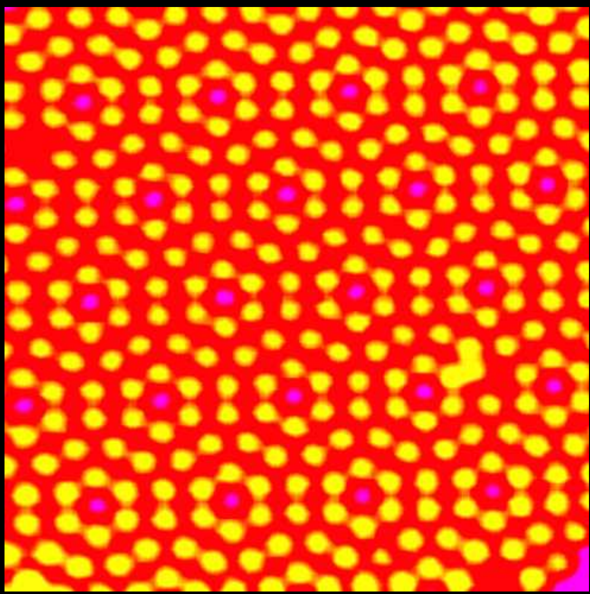
Constant Height

Constant Current




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

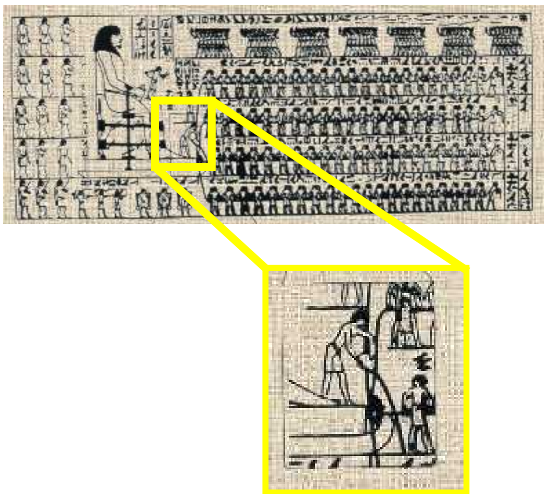

Steps at a Silicon
single crystal surface.



Si(111)7x7 reconstructed surface

Importance of Friction

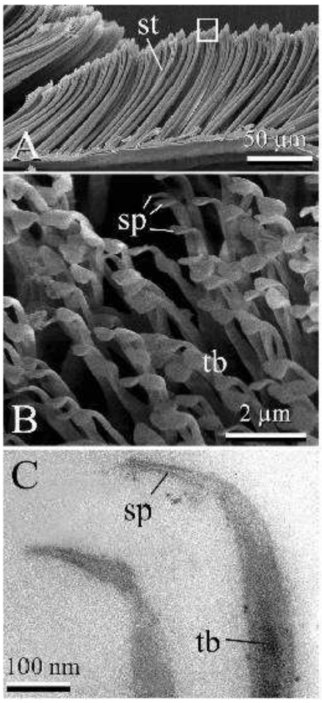
Long time ago...



Nowadays...

In all cases: It is higly desirable to reduce and <u>control</u> friction

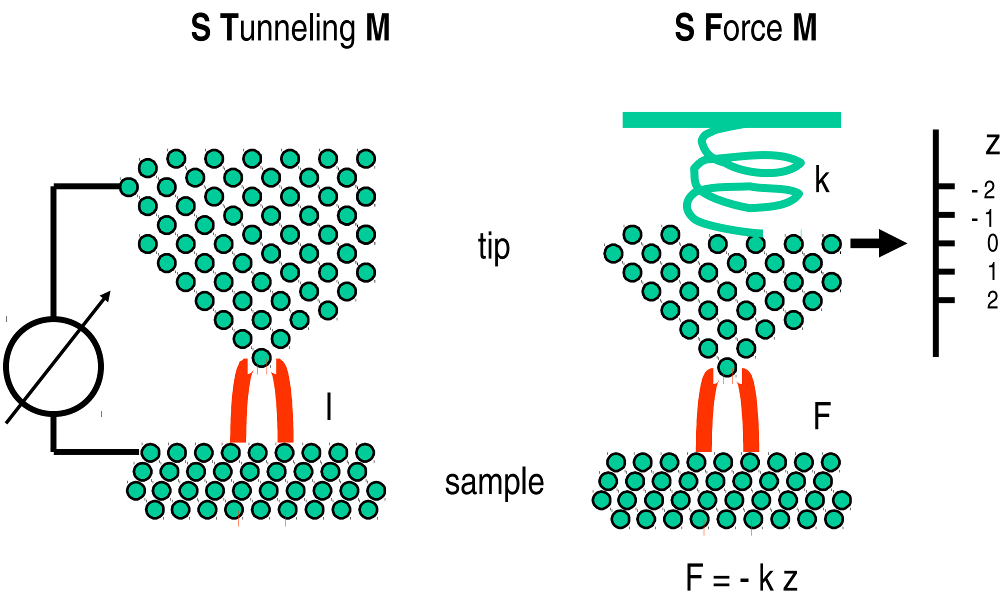
Gecko uses nanometer-sized contacts to climb walls



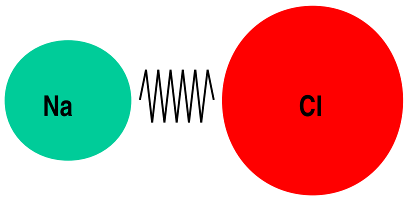
Gecko is able to control the contact area on all length scales

From B. Persson and S. Gorb JCP, 119, 11437 (2003)

Scanning X Microscopy



Kräfte zwischen zwei Atomen

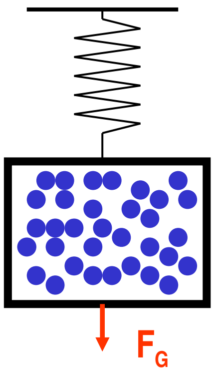


Chemische Bindung

F_{chem} = 1eV/ 0.1 nm

1.6 nN

„Kräfte Spüren“



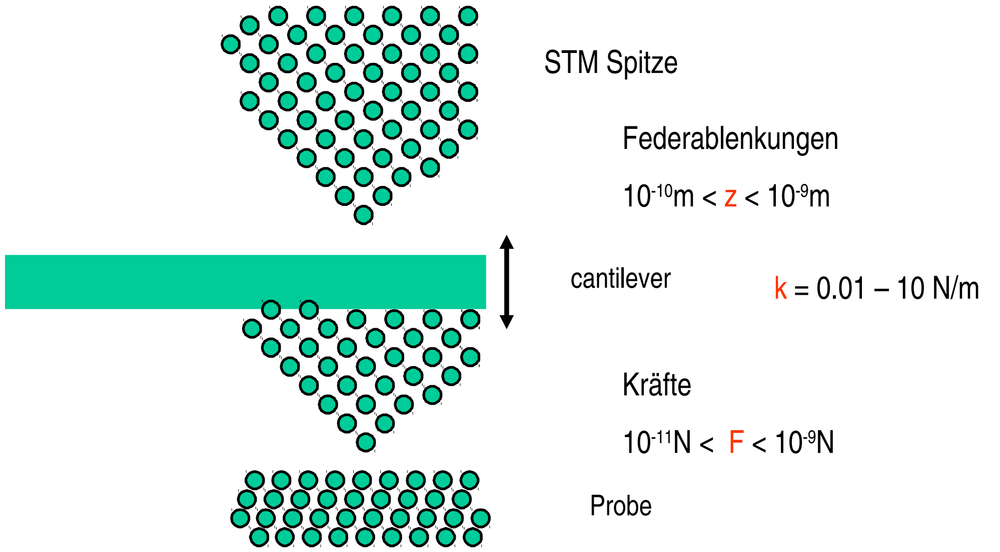
1 nm³ Wasser (33 Moleküle)

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

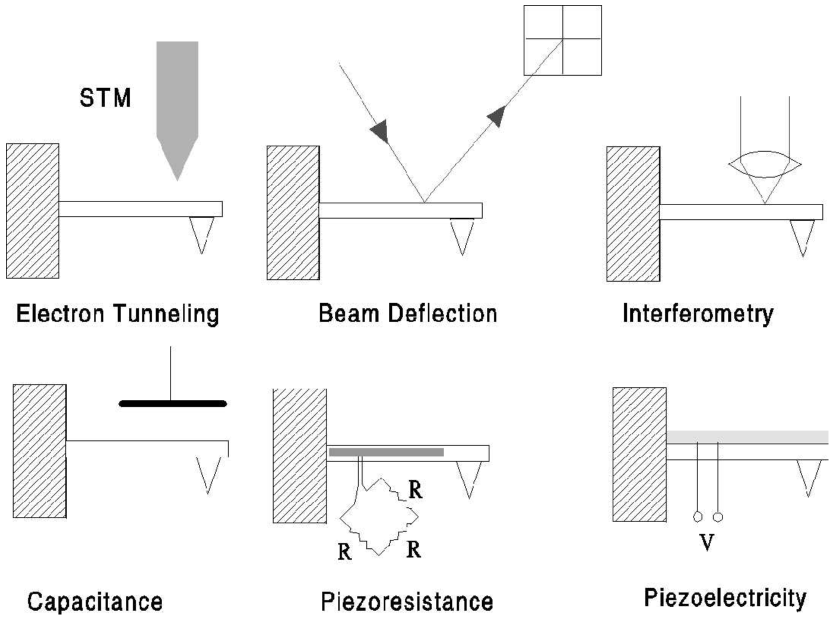
0.01 g

F= 0.1 mN = 10^5 nN

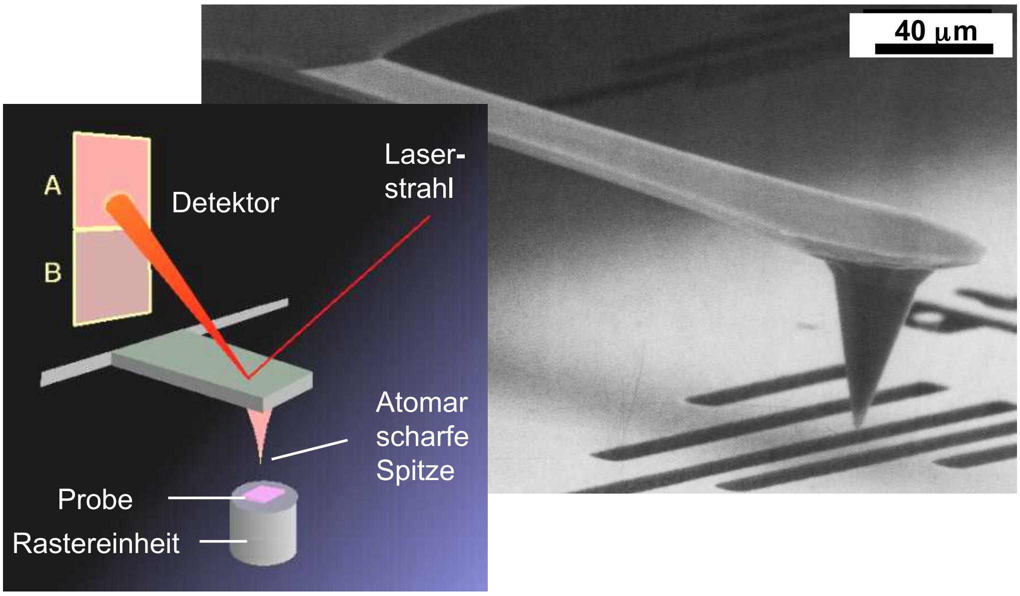
Prinzip des ersten AFMs



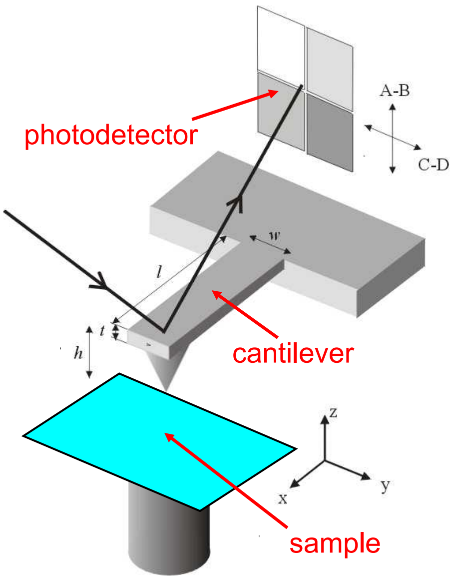
Ablenkungssensoren



„Beam deflection“-Methode

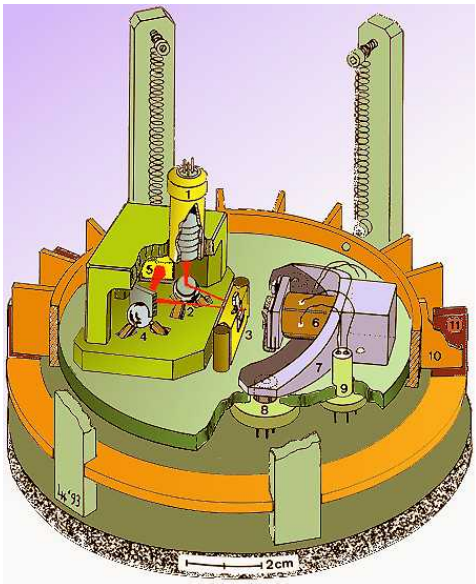


Atomic Force Microscopy (beam defelction)

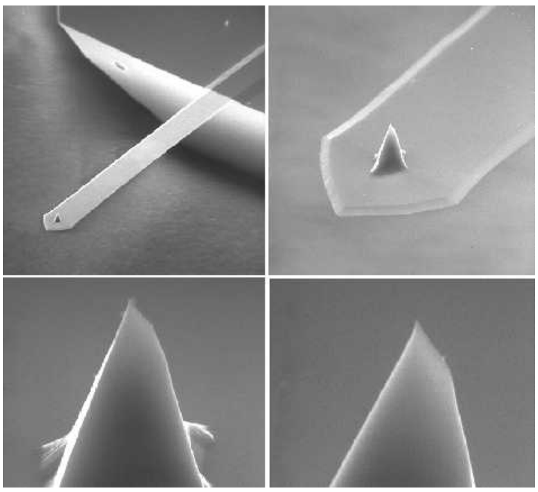


- The normal and lateral forces on a sharp tip sliding on a surface are sensed using a laser beam
- Forces < 1 nN can be measured

Beispiele



Microfabrizierte “Cantilever”



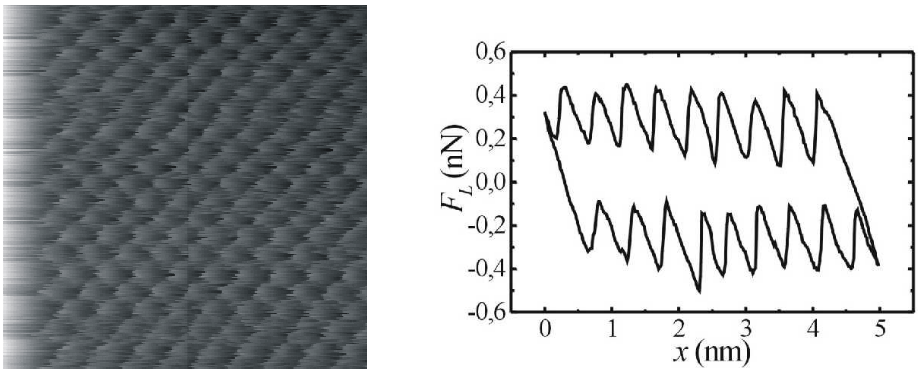
Länge : l = 450 μm
Breite : w = 45 μm
Dicke: t = 1.5 μm
$E=1.69\ 10^{11} N/m^2$

Spitzenhöhe: 12 μm
Spitzenradius: 10 nm

Federkonstante k:

$$k = \frac{Ewt^3}{4l^3} = 0.15\ \mathrm{N/m}$$

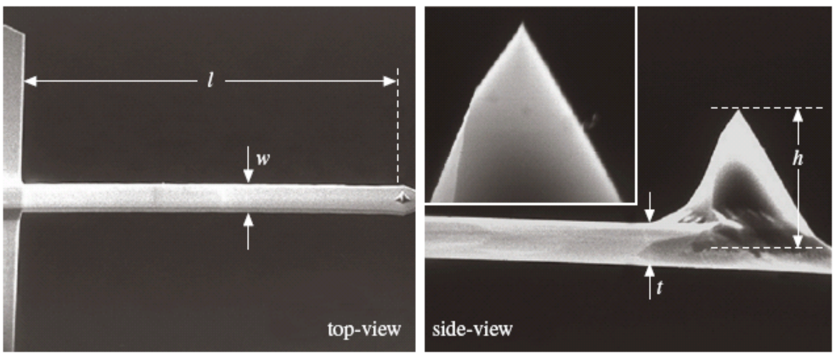
Atomic stick-slip



(friction map and friction loop on NaCl(100) in UHV)

Force Calibration

- Simple if **rectangular** cantilevers are used
- Cantilever width, thickness and length, tip height: from **SEM pictures**



Force Calibration

- Cantilever **thickness** also **from** the **resonance frequency**:

$$t = \frac{2\sqrt{12}\pi}{1.875^2}\sqrt{\frac{\rho}{E}} f_0 l^2$$

- ρ, E: density and Young modulus

(Nonnenmacher et al., JVSTB 1991)

- For pure silicon:

$$\rho = 2.33 \cdot 10^3 \text{ kg/m}^3$$

$$E = 1.69 \cdot 10^{11} \text{ N/m}^2$$

Force Calibration

- **Normal** and **lateral spring constants** of cantilever:

$$c_N = \frac{Ewt^3}{4l^3} \qquad c_L = \frac{Gwt^3}{3h^2 l}$$

- G: shear modulus
- For pure silicon:

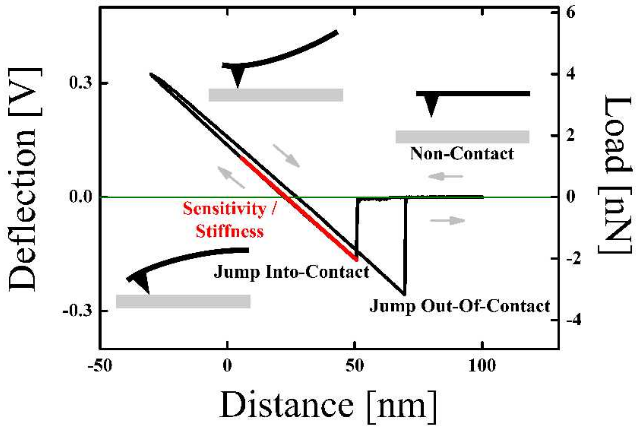
$$\rho = 2.33 \cdot 10^3 \text{ kg/m}^3$$

$$E = 1.69 \cdot 10^{11} \text{ N/m}^2$$

$$G = 0.5 \cdot 10^{11} \text{ N/m}^2$$

Force Calibration

- Next step: **sensitivity of photodetector**
- Force-distance curves on hard surfaces (e.g. Al_2O_3):



- Scanner movement = cantilever deflection
- Slope → sensitivity

Force Calibration

- **Normal** and **lateral forces**:

$$F_N = c_N S_z V_N \qquad F_L = \frac{3}{2} c_L \frac{h}{l} S_z V_L$$

(if the laser beam is above the probing tip!)

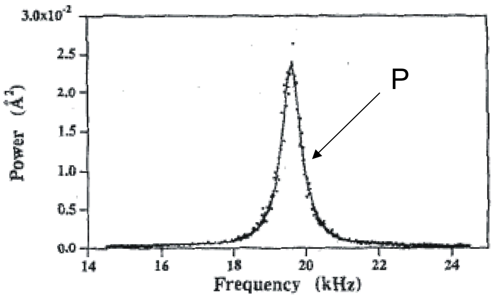
- V_N, V_L: normal and lateral signals

Force Calibration

• Alternative method: Spring constant **from thermal power spectrum** (Hutter et al., RSI 1993)

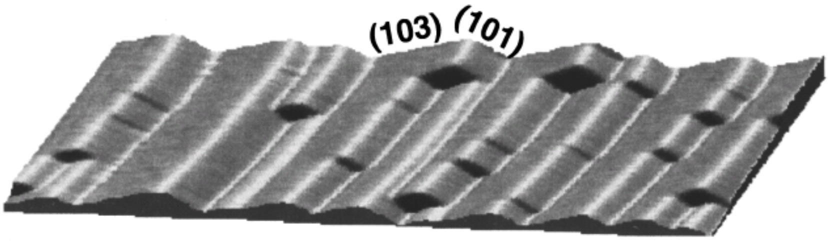
• Correct relation (Butt et al., Nanotech. 1995):

$$c_N = \frac{4k_B T}{3P}$$

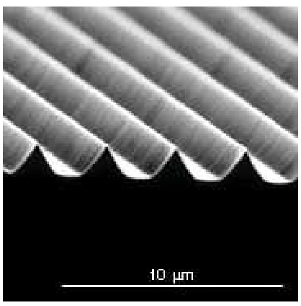


Force Calibration

• Alternative method: Scanning over profiles with **well-defined slope** (Ogletree et al., RSI 1996)



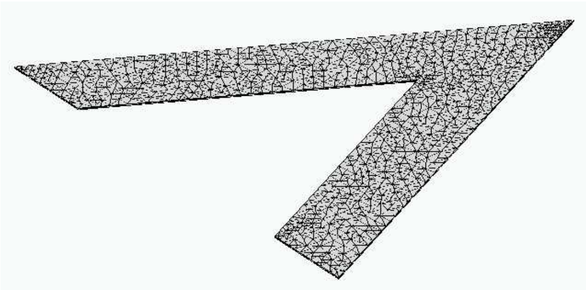
Commercially available grating:

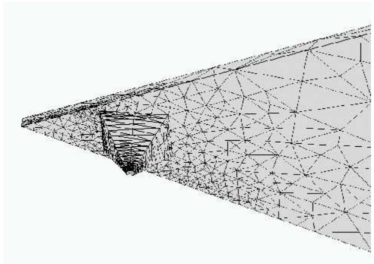


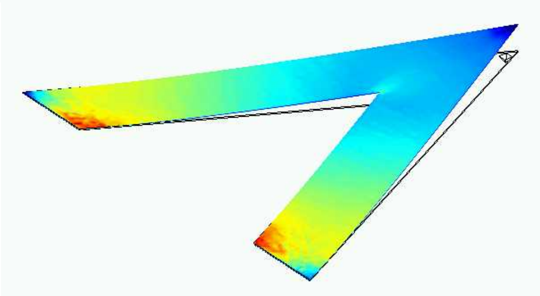
(TGG01, NT-MDT, Moscow)

Force Calibration

• Different shapes → **Finite elements analysis**



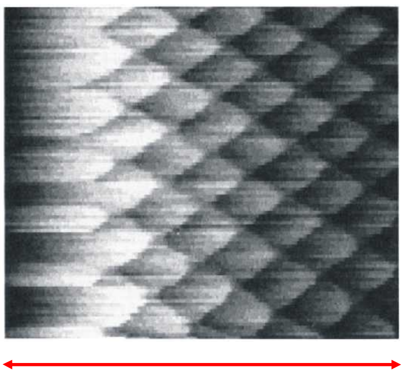




(Femlab™ 3.0)

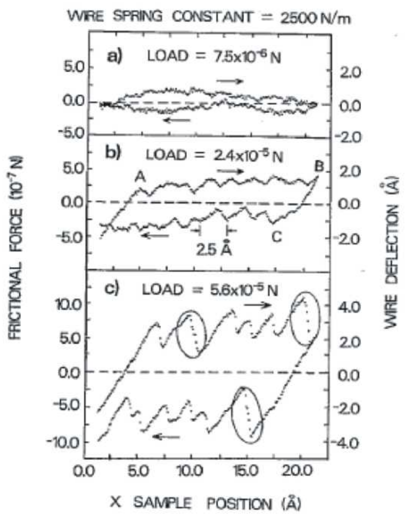
Atomic-Scale Measurements

• Atomic friction on **graphite**:



2 nm

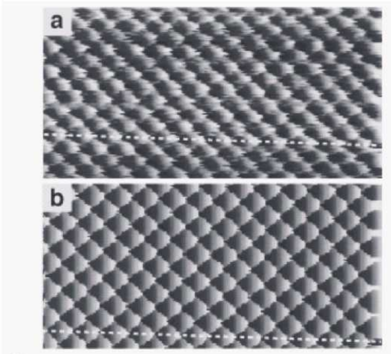
(Mate at al., PRL 1987)



Atomic-Scale Measurements

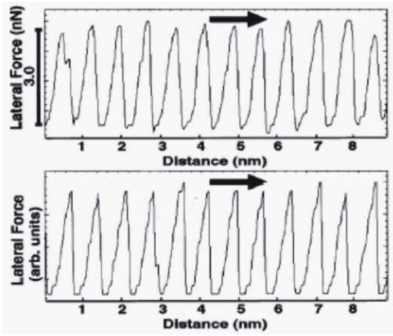
- Friction on **insulating surfaces** (Lüthi et al., JVSTB 1996):

KBr



Exp

Theo

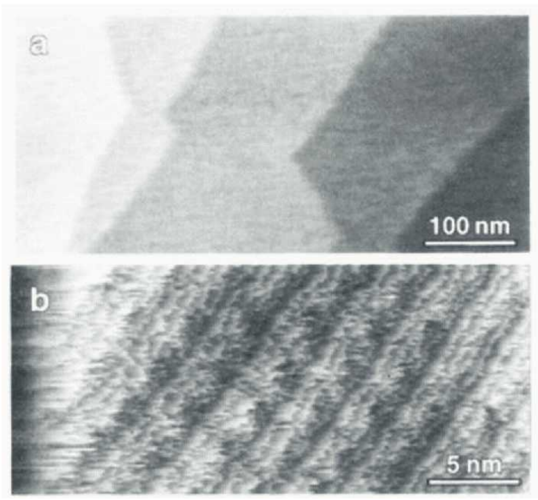


- No individual defects are observed

Atomic-Scale Measurements

- Friction on **semiconductors** (Howald et al., PRB 1995):

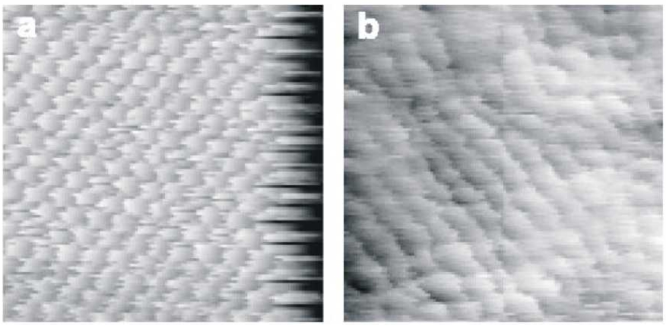
Si(111)7x7



(tip coated with PTFE)

Atomic-Scale Measurements

• Friction on **metal surfaces** (Bennewitz et al., Trib. Lett. 2001):

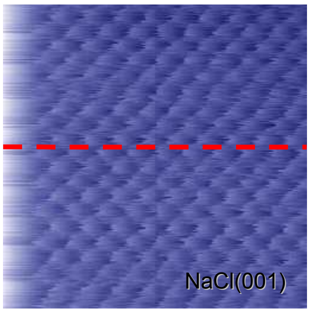


Cu(111) Cu(100)

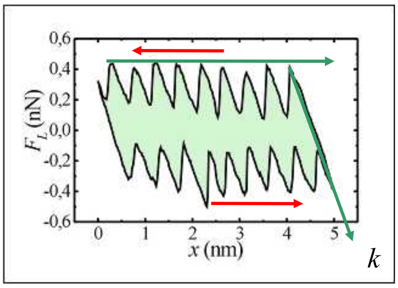
Irregular features on the (100) surface (less packed!)

Atomic friction on crystal surfaces

Our model systems: alkali halide surfaces (easy preparation, simple structure)

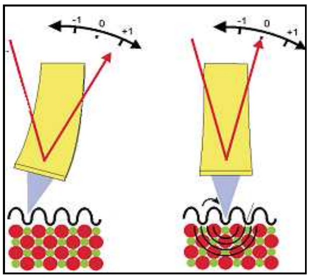


5 nm



$$F_L^{max} = \frac{2\pi V_0}{a}$$

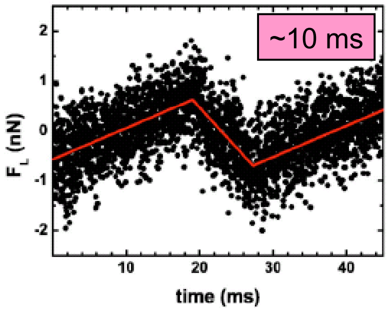
Tomlinson model:
(Phyl. Mag. 1929)

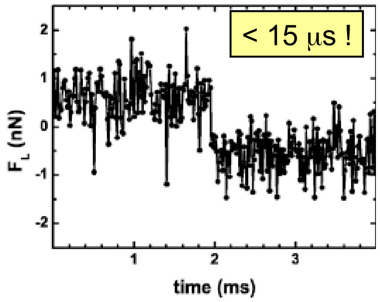


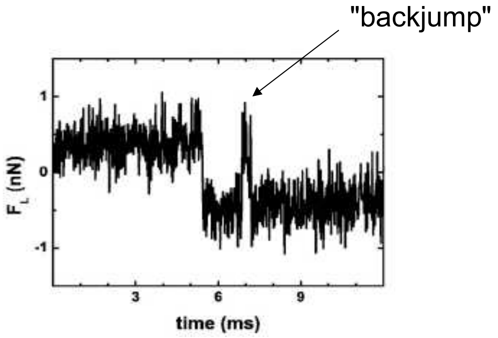
$$V_0 \sim 1\,\text{eV}$$
$$k \sim 1\,\text{N/m}$$

Atomic-Scale Measurements

• Wide distribution of slip durations:







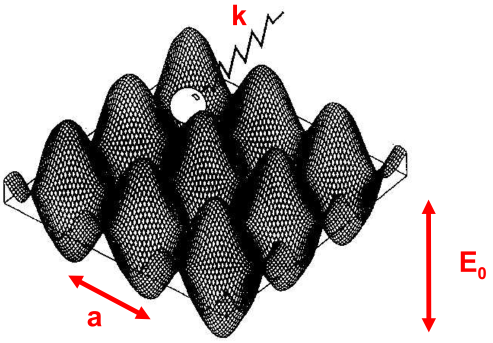
Why?

Modelling Atomic Friction

• The tip is subject to

1) periodic interaction with the underlying surface

2) elastic deformation of the cantilever



• In 1D the corresponding potential energies are represented by

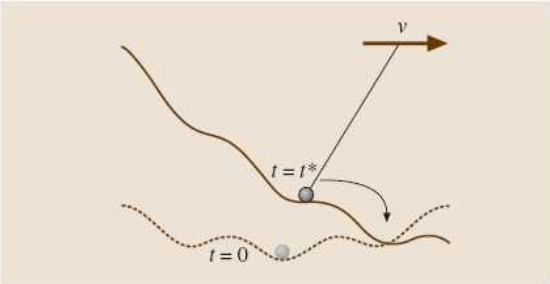
1) a sinusoid

2) a parabola

Modelling Atomic Friction

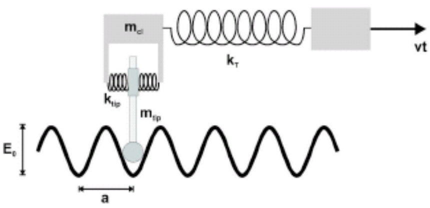
- Total energy of the system:

$$U_{\text{tot}}(x,t) = -\frac{E_0}{2}\cos\frac{2\pi x}{a} + \frac{1}{2}k_{eff}(vt - x)^2$$



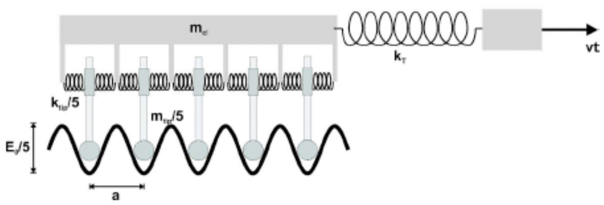
- The tip can "stick" to the minima of the potential profile

Modelling Atomic Friction



single contact

multiple contact

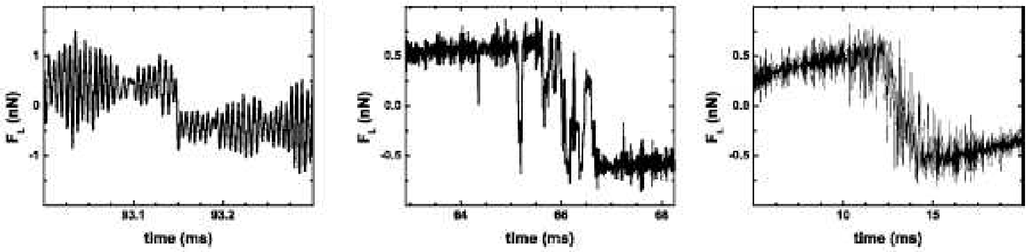


Modelling Atomic Friction

• Tip → Langevin equation (including thermal noise)

• Cantilever → Newton equation (without thermal noise)

One tip **Three tips** **Five tips**

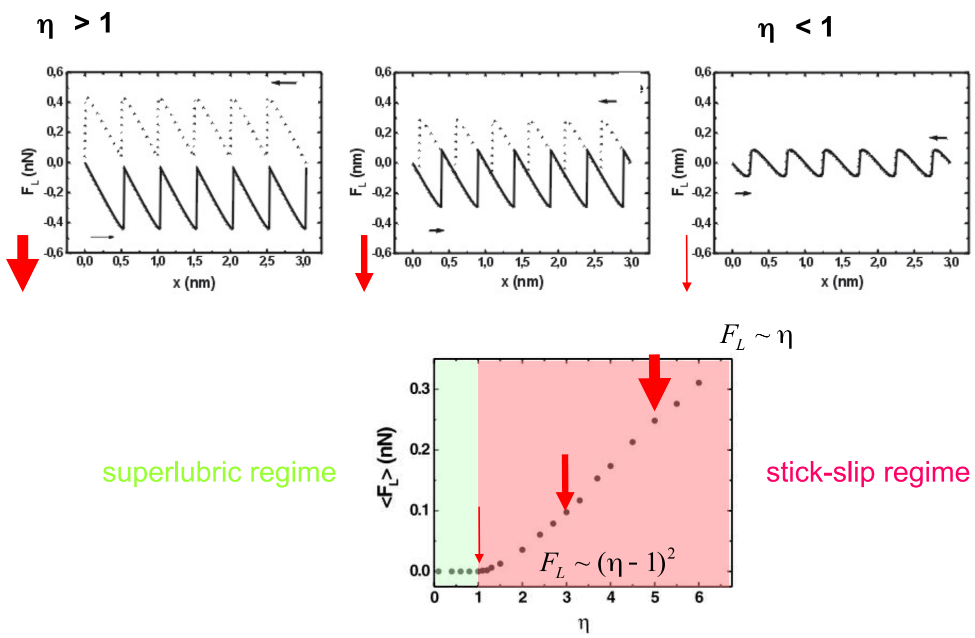


• Long slip times are found with multiple tips only

(Maier et al., PRB 2005)

Superlubricity

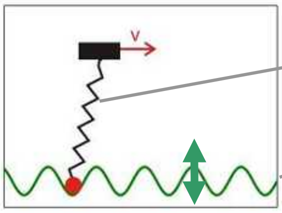
• From the Tomlinson model (without thermal activation):



A. Socoliuc et al., Phys. Rev. Lett. 92 (2004) 134301

"Dynamic superlubricity"

A third way to reduce friction: Tomlinson model with TIME modulation



$$V_{elas} = \frac{ka^2}{2}$$

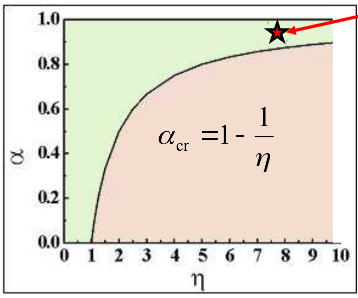
$$V_{int} = V_0 \cos\frac{2\pi x}{a}$$

$$\eta = \frac{(2\pi)^2 V_0}{ka^2}$$

$$V_0 \rightarrow V_0(1 + \alpha\cos\omega t)$$

$$\eta_{eff} = \eta(1 - \alpha)$$

Phase-diagram in the η-α plane:

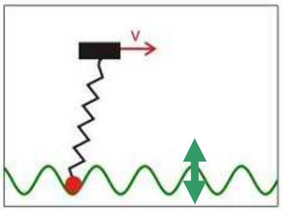


High loads can be applied!

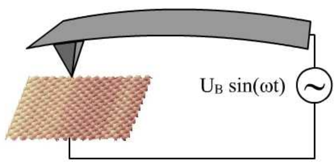
E. Gnecco et al., J. Phys.: Condens. Matt. a20 (2008) 354004

"Dynamic superlubricity"

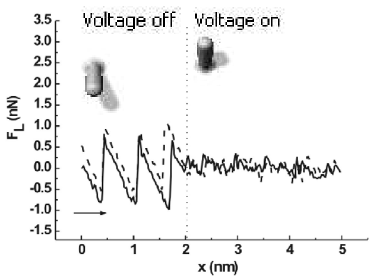
A third way to reduce friction: Tomlinson model with TIME modulation

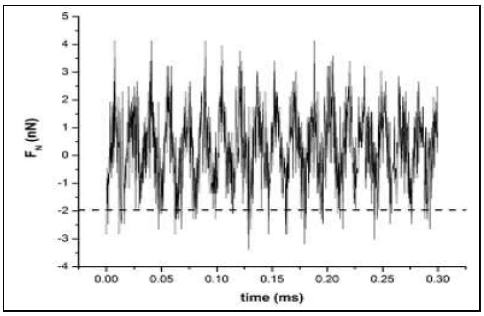


AC actuation of the nanocontact:



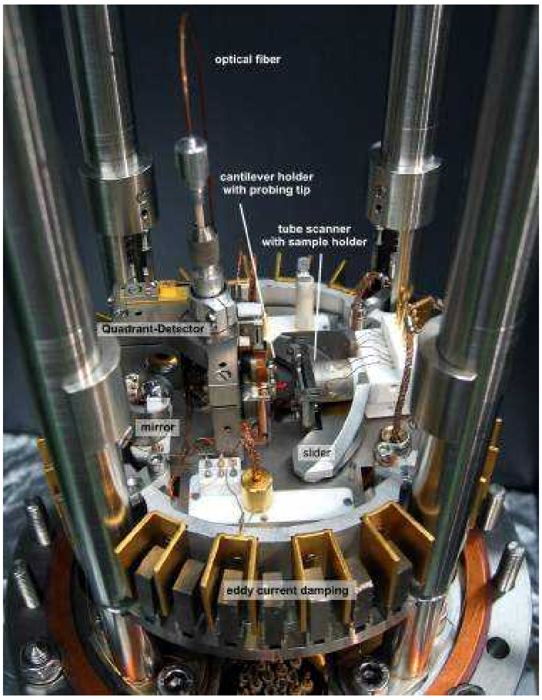
NaCl(001)





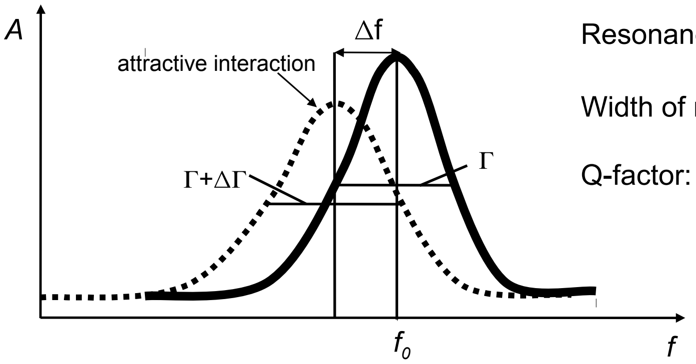
A. Socoliuc et al., Science 313 (2006) 207

Noncontact-AFM (nc-AFM)



- UHV: Base pressure below 1×10^{-10} mbar
- Operation at room temperature
- Mixed mode: AFM/STM
- Beam deflection method
- Bandwidth of the photodetector: 3MHz
- Evaporation of molecules from a k-cell kept at 165ºC or 170ºC

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

Forces in nc-AFM

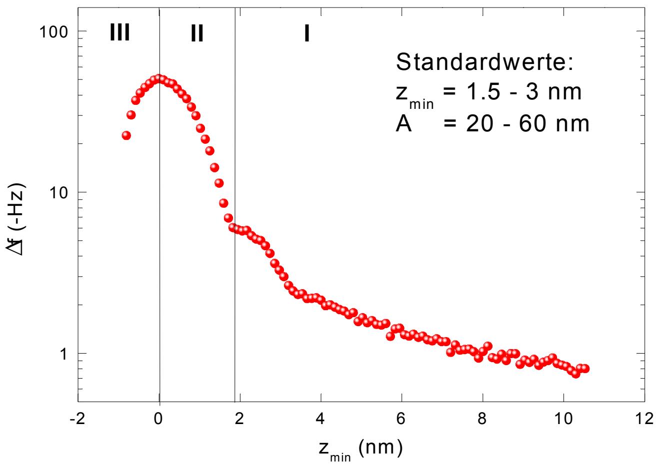
Frequency modulation: $f_0 = \frac{1}{2\pi}\sqrt{\frac{k}{m^*}}$ $\quad \Delta f = -\frac{f_0}{2k}\frac{\partial F_{tot}}{\partial z}$

⇒ 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

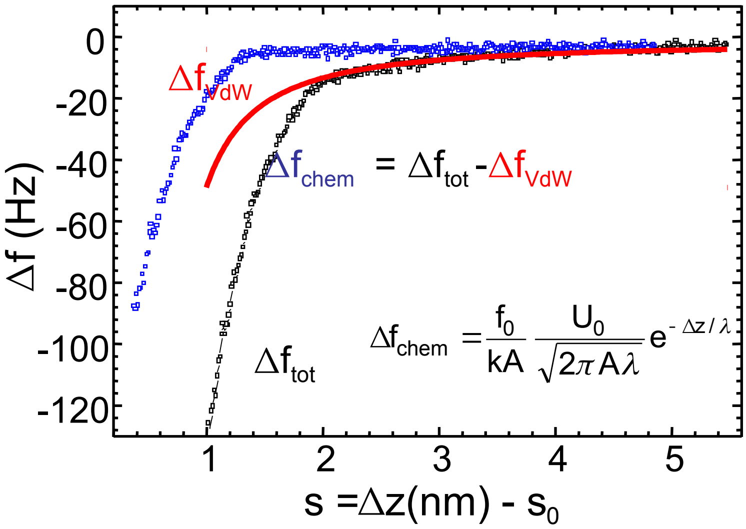


region I:
attractive forces
non-contact mode

region II:
attractive forces
atomic resolution

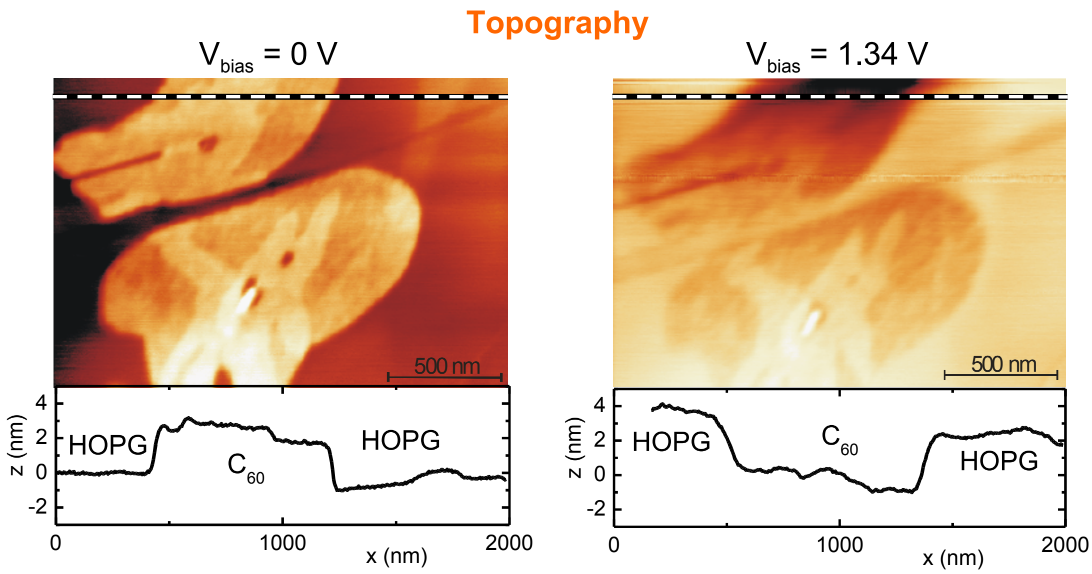
region III:
repulsive forces
tapping mode

Short range interaction



λ = 0.35 nm
U_0 = -4.7 eV
s_0 = 0.45 nm

inhomogeneous sample: HOPG + ½ monolayer C60

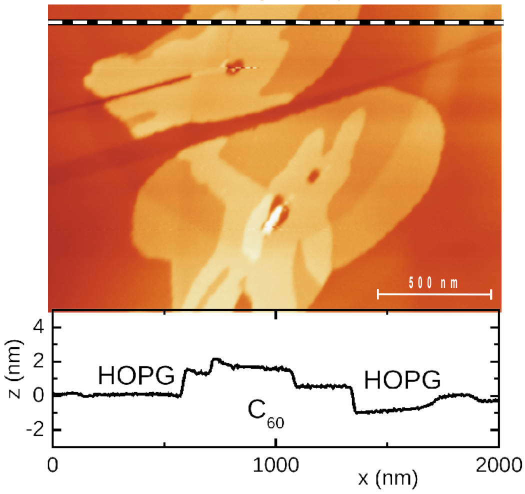


→ **contrast inversal: HOPG ↔ C_{60}**

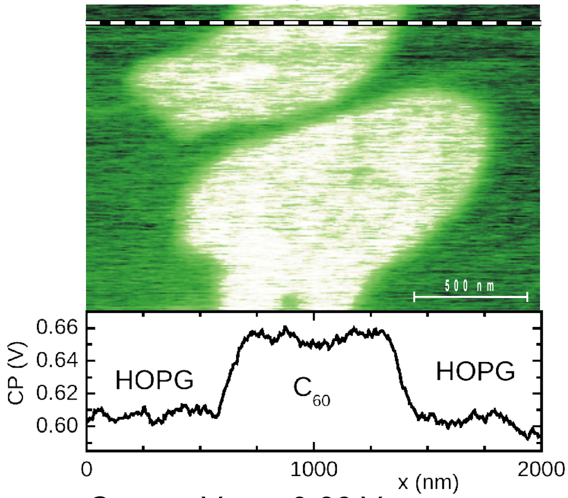
S. Sadewasser et al., PRL 91 266101 (2003)

inhomogeneous sample: HOPG + ½ monolayer C60

topography



contact potential



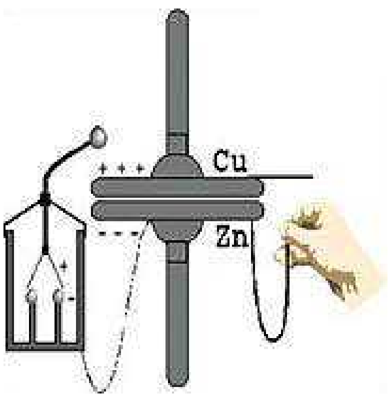
HOPG: $V_{CP} \cong 0.61$ V

C_{60}: $V_{CP} \cong 0.66$ V

⇒ NC-AFM: residual electrostatic force for fixed V_{bias}

Makroskopische Kelvin-Sonde

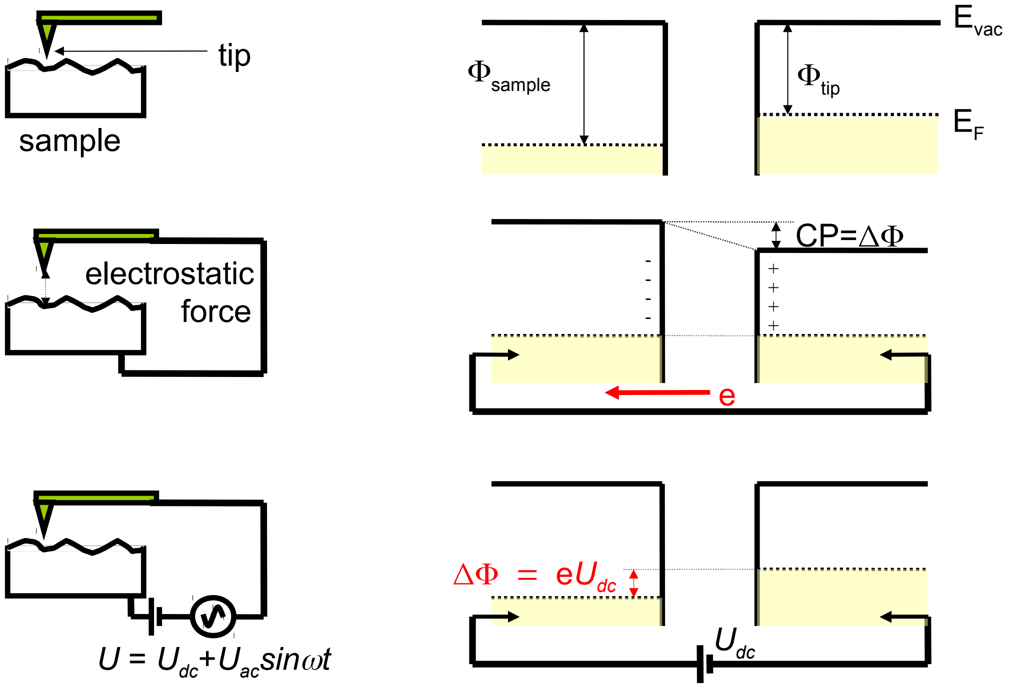
Lord Kelvin 1861



Verschiebestrom

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

Kelvin Principle



Electrostatic Forces in nc-AFM

$$F_{el} = - \frac{1}{2} \frac{\partial C}{\partial z} V_{eff}^2 \quad \Rightarrow \quad F_{el} = - \frac{1}{2} \frac{\partial C}{\partial z} (V_{bias} - V_{CP})^2$$

$$V_{CP} = 1/e \cdot (\Phi_{tip} - \Phi_{sample})$$

contact potential

Φ - work function

apply bias: $V_{bias} = V_{dc} + V_{ac} \cdot \sin(\omega t)$

Kelvin Probe Force Microscopy

$$F_{el} = -\frac{1}{2}\frac{\partial C}{\partial z}V_{eff}^2 = F_{dc} + F_{\omega} + F_{2\omega}$$

$$F_{dc} = -\frac{\partial C}{\partial z}\left[\frac{1}{2}(V_{dc} - V_{CP})^2 + \frac{V_{ac}^2}{4}\right]$$

$$F_{\omega} = -\frac{\partial C}{\partial z}(V_{dc} - V_{CP})V_{ac}\sin(\omega t)$$

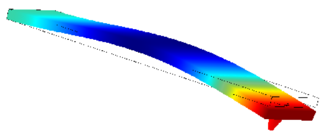
$$F_{2\omega} = \frac{\partial C}{\partial z}\frac{V_{ac}^2}{4}\cos(2\omega t)$$

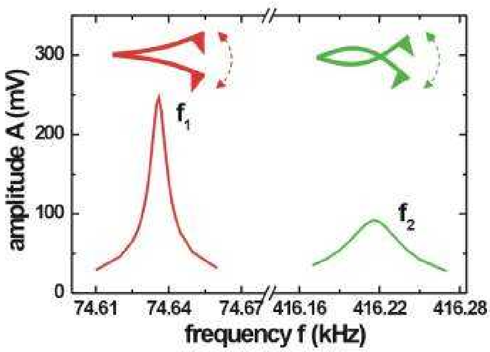
AM-KPFM
Amplitude Modulation

FM-KPFM
Frequency Modulation

AM – KPFM
Amplitude Modulation Detection

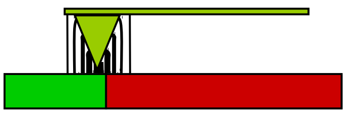
$$F_{\omega} = -\frac{\partial C}{\partial z}(V_{dc} - V_{CP})V_{ac}\sin(\omega t)$$



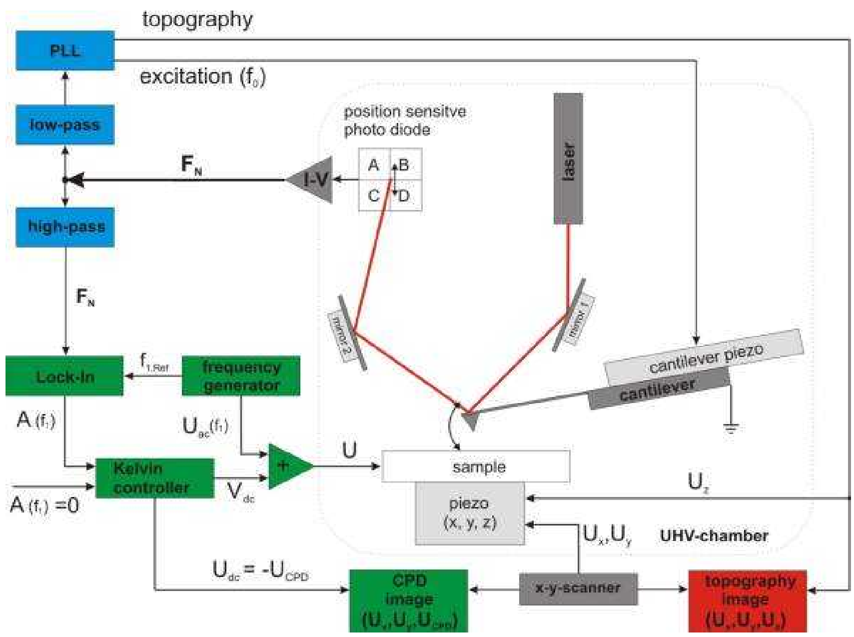


- tune ω to the second resonance f_2
- detection of the oscillation amplitude A_{ω} with a lock-in
- limiting factor: bandwidth of the photodiode

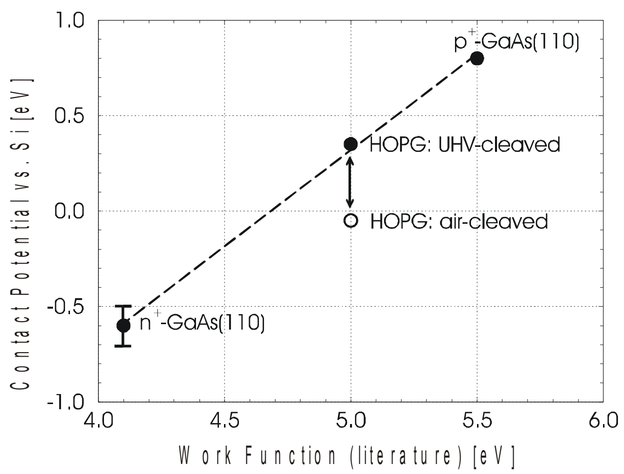
$A_{\omega} \propto F_{\omega}$



Experimental Setup
nc-AFM & AM-KPFM



KPFM calibration and absolute work function



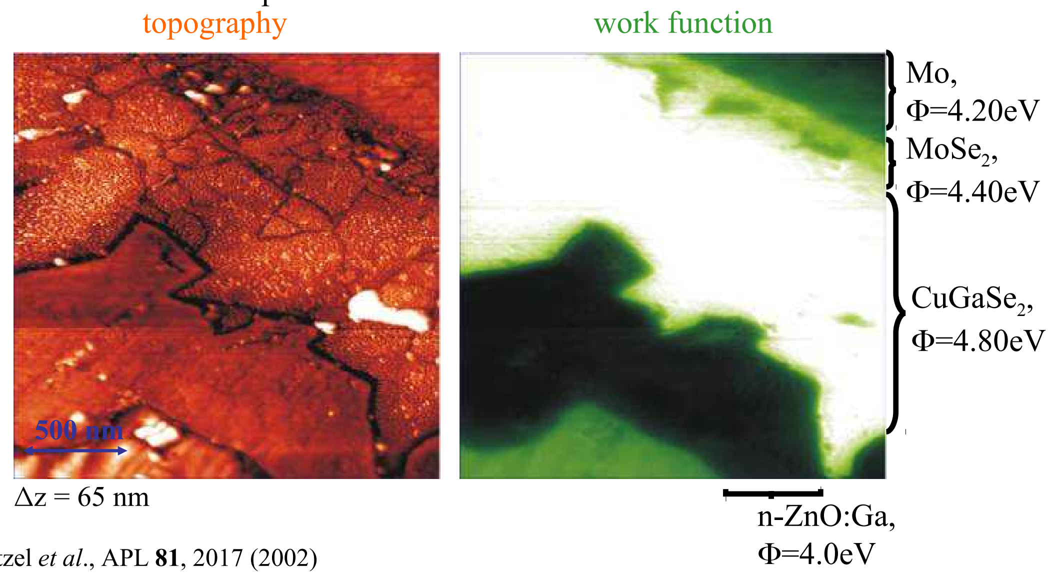
Φ-Si-Cantilever = 4.70 (±0.1) eV **U_{ac} = 100 mV**

→ absolute and quantitative work function determination

Polished Cross Section of a $CuGaSe_2$ Solar Cell

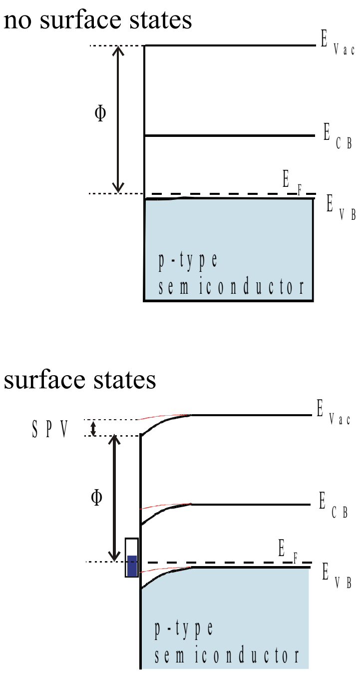
$CuGaSe_2$ solar cell device: V_{oc} = 820 mV, η = 4.6 %

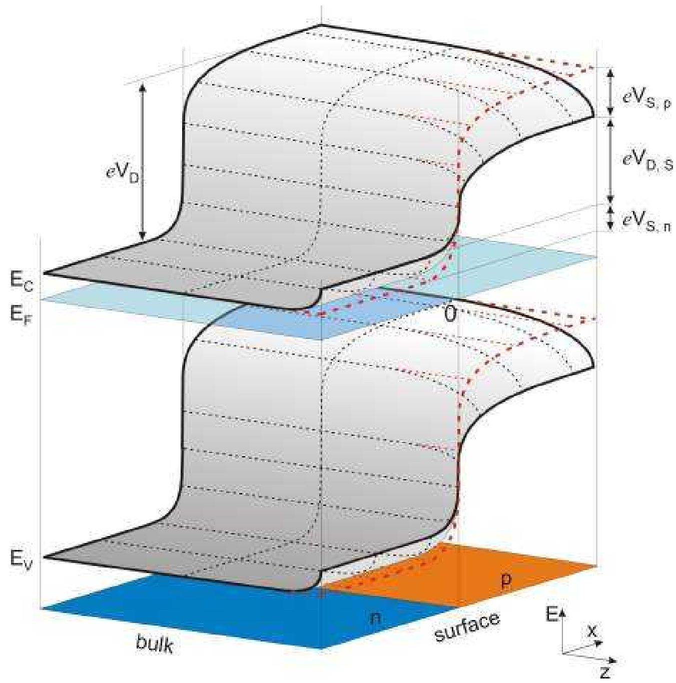
polished and Ar-ion sputtered cross section



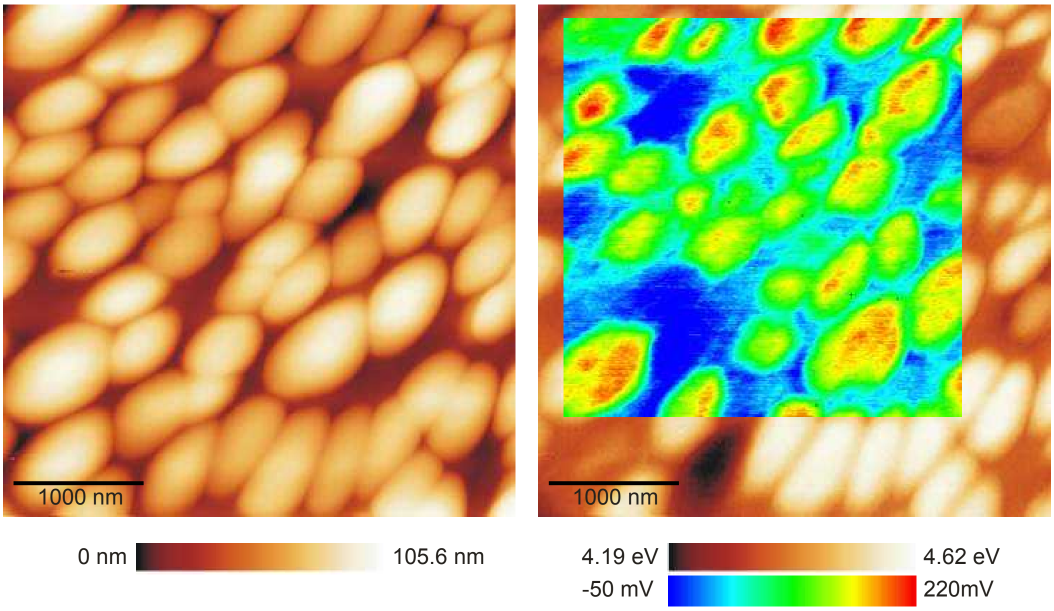
Glatzel *et al.*, APL **81**, 2017 (2002)

Surface Effects

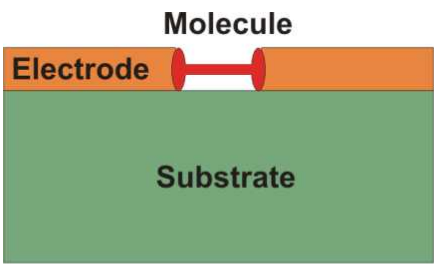


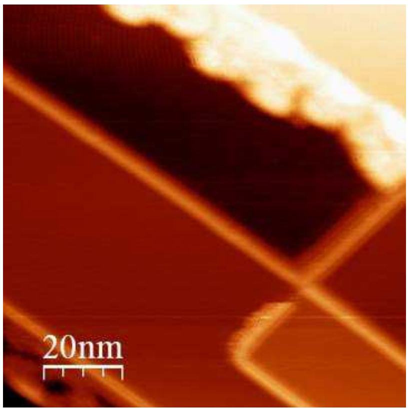


Surface Photovoltage
MDMO-PPV/PCBM – 675nm



Motivation
Molecular electronics



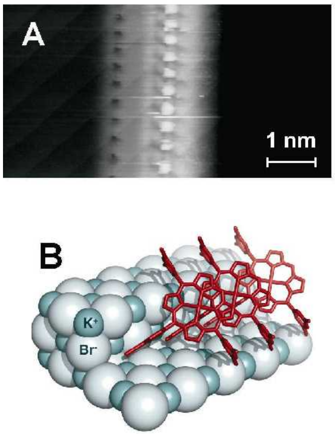


Molecules on Insulators:

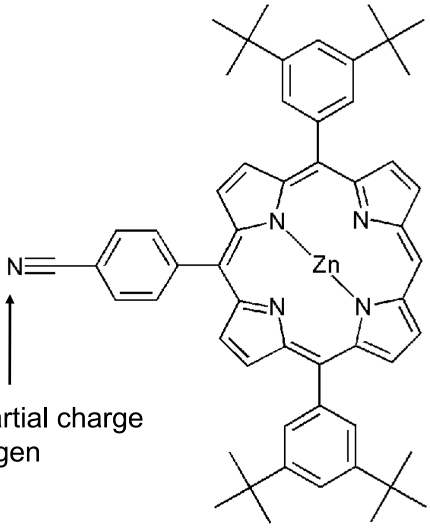
- No STM possible – nc-AFM mandatory
- Low diffusion barrier but high intermolecular interaction
- Low temperatures – easier to “fix” molecules but not so easy to find applications

Asymmetric Cyano-Porphyrins

Natural light harvesting complexes



S. Meier et al., Small, 2008, 4, 1115



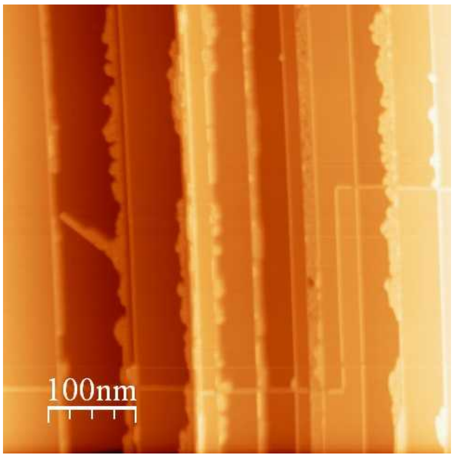
Negative partial charge on the nitrogen

Balaban et al., *Acc. Chem. Res.* **2005**, 38, 612 – 623

Wire Formation

Decoration of step edges on KBr(100)

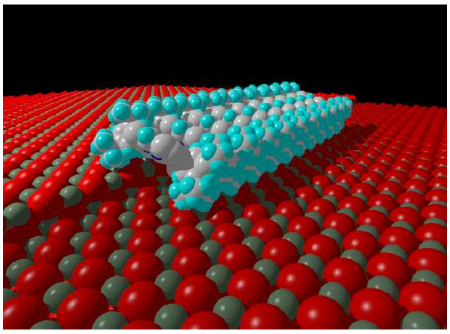
- In situ cleaved KBr with 0.5 ML of molecules
- Steps (< 1nm) are decorated with monowires
- Higher steps act as nucleation sites for structure growth across terraces

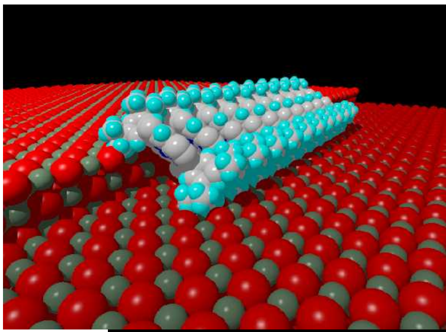


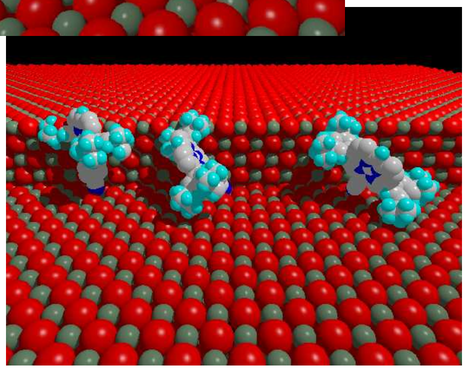
L. Zimmerli et al., J. Phys.: Conf. Ser., 2007, 61, 1357

Wire Formation

Structural model



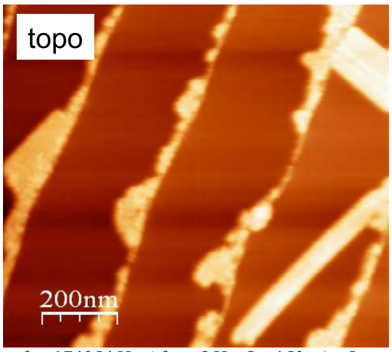




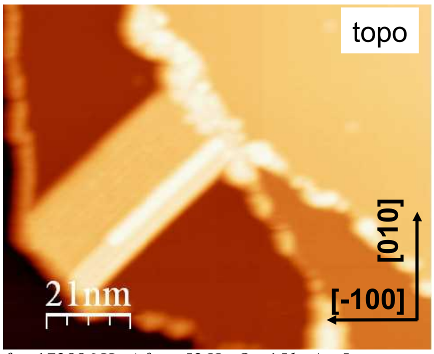
- The tilt angle of the molecules is determined by the side groups, the π-π stacking and the step height.
- Steps higher than 3 ML prevent a π-π stacking.

Molecular Assemblies

Multiwires on KBr



$f_0 \approx 174054 Hz, \Delta f = -8 Hz, Q = 15k, A = 5nm$

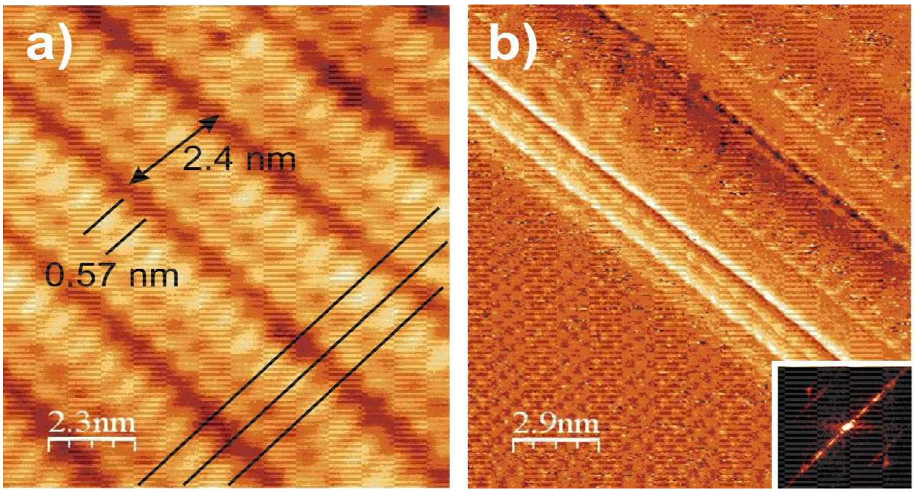


$f_0 \approx 173886 Hz, \Delta f = -52 Hz, Q = 15k, A = 5nm$

- Multiwire growth across terraces
- The <110> directions are clearly preferred
- Different heights are visible

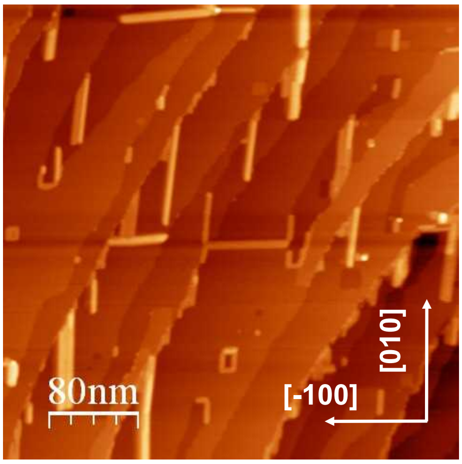
S. Meier et al., Small, 2008, 4, 1115

Molecular Assemblies
High resolution imaging

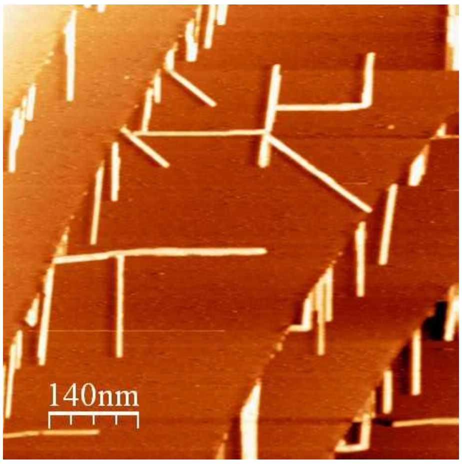


S. Meier et al., Small, 2008, 4, 1115

Molecular Assemblies
Molecular wires on NaCl



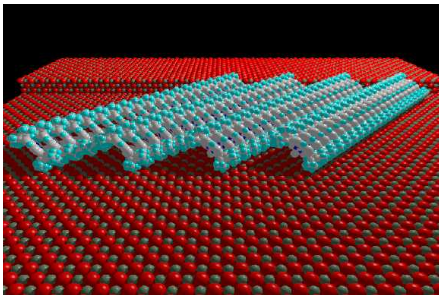
$f_0 \approx 170992Hz, \Delta f = -9.5Hz, Q = 15k, A = 40nm$

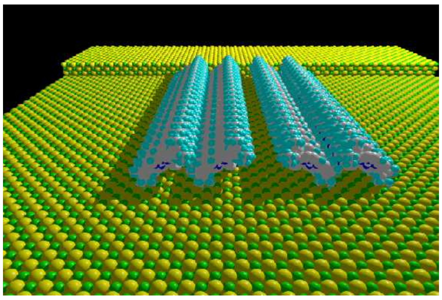


$f_0 \approx 170992Hz, \Delta f = -11Hz, Q = 15k, A = 40nm$

Molecular Assemblies

Structural model

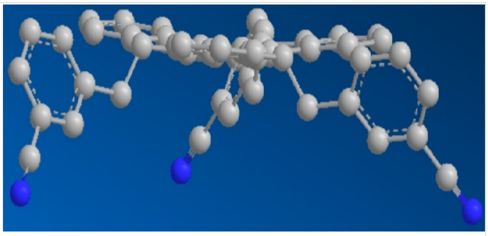


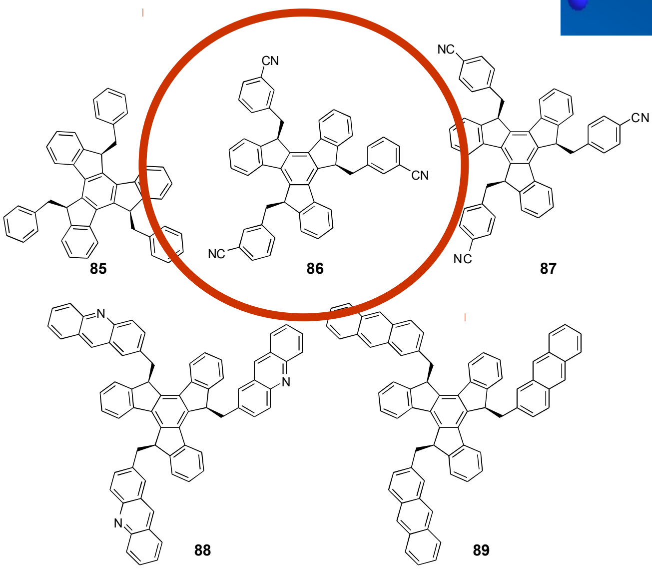


- Intermolecular equilibrium separation ~ 5.7 Å
- Directed growth by the substrate

Functionalized Truxenes

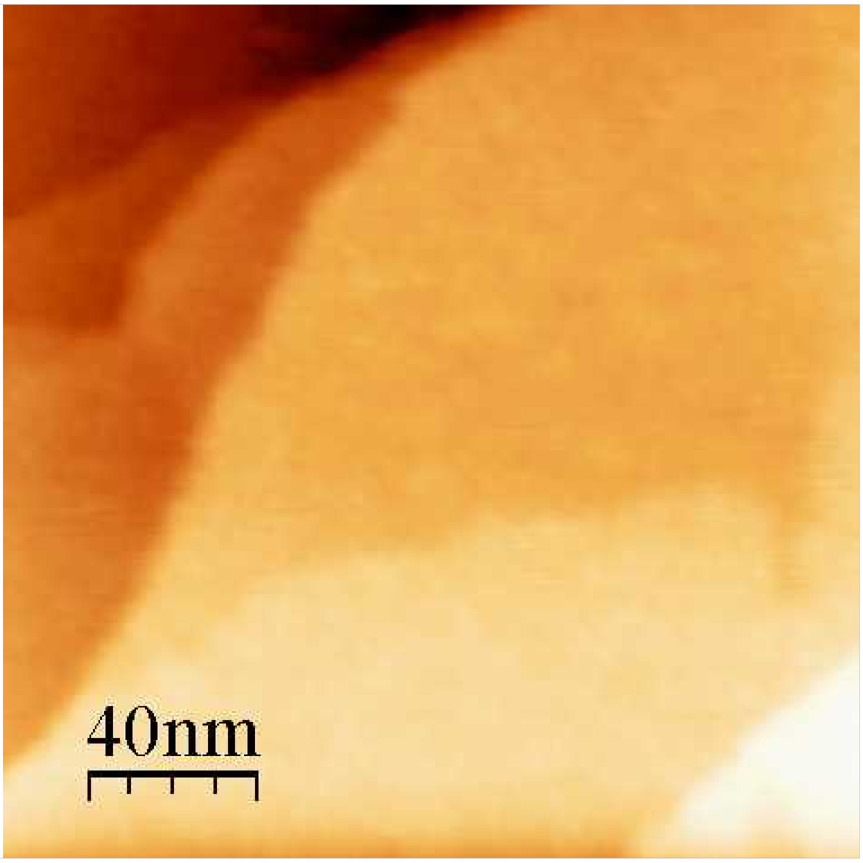
Structure



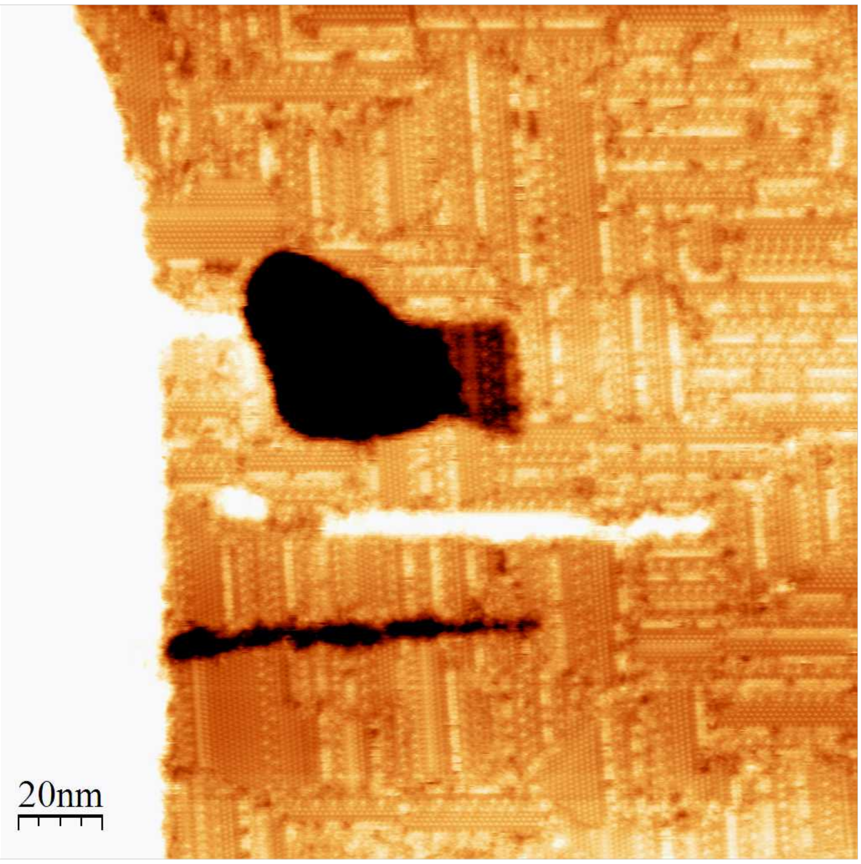


O. de Frutos et al., Chem. Eur. J. 8(13), 2879 (2002)

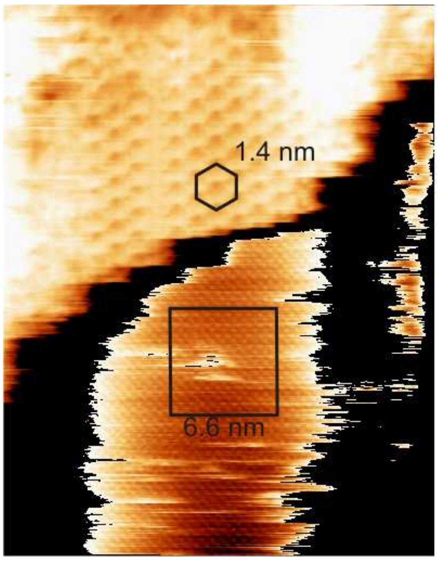
evaporation onto
the sample at RT

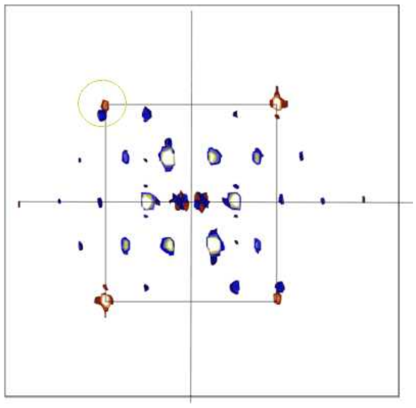


and the result of
post annealing at
155 C for 15 mins

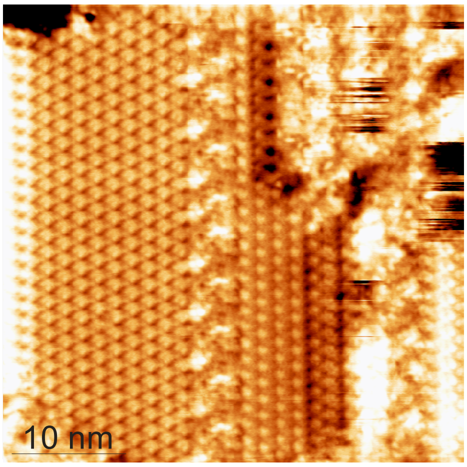


Truxene Self Assemblies
Hexagonal coordination on KBr

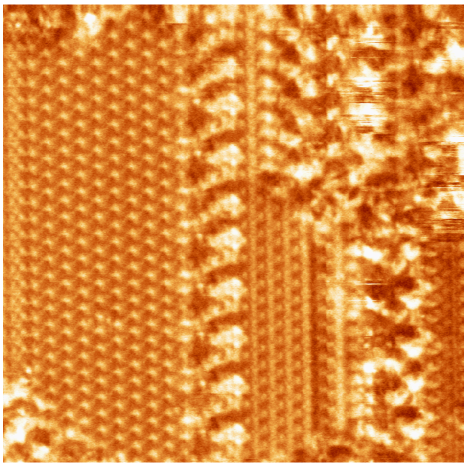




Truxene Self Assemblies
Various distinct structures



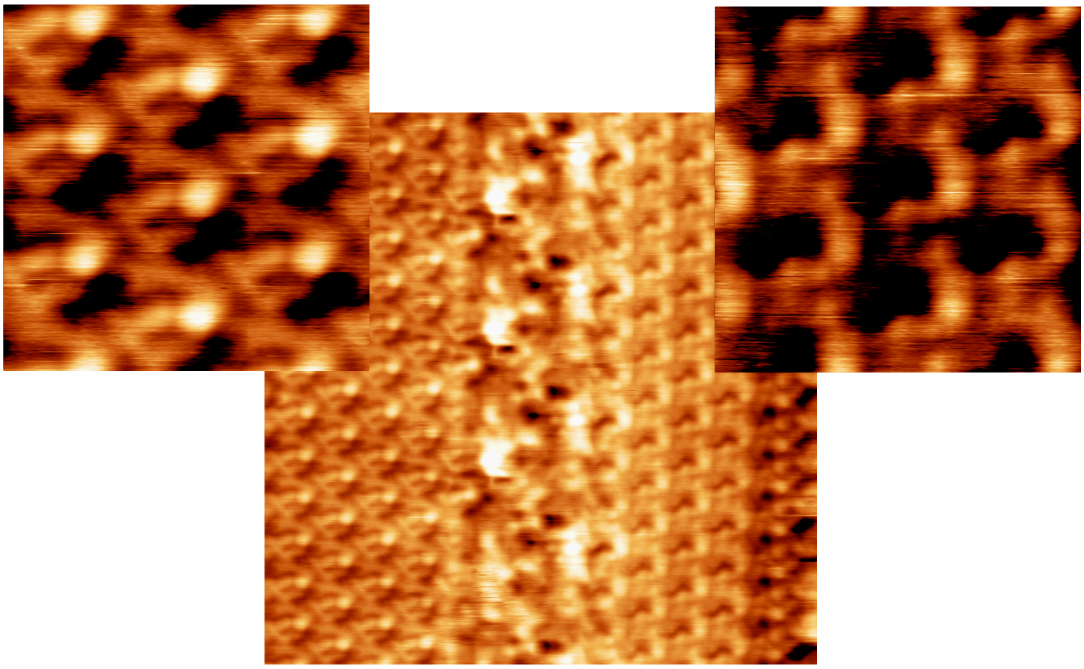
topography



dissipation

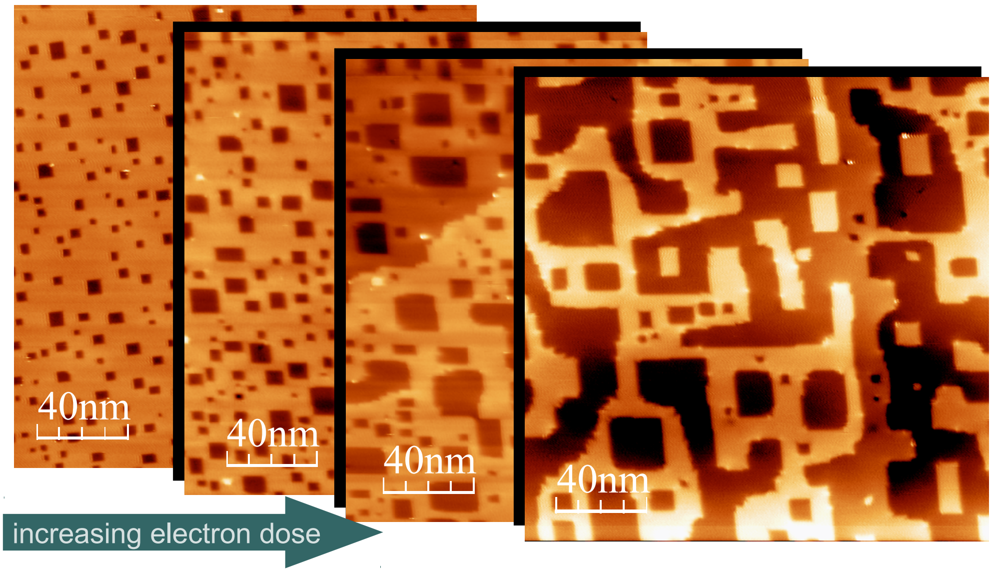
Truxene Self Assemblies

Heigh resolution measurements



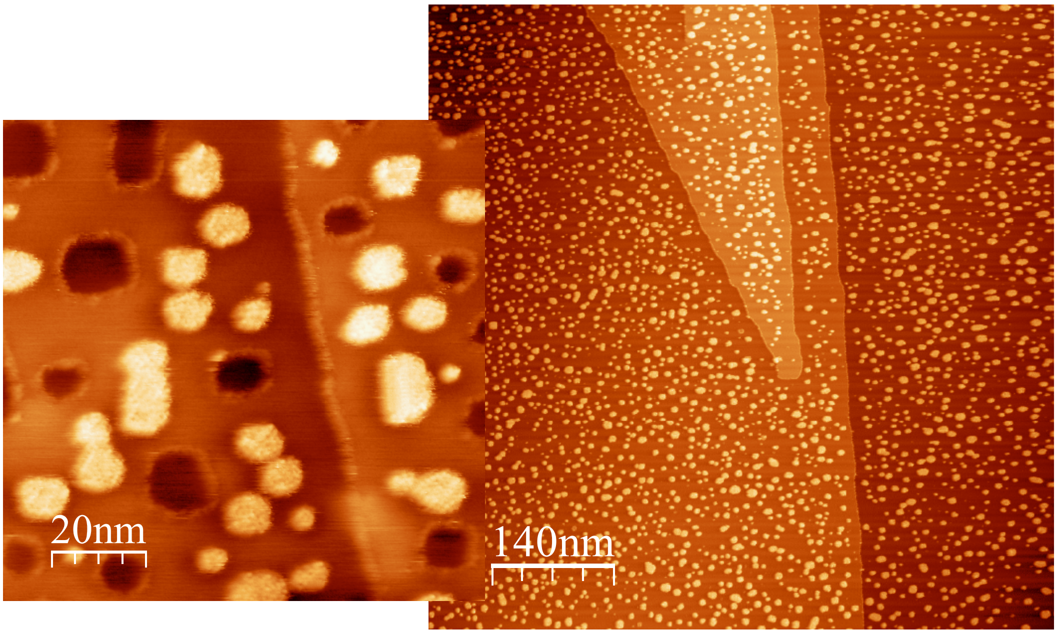
Single Crystal KBr

Substrate patterning by electron irradiation



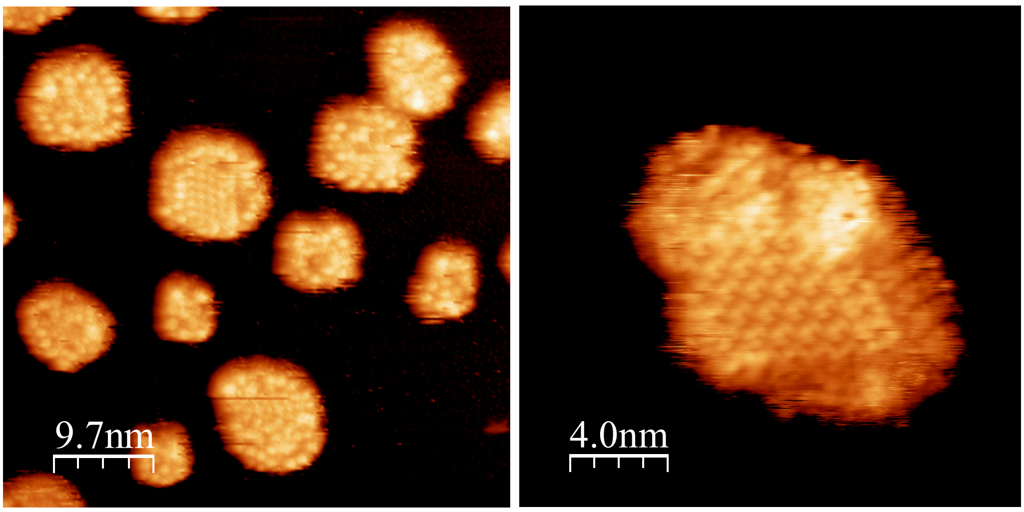
Truxenes on patterned surface

Filled and unfilled pits



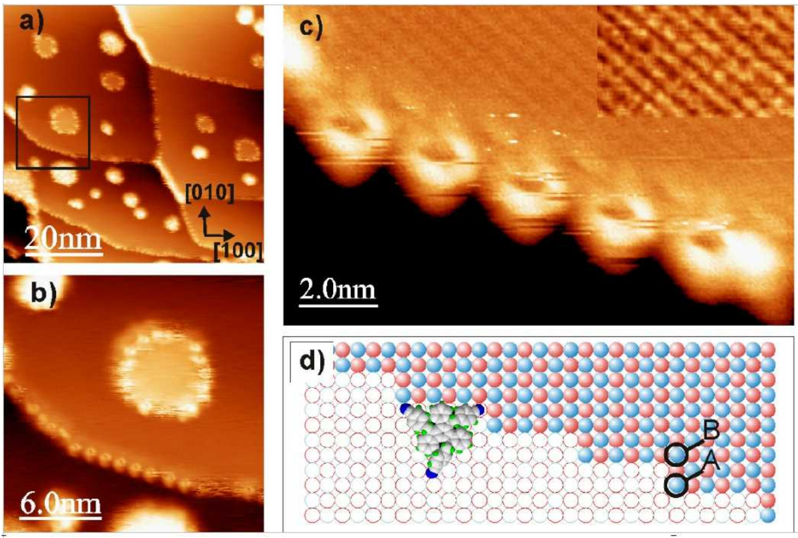
Truxenes on patterned surface

Organization within the pits



Imaging a Single Molecule

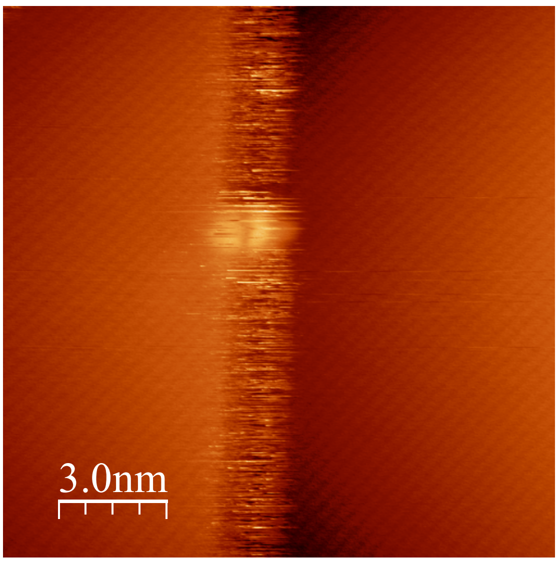
Measurements at RT



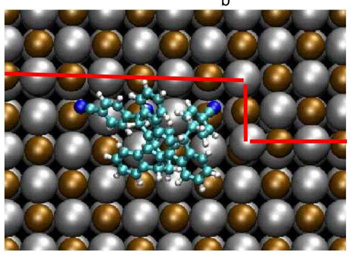
- Re-arrangement of the substrate, edges are running in the [-3 1 0] direction
- no chemical interaction with the surface
- adsorbed on K or Br terminated double atomic kink

Imaging a Single Molecule

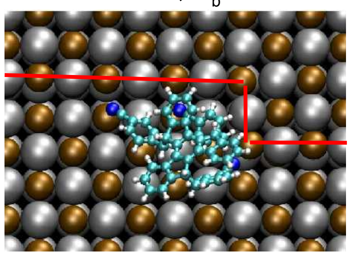
Measurements at RT



Br terminated, E_b=1.33eV

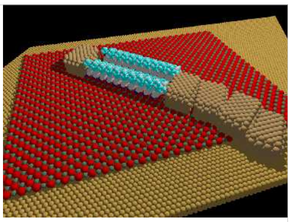


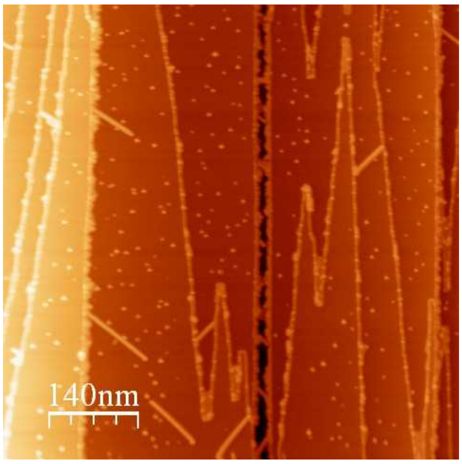
K terminated, E_b=1.17eV

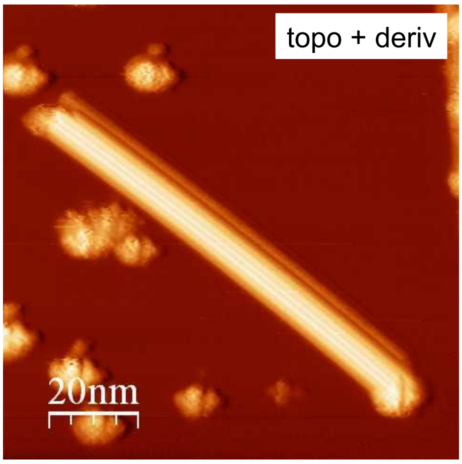


Contacting Molecular Assemblies

Au-Molecules-Au







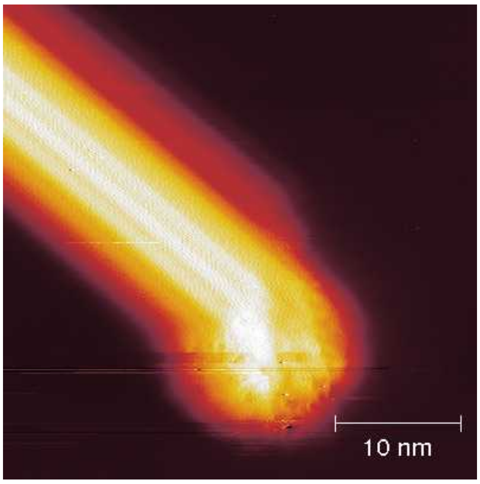
- Molecules arrange at steps and across terraces
- The growth is started/stopped at gold clusters.

Glatzel et al., Appl. Phys. Lett., **2009**, 94, 063303

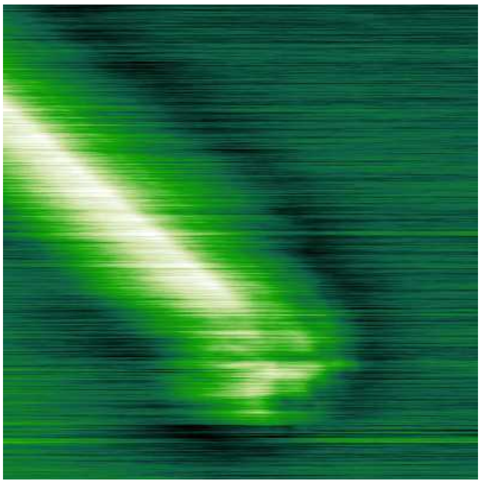
Contacting Molecular Assemblies

KPFM

Topography



LCPD

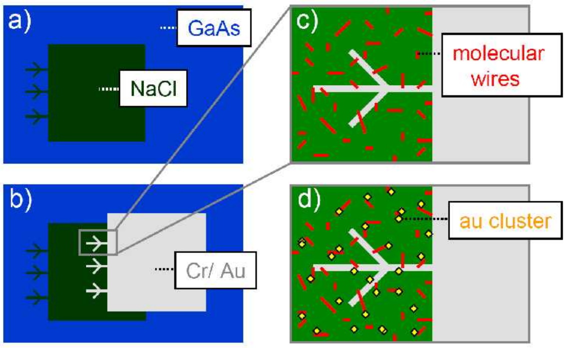


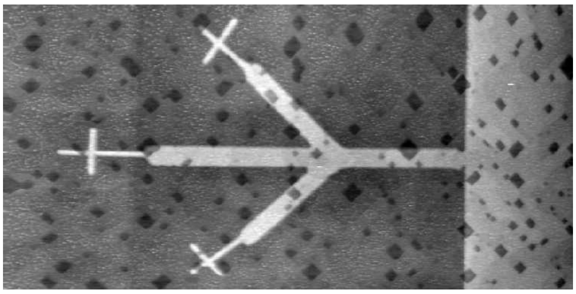
LCPD= -0.5...0.2eV

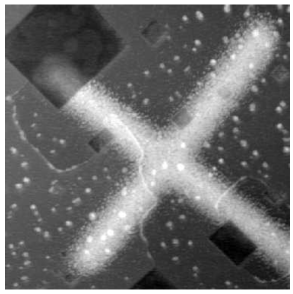
Glatzel et al., Appl. Phys. Lett., **2009**, 94, 063303

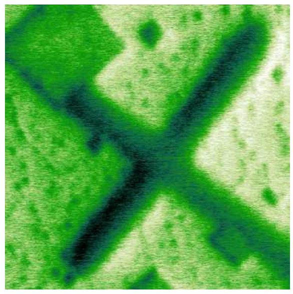
Contacting Molecular Assemblies

Nanostencil (IBM Rüschlikon)



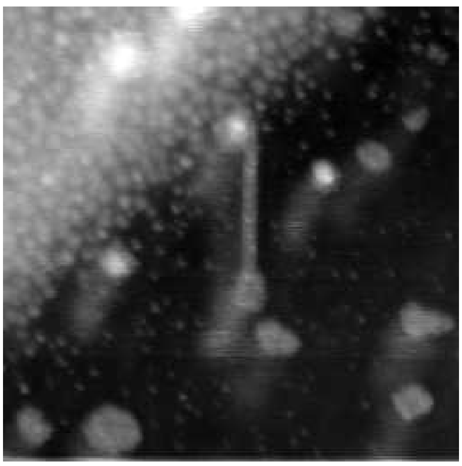




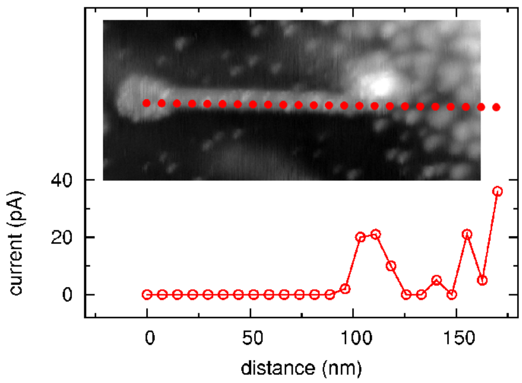


Contacting Molecular Assemblies

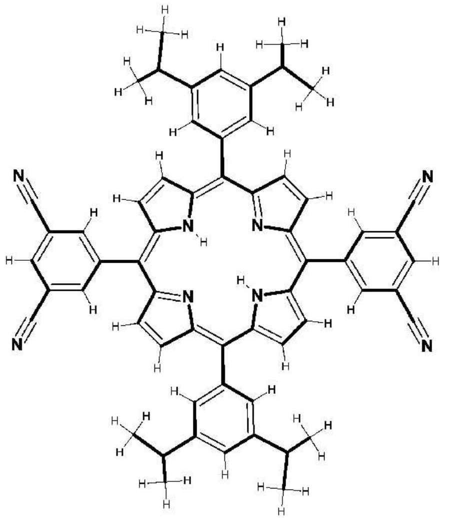
Nanostencil (IBM Rüschlikon)



$300x300nm^2$

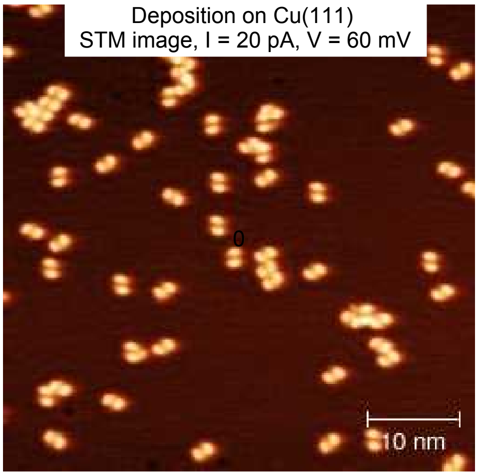


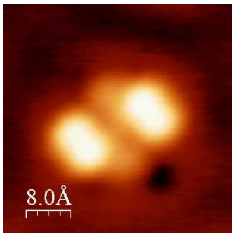
Porphyrin with bicyanophenyl legs



2-bicyanophenyl, 2-aryl H2-porphyrin
synthesized by F. Diederich (ETH, Zurich)

Deposition on Cu(111)
STM image, I = 20 pA, V = 60 mV

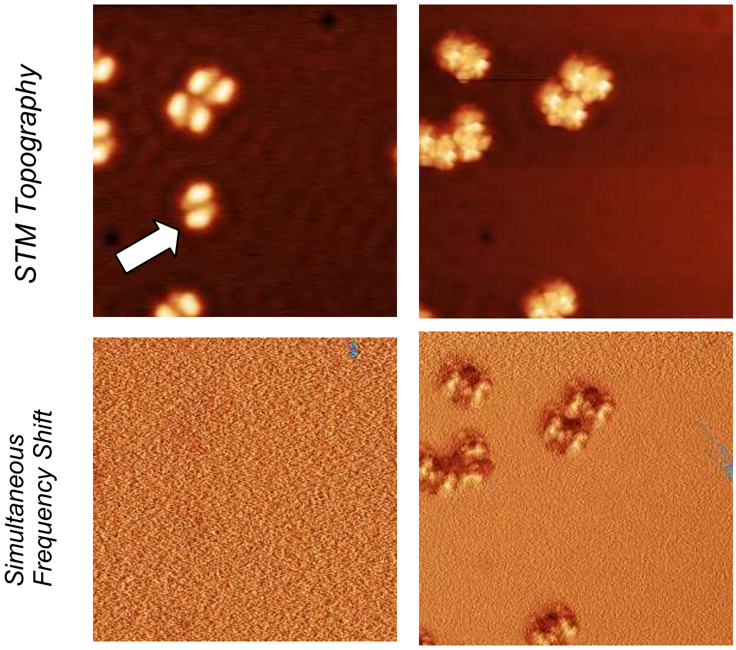




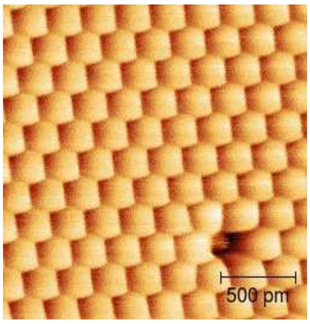
R. Pawlak et al.

Vertical manipulation: Catch the molecule…

Method: Z spectroscopic curve in the **center** of the molecule

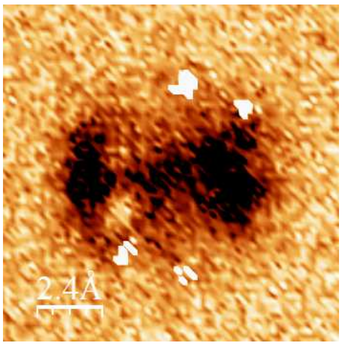


Friction measurement with a molecule linked to the tip

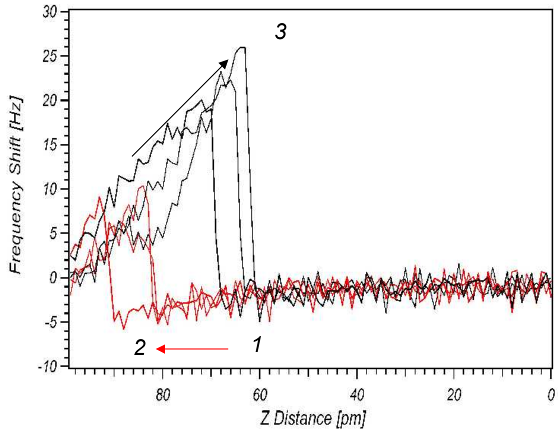


Atomic resolution on Cu(111)

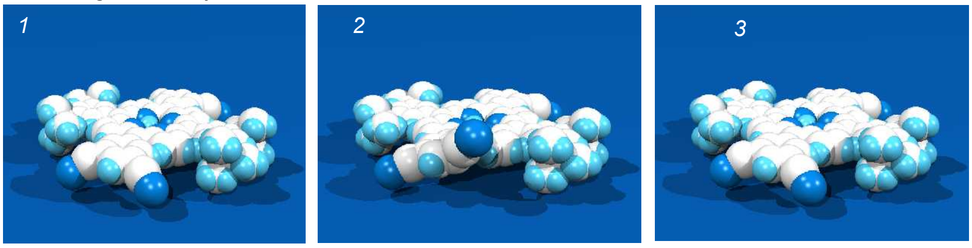
3d-force spectroscopy: Observations of localized instabilities



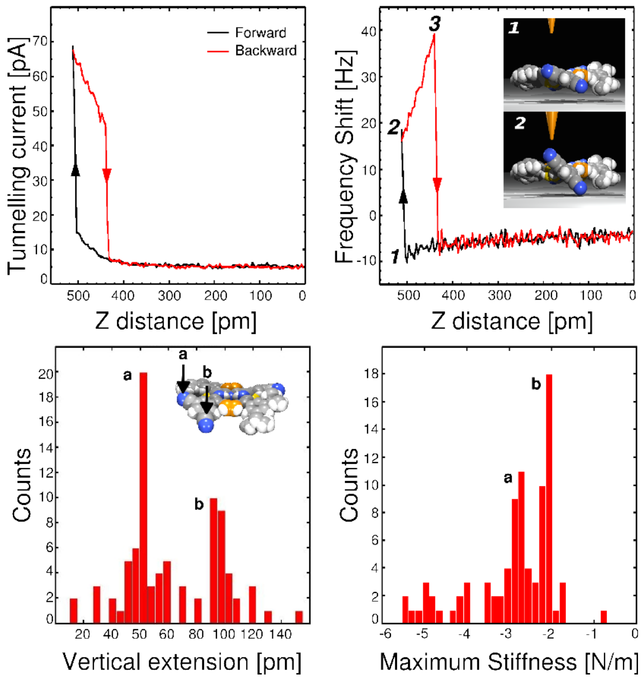
Three-dimensional
Force Field Spectroscopy



Origin of the hysteresis



Vertical switching and statistics



Vertical switching:

- **Tip-molecule junction between a CN function and the Cu-terminated tip.**
- **Attractive interaction force** *(= -150 pN)* **to create the bond.**
- **Possibility to lift the porphyrin leg up by retracting the tip.**
- *Elastic process* **independent of the targeted CN functions as well as the enantiomeric form.**

Rotation by controlled force interations

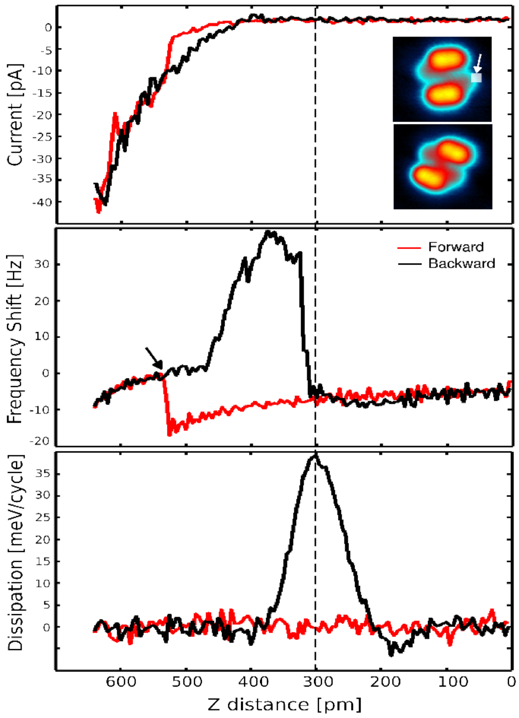
Rotational switching of the molecule:

• **Tip-induced motion of the porphyrin by manipulating the CN function with a single *z* spectroscopic curve.**

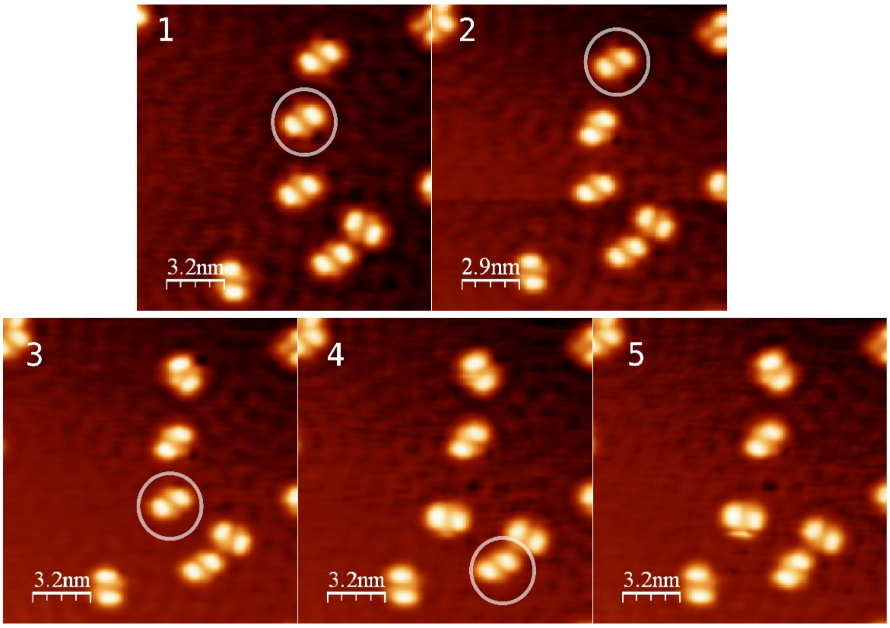
• **Rotation of 60° with respect to the initial conformation.**

• **Absolute interaction force =** - 500 pN **during manipulation, dissipated energy =** 30-80 meV/cycle**.**

• Fully elastic process **(no tunnelling current and bias variation).**

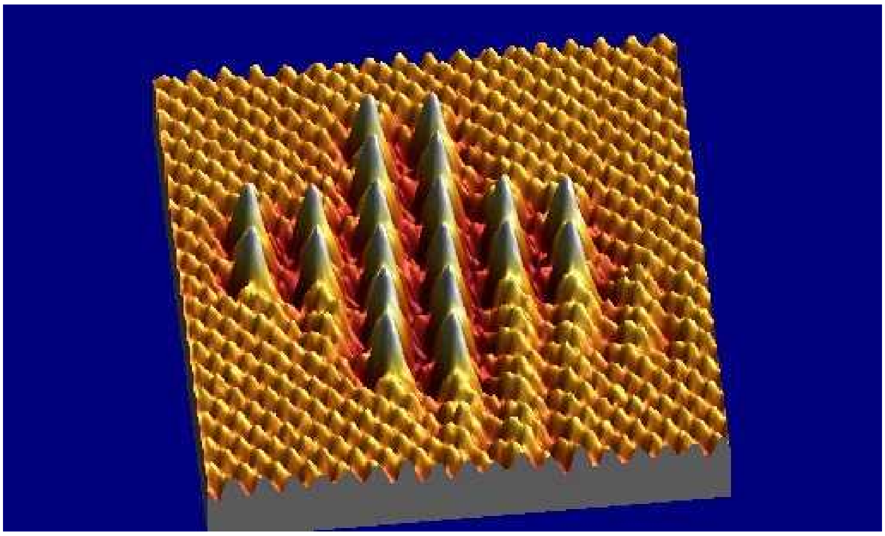


Rotation of molecules clockwise and anticlockwise



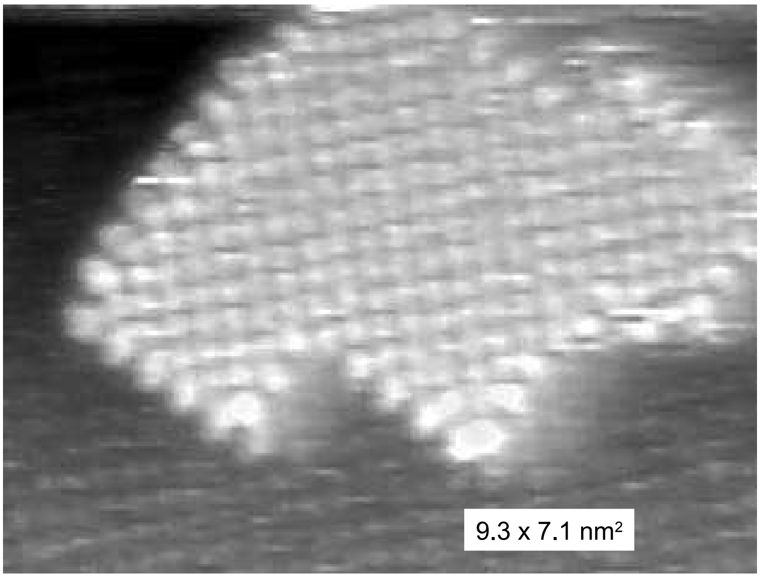
- Possibility to rotate molecules in both directions (clockwise and anticlockwise) without consideration to their symmetry

A Small Swiss Cross made by AFM at room temperature
torsional resonance imaging



S. Shigeki et al.

Die “Nano-Schweiz”



NaCl-Insel mit AFM abgebildet