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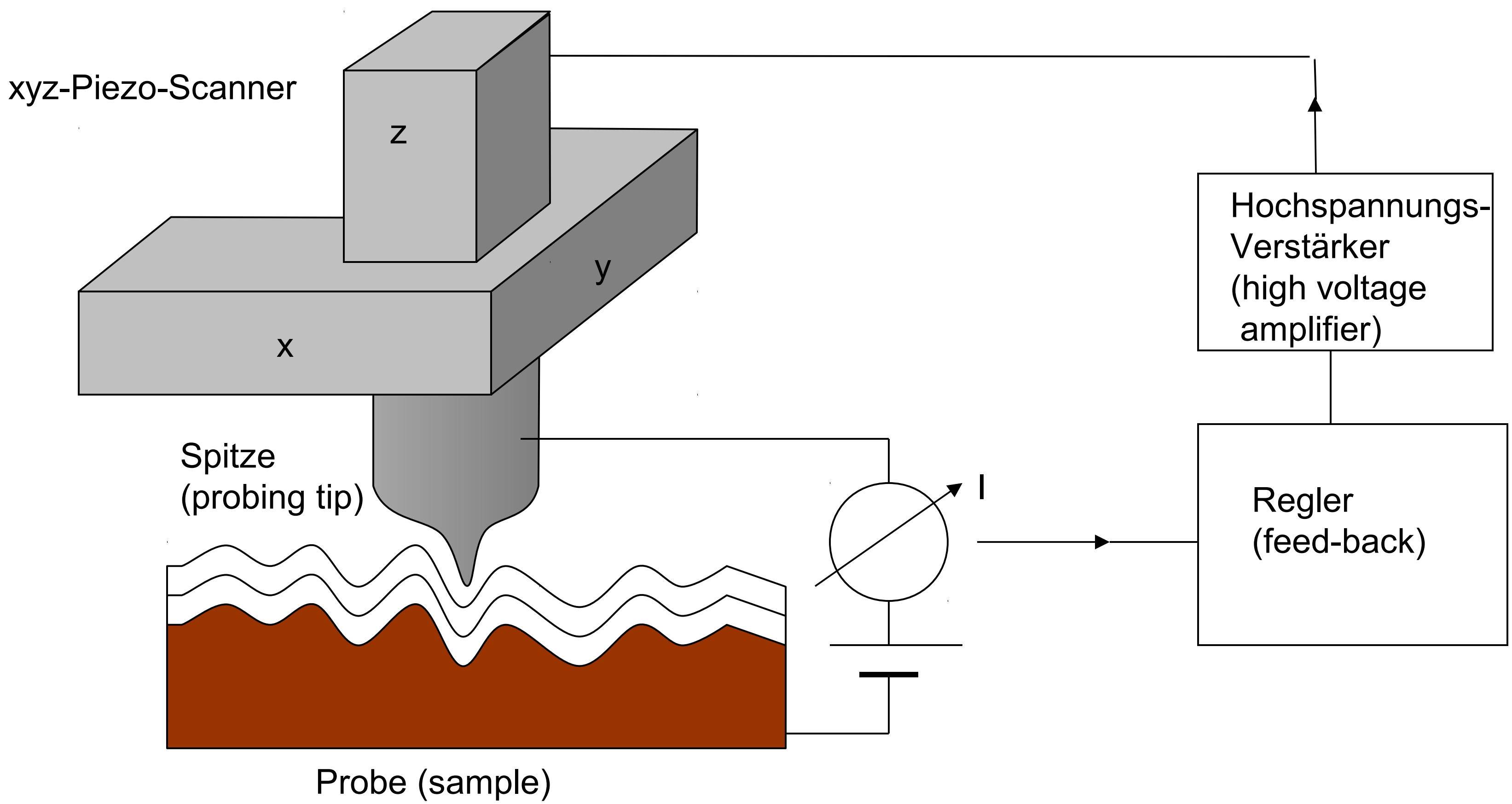
Nanostrukturen-Analysemethoden

Scanning Probe Microscopy

- **Scanning Tunneling Microscopy**
- Tunnel Current
- G. Binnig and H. Rohrer, Nobelpreis 1986
- Experimental Setup
- **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

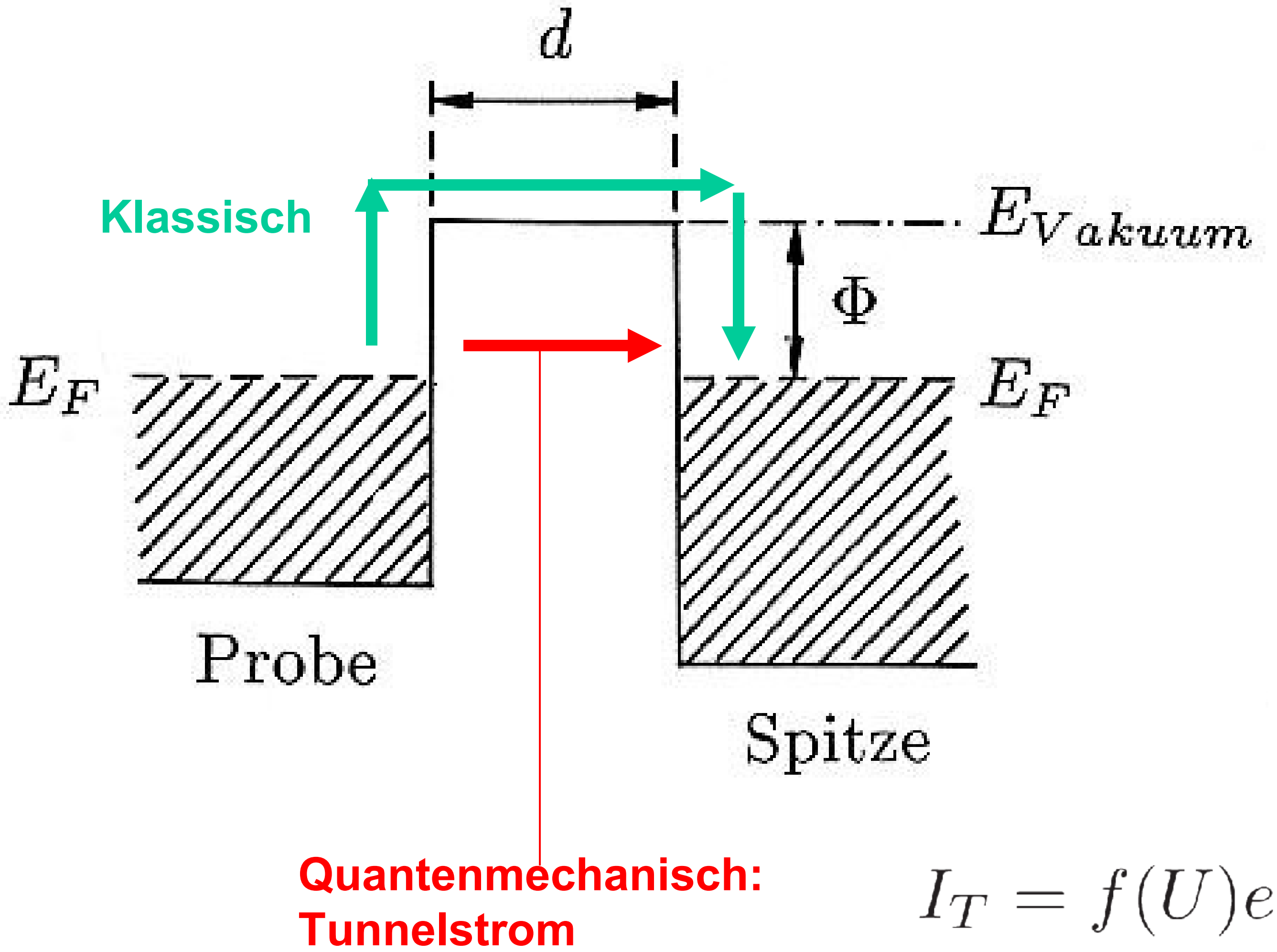
Thilo Glatzel, thilo.glatzel@unibas.ch
NANOlino Lab

Rastertunnelmikroskop (STM)



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

Tunneleffekt



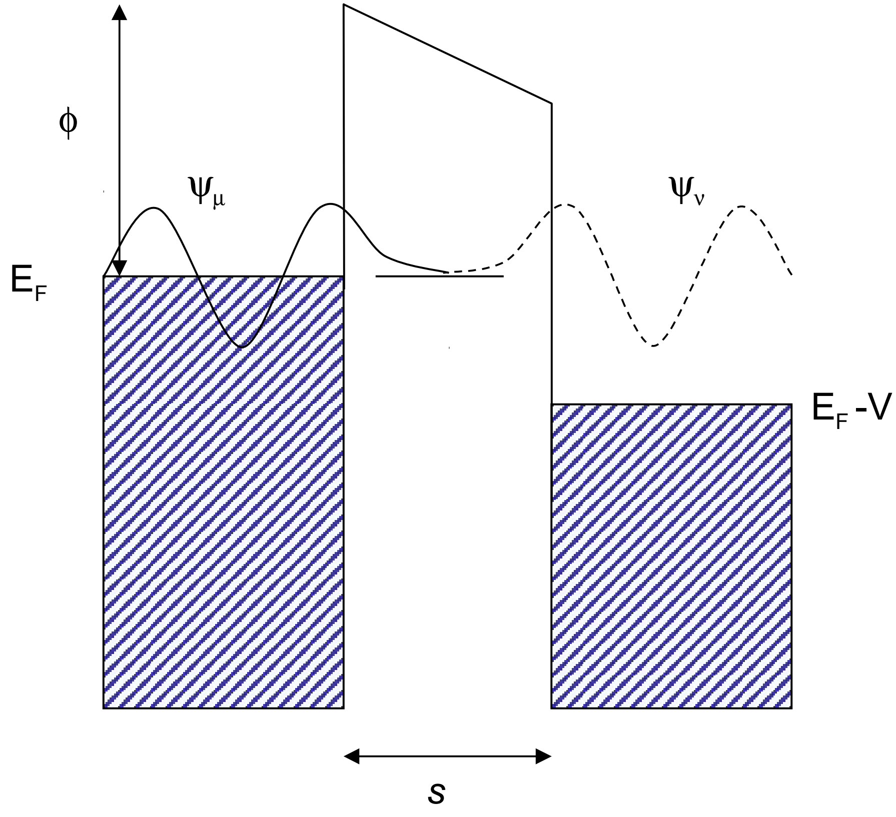
$$I_T = f(U)e^{-A\sqrt{\Phi d}}$$

$$I_T \approx 1nA$$

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

Tunneleffekt

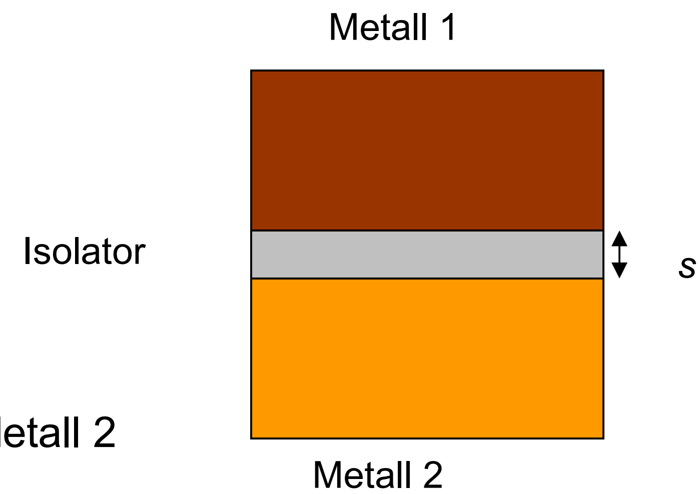
Schon zu Beginn der Quantenmechanik wurde der Tunneleffekt vorausgesagt. Der Überlapp der Wellenfunktionen führt zu einer Transmission von Elektronen durch ein klassisch verbotenenes Gebiet. Zwischen zwei Metallen, die durch Vakuum oder ein Oxid getrennt sind, fliesst ein Tunnelstrom.



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

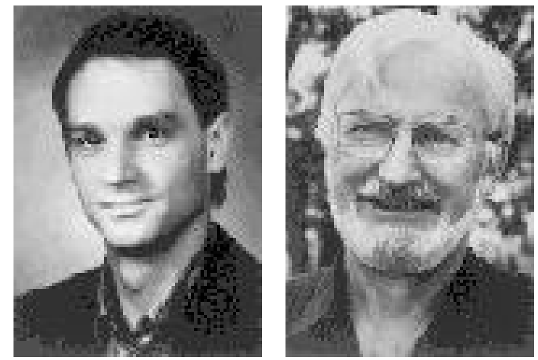
$$A = 2\sqrt{\frac{2m}{\hbar^2}} = 1.025\text{Å}^{-1}eV^{-1/2}$$

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

Der 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. Historisch wurde zuerst das Oxidtunneln realisiert. Erst mit dem STM konnte Vakuumtunneln beobachte werden.

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

Scanning Tunneling Microscope (STM)

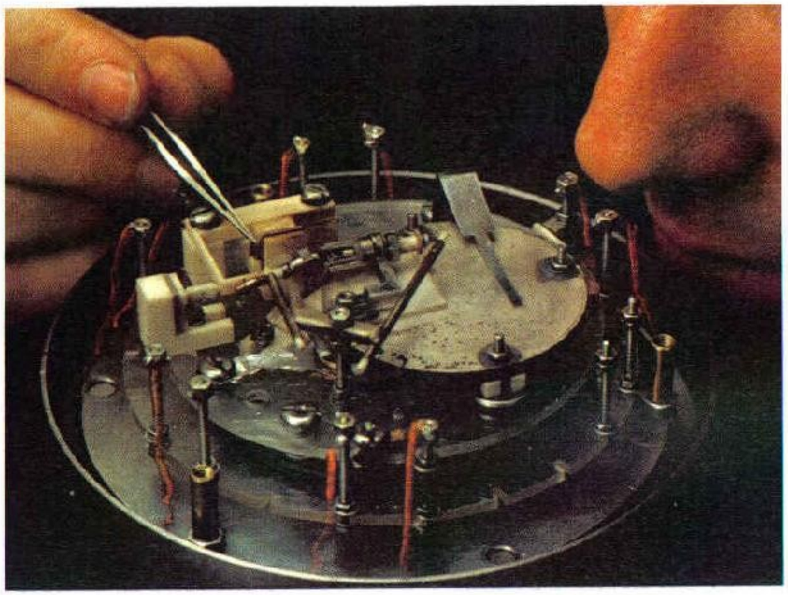


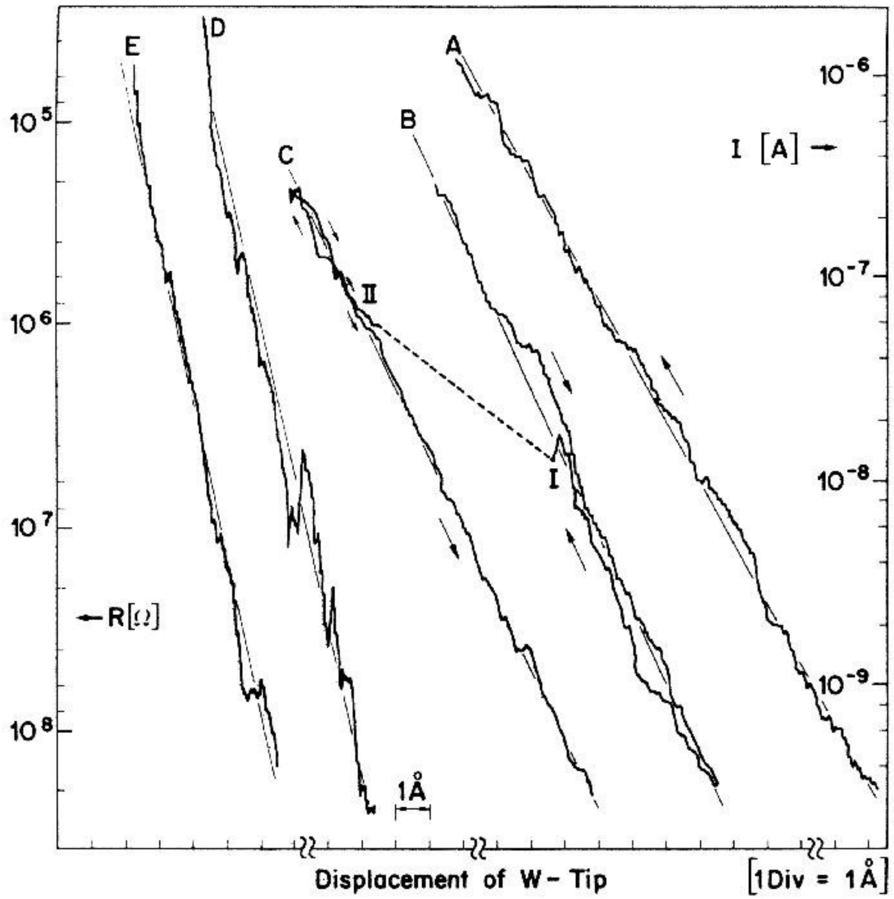
G. Binnig and H. Rohrer
Nobelpreis 1986

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)

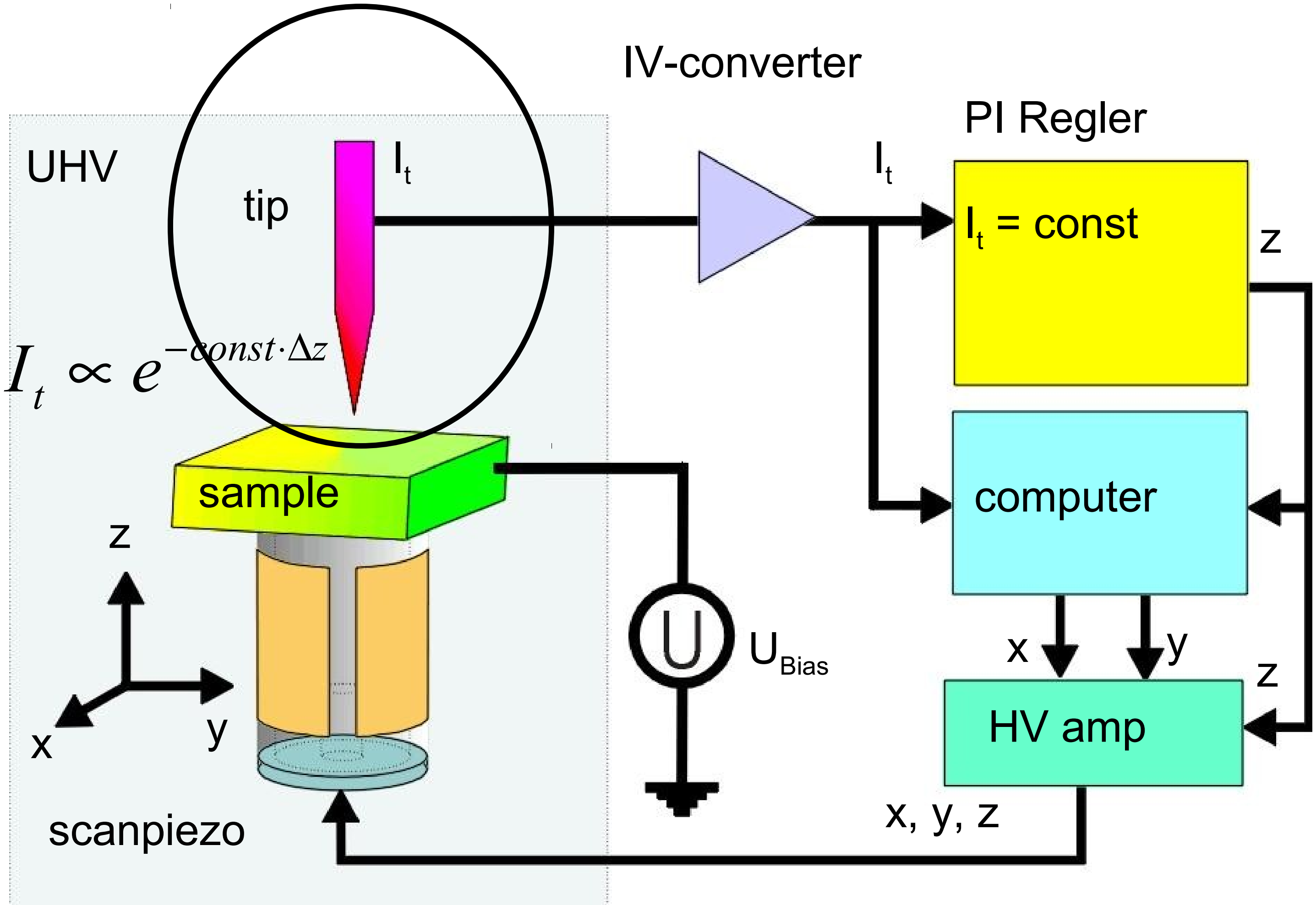




Exponentieller Abfall des Tunnelstromes mit dem Abstand

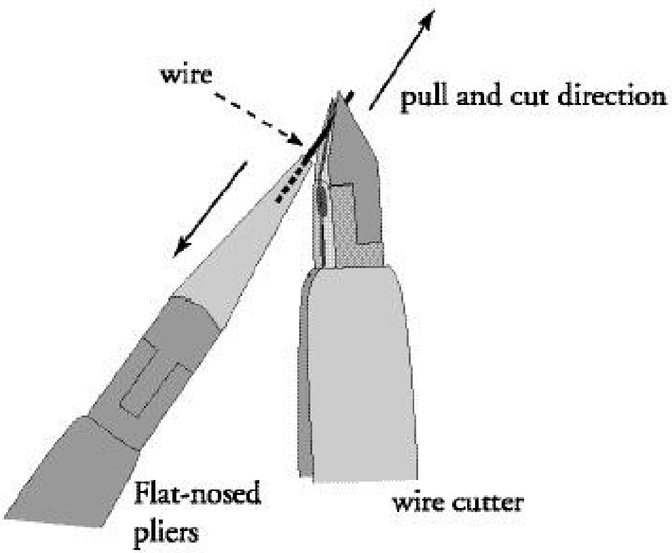
G. Binnig, H. Rohrer, Ch. Gerber, and E. Weibel, Appl. Phys. Lett., Vol. 40, Issue 2, pp. 178-180 (1982)

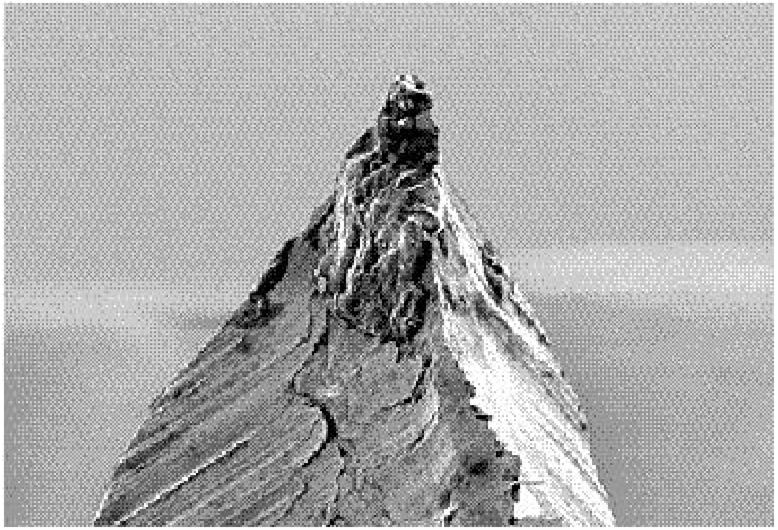
Blockschaltbild STM



Spitzen

1. Abgerissener PtIr Draht



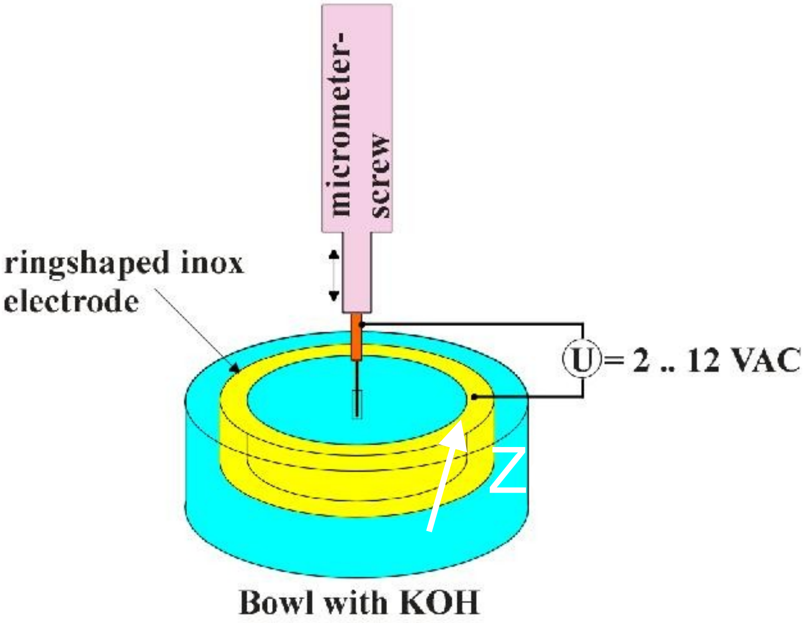


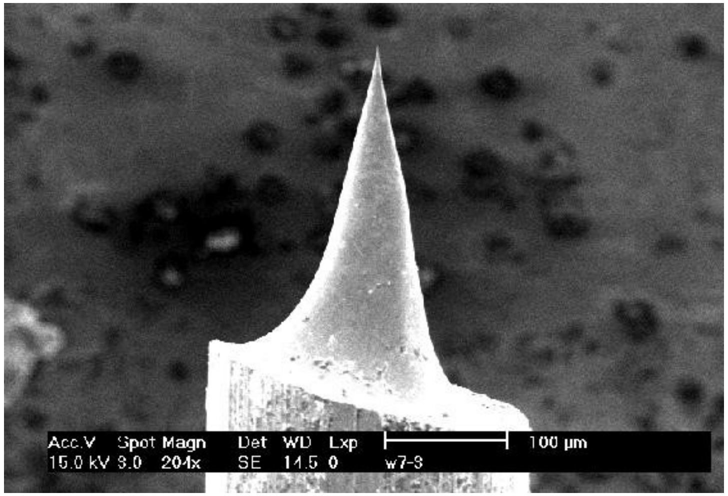
Oder...

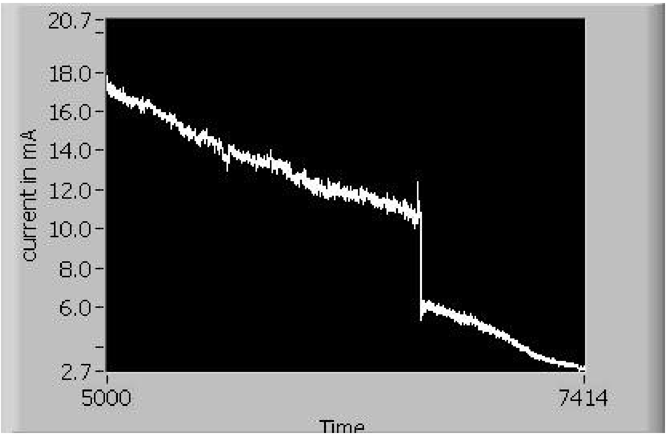
Spitzen

2. Elektrochemisch

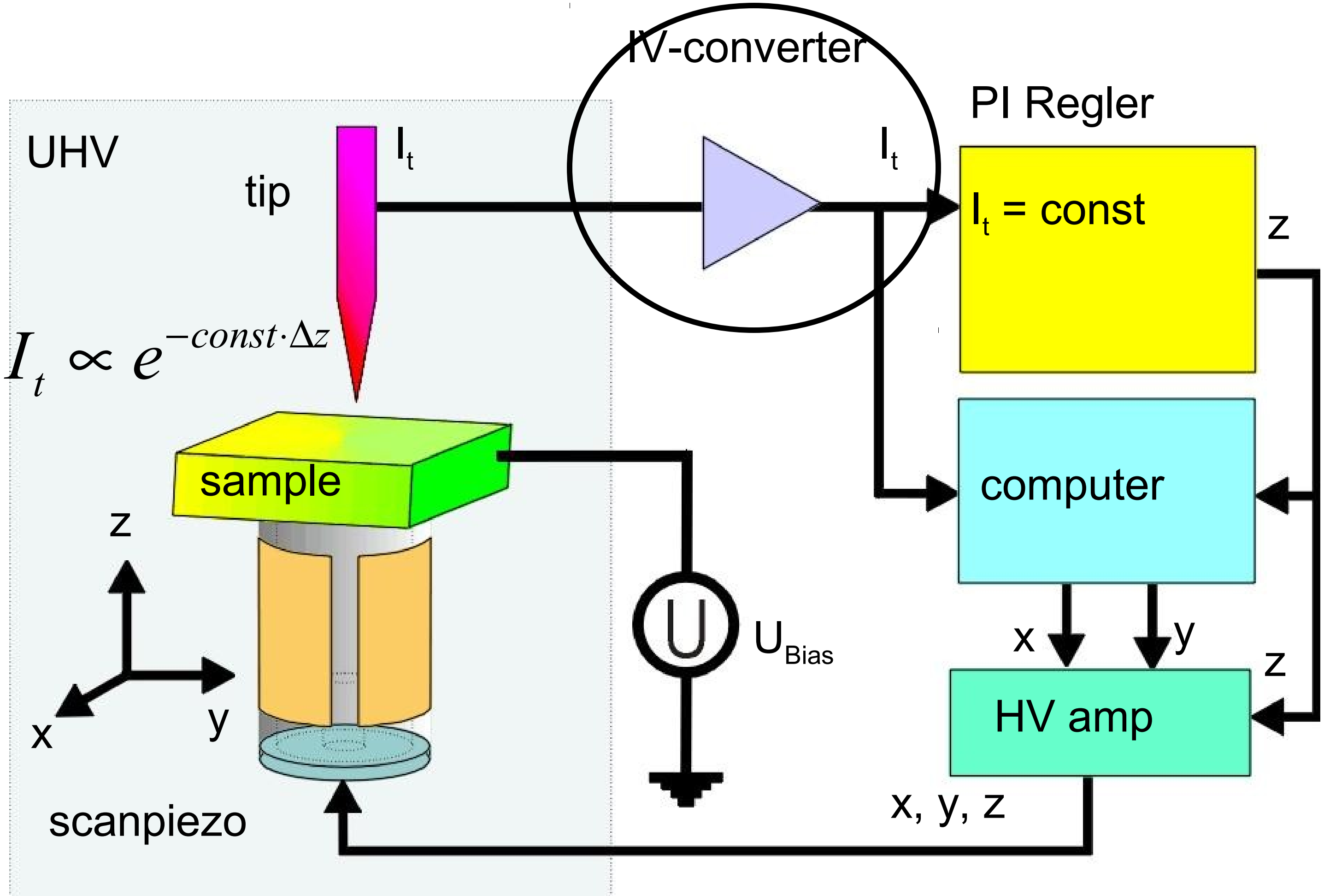
geätzte Wolframspitzen:



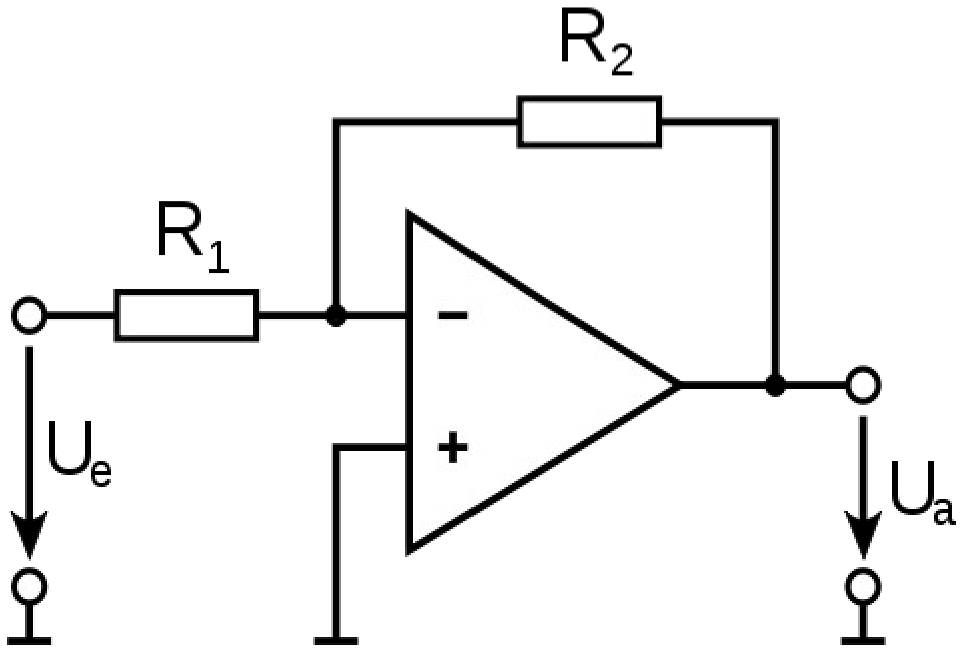




Blockschaltbild STM



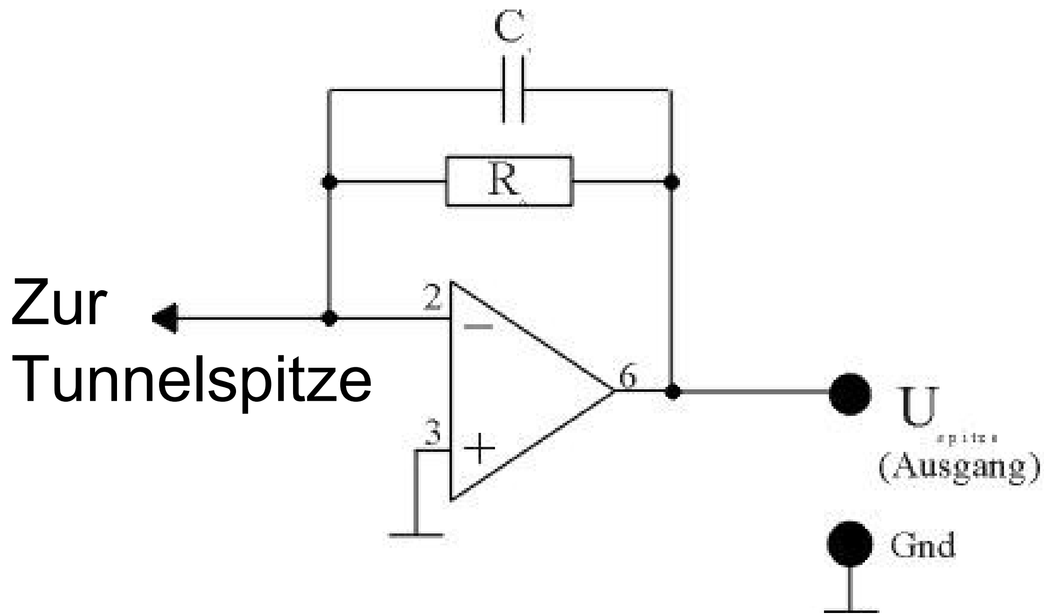
Invertierender Verstärker

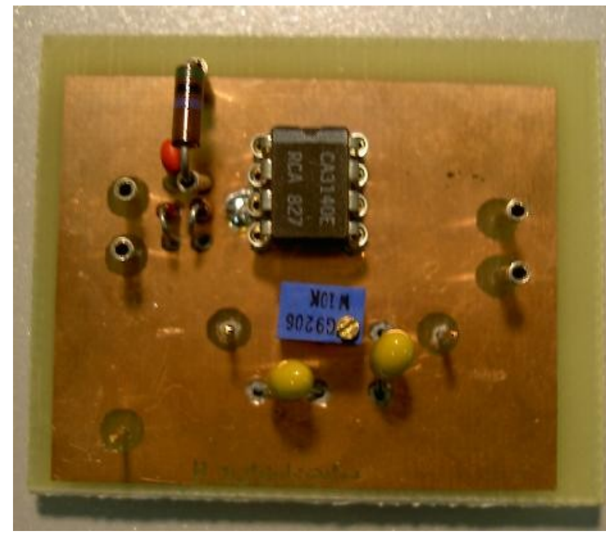


$$U_a = -\frac{R_2}{R_1} U_e$$

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

Strom-Spannungswandler

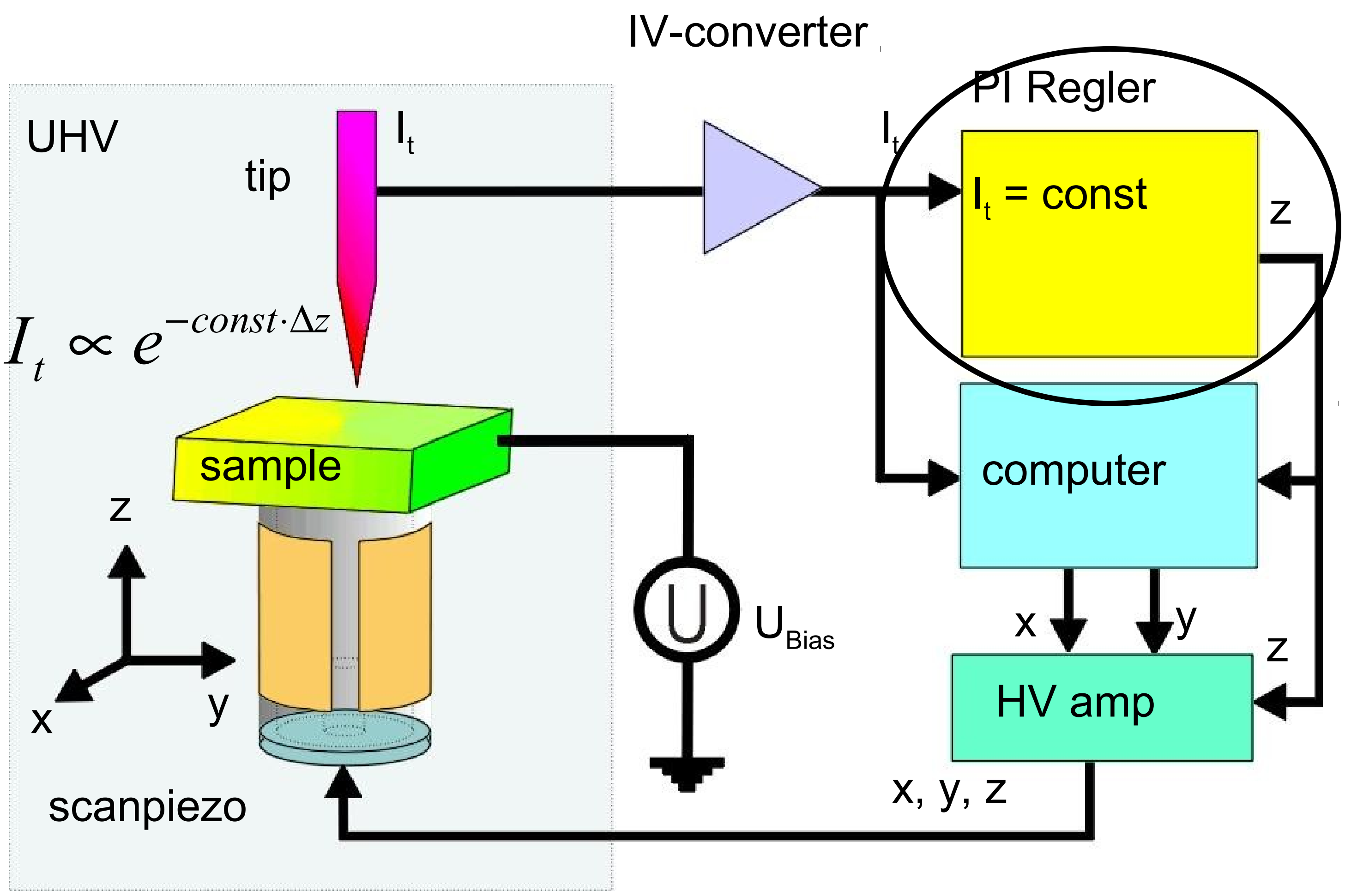




$$U_A = -R \cdot I_t$$

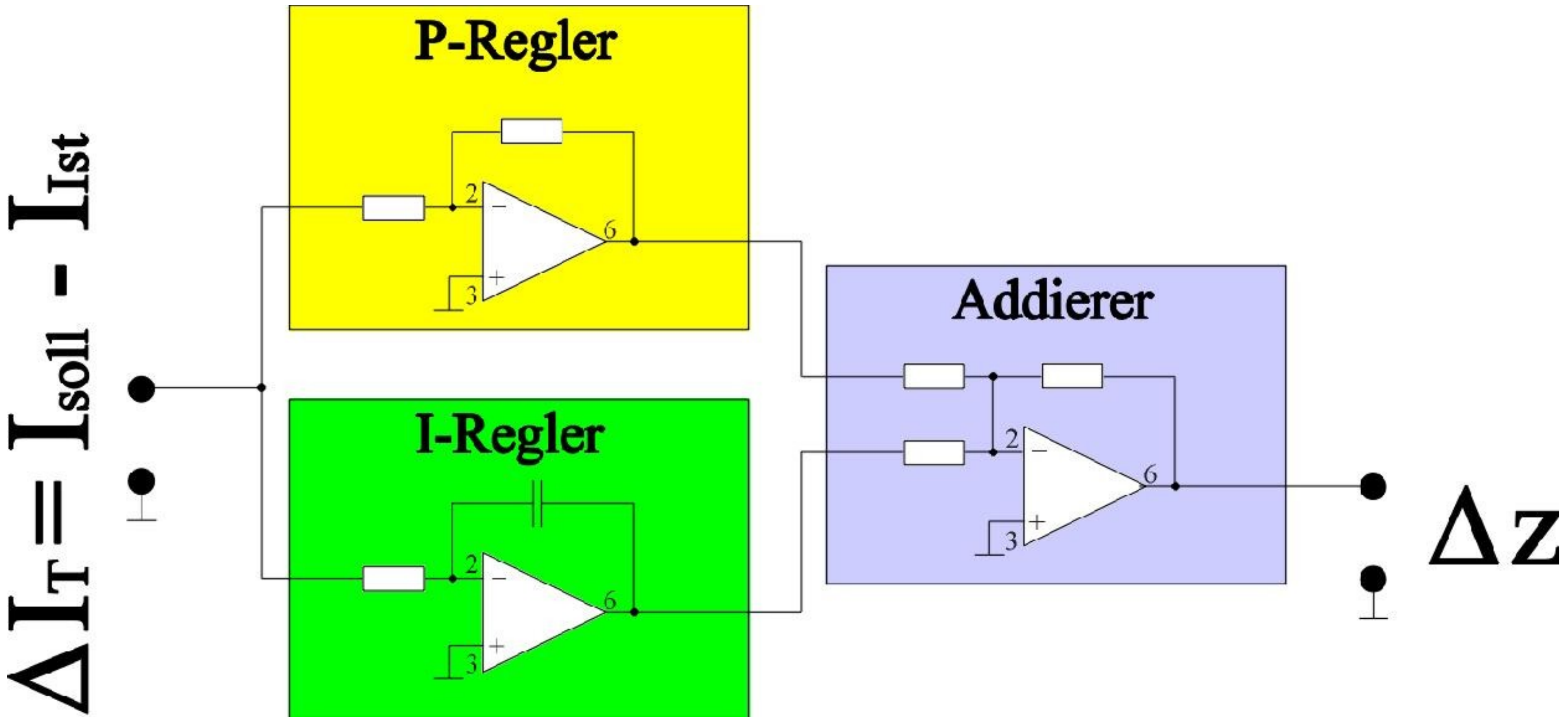
Bei R = 100MΩ entspricht U_A = 1V einem Tunnelstrom von 10nA

Blockschaltbild STM

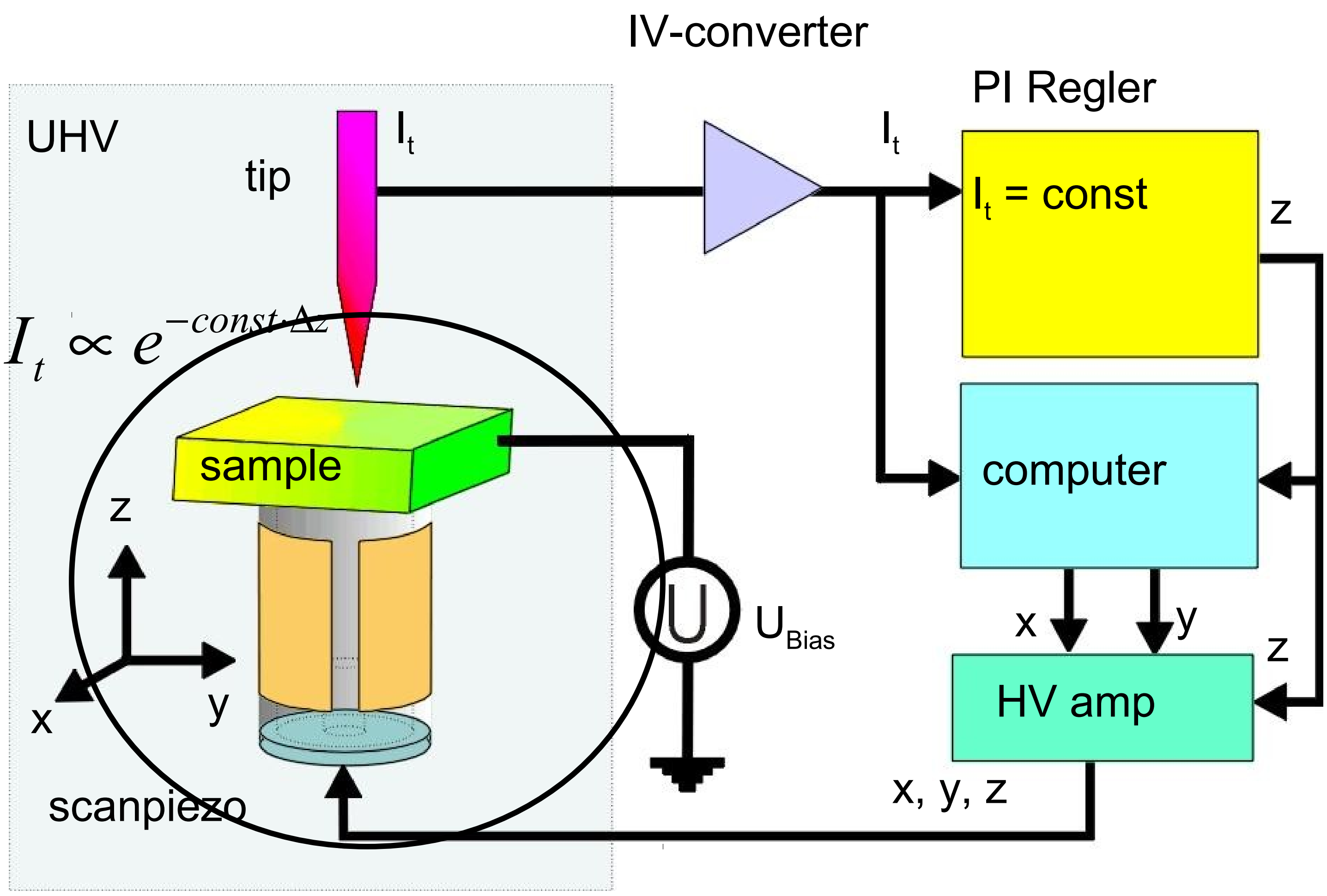


PI Regler

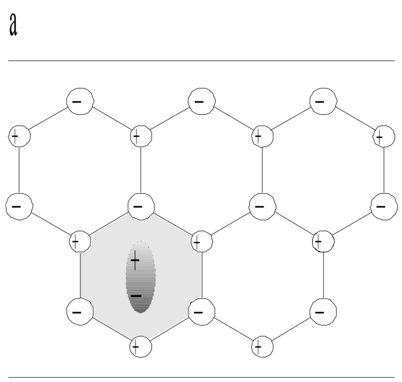
Regelt den Abstand Spitze-Probe so, dass der Tunnelstrom konstant bleibt



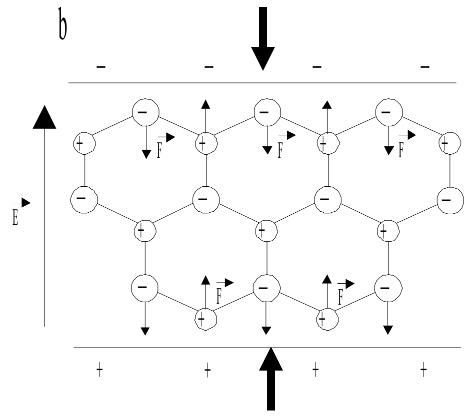
Blockschaltbild STM



Piezos



Verschiedene Ladungsschwerpunkte

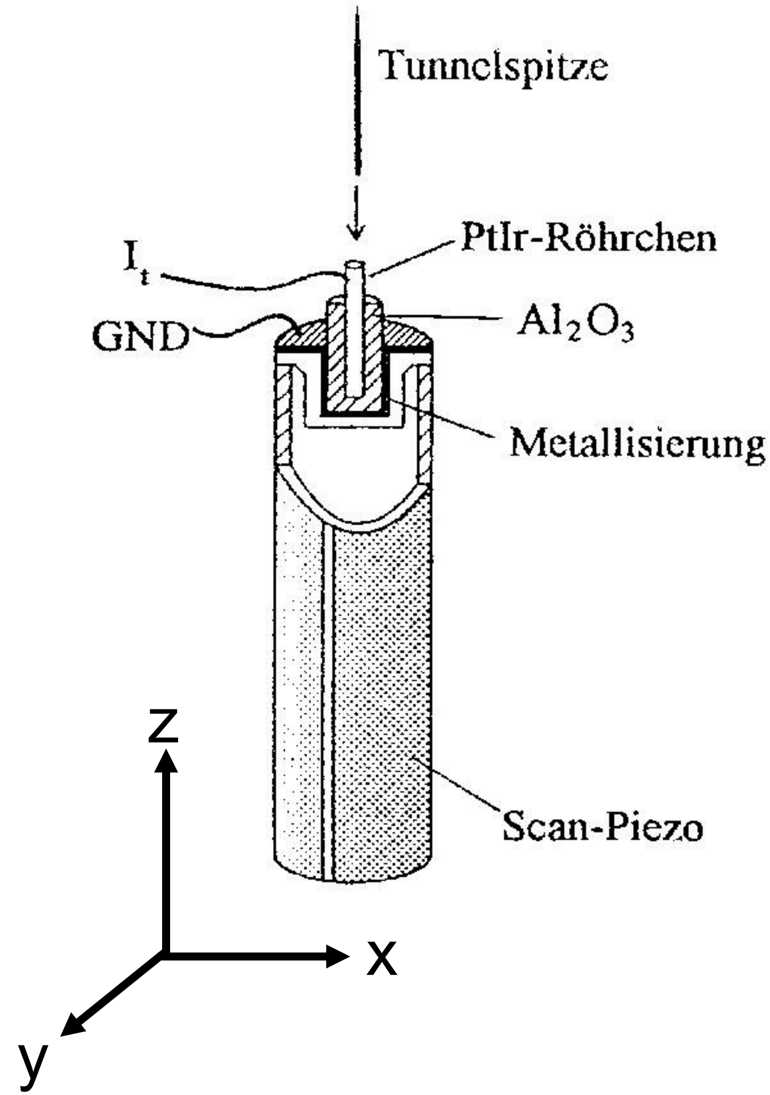


Verformung durch Anlegen einer elektrischen Spannung

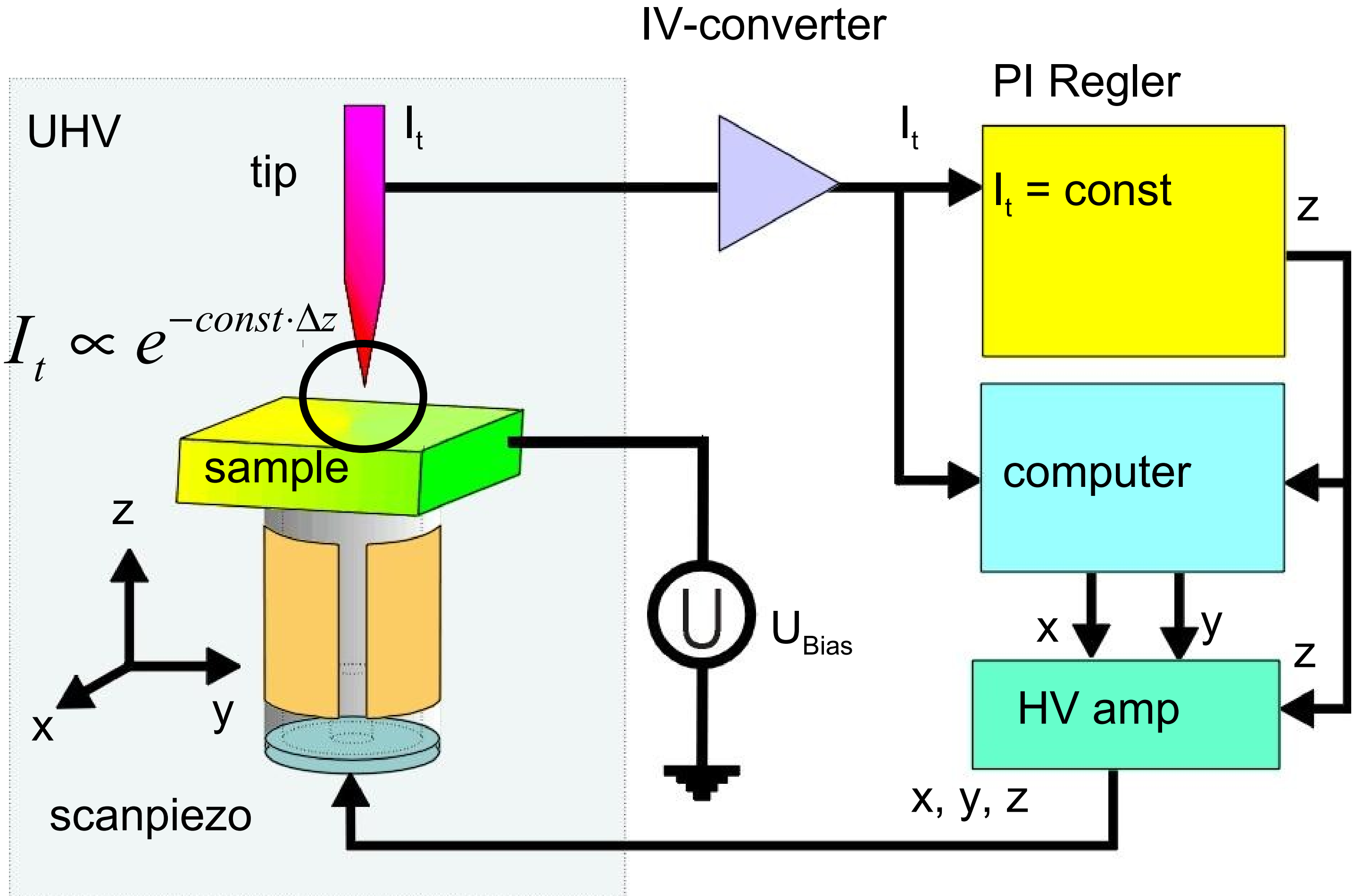
Typische Piezoelektrische Materialien:
- Quarz
- Bariumtitanat
- Bleizirkontitanat (PZT)
- Etc.

Piezotubes

XYZ-Stellglieder

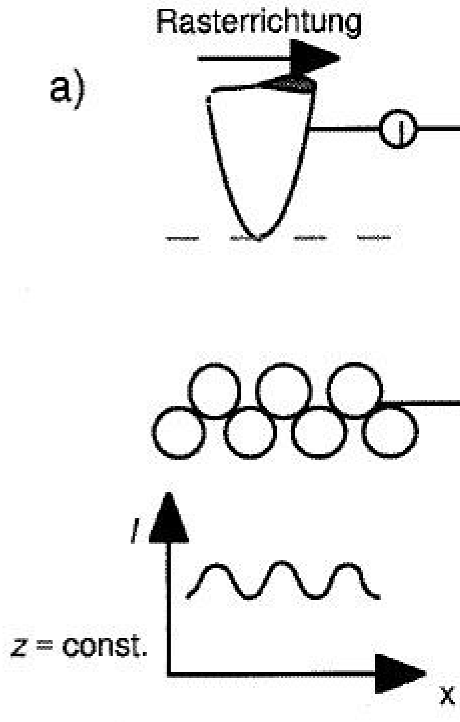


Blockschaltbild STM

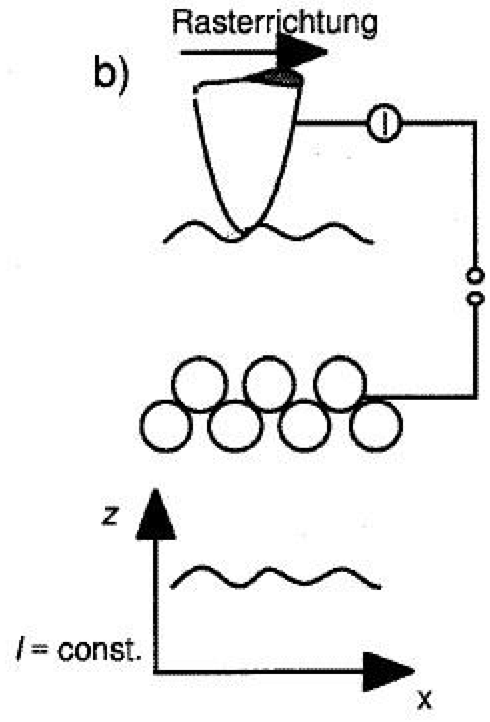


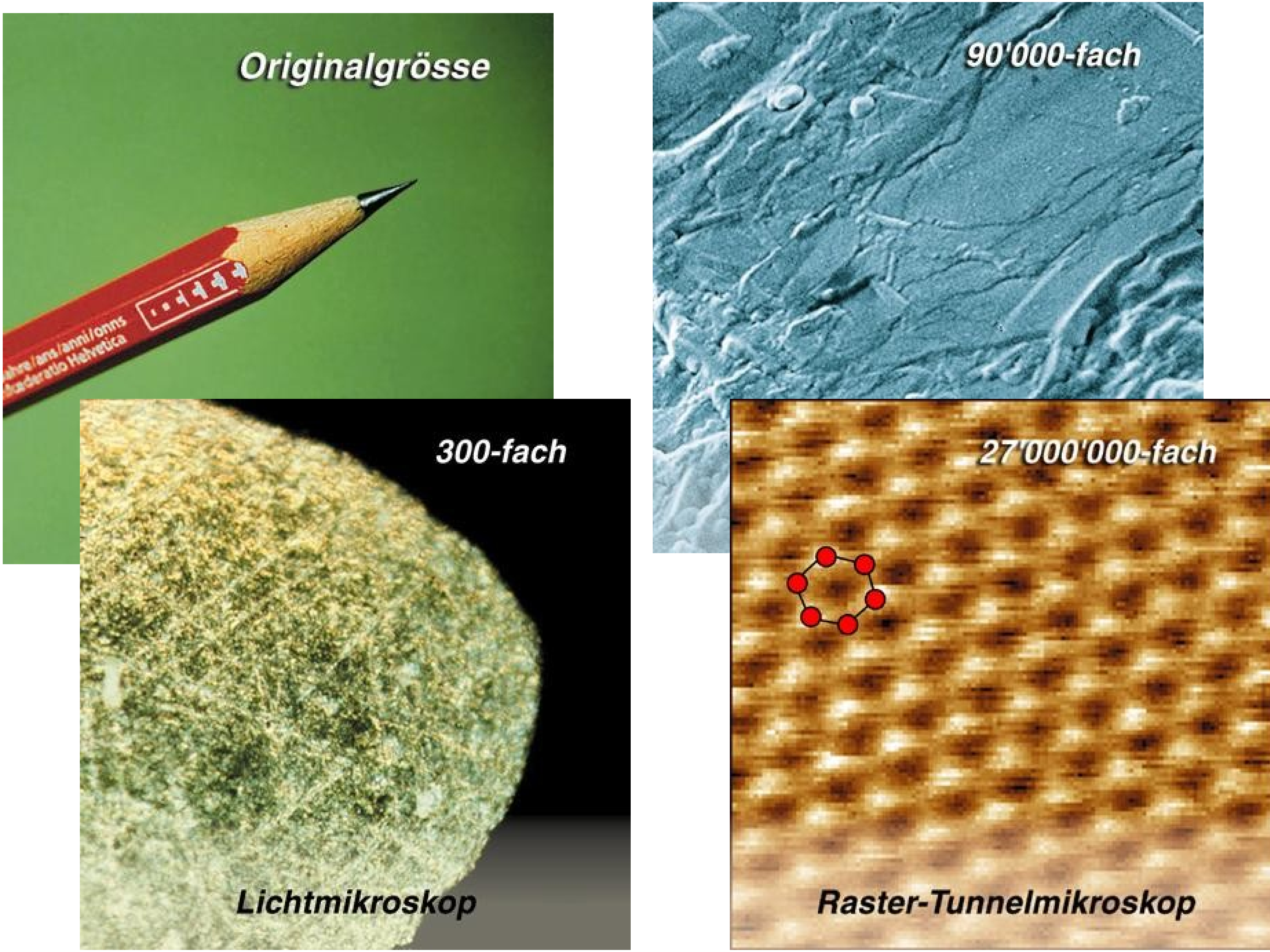
Messmodi

Constant Height



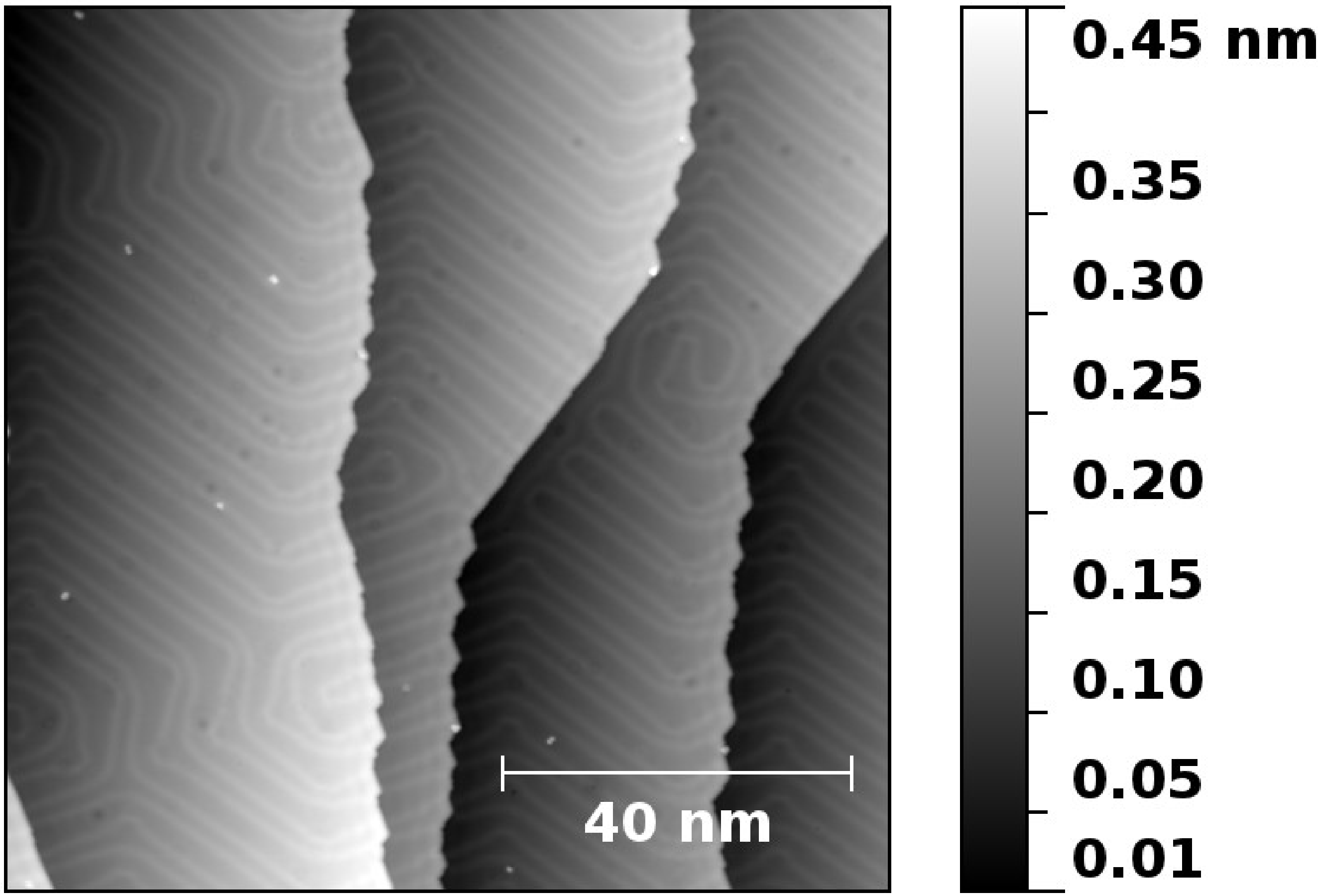
Constant Current




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

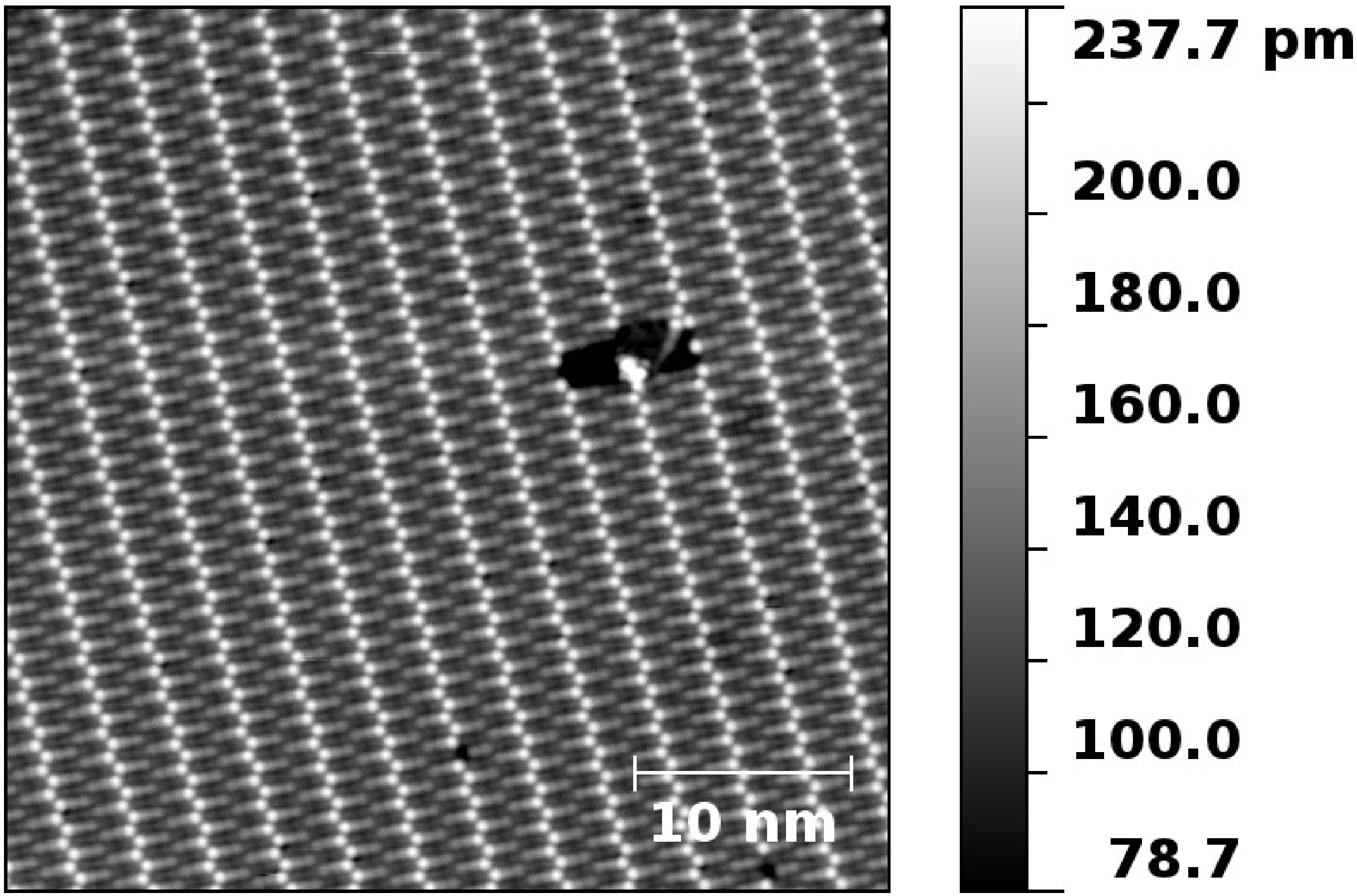
Au (111) surface

V_{bias}=200mV, I_T=10pA, T=4K



DA molecules on Ag(111)

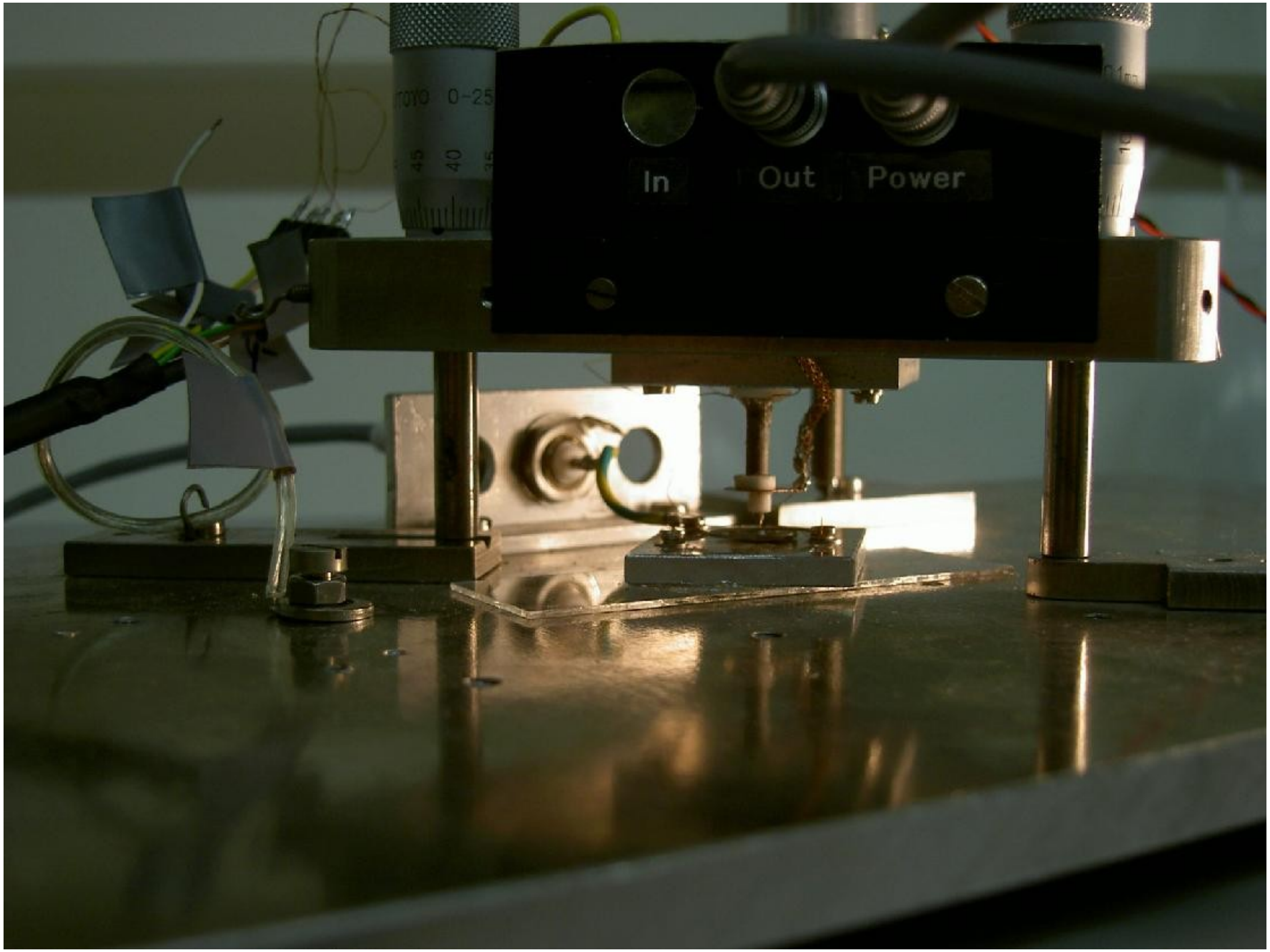
V_{bias}=200mV, I_T=2pA, T=4K



http://www.nanosurf.com/

Nanosurf AG, Liestal

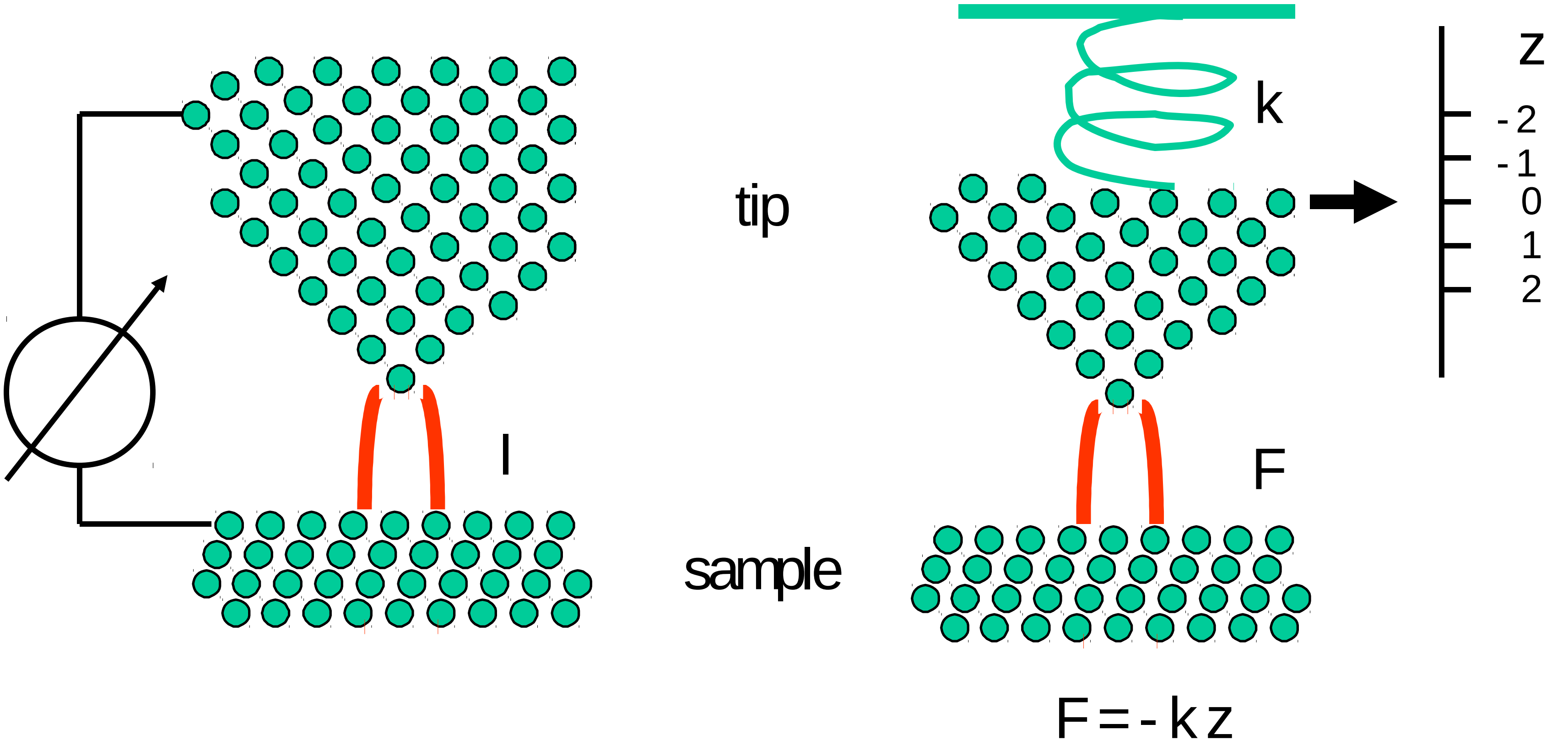
Do-it-yourself-STM
Projektstudie



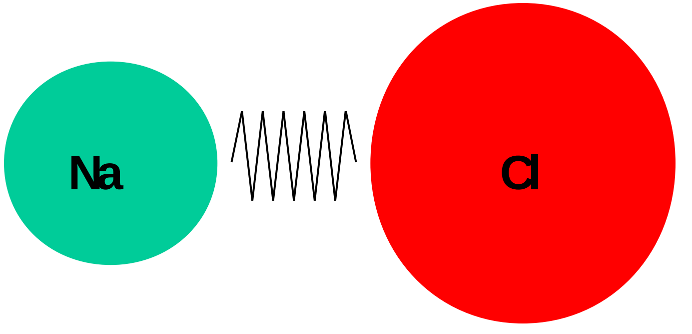
Blockkurs SPM !

Scanning X Microscopy

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



Kräfte zwischen zwei Atomen

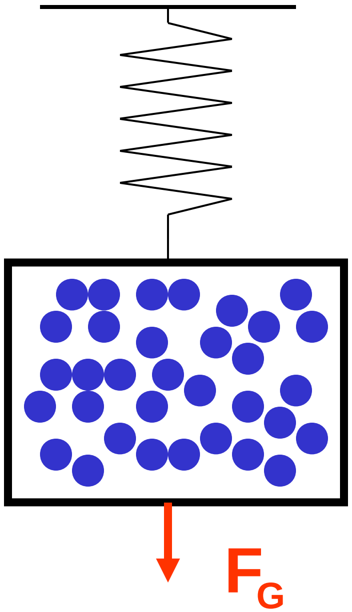


Chemische Bindung

F_{chem} = 1eV/ 0.1 nm

1.6 nN

„Kräfte Spüren“



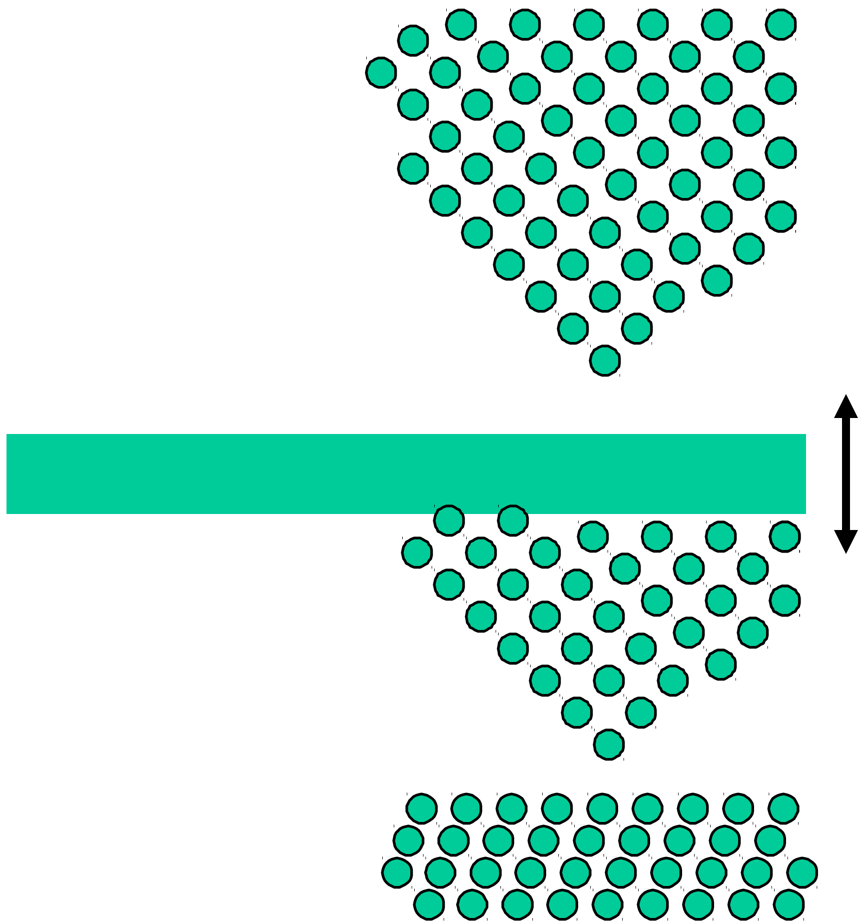
1 nm³ Wasser (33 Moleküle)

0.01 g

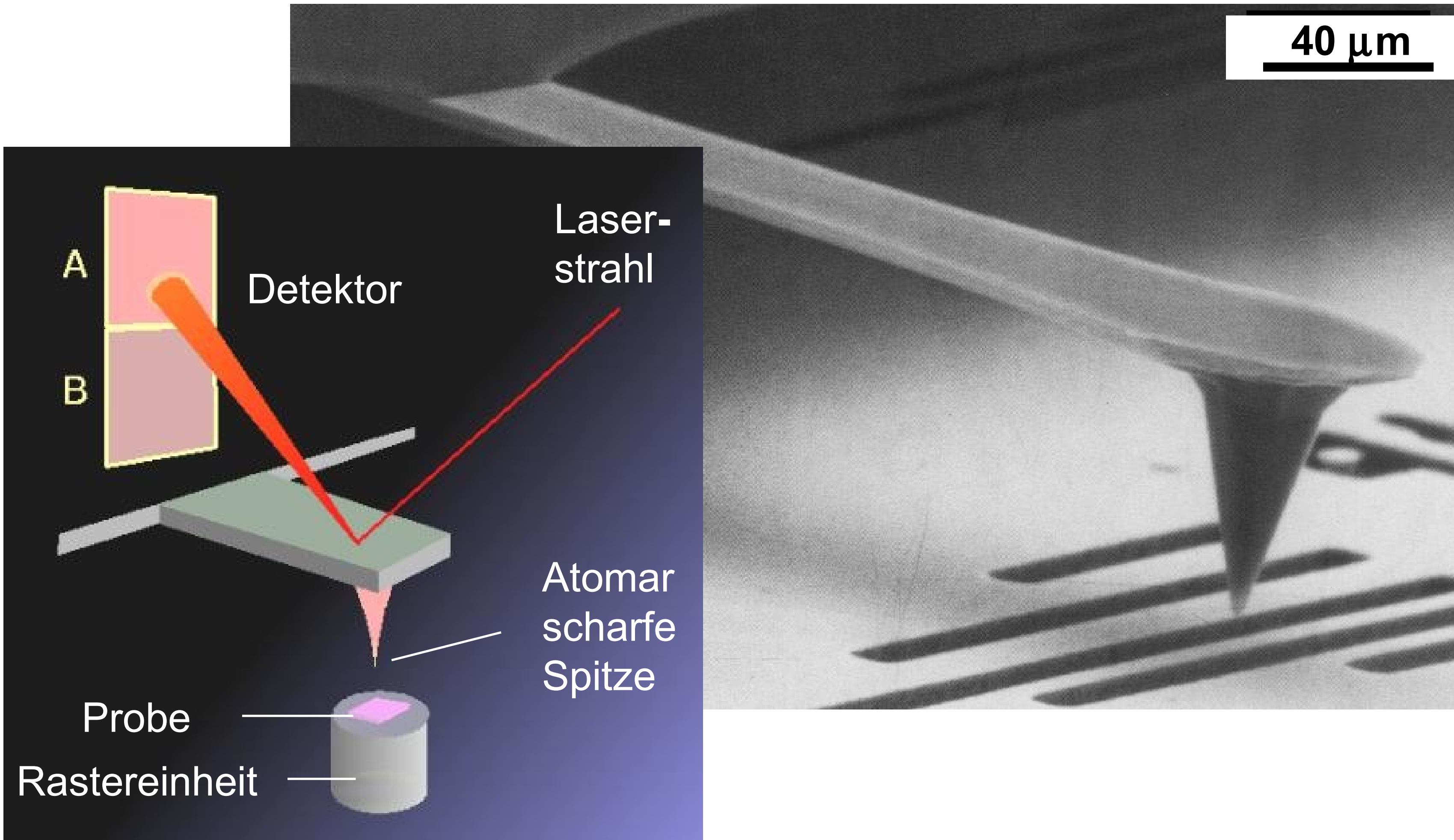
$F_G = 10^{-23}$ N = 10^{-14} nN

F = 0.1 mN = 10^{5} nN

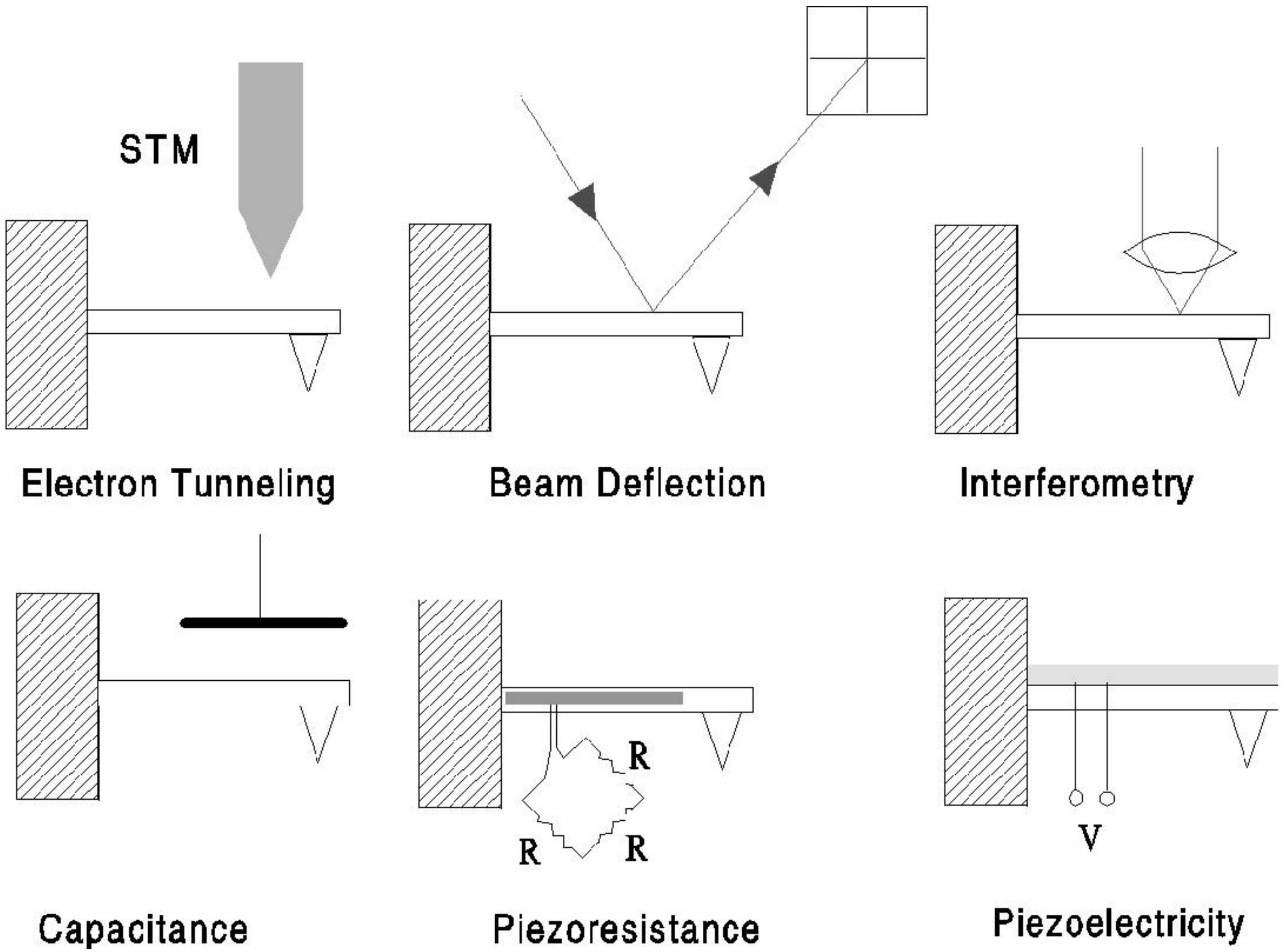
Prinzip des ersten AFMs



„Beam deflection“-Methode



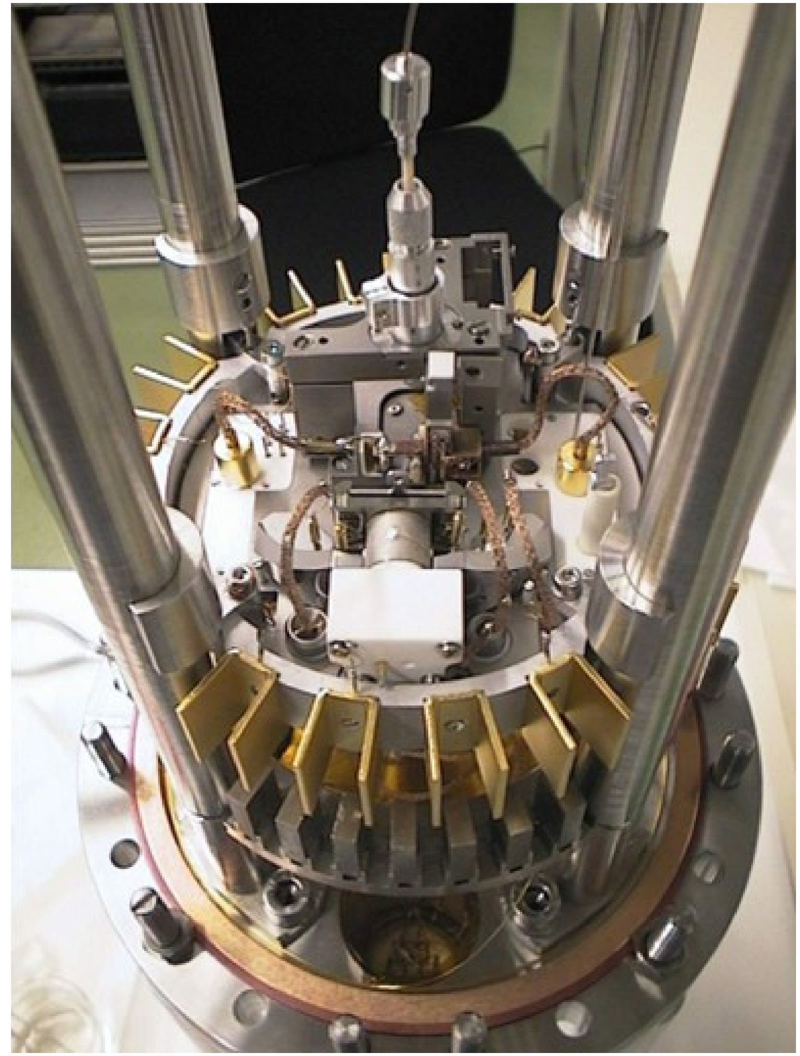
Ablenkungssensoren



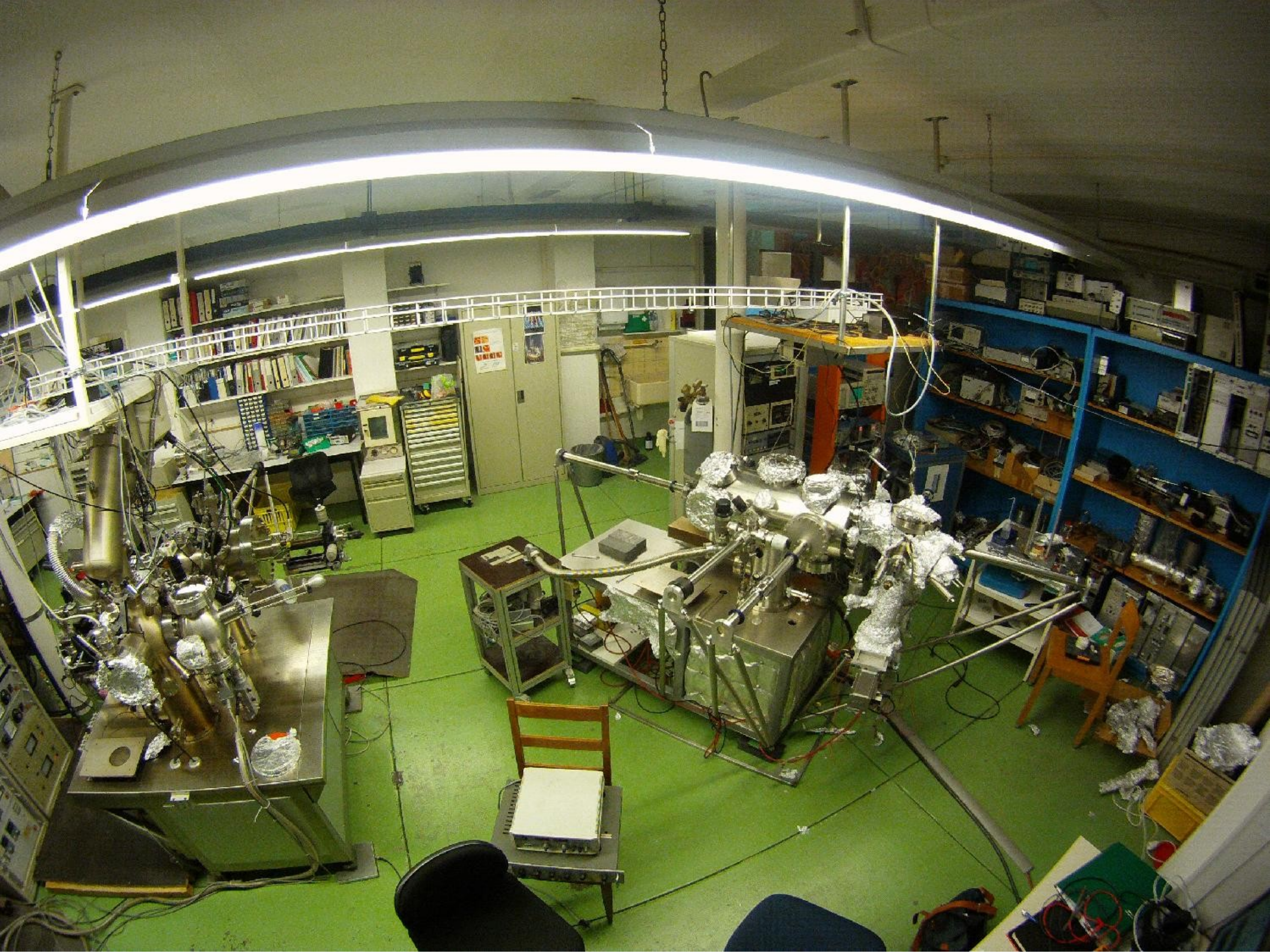
Beispiele

Multimode (Bruker)

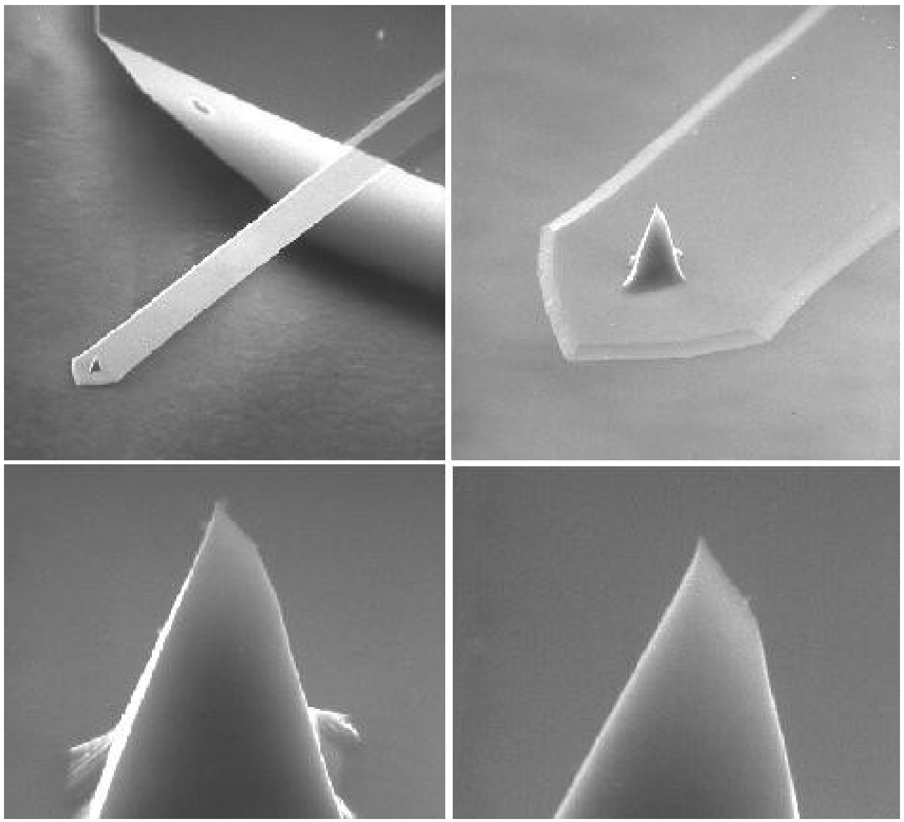
Nanosurf



Uni Basel, UHV AFM/STM



Microfabrizierte “Cantilever”



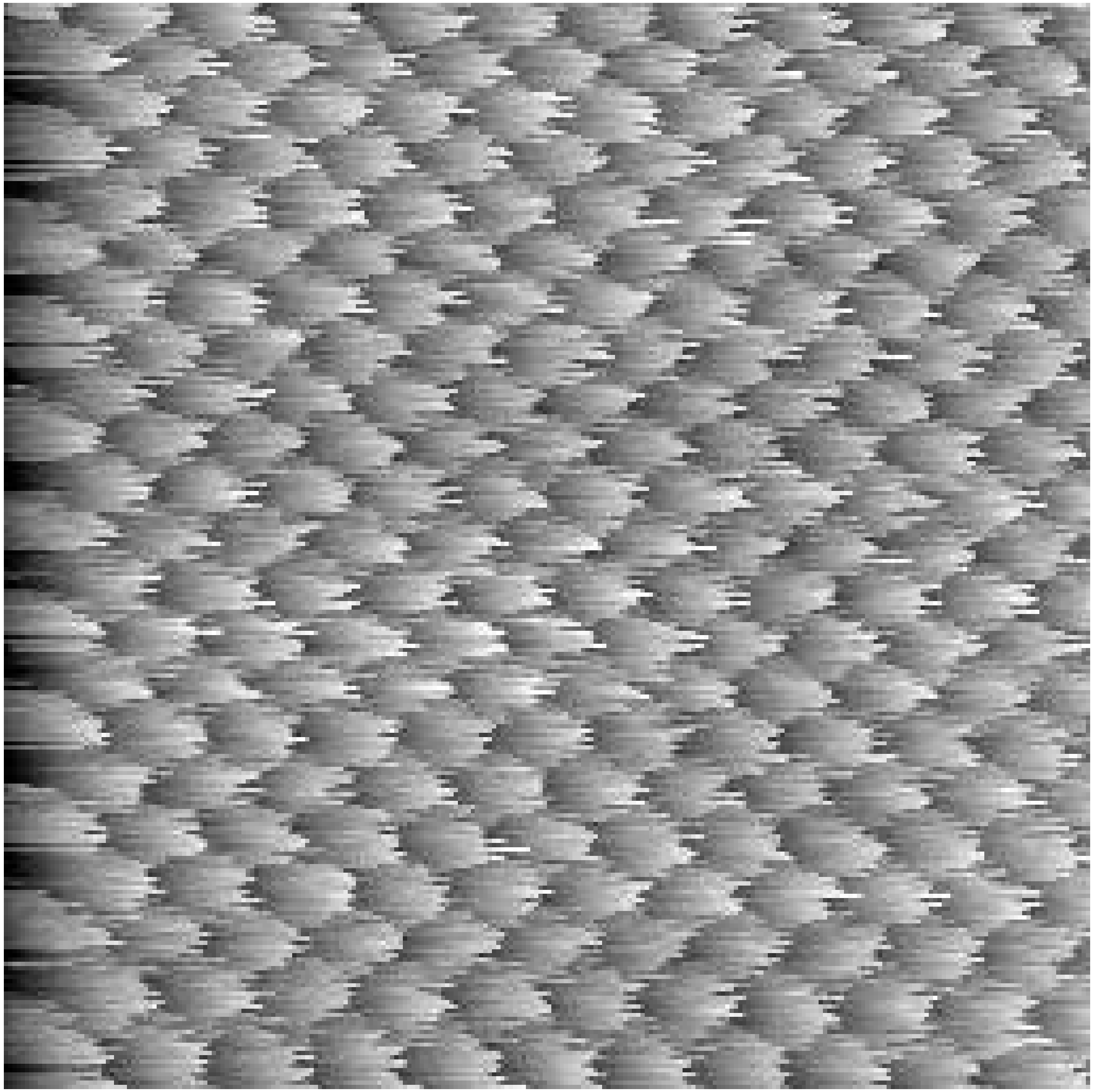
Länge : l = 450 μm
Breite : w = 45 μm
Dicke: t = 1.5 μm
E=1.69 10^{11} N/m^2

Spitzenhöhe: 12 μm
Spitzenradius: 10 nm

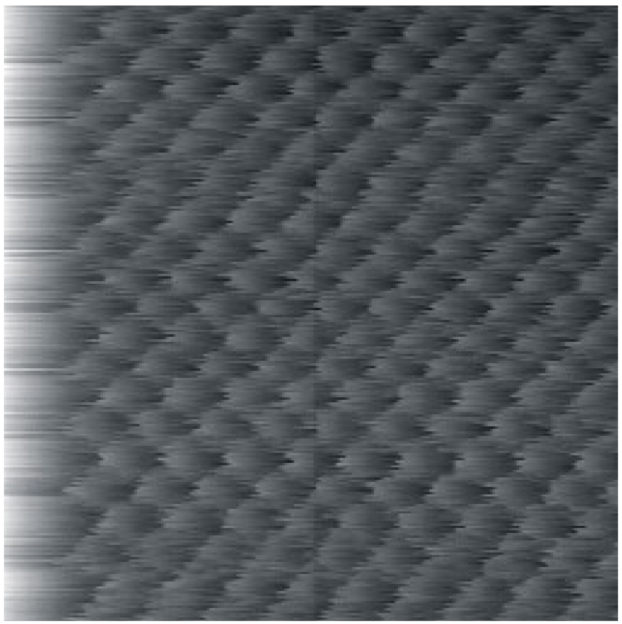
Federkonstante k:

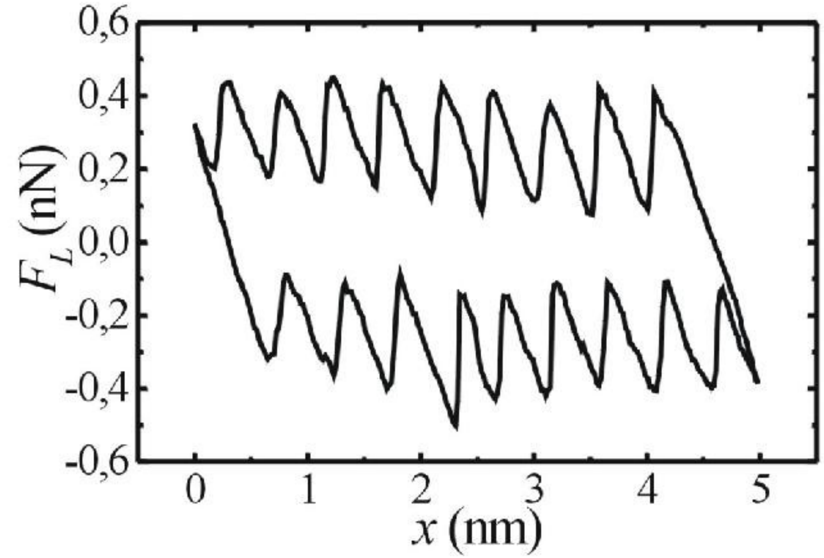
$$k = \frac{Ewt^3}{4l^3} = 0.15 \text{ N/m}$$

atomare Reibung von NaCl Oberflächen



Atomic stick-slip



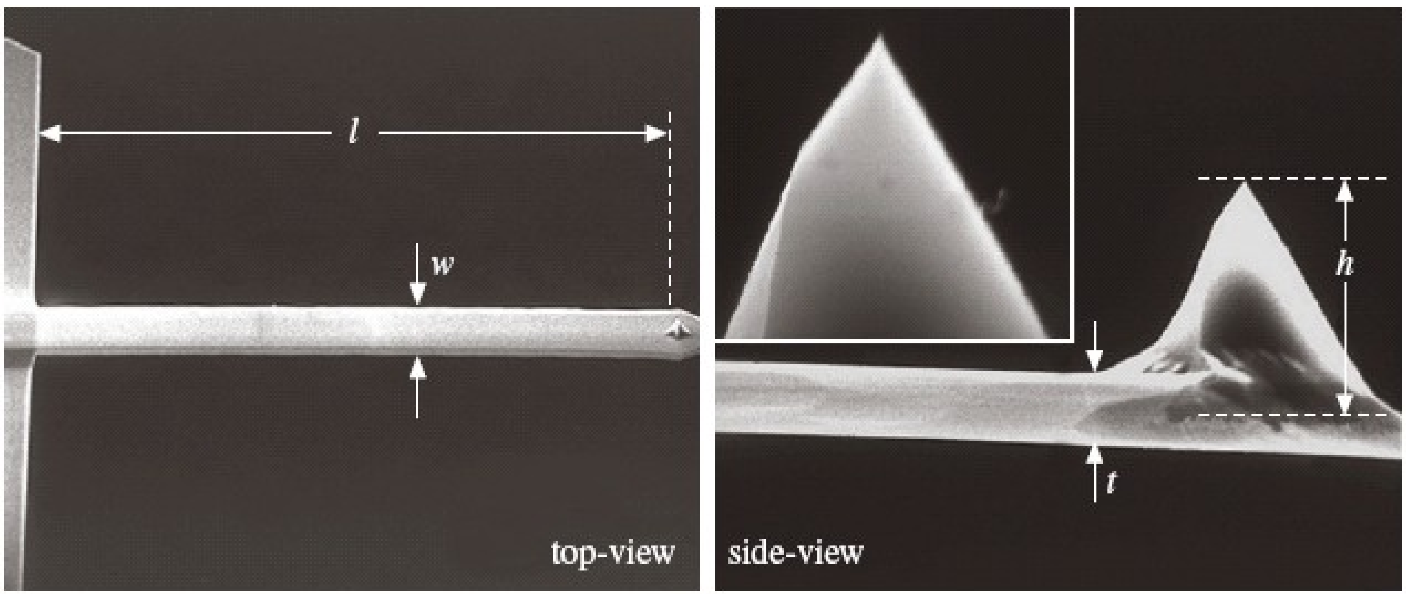


(friction map and friction loop on NaCl(100) in UHV)

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:

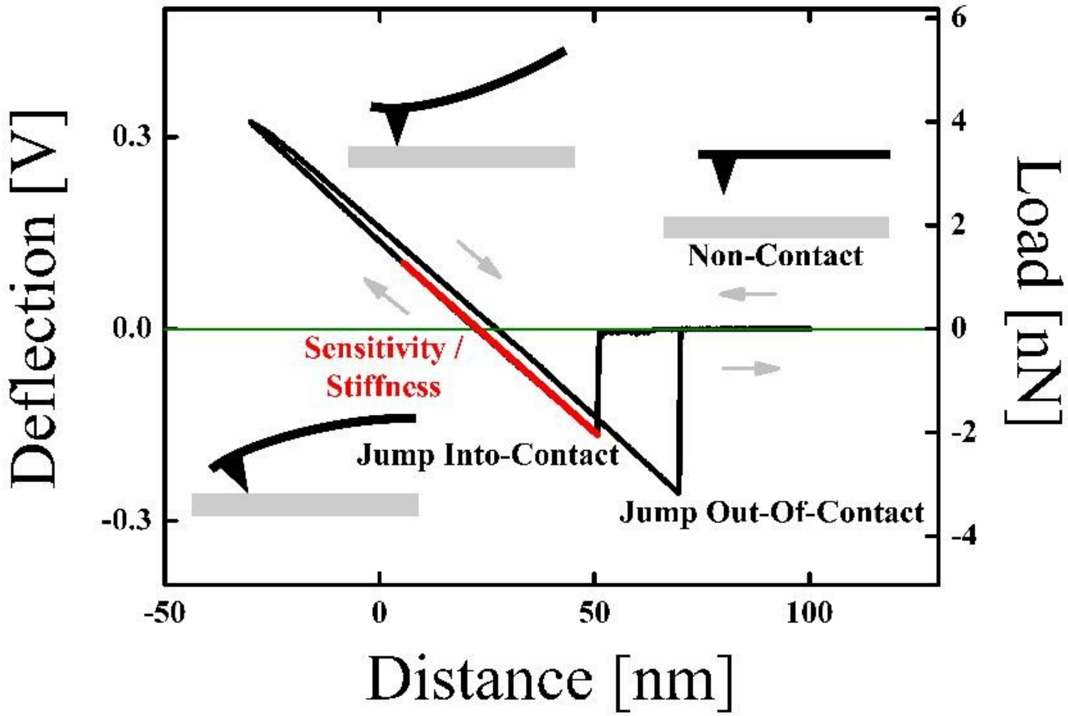
$$\rho = 2.33 \cdot 10^3 \text{ kg/m}^3$$

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

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

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**:

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

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

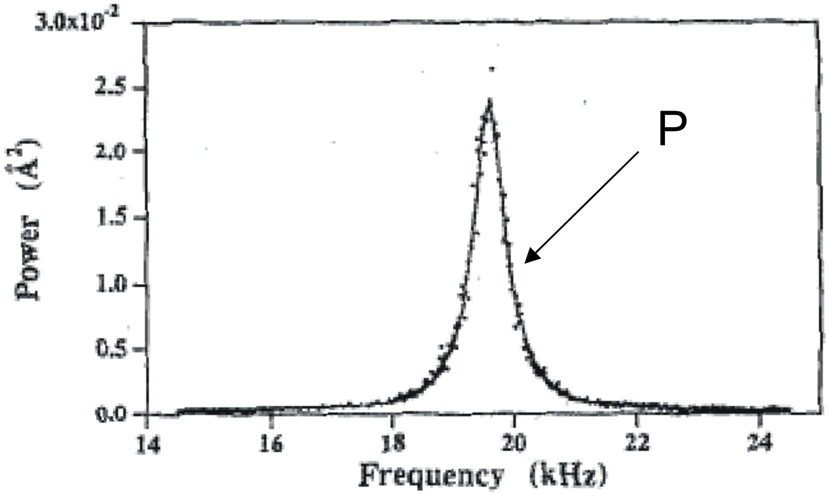
- V_N, V_L: normal and lateral signals

Force Calibration

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

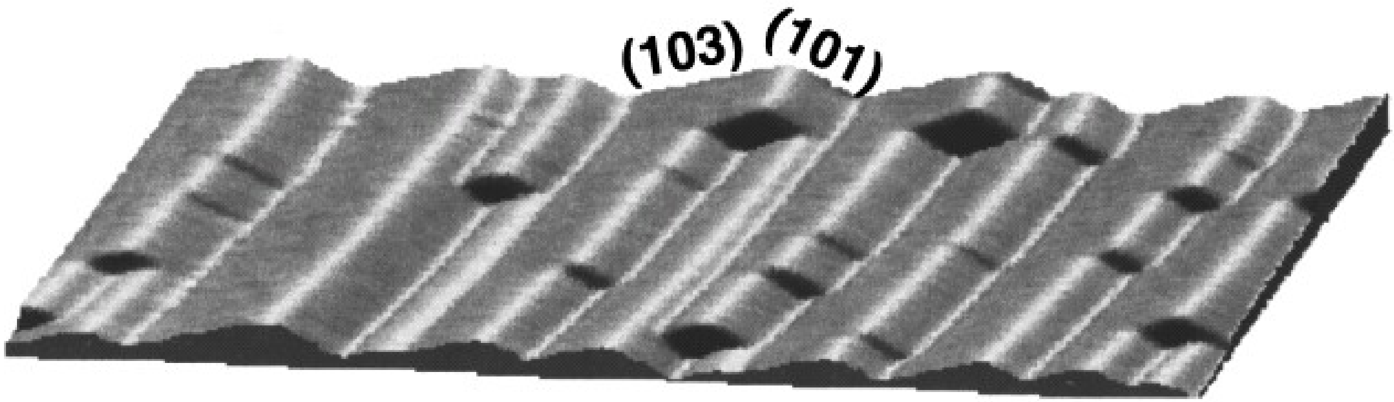
• Correct relation (Butt et al., Nanotech. 1995):

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

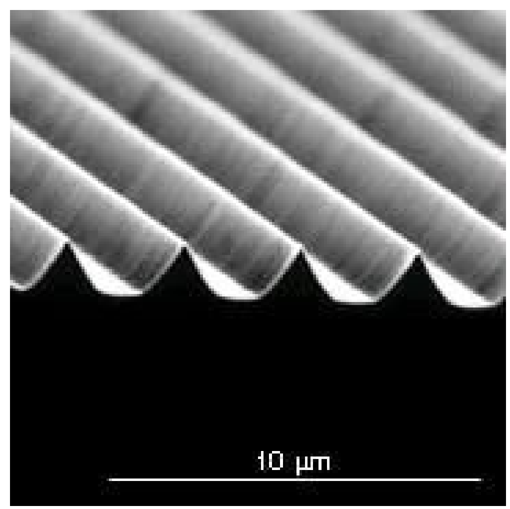


Force Calibration

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



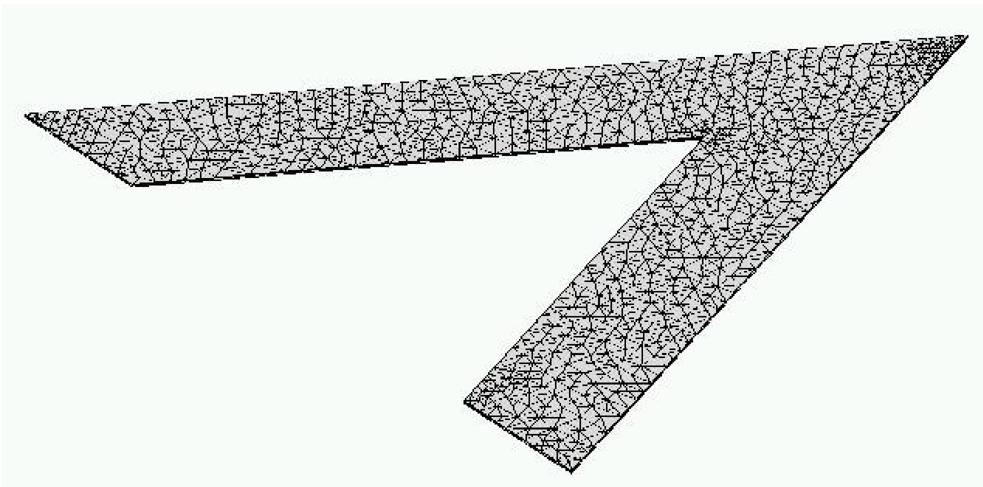
Commercially available grating:

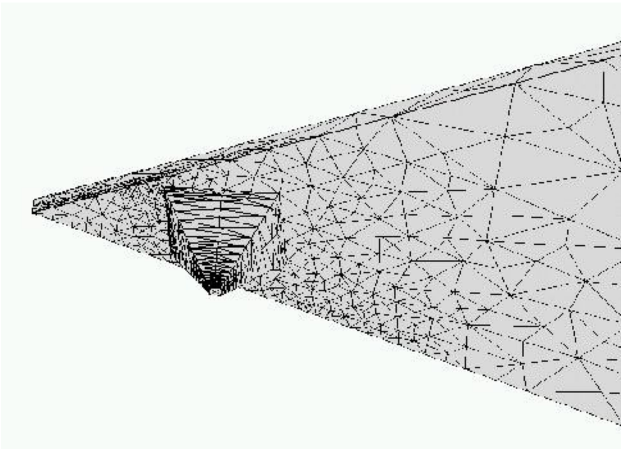


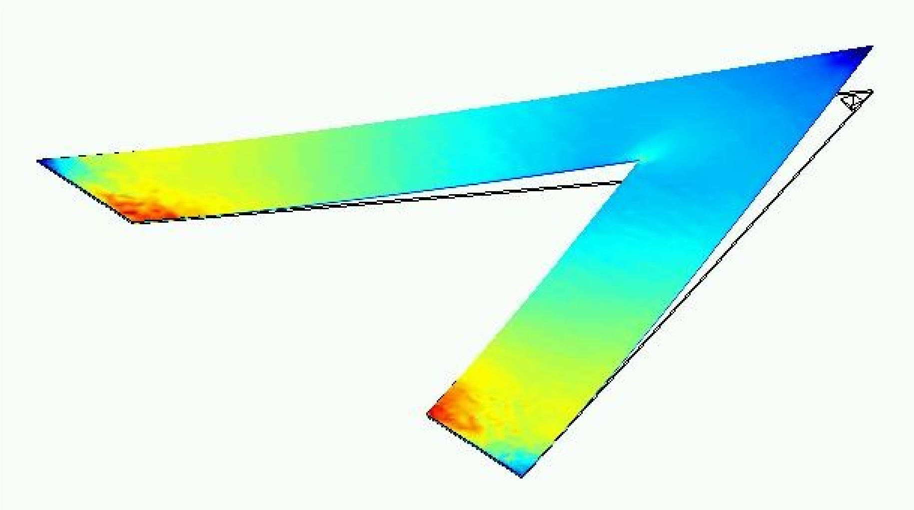
(TGG01, NT-MDT, Moscow)

Force Calibration

- Different shapes → **Finite elements analysis**



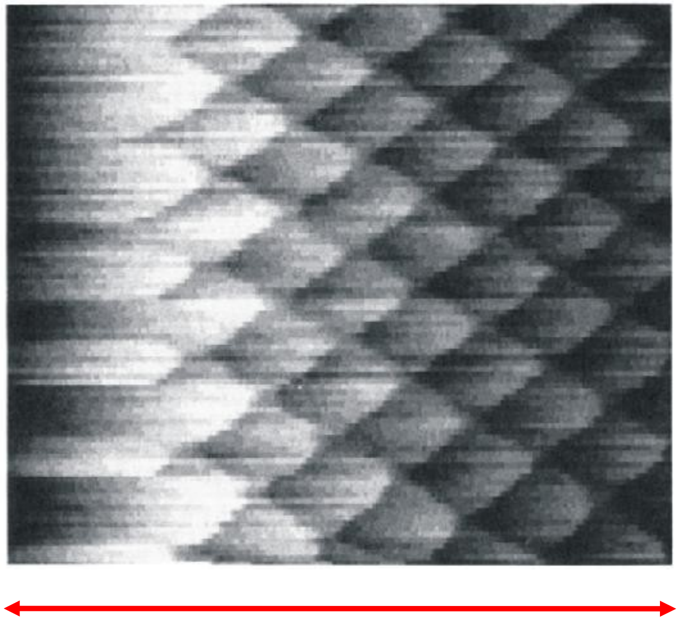


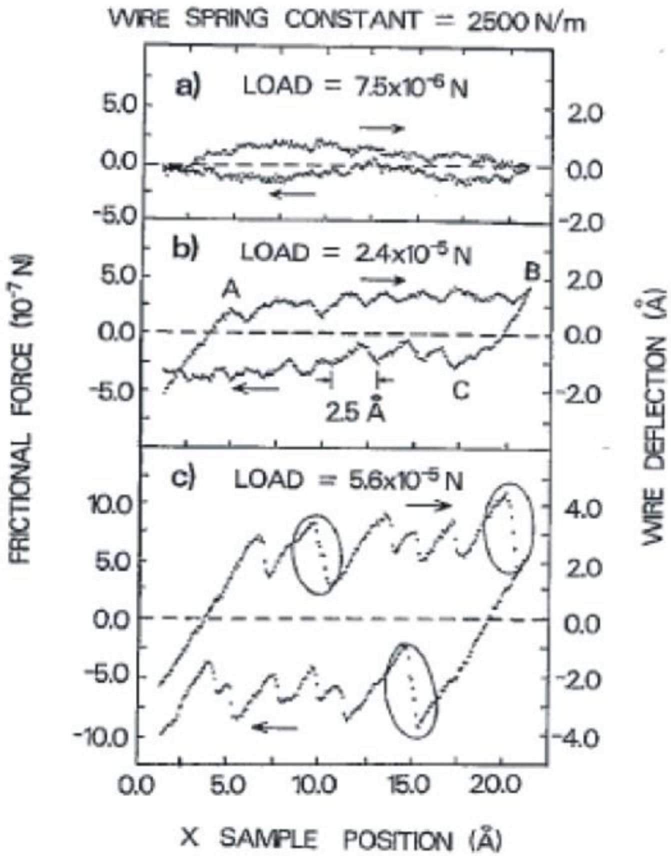


(Femlab™ 3.0)

Atomic-Scale Measurements

- Atomic friction on **graphite**:



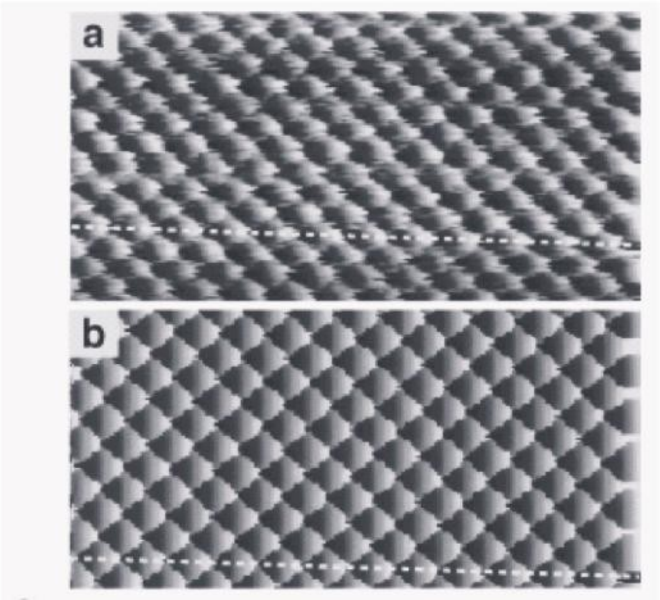


(Mate at al., PRL 1987)

Atomic-Scale Measurements

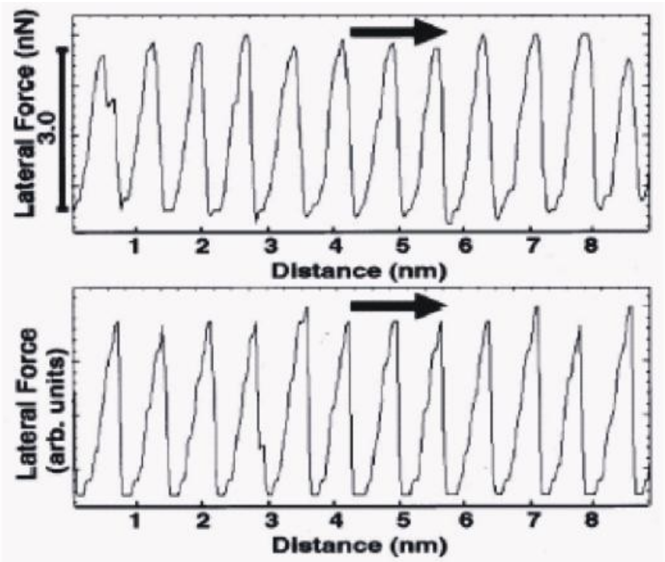
- Friction on **insulating surfaces** (Lüthi et al., JVSTB 1996):

KBr



Exp

Theo

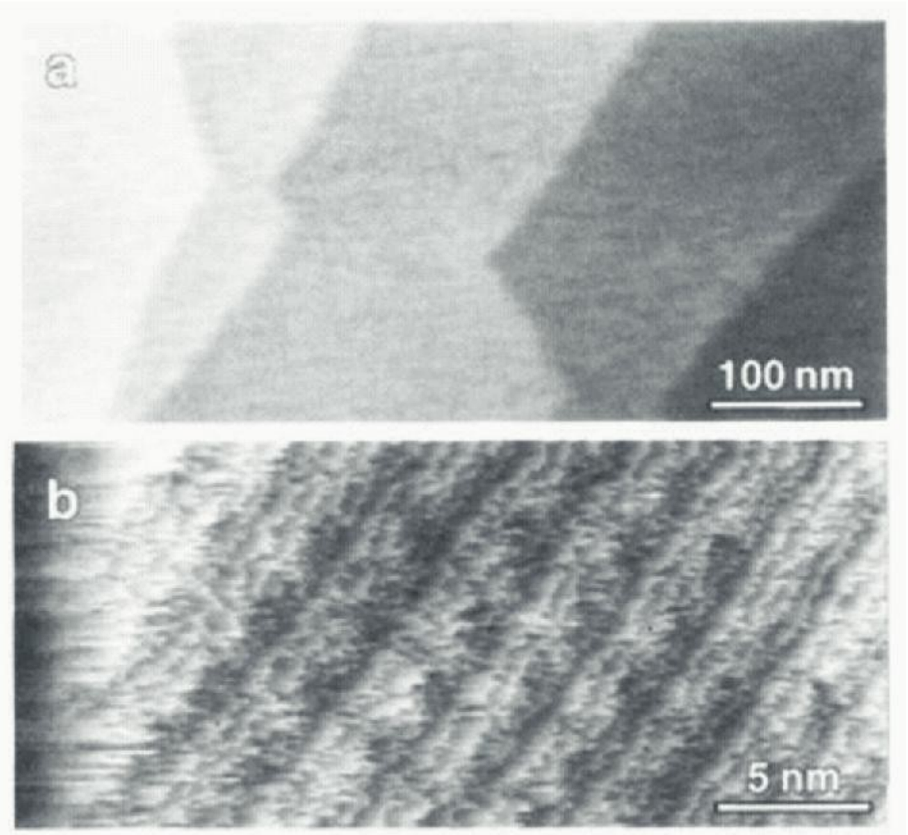


- No individual defects are observed

Atomic-Scale Measurements

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

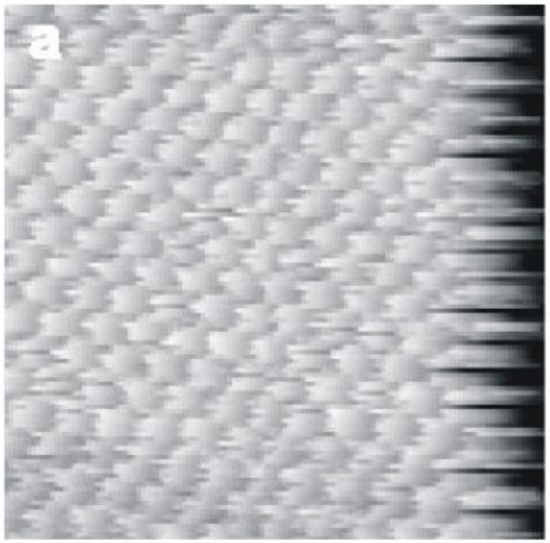
Si(111)7x7



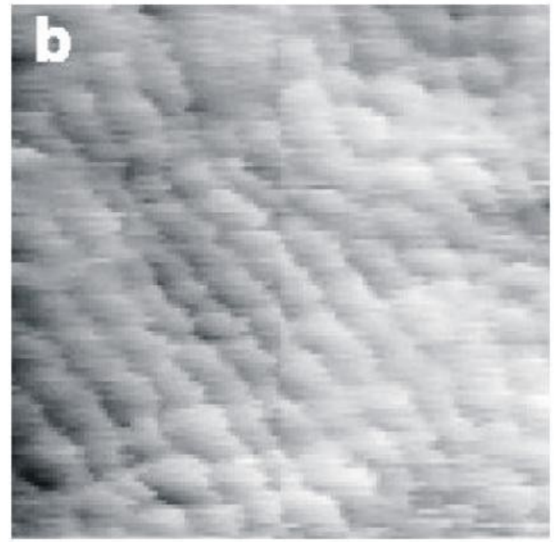
(tip coated with PTFE)

Atomic-Scale Measurements

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



Cu(111)

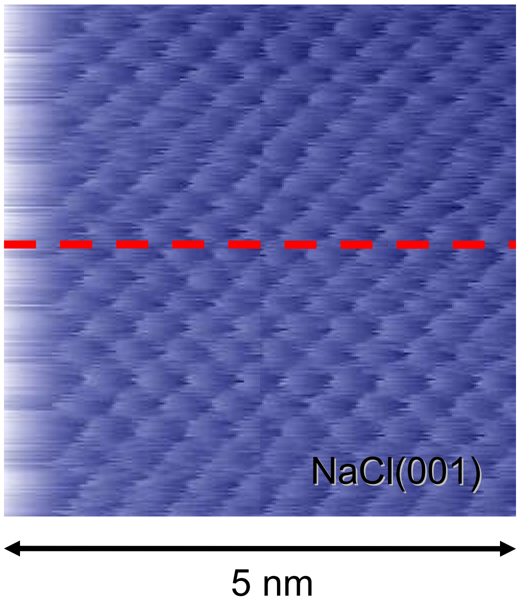


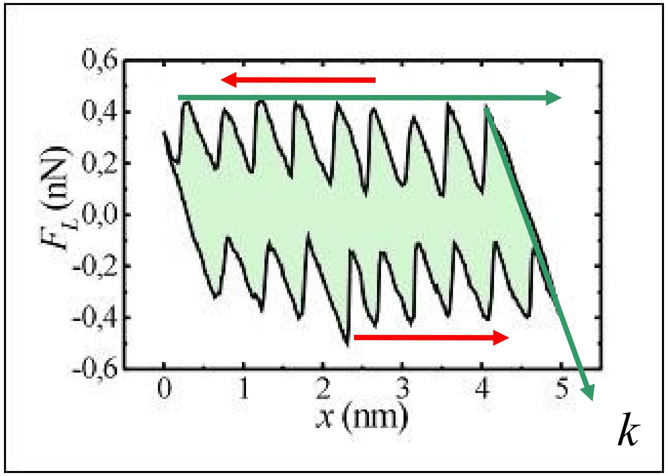
Cu(100)

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

Atomic friction on crystal surfaces

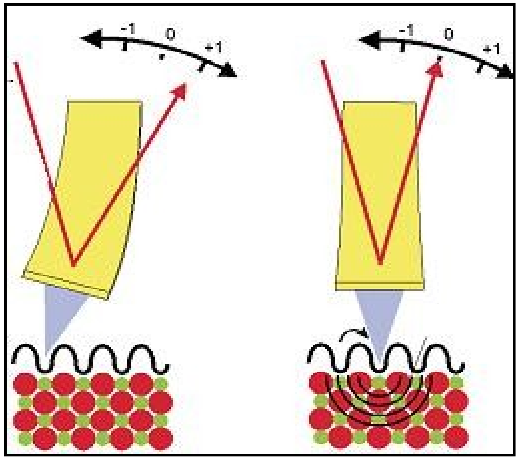
Our model systems: alkali halide surfaces (easy preparation, simple structure)





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

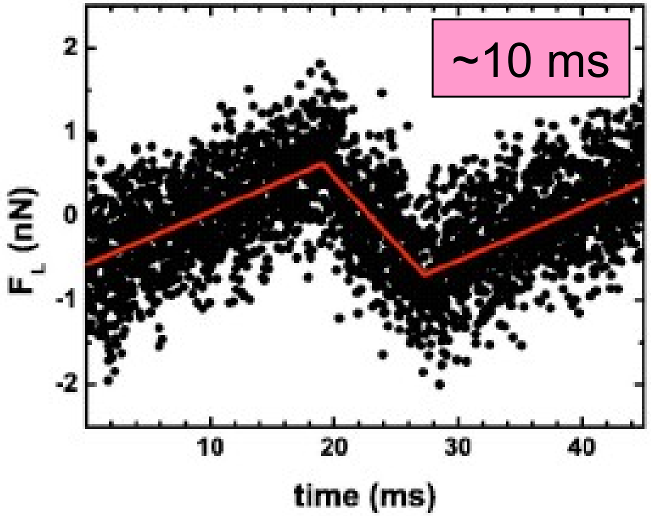
Tomlinson model:
(Phyl. Mag. 1929)

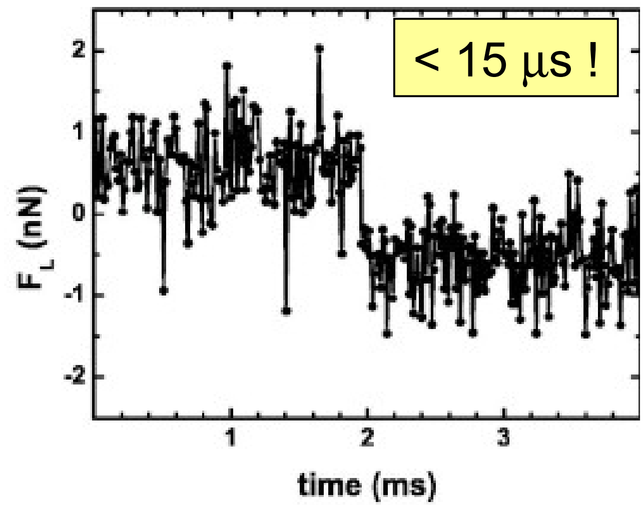


$$V_0 \sim 1\ \mathrm{eV}$$
$$k \sim 1\ \mathrm{N/m}$$

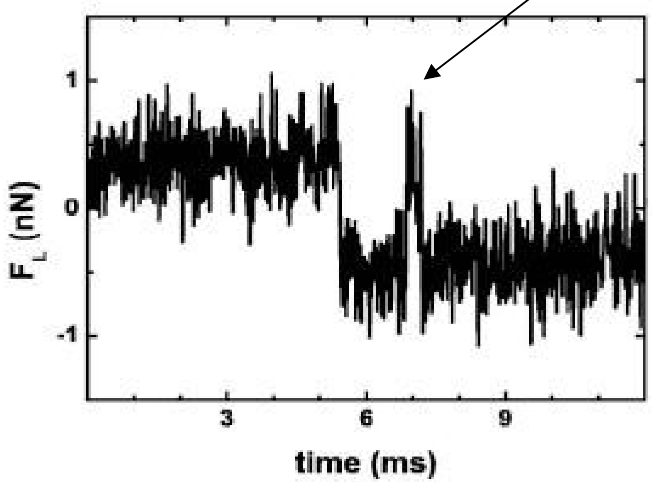
Atomic-Scale Measurements

- Wide distribution of slip durations:





"backjump"



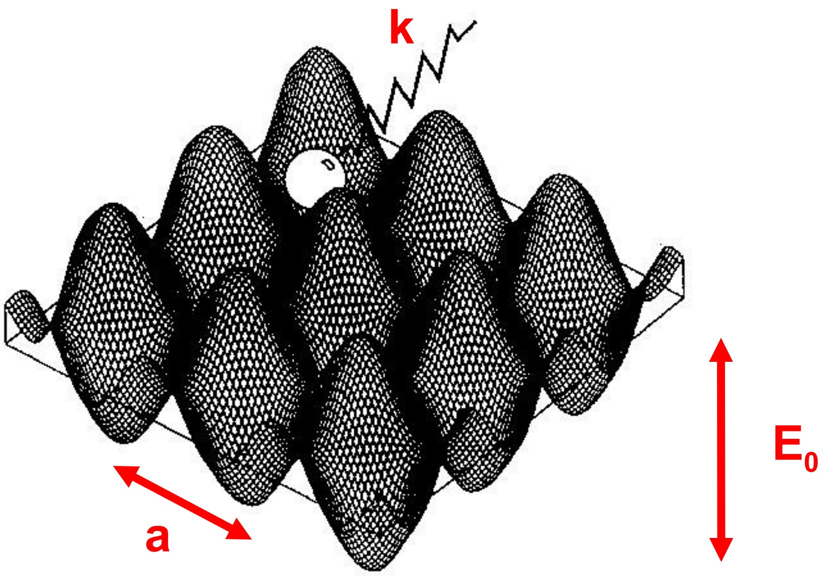
Why?

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

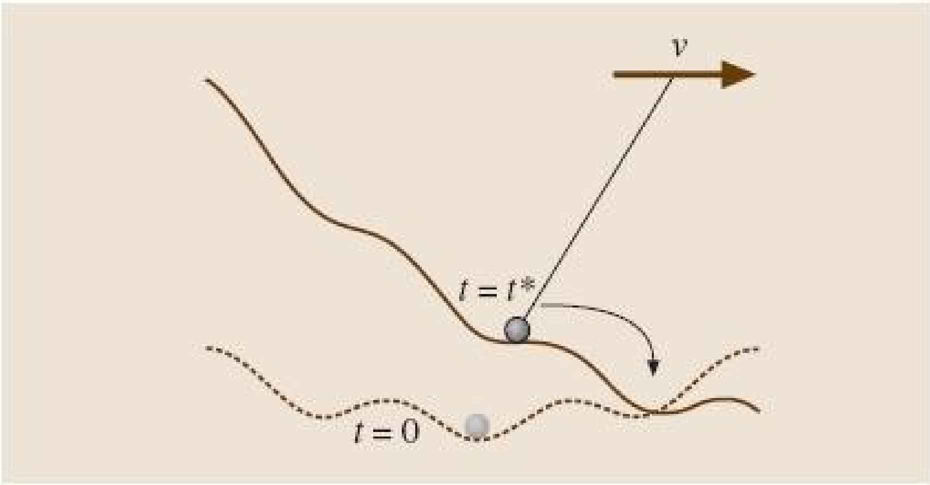
1) a sinusoid

2) a parabola

Modelling Atomic Friction

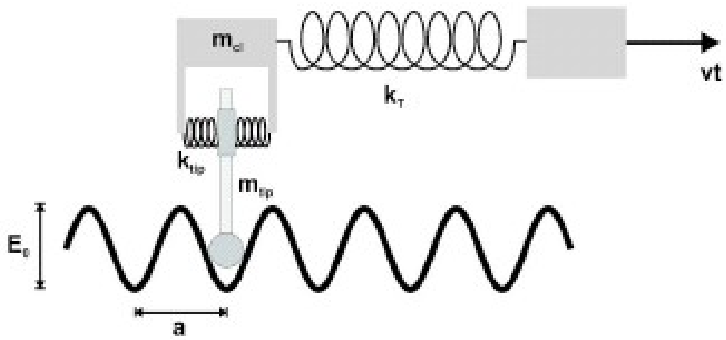
- Total energy of the system:

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



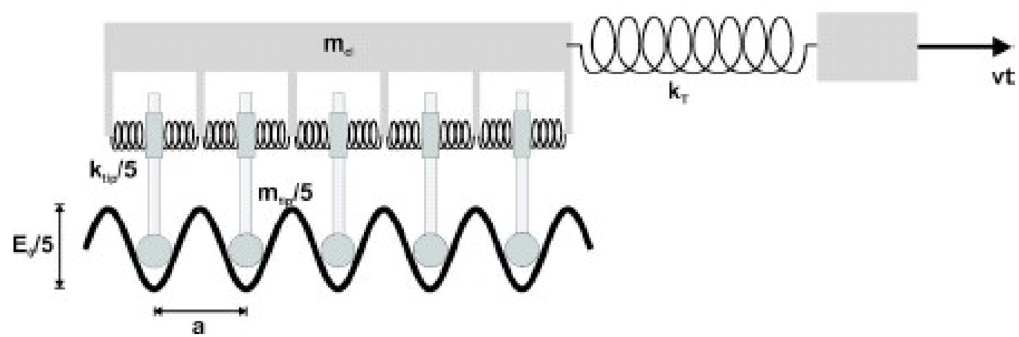
- The tip can "stick" to the minima of the potential profile

Modelling Atomic Friction



single contact

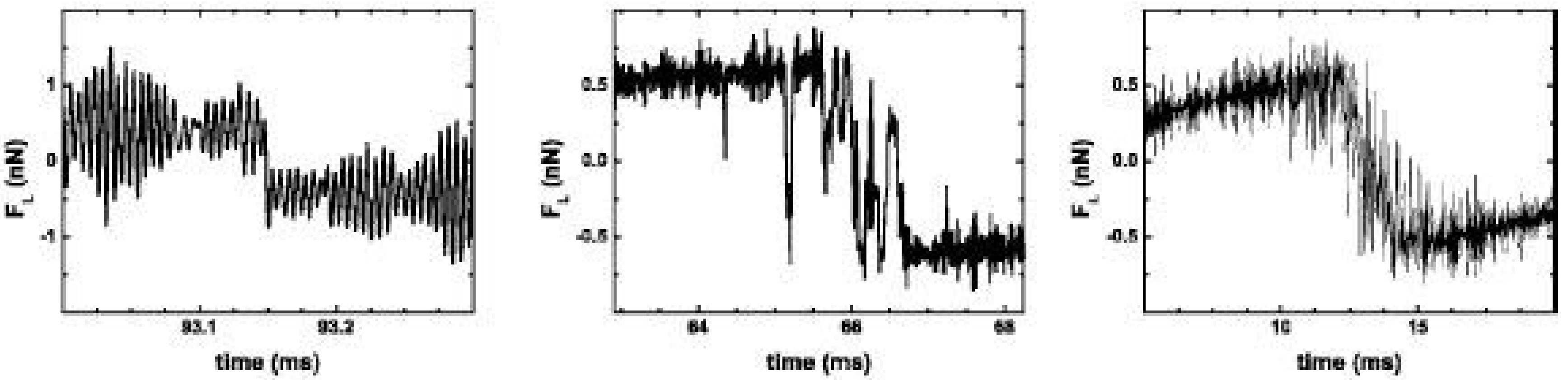
multiple contact



Modelling Atomic Friction

- Tip → Langevin equation (including thermal noise)
- Cantilever → Newton equation (without thermal noise)

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



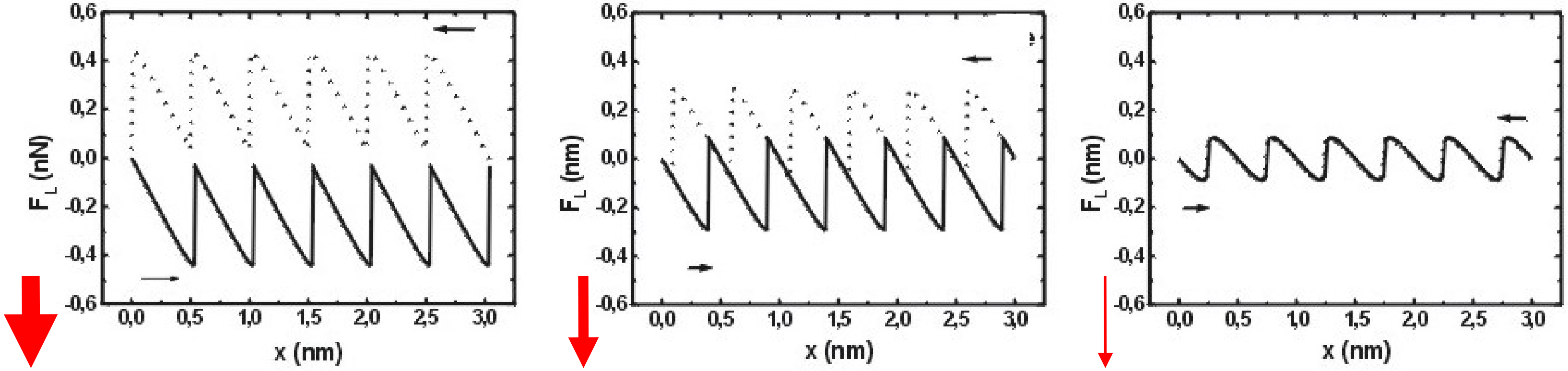
- Long slip times are found with multiple tips only

(Maier et al., PRB 2005)

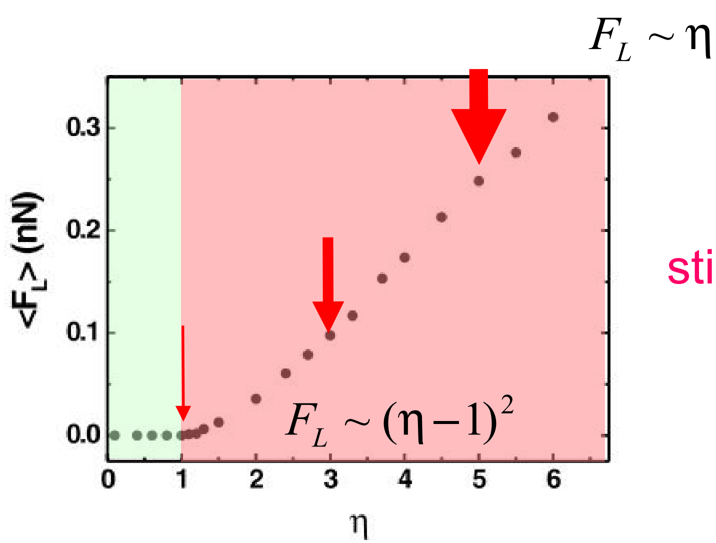
Superlubricity

- From the Tomlinson model (without thermal activation):

$\eta > 1$ **$\eta < 1$**



superlubric regime

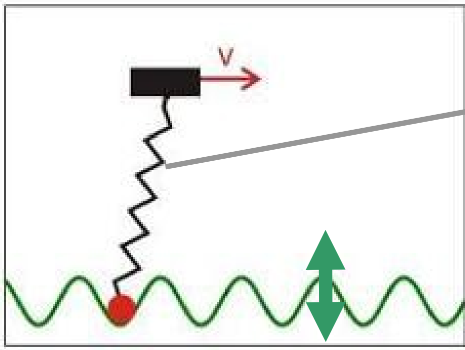


stick-slip regime

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

"Dynamic superlubricity"

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



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

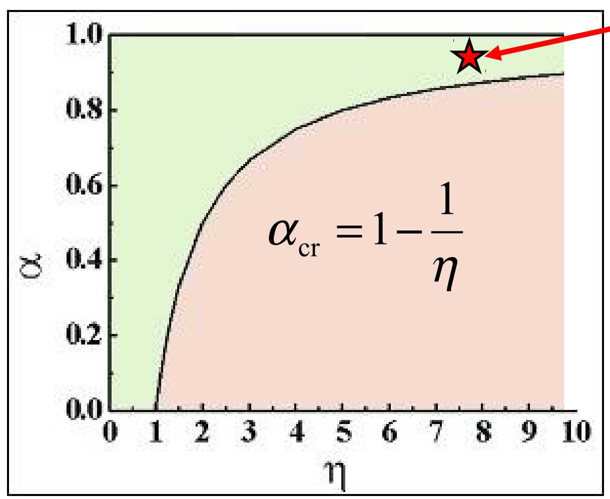
$$V_{\mathrm{int}} = V_0 \cos\frac{2\pi x}{a}$$

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

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

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

Phase-diagram in the η–α plane:

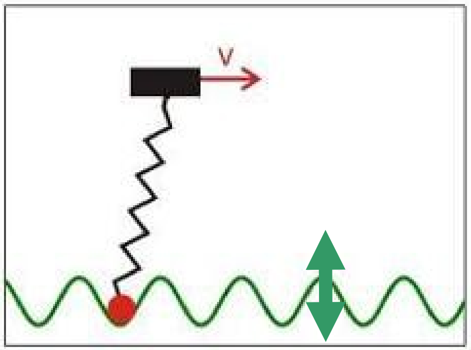


High loads can be applied!

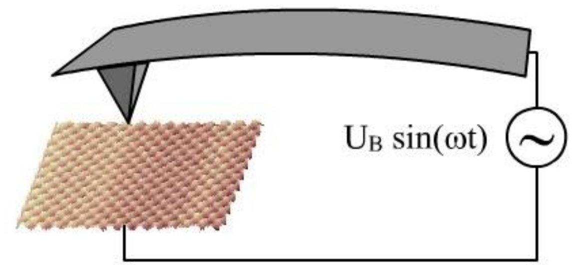
E. Gnecco et al., J. Phys.: Condens. Matt. a20 (2008) 354004

“Dynamic superlubricity”

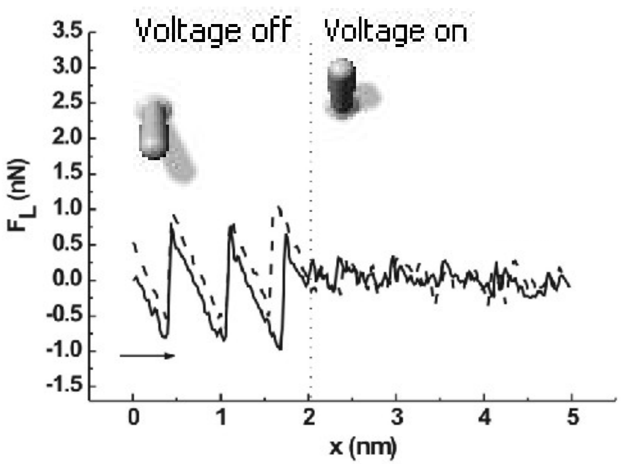
A third way to reduce friction: Tomlinson model with TIME modulation

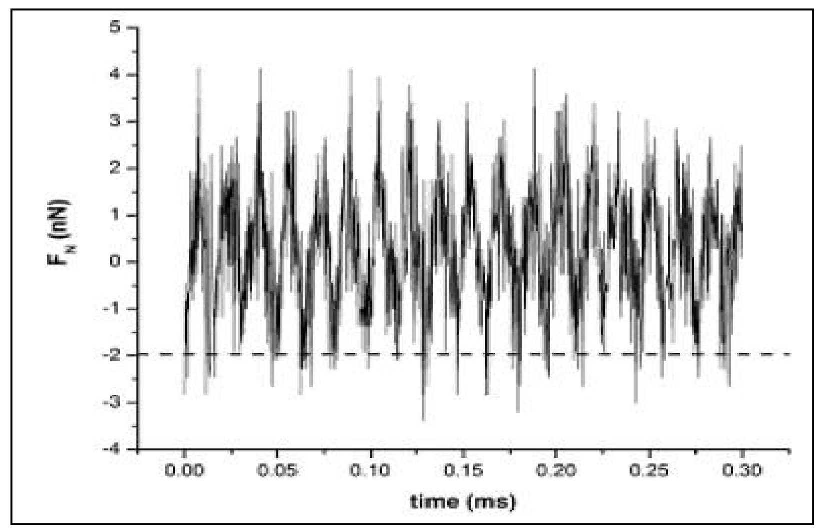


AC actuation
of the nanocontact:



NaCl(001)





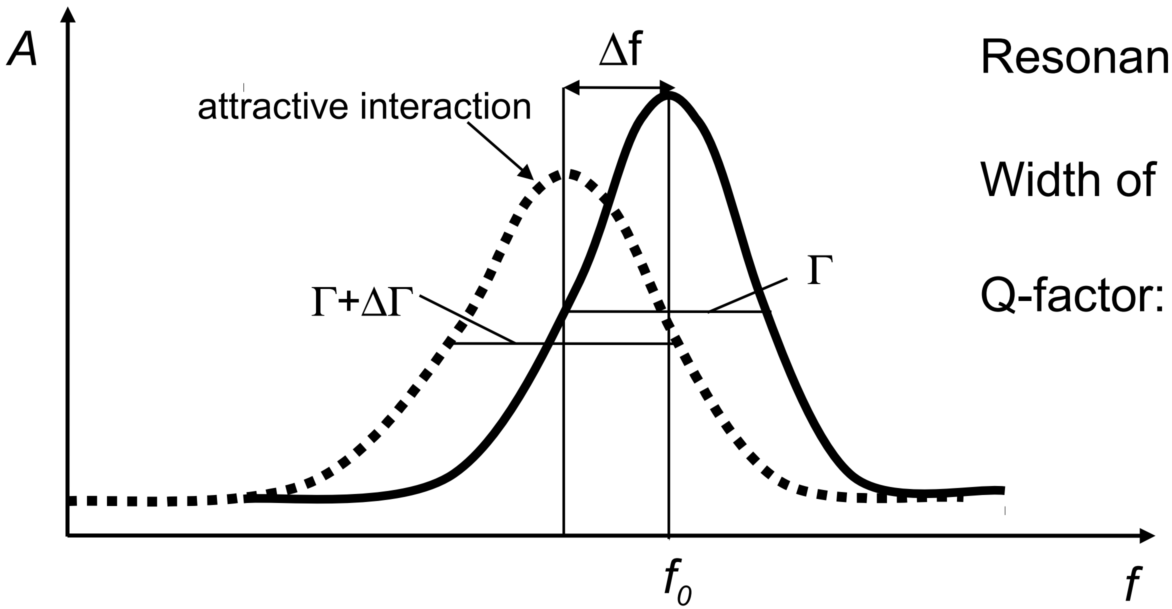
A. Socoliuc et al., Science 313 (2006) 207

Wieviel Kraft braucht man für einen molekularen Schalter?

Noncontact-AFM (nc-AFM)

- UHV: Base pressure below $1x10^{-10}$ 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 $\Rightarrow$ shift of resonance curve Δf

Dissipative forces $\Rightarrow$ broadening of curve $\Delta\Gamma$

Forces in nc-AFM

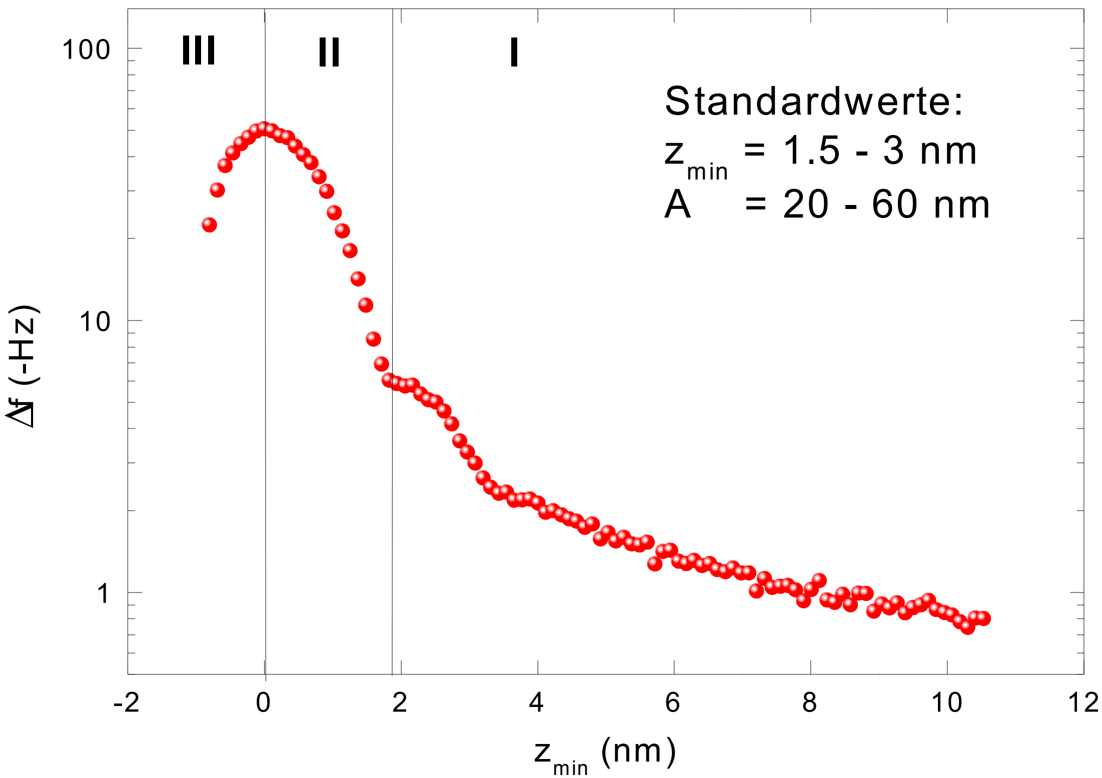
Frequency modulation: $f_0 = \frac{1}{2\pi}\sqrt{\frac{k}{m^*}}$ $\Delta f = -\frac{f_0}{2k}\frac{\partial F_{tot}}{\partial z}$

$\Rightarrow$ 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

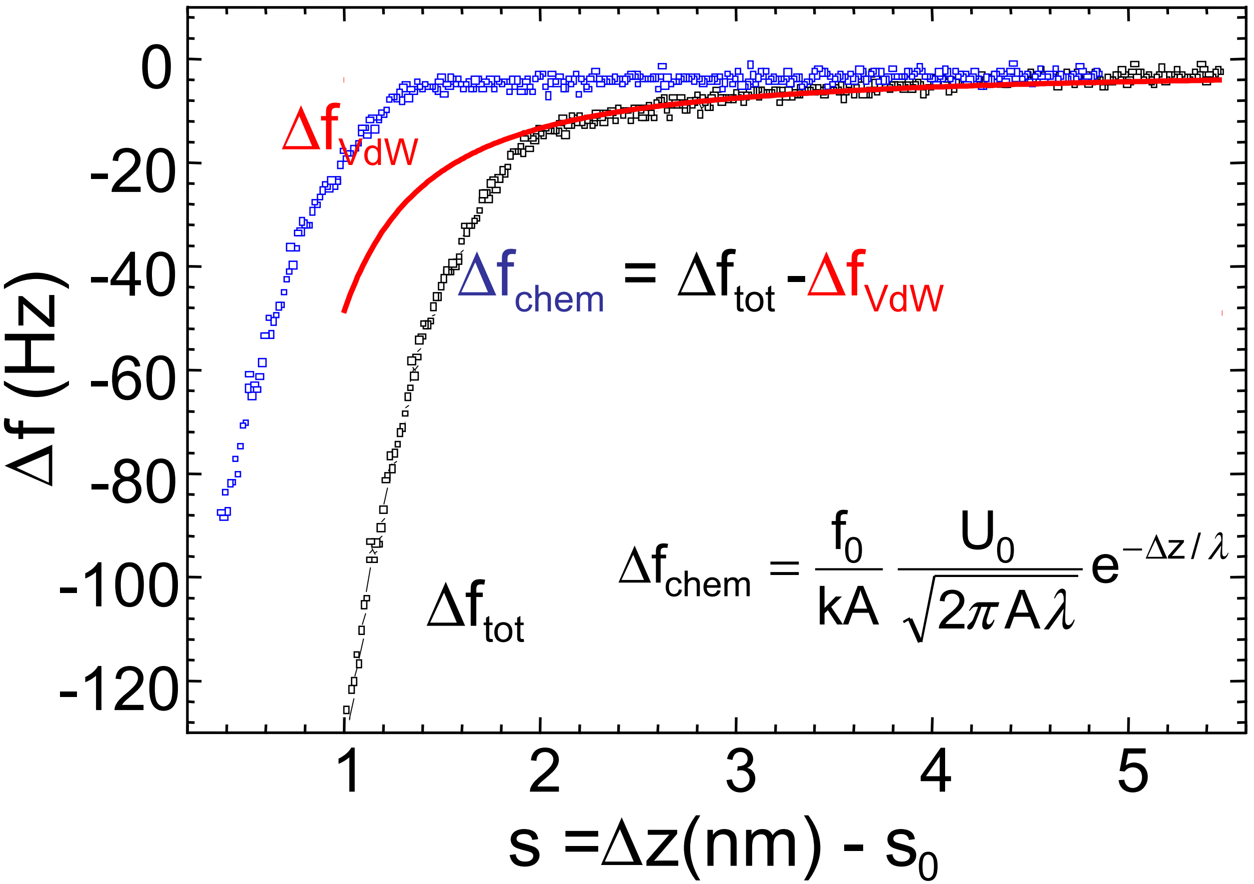


region I:
attractive forces
non-contact mode

region II:
attractive forces
atomic resolution

region III:
repulsive forces
tapping mode

Short range interaction



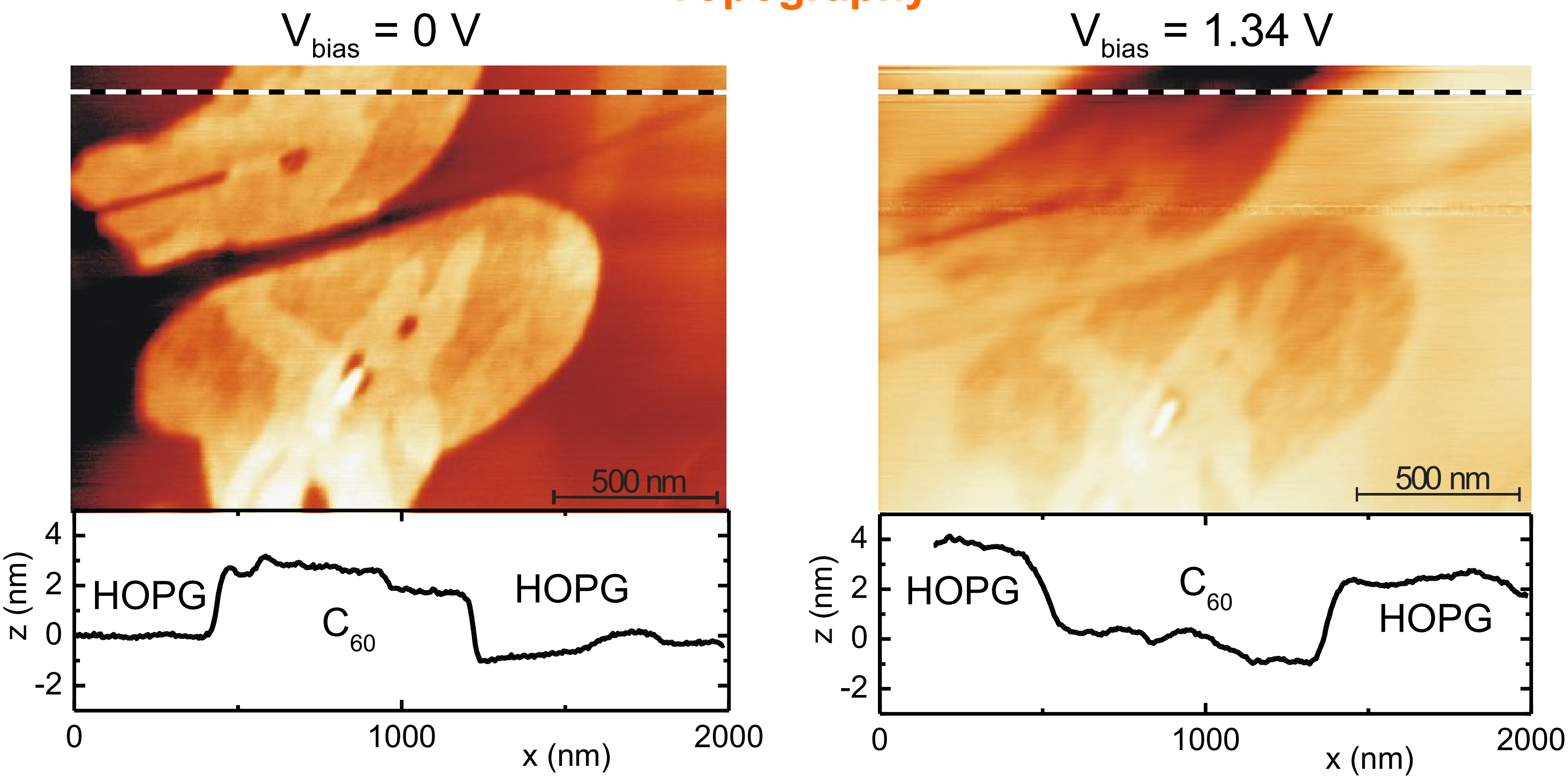
λ = 0.35 nm

U_0 = -4.7 eV

s_0 = 0.45 nm

inhomogeneous sample: HOPG + ½ monolayer C60

Topography

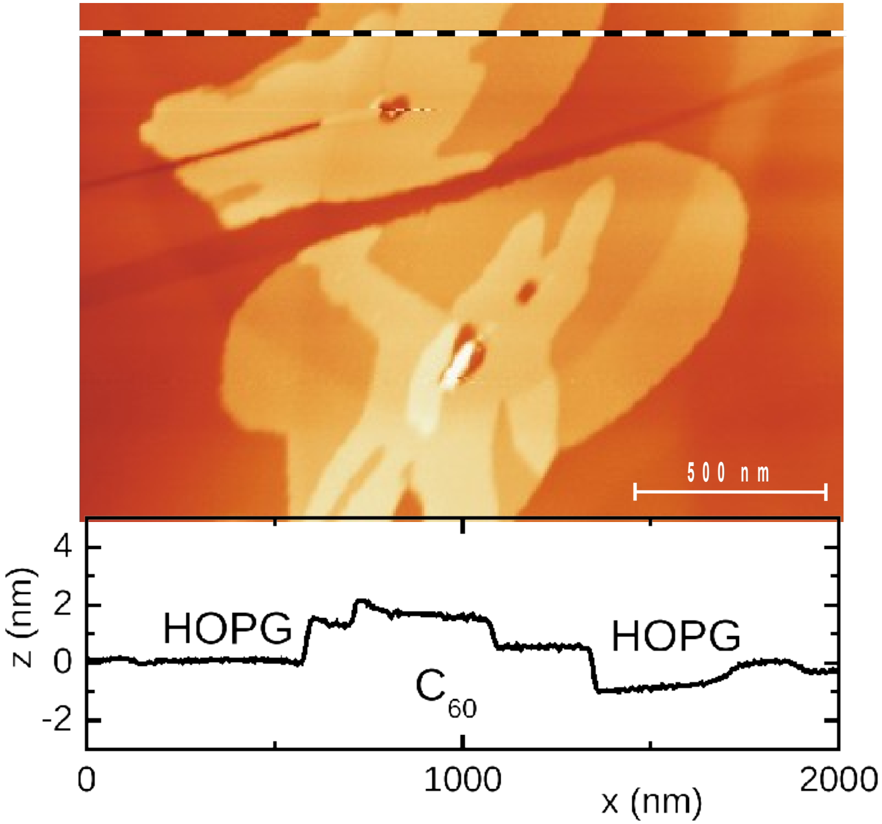


→ contrast inversal: HOPG ↔ C_{60}

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

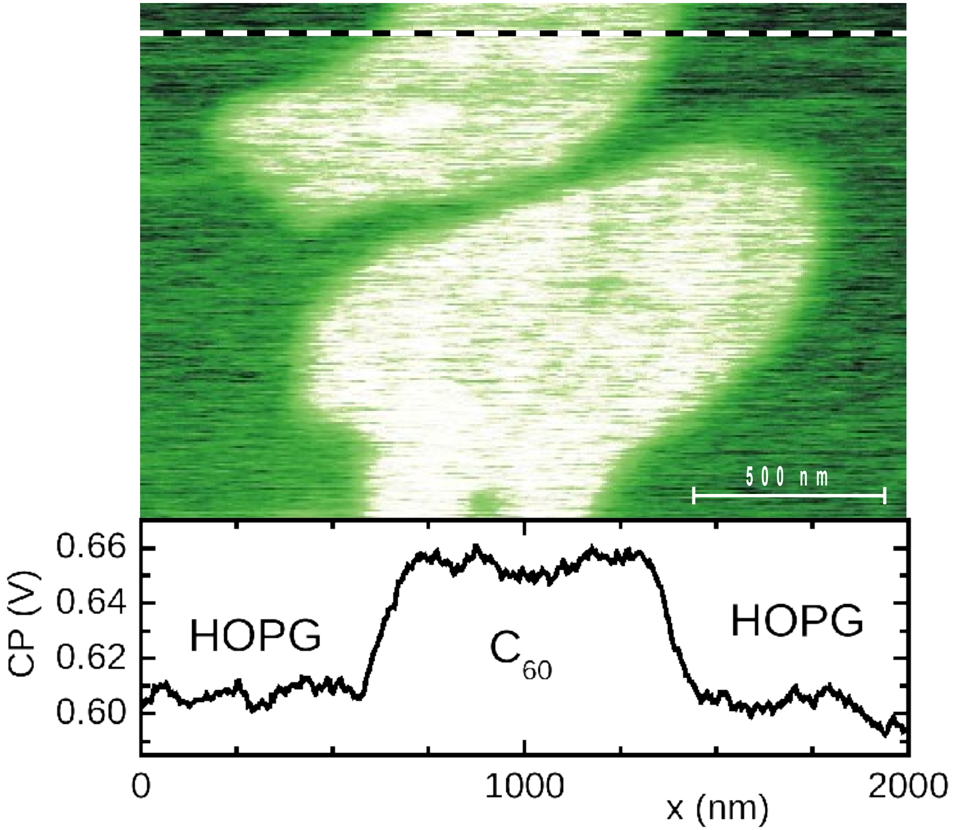
inhomogeneous sample: HOPG + ½ monolayer C60

topography



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

contact potential

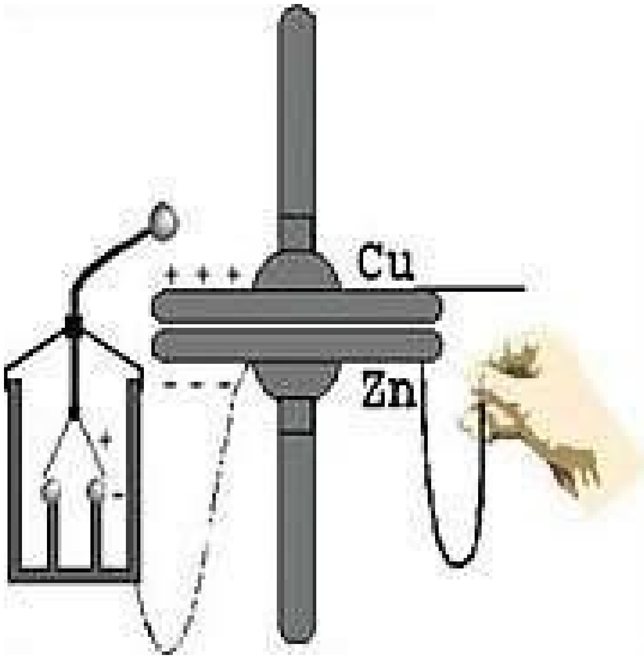


C_{60}: $V_{CP} \cong 0.66$ V

$\Rightarrow$ NC-AFM: residual electrostatic force for fixed V_{bias}

Makroskopische Kelvin-Sonde

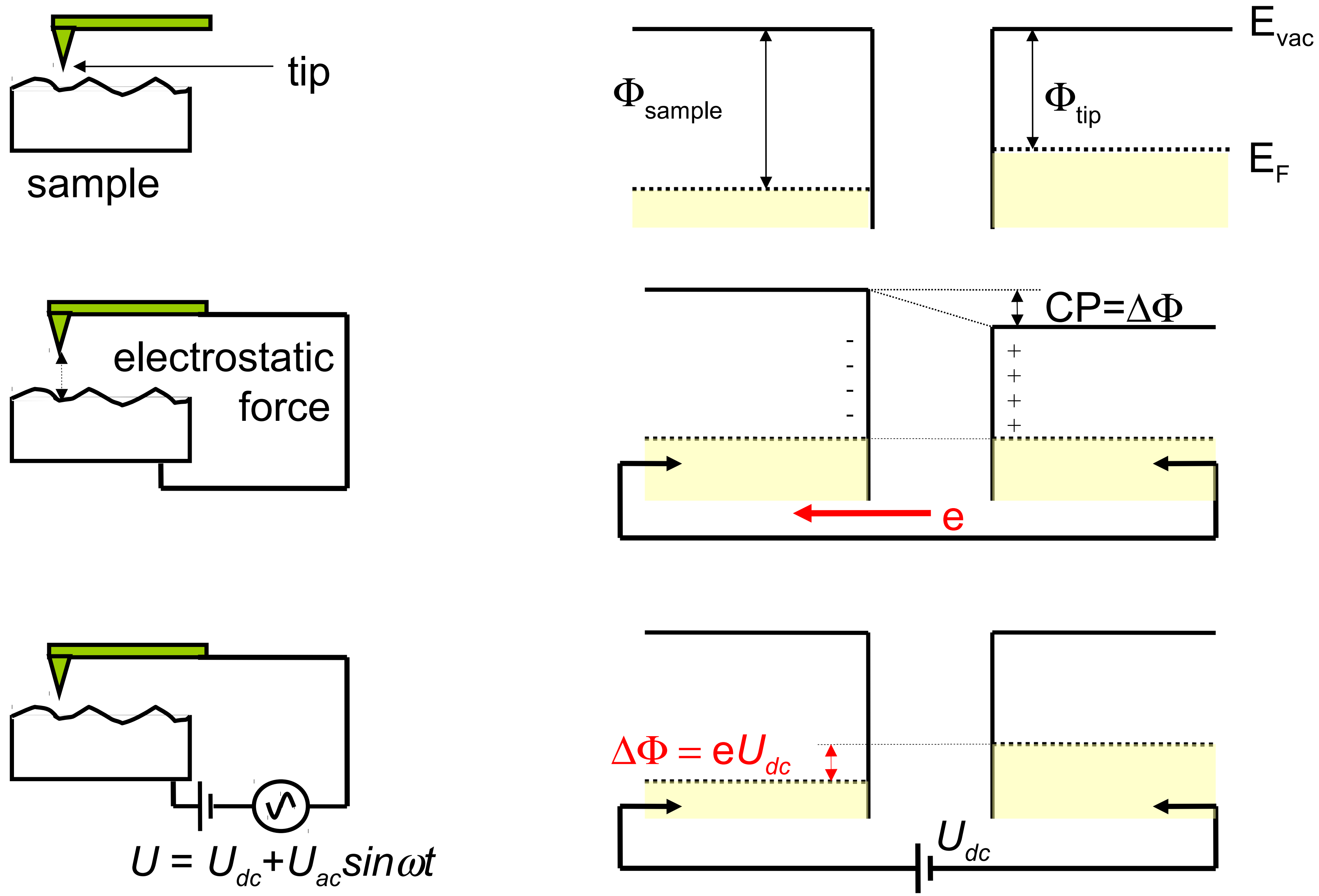
Lord Kelvin 1861



Verschiebestrom

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

Kelvin Principle



Electrostatic Forces in nc-AFM

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

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

contact potential

Φ - work function

apply bias:

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

Kelvin Probe Force Microscopy

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

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

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

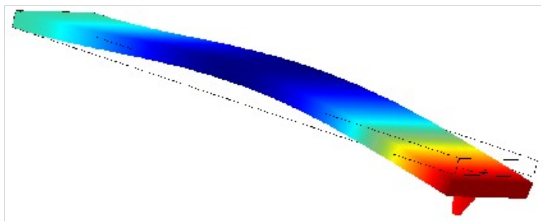
$$F_{2\omega} = \frac{\partial C}{\partial z}\frac{V_{ac}^2}{4}\cos(2\omega t)$$

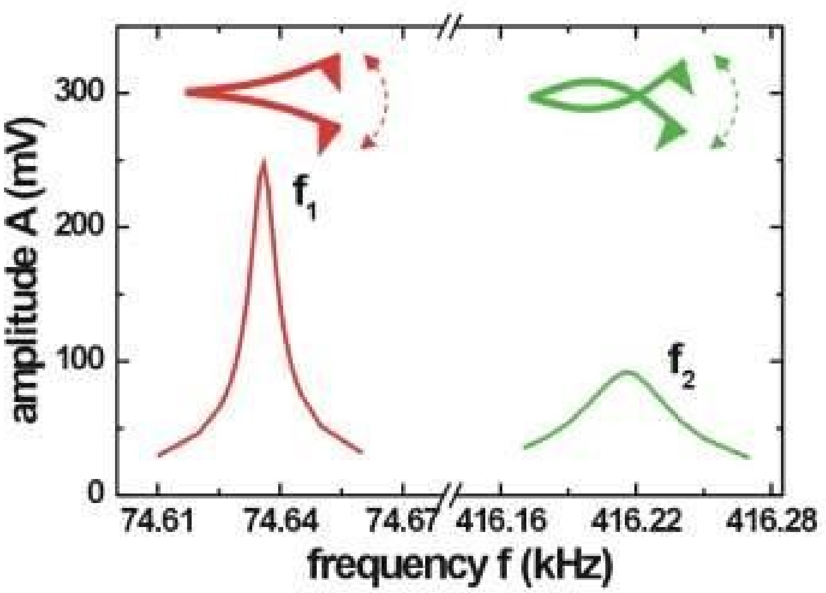
AM-KPFM
Amplitude Modulation

FM-KPFM
Frequency Modulation

AM – KPFM
Amplitude Modulation Detection

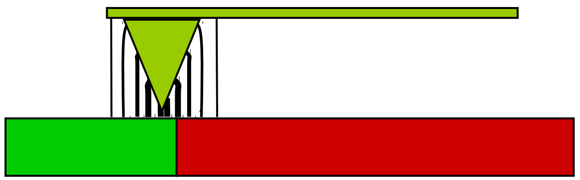
$$F_\omega = -\frac{\partial C}{\partial z}\left(V_{dc} - V_{CP}\right) V_{ac} \sin(\omega t)$$



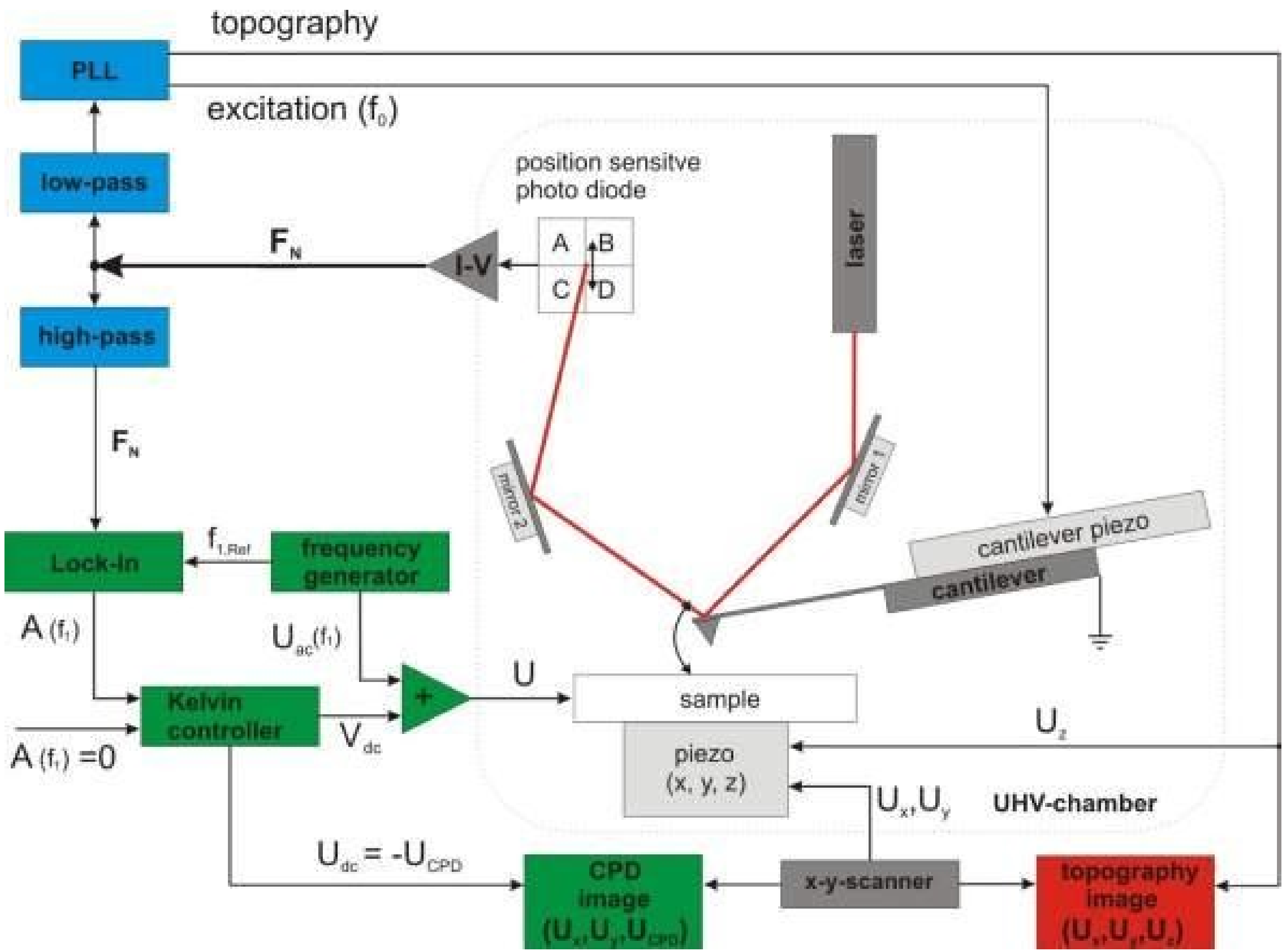


- tune ω to the second resonance f_2
- detection of the oscillation amplitude A_ω with a lock-in
- limiting factor: bandwidth of the photodiode

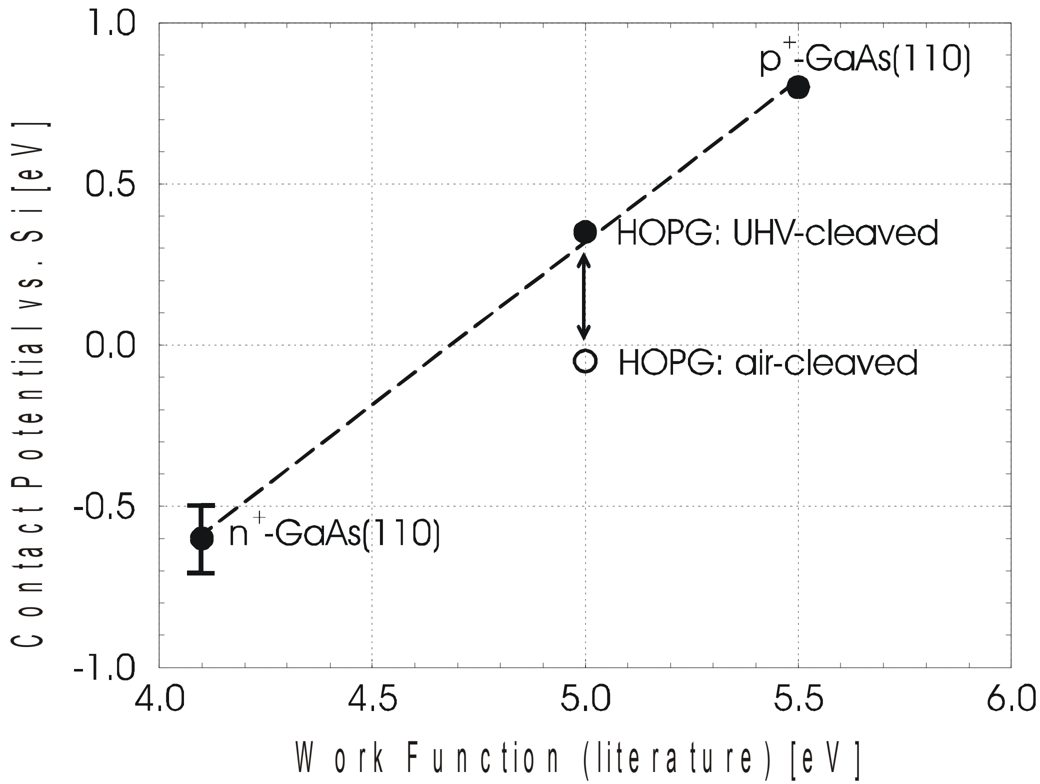
$$A_\omega \propto F_\omega$$



Experimental Setup
nc-AFM & AM-KPFM



KPFM calibration and absolute work function



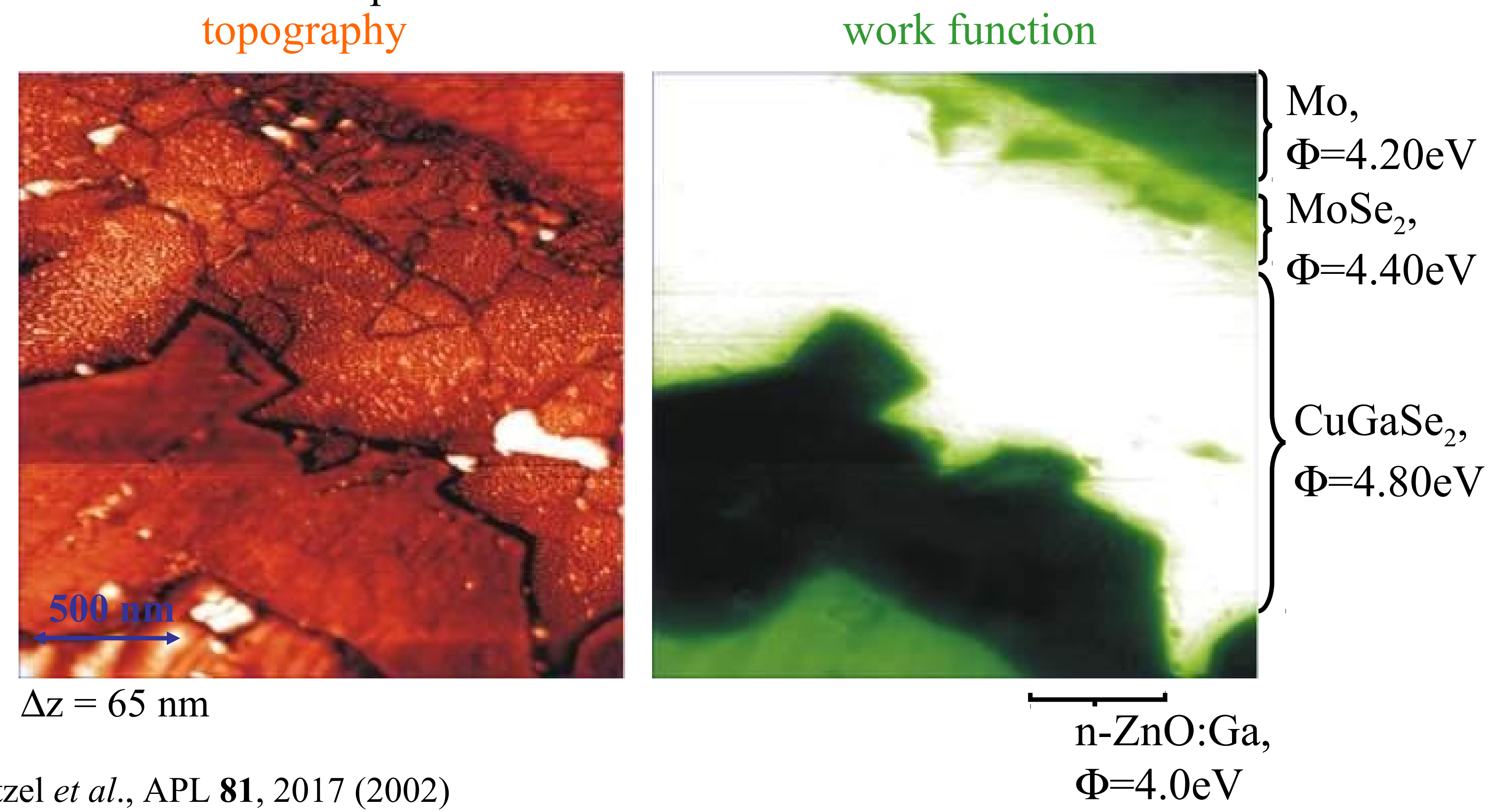
Φ-Si-Cantilever = 4.70 (±0.1) eV **U_{ac} = 100 mV**

→ 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 %

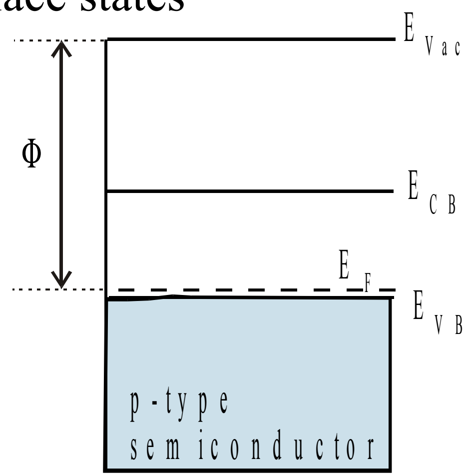
polished and Ar-ion sputtered cross section



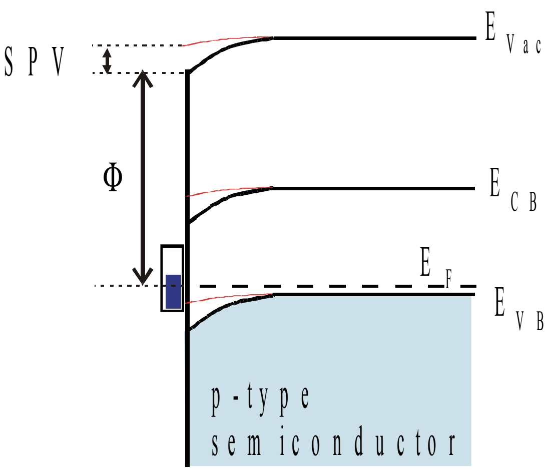
Glatzel *et al*., APL **81**, 2017 (2002)

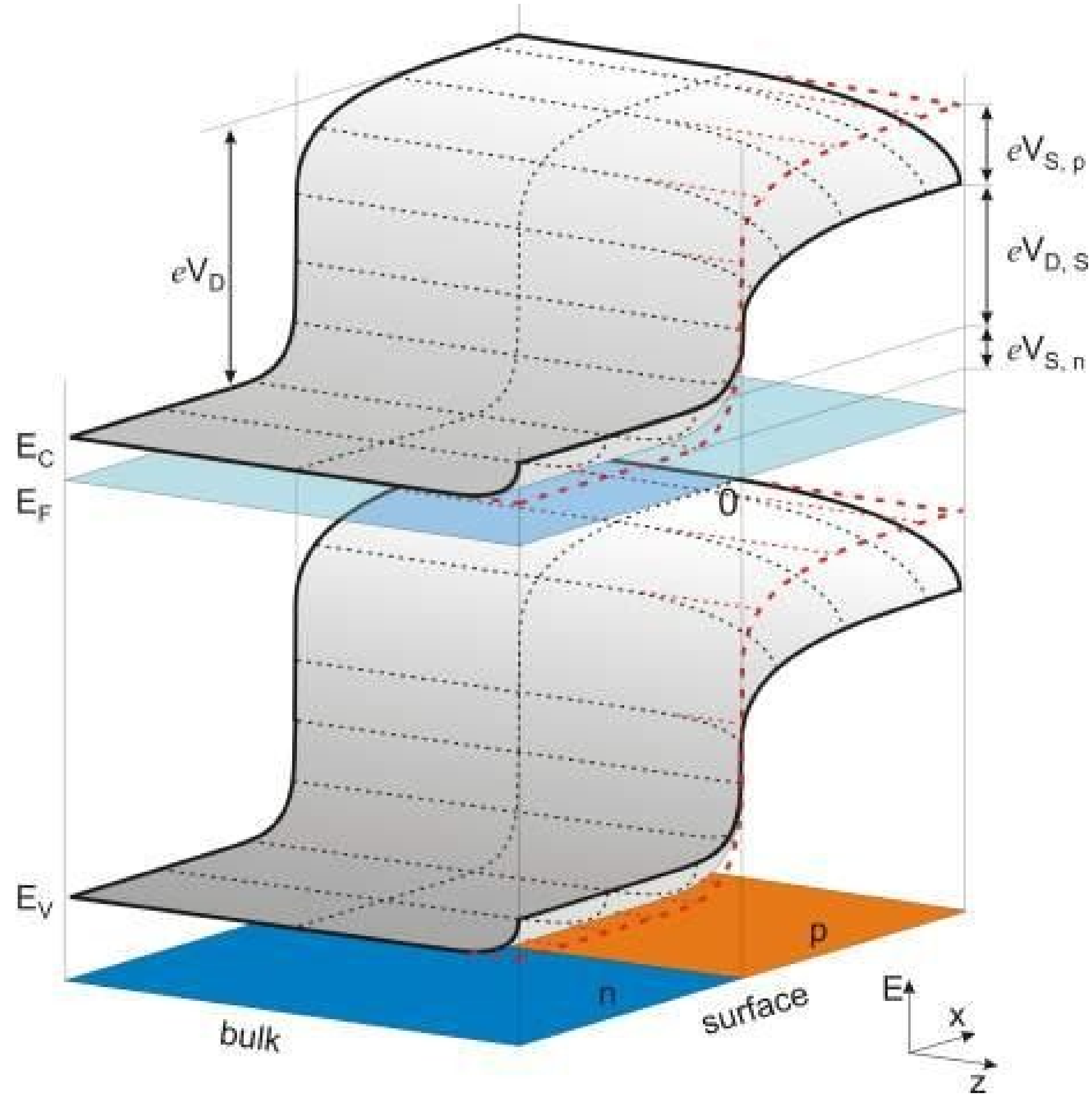
Surface Effects

no surface states

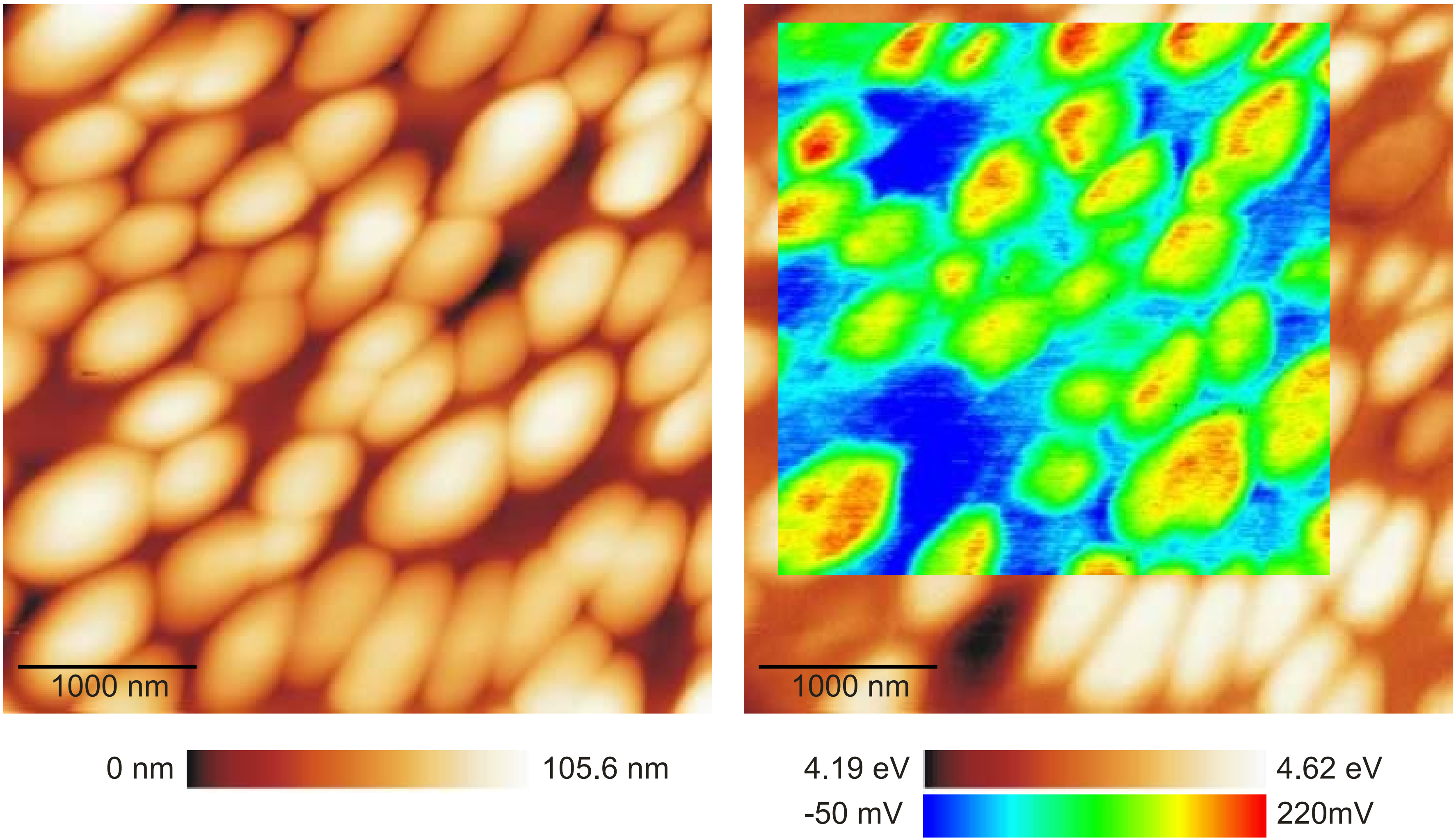


surface states



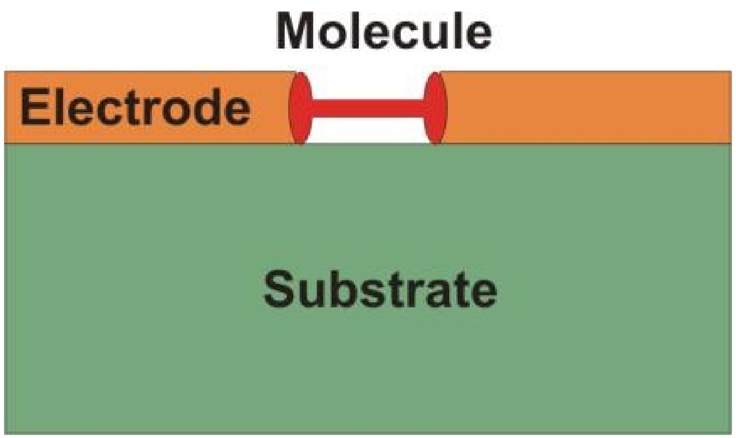


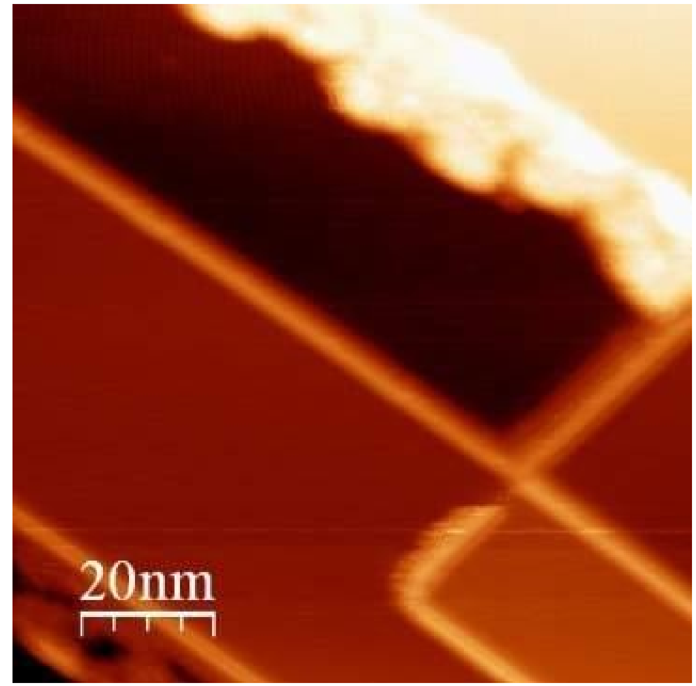
Surface Photovoltage
MDMO-PPV/PCBM – 675nm



Motivation

Molecular electronics



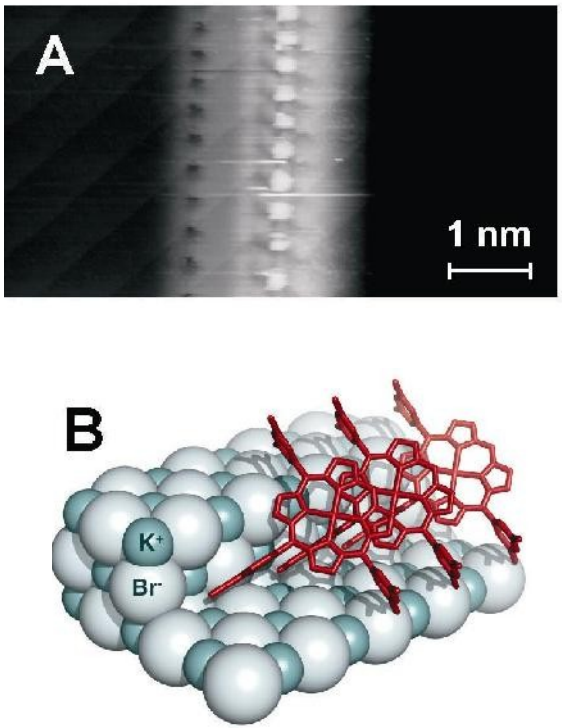


Molecules on Insulators:

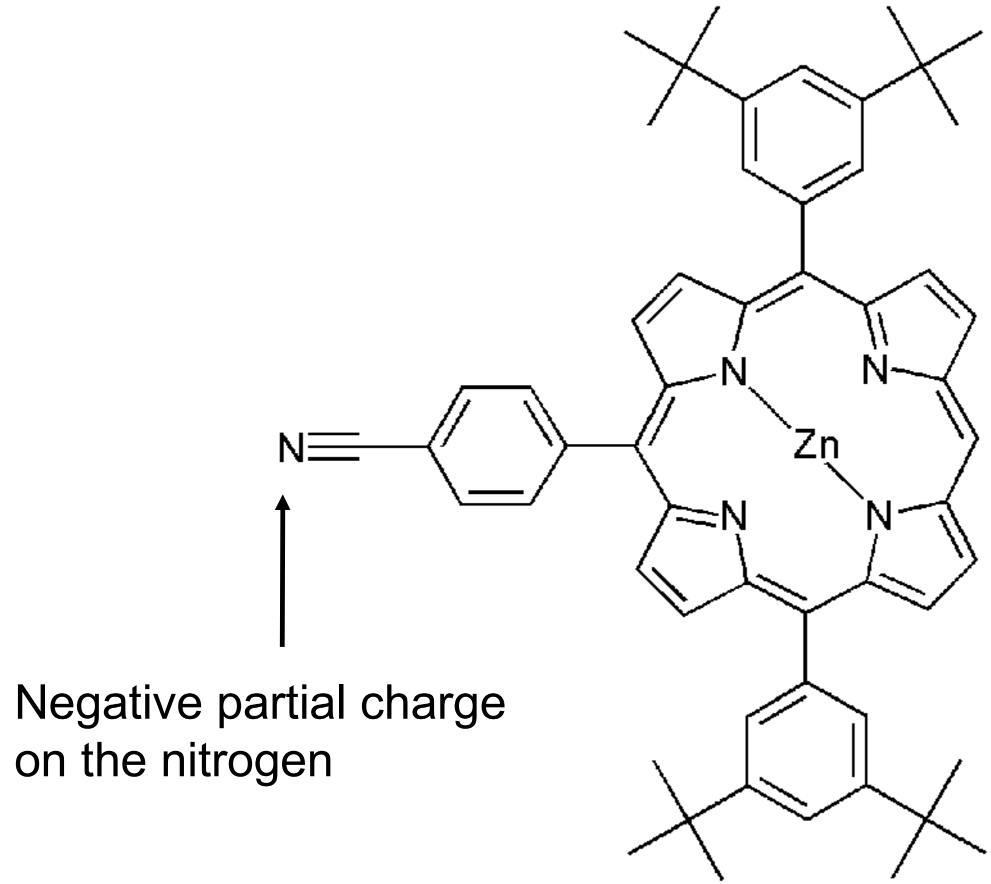
- No STM possible – nc-AFM mandatory
- Low diffusion barrier but high intermolecular interaction
- Low temperatures – easier to “fix” molecules but not so easy to find applications

Asymmetric Cyano-Porphyrins

Natural light harvesting complexes



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

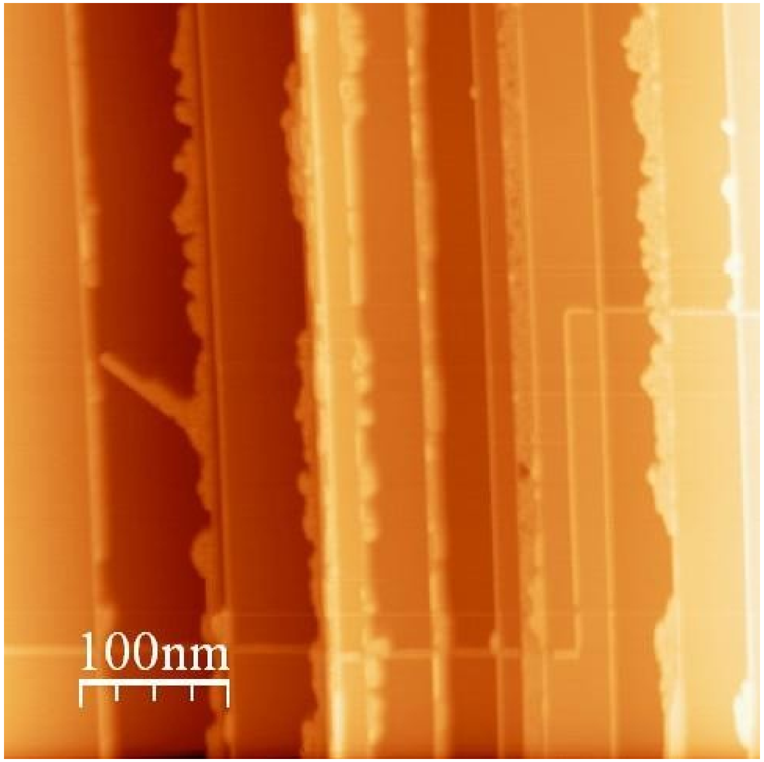


Balaban et al., *Acc. Chem. Res.* **2005**, 38, 612 – 623

Wire Formation

Decoration of step edges on KBr(100)

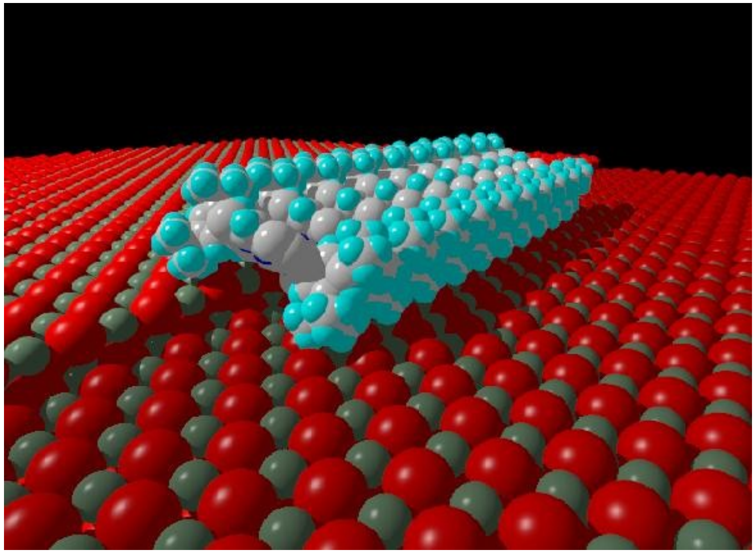
- In situ cleaved KBr with 0.5 ML of molecules
- Steps (< 1nm) are decorated with monowires
- Higher steps act as nucleation sites for structure growth across terraces

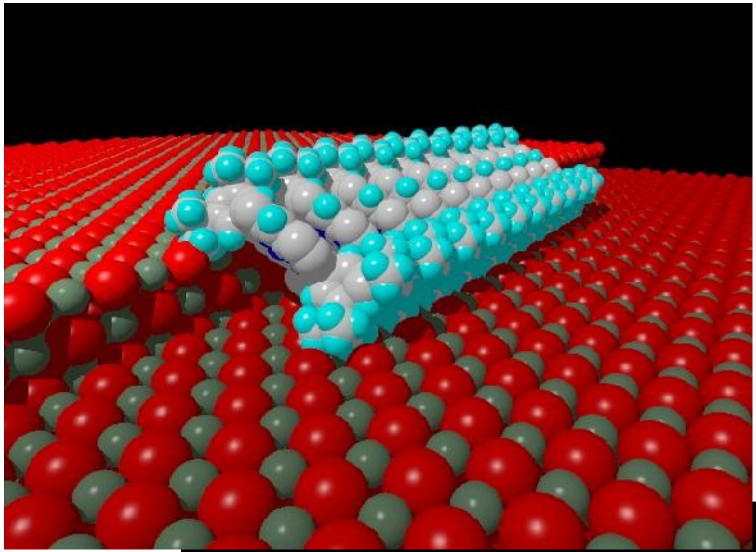


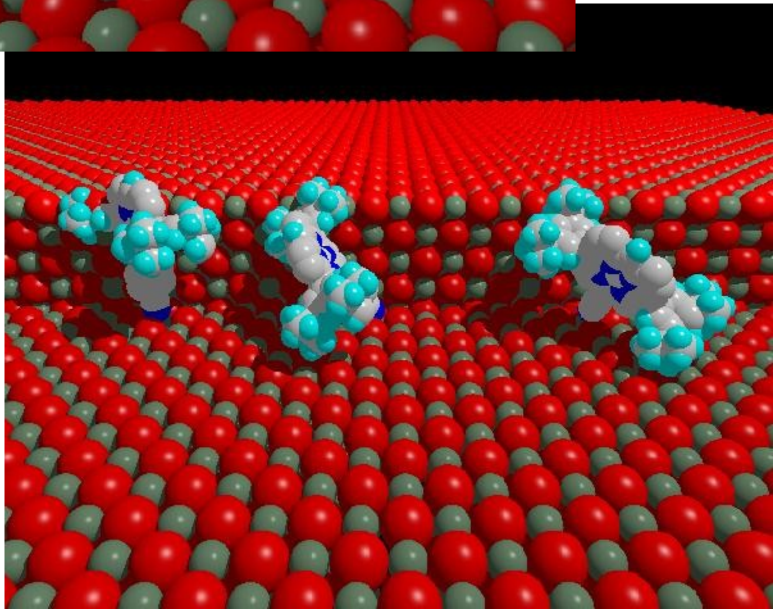
L. Zimmerli et al., J. Phys.: Conf. Ser., 2007, 61, 1357

Wire Formation

Structural model



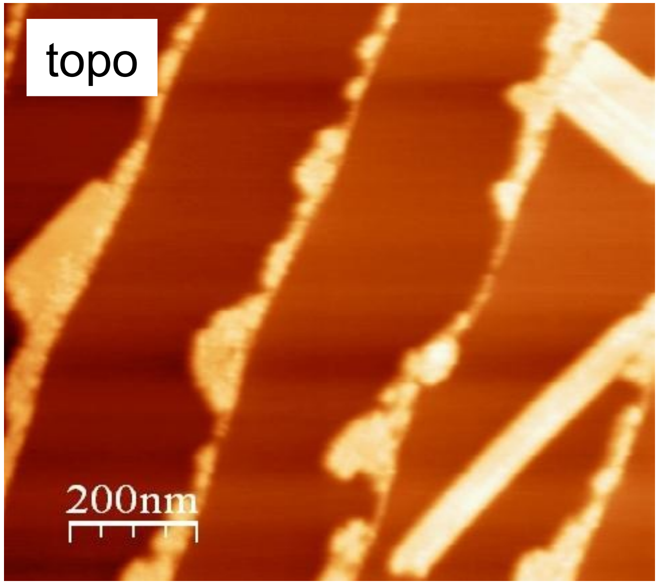




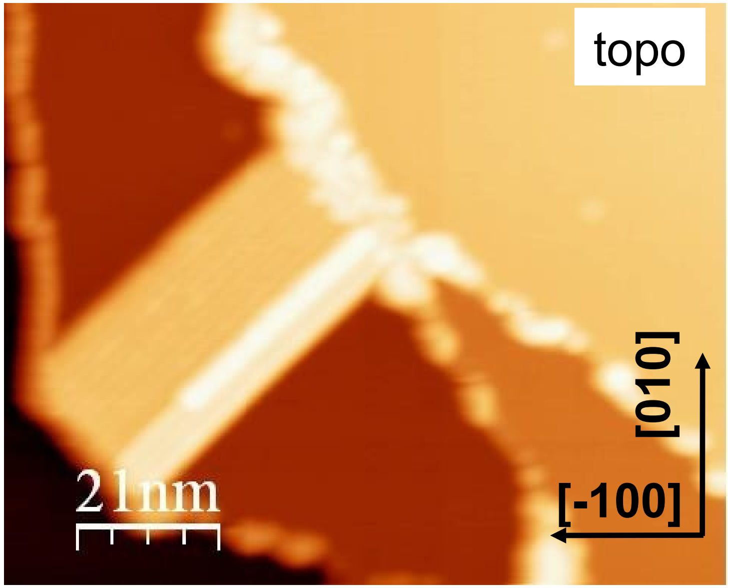
- The tilt angle of the molecules is determined by the side groups, the π-π stacking and the step height.
- Steps higher than 3 ML prevent a π-π stacking.

Molecular Assemblies

Multiwires on KBr



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



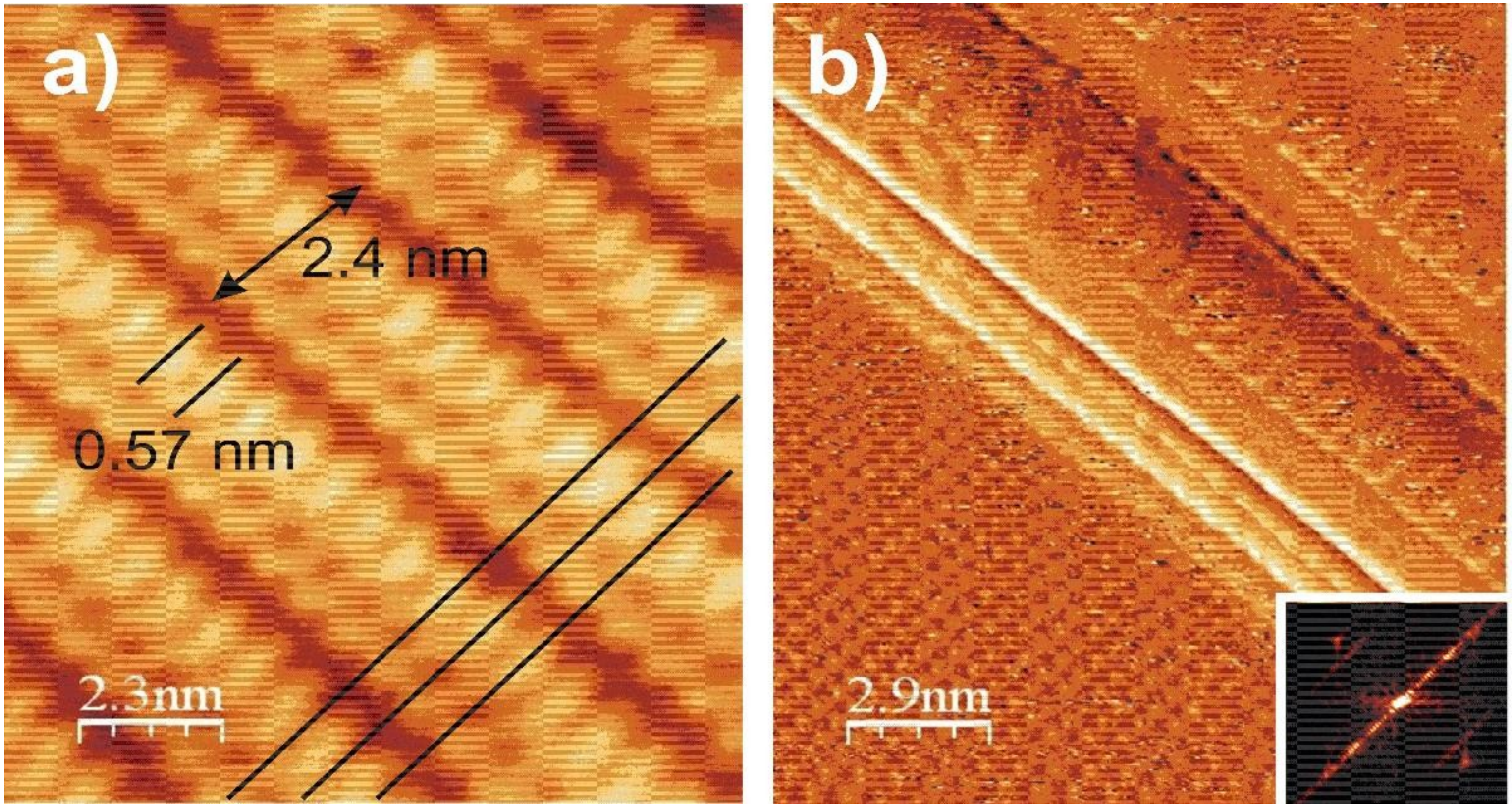
$f_0 \approx 173886Hz, \Delta f = -52Hz, Q = 15k, A = 5nm$

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

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

Molecular Assemblies

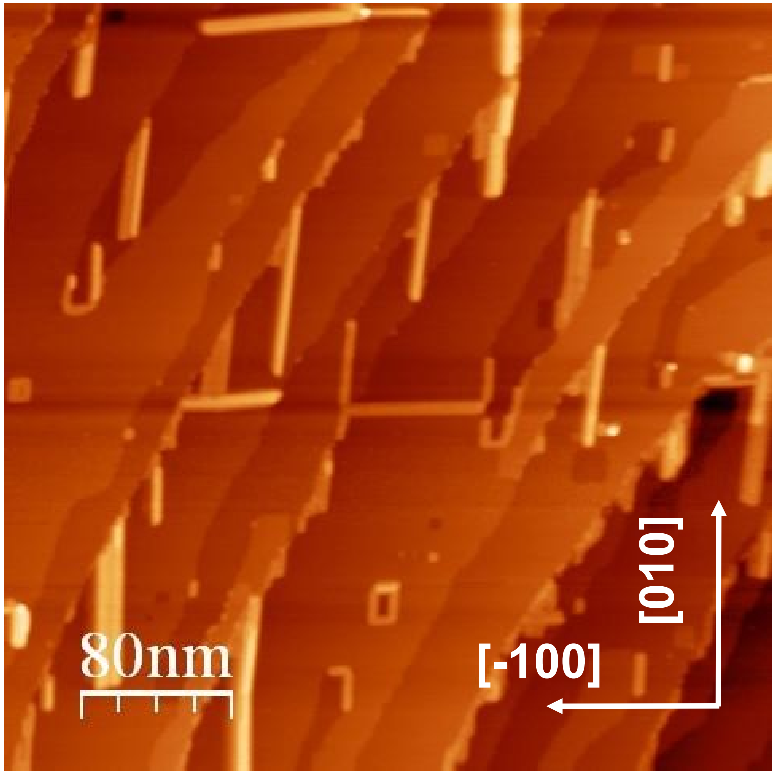
High resolution imaging



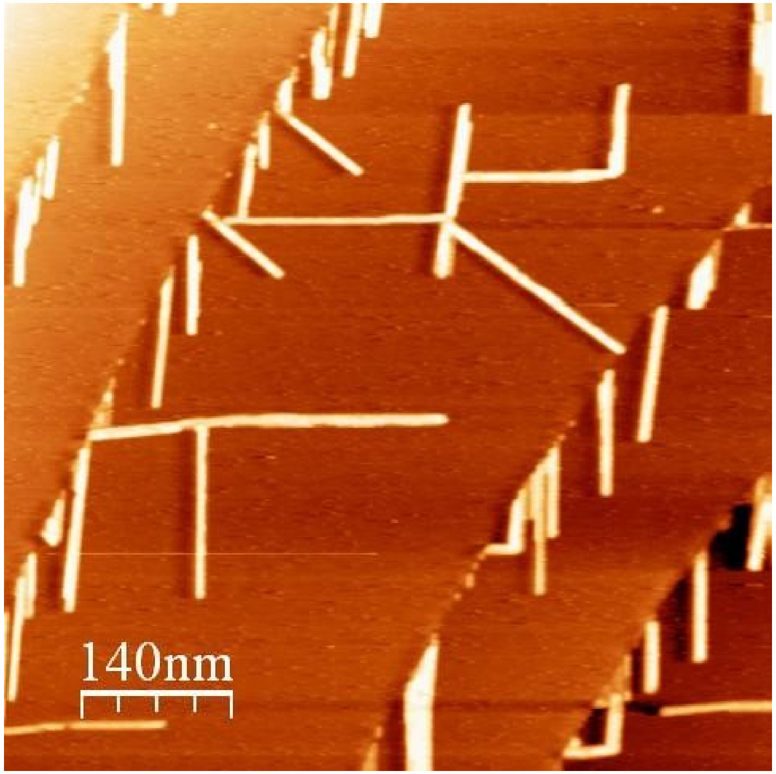
S. Meier et al., Small, 2008, 4, 1115

Molecular Assemblies

Molecular wires on NaCl

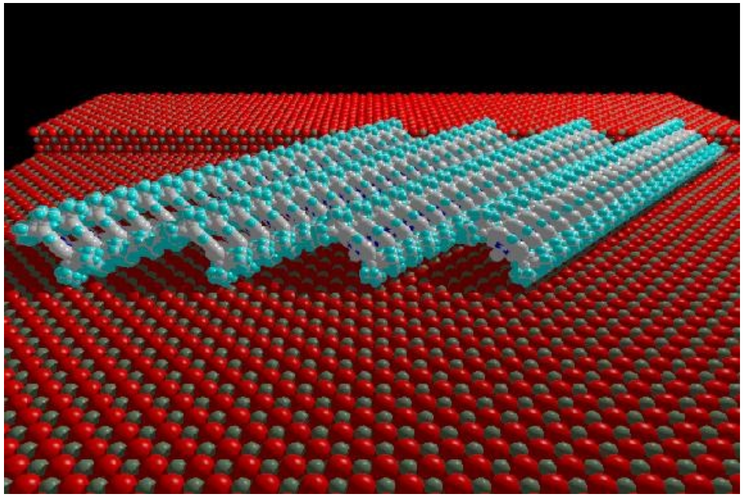


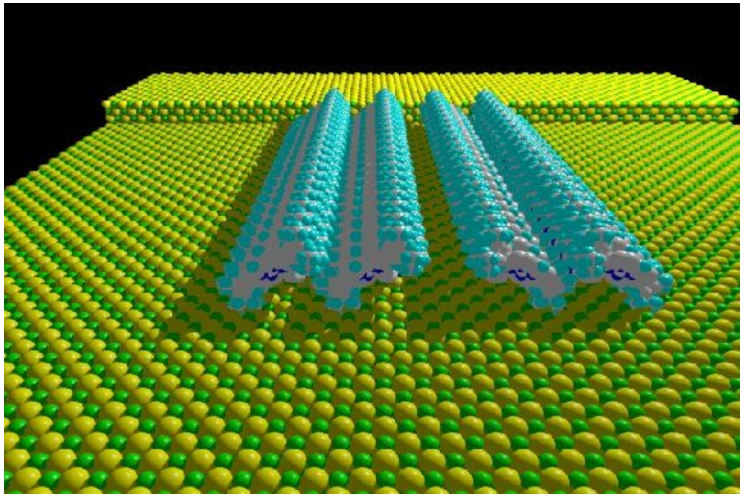
$f_0 \approx 170992 Hz, \Delta f = -9.5 Hz, Q = 15k, A = 40nm$



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

Molecular Assemblies
Structural model

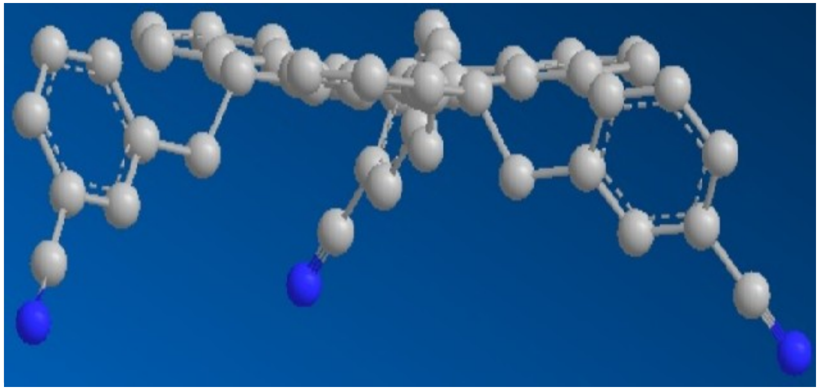


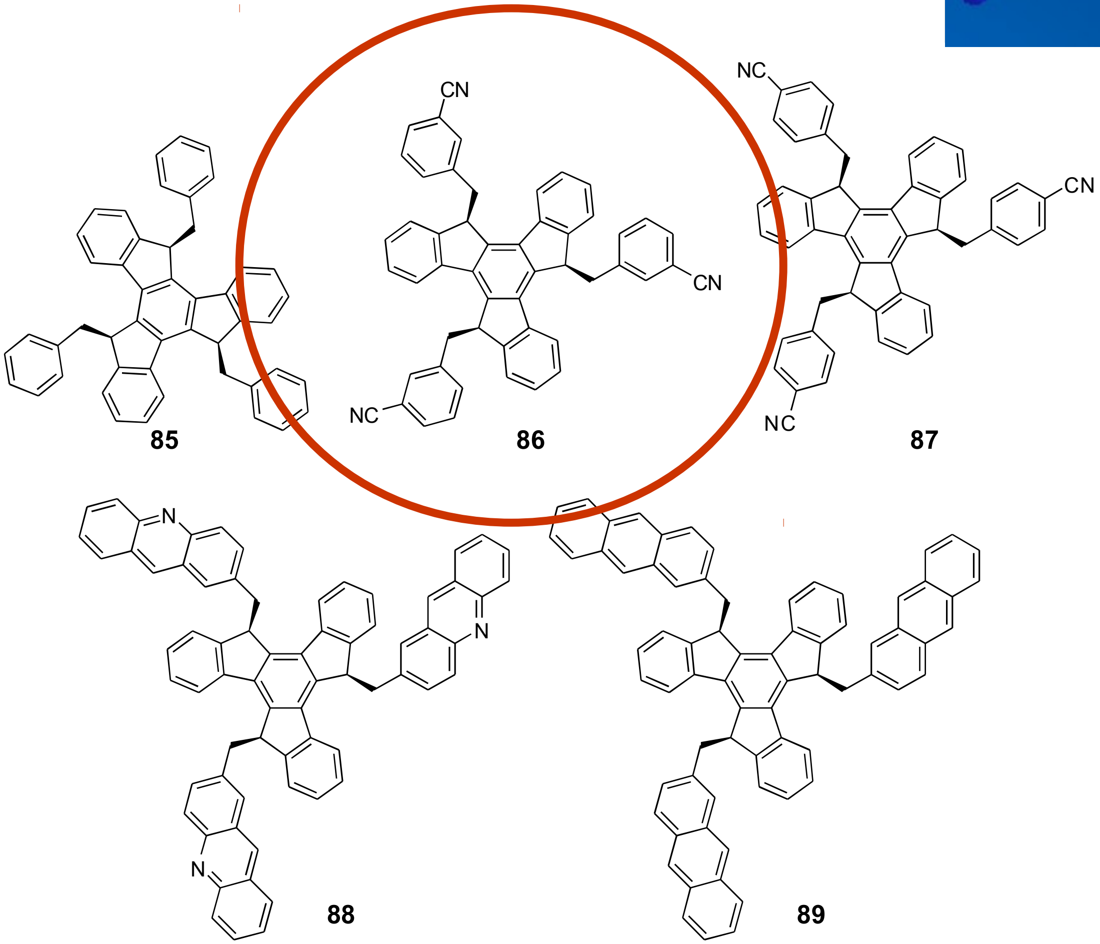


- Intermolecular equilibrium separation ~ 5.7 Å
- Directed growth by the substrate

Functionalized Truxenes

Structure

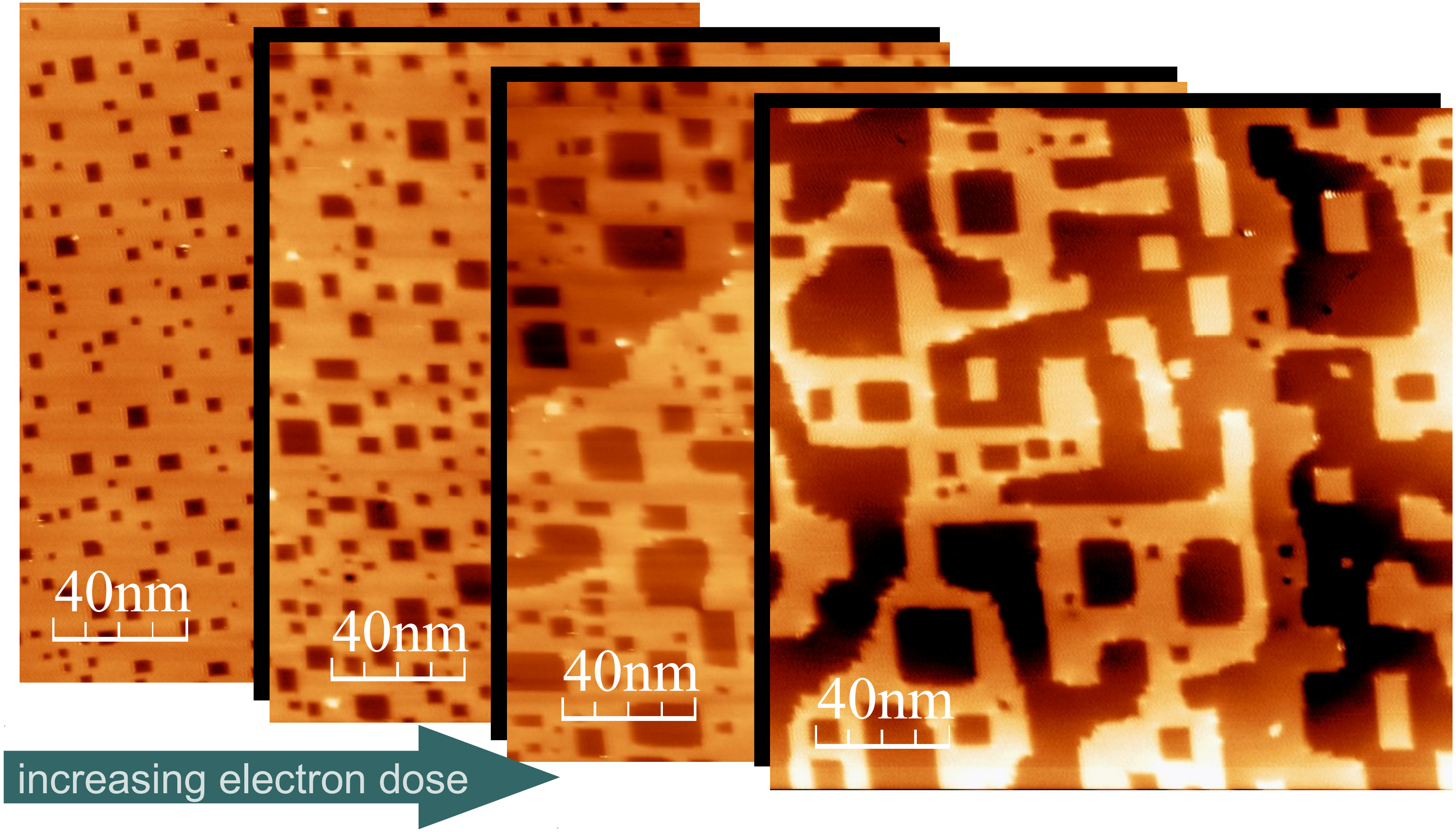




O. de Frutos et al., Chem. Eur. J. 8(13), 2879 (2002)

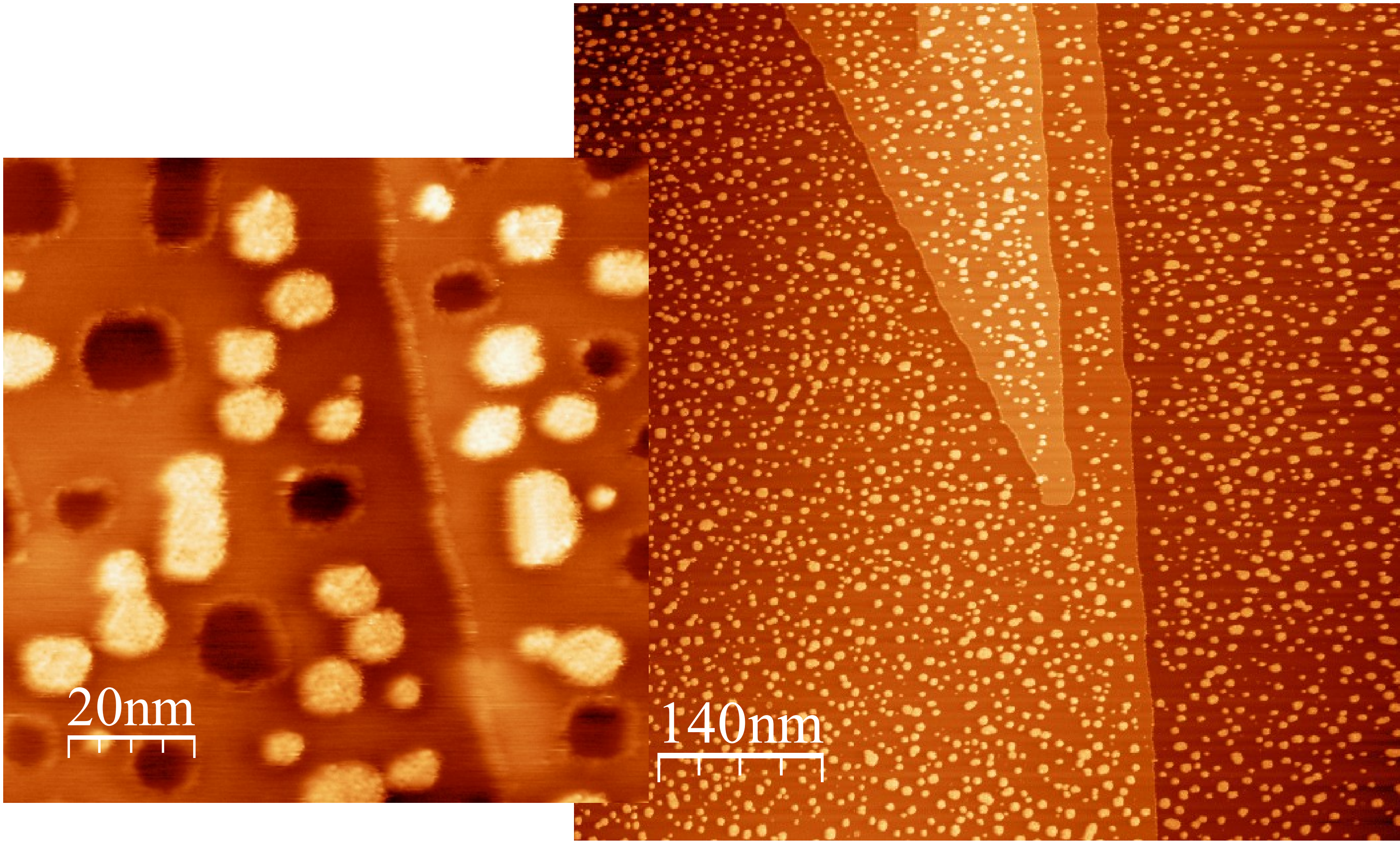
Single Crystal KBr

Substrate patterning by electron irradiation



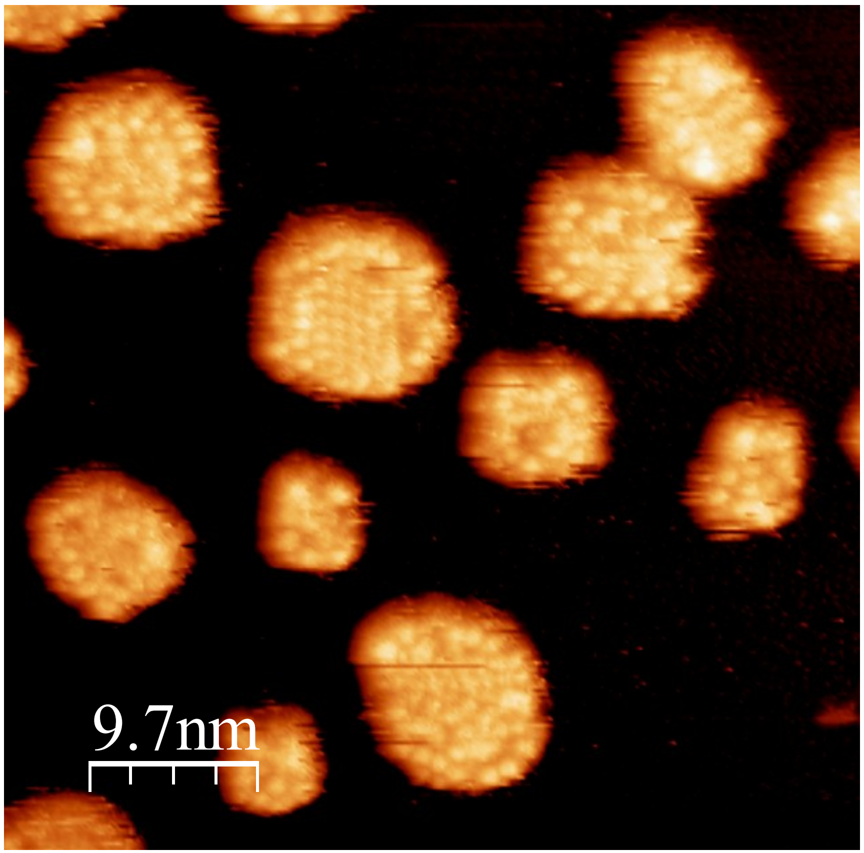
Truxenes on patterned surface

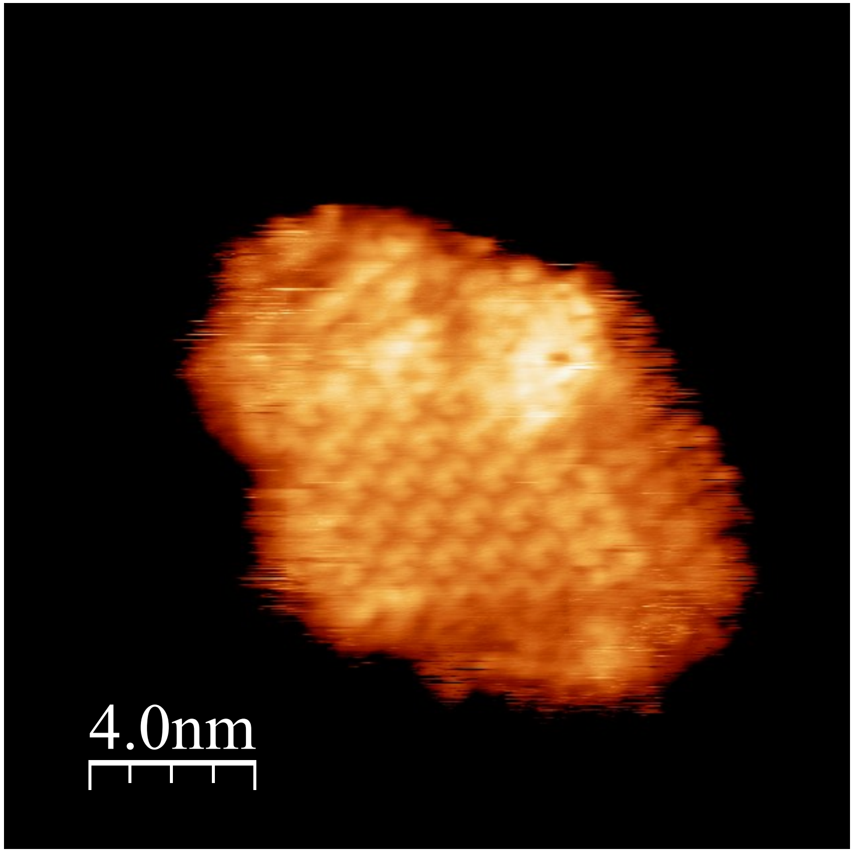
Filled and unfilled pits



Truxenes on patterned surface

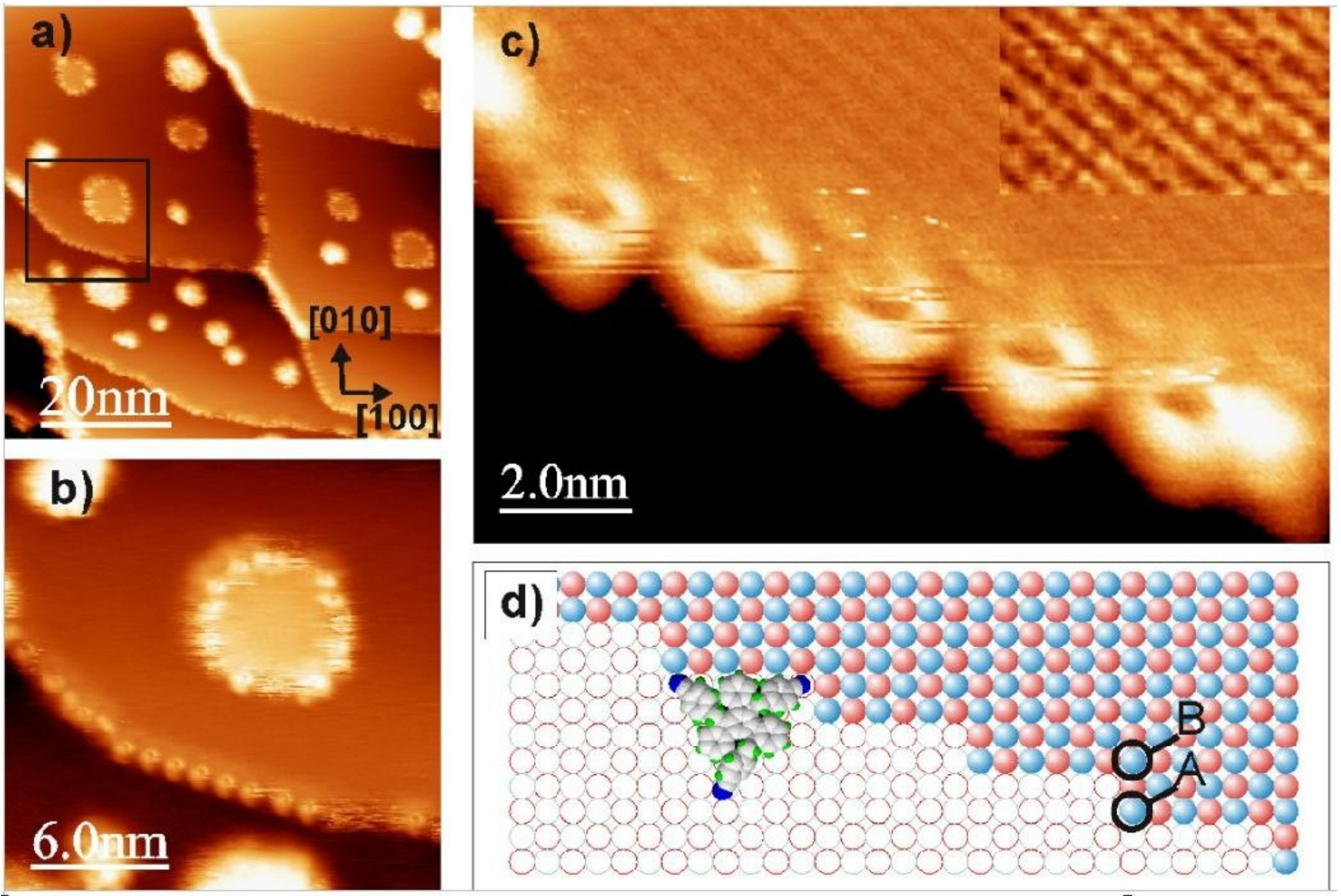
Organization within the pits





Imaging a Single Molecule

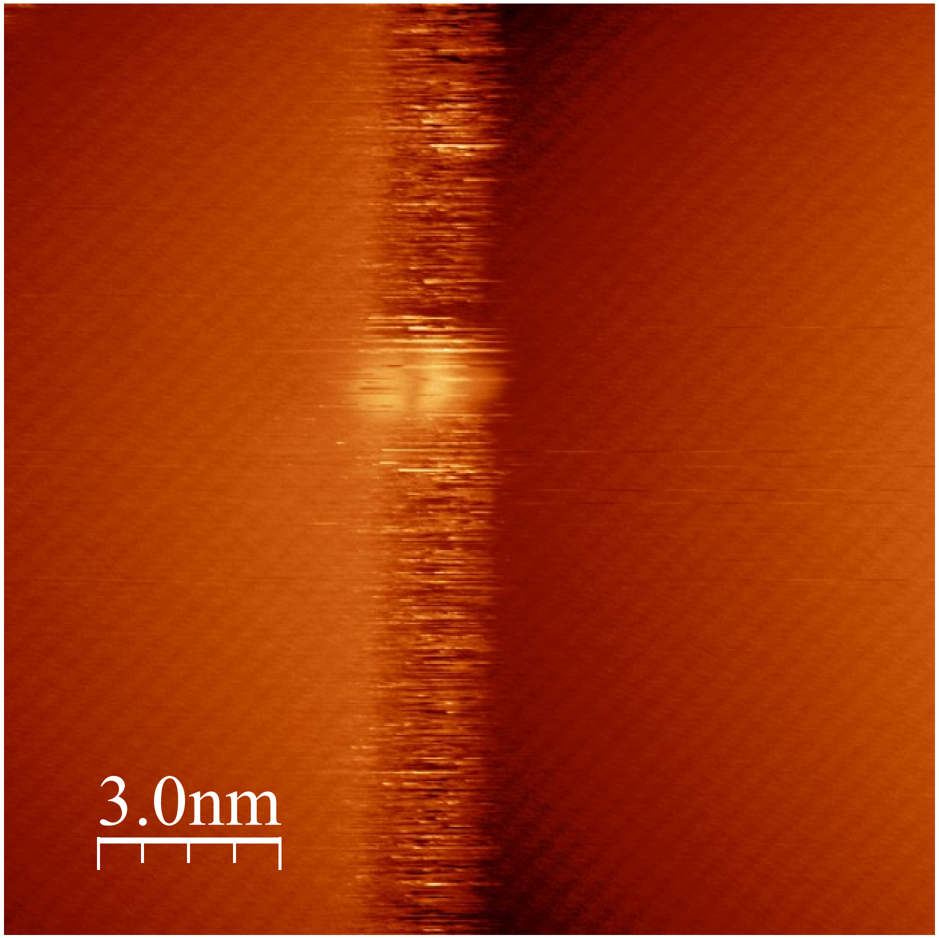
Measurements at RT



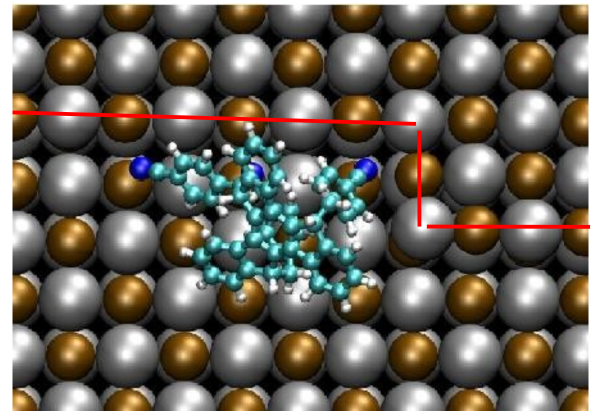
- Re-arrangement of the substrate, edges are running in the [-3 1 0] direction
- no chemical interaction with the surface
- adsorbed on K or Br terminated double atomic kink

Imaging a Single Molecule

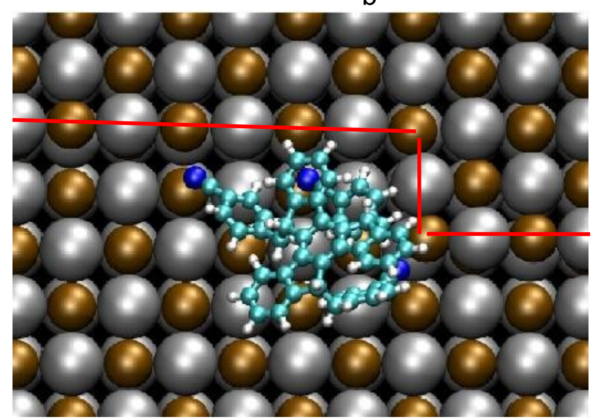
Measurements at RT



Br terminated, E_b=1.33eV

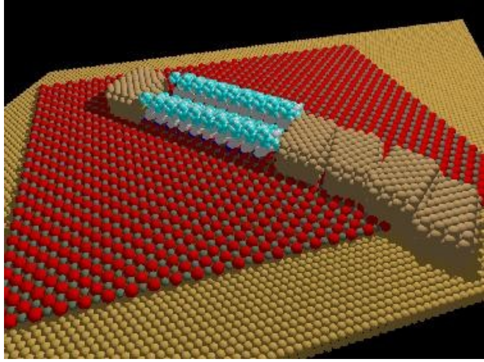


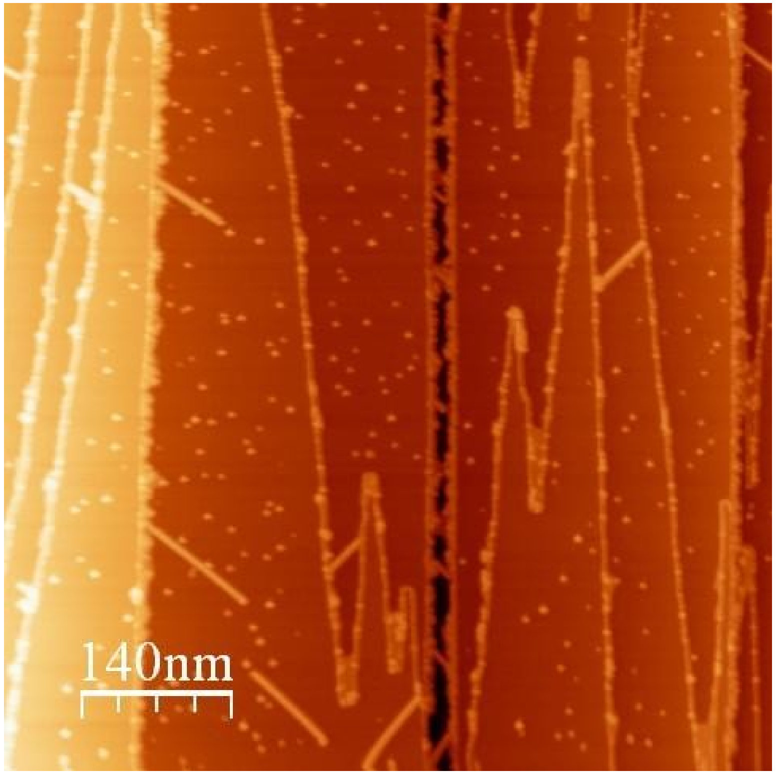
K terminated, E_b=1.17eV

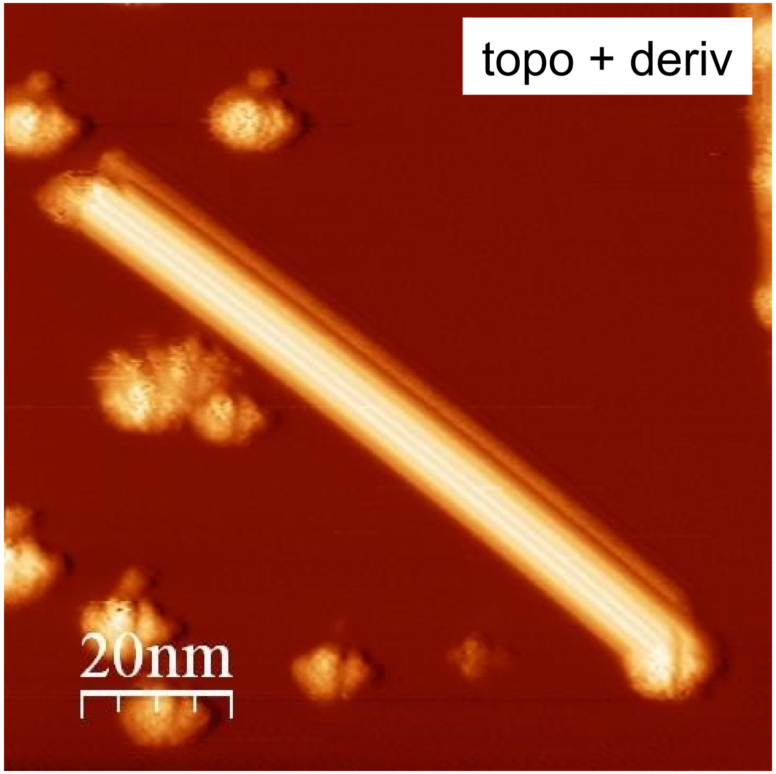


Contacting Molecular Assemblies

Au-Molecules-Au







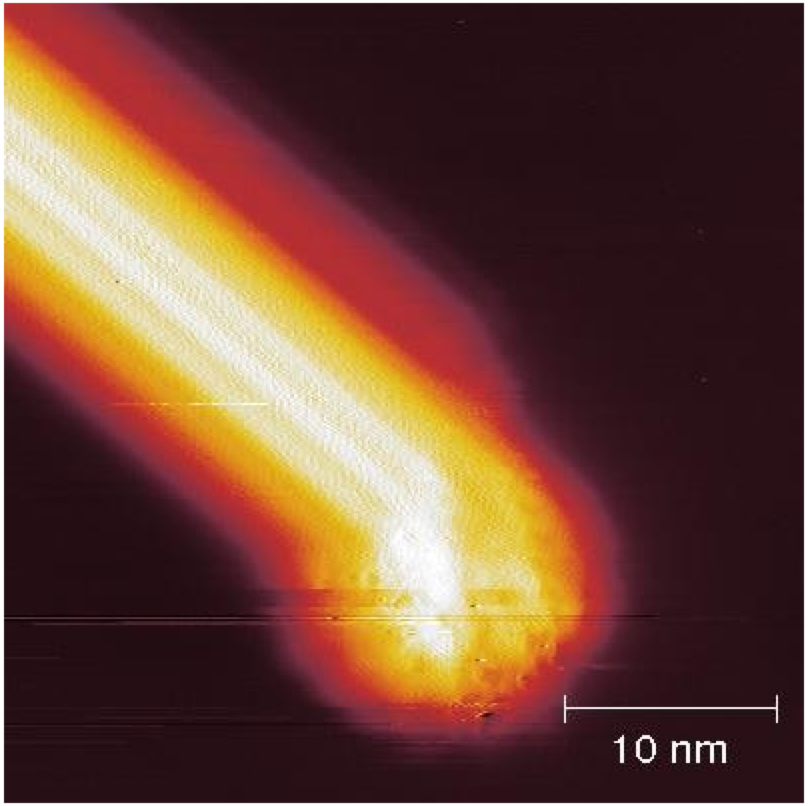
- Molecules arrange at steps and across terraces
- The growth is started/stopped at gold clusters.

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

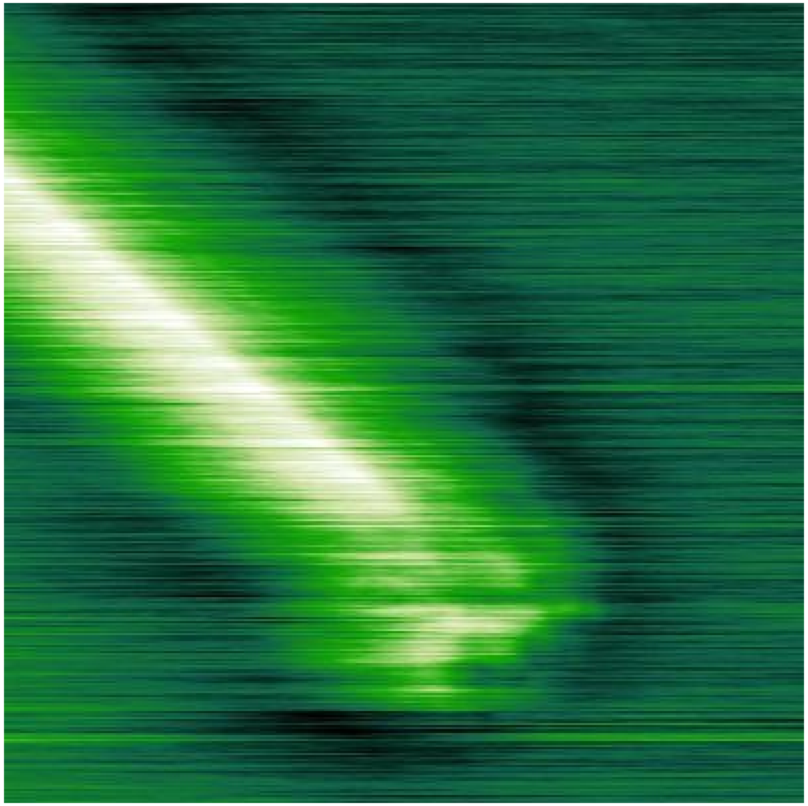
Contacting Molecular Assemblies

KPFM

Topography



LCPD

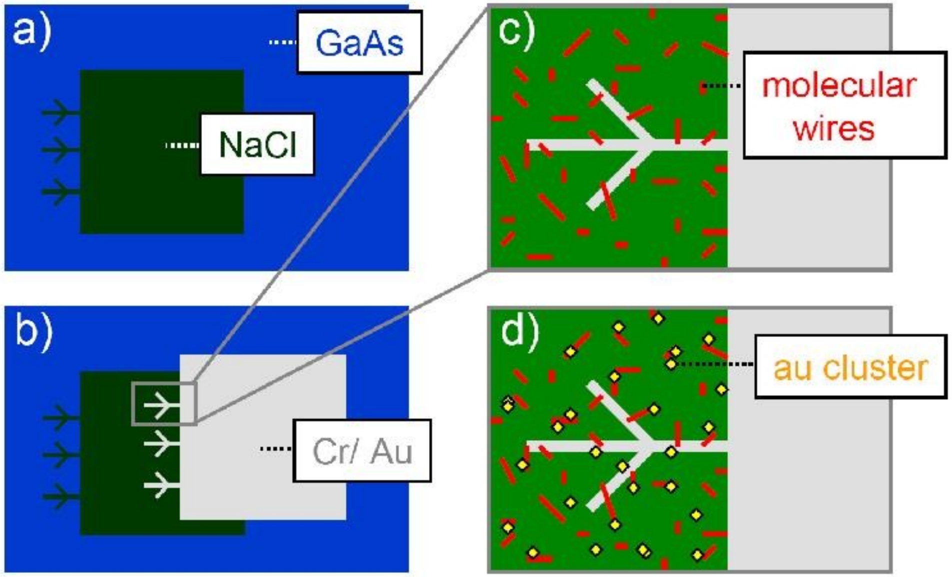


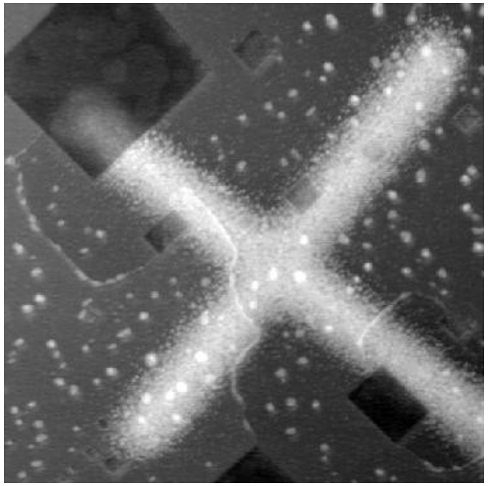
LCPD= -0.5...0.2eV

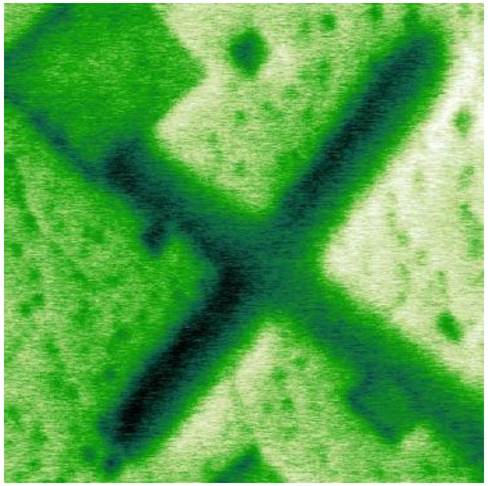
Glatzel et al., Appl. Phys. Lett., **2009**, 94, 063303

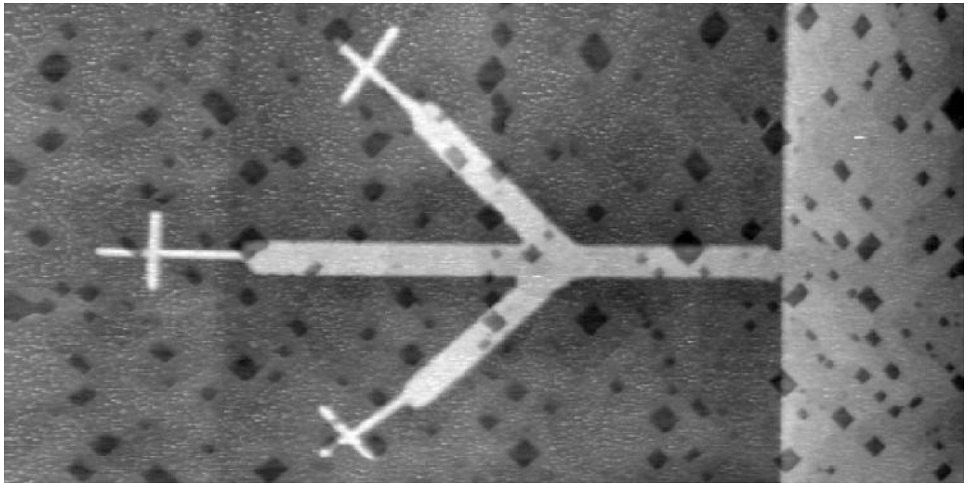
Contacting Molecular Assemblies

Nanostencil (IBM Rüschlikon)



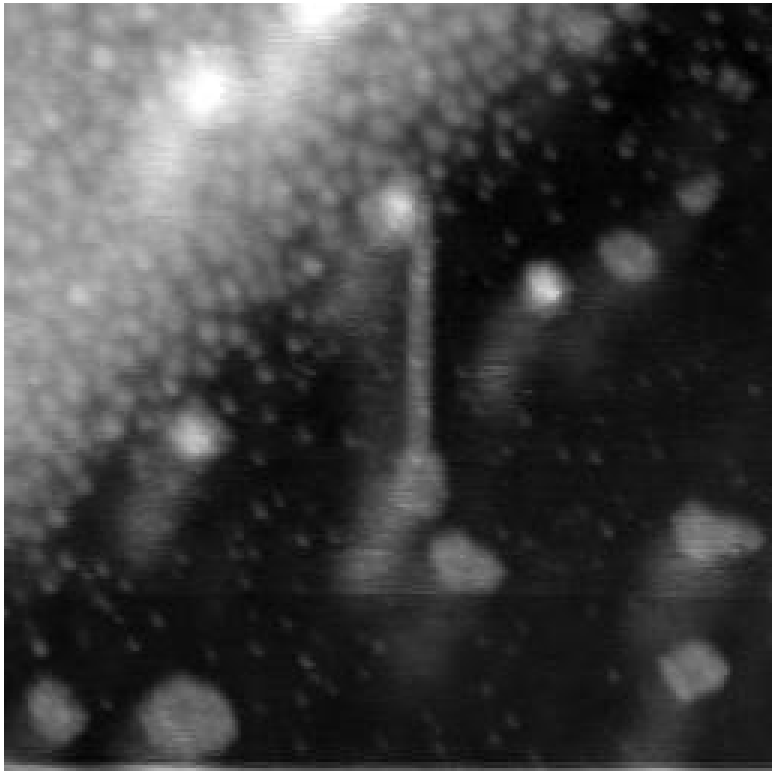




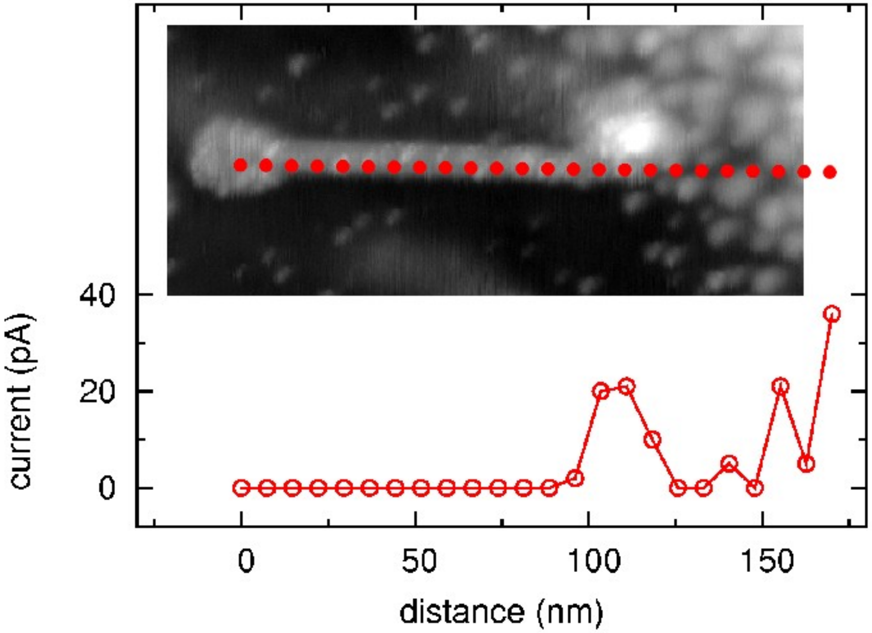


Contacting Molecular Assemblies

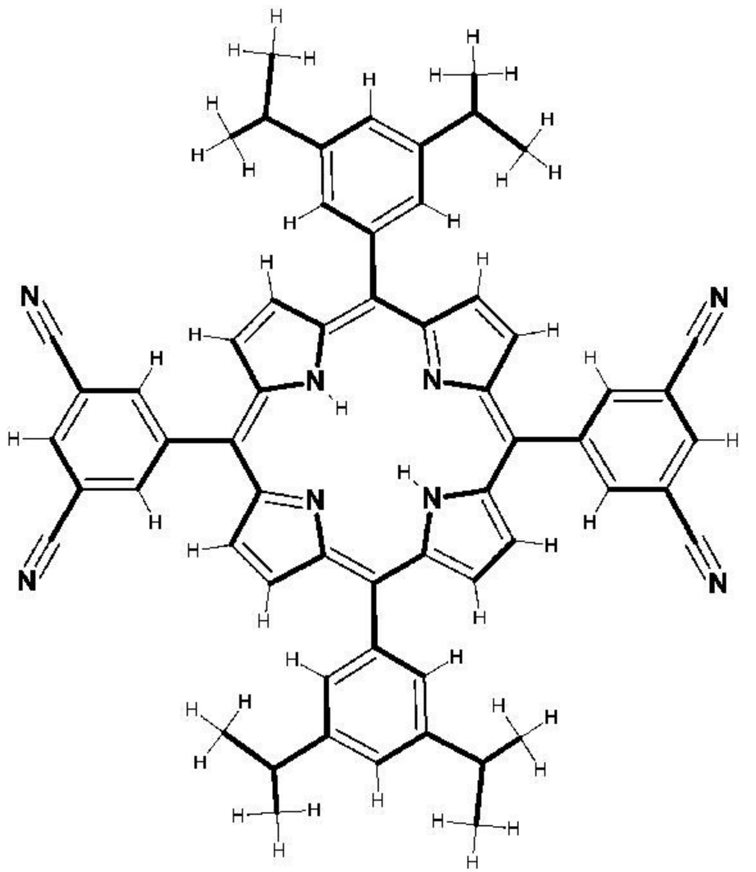
Nanostencil (IBM Rüschlikon)



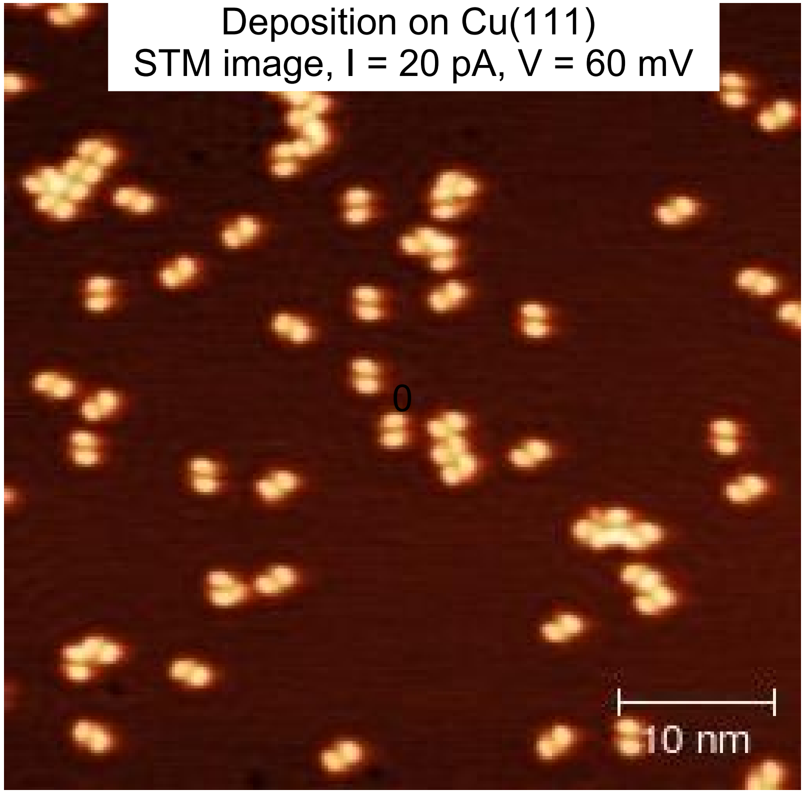
300x300nm^2

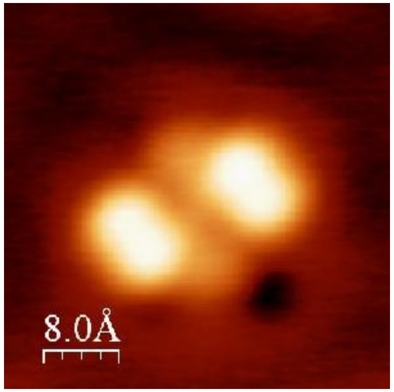


Porphyrin with bicyanophenyl legs



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



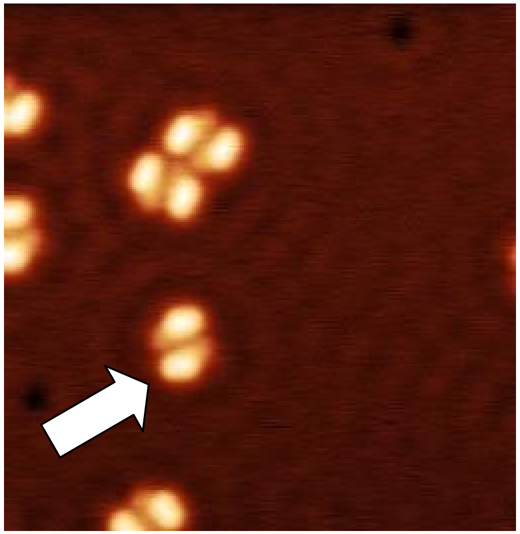


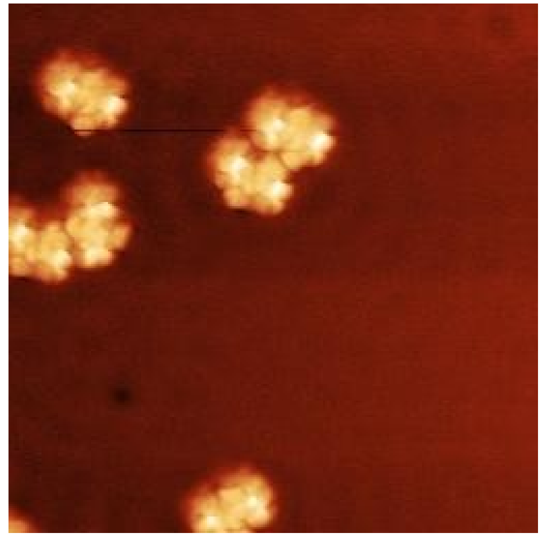
R. Pawlak et al.

Vertical manipulation: Catch the molecule…

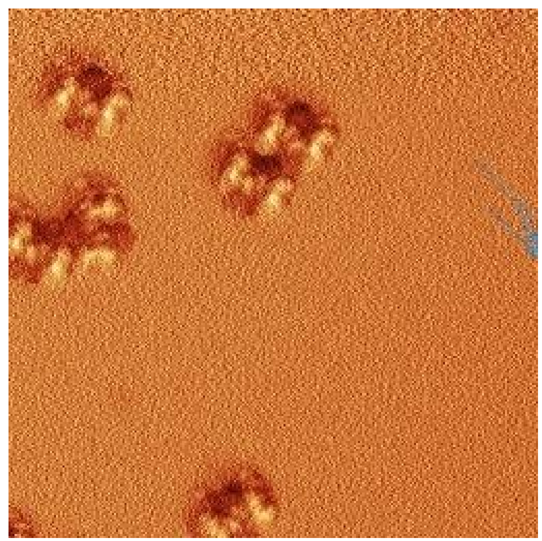
Method: Z spectroscopic curve in the **center** of the molecule

STM Topography

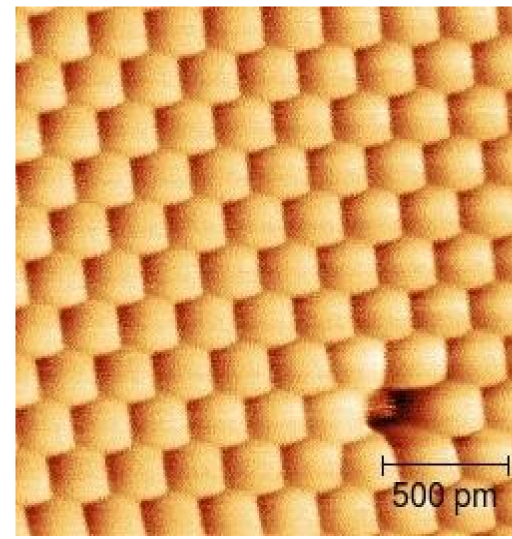




Simultaneous Frequency Shift

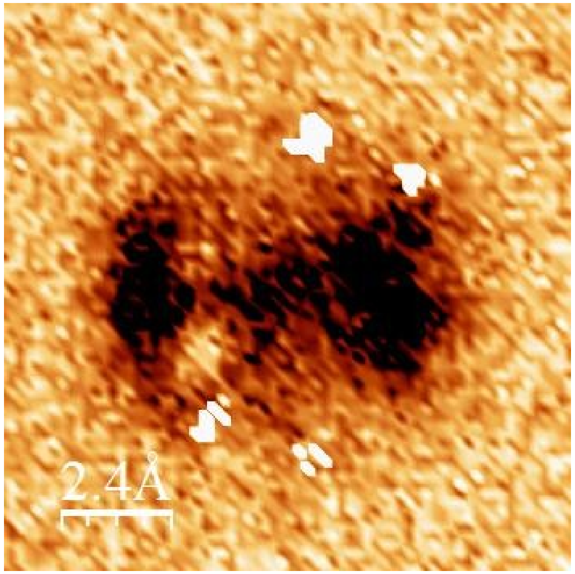


Friction measurement with a molecule linked to the tip

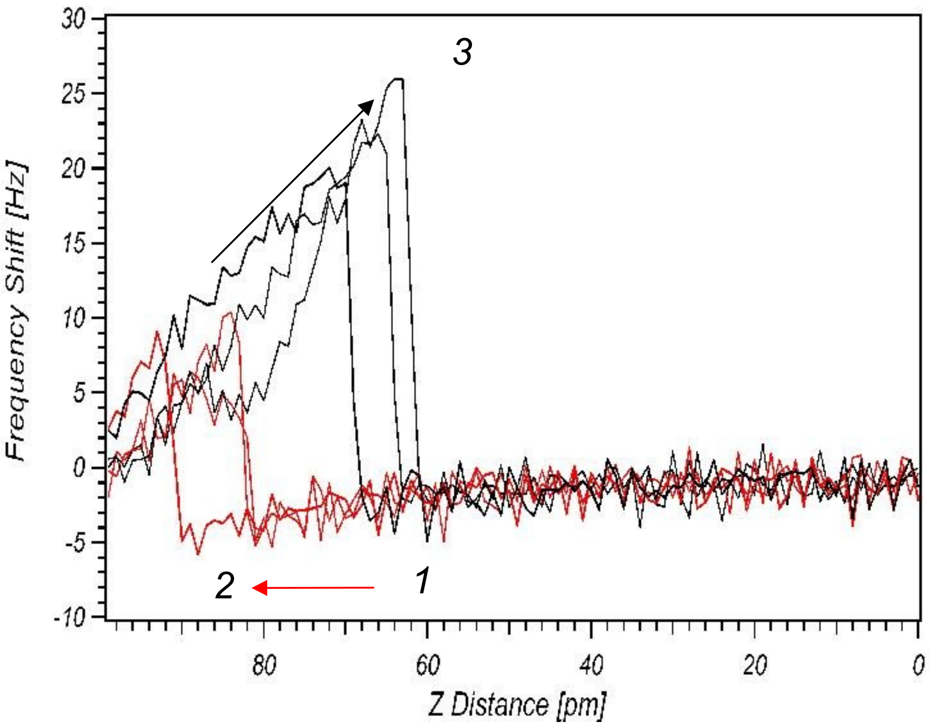


Atomic resolution on Cu(111)

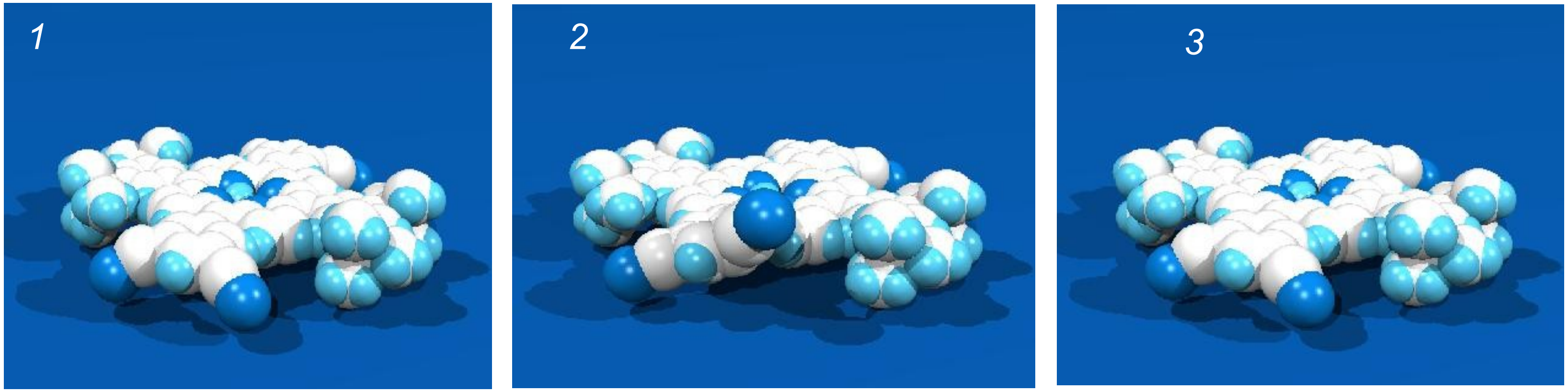
3d-force spectroscopy: Observations of localized instabilities



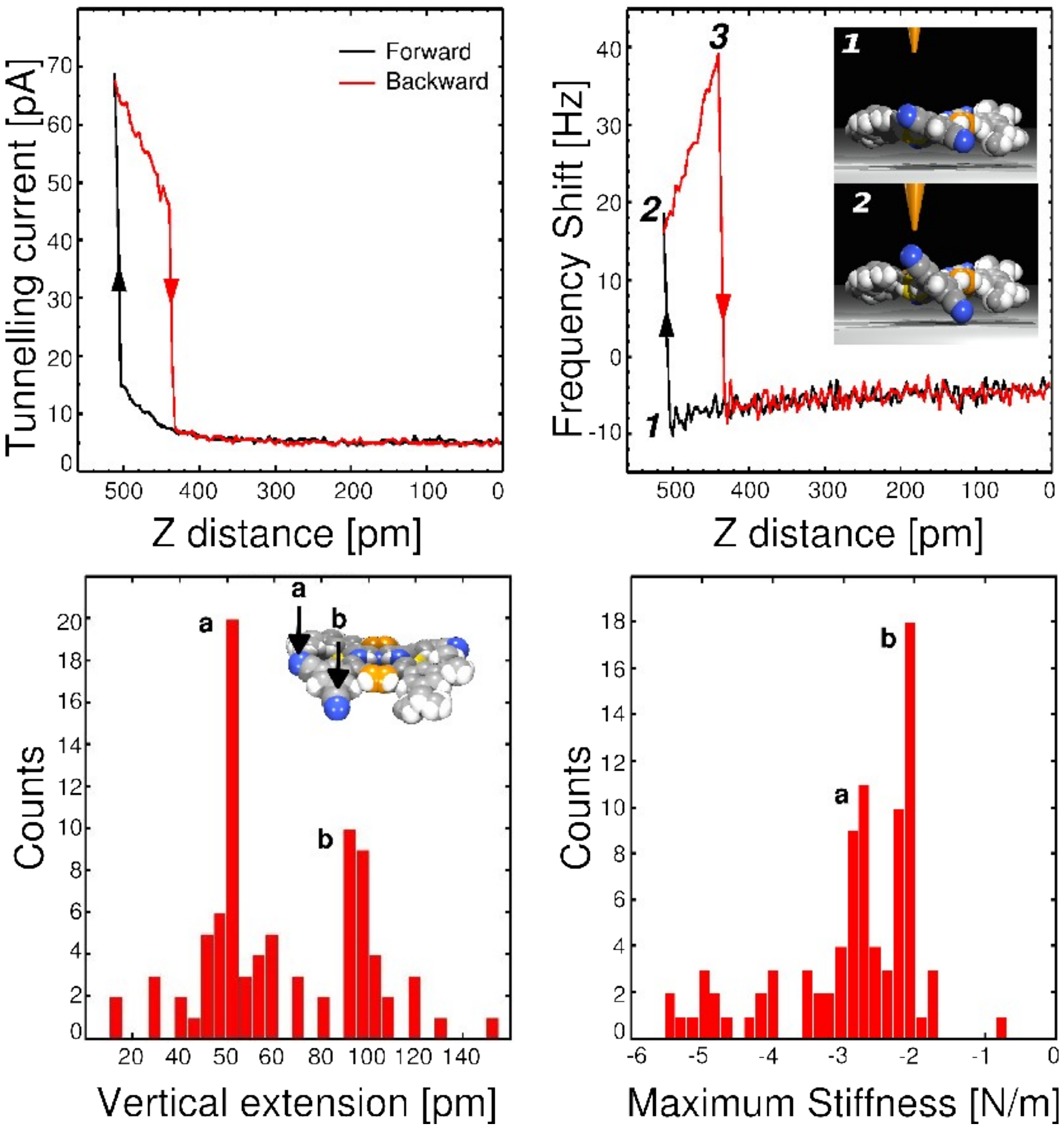
Three-dimensional
Force Field Spectroscopy



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

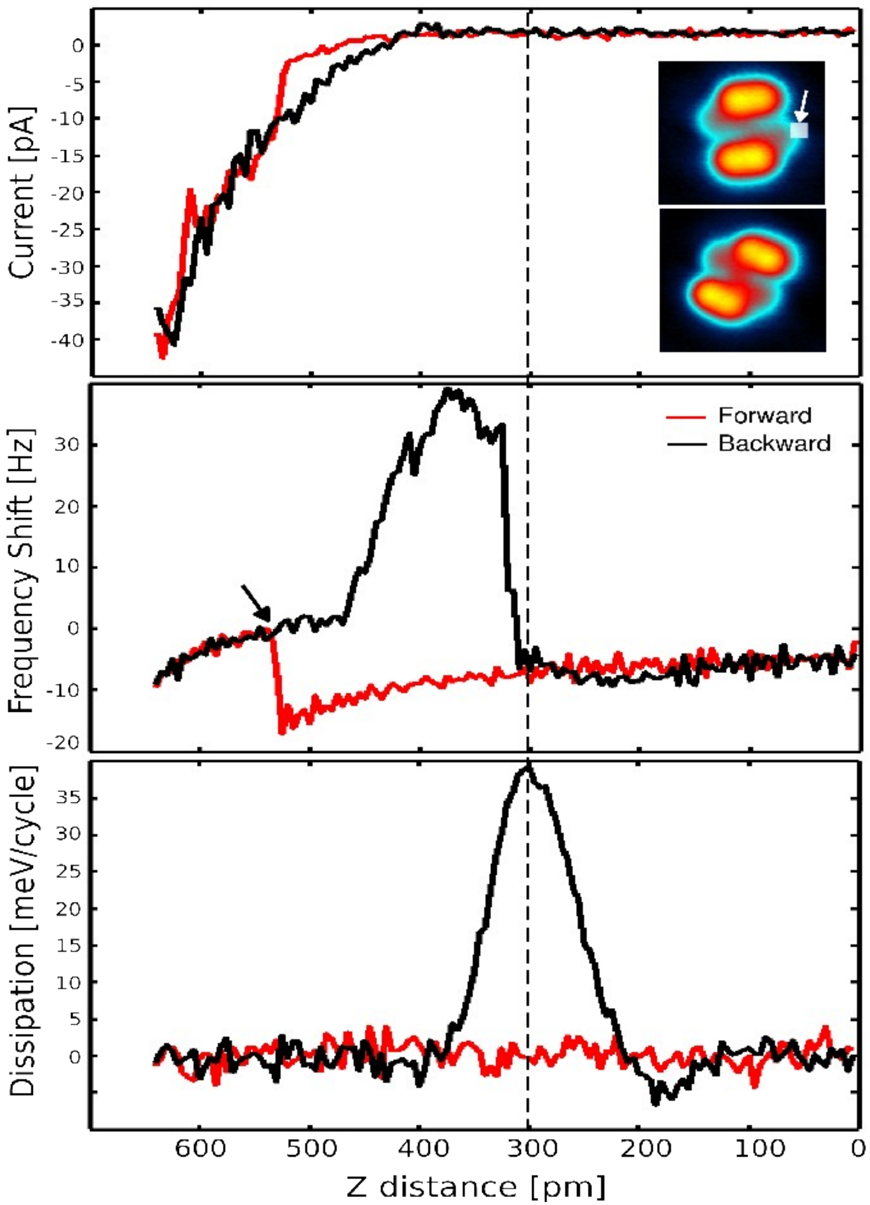
Rotational switching of the molecule:

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

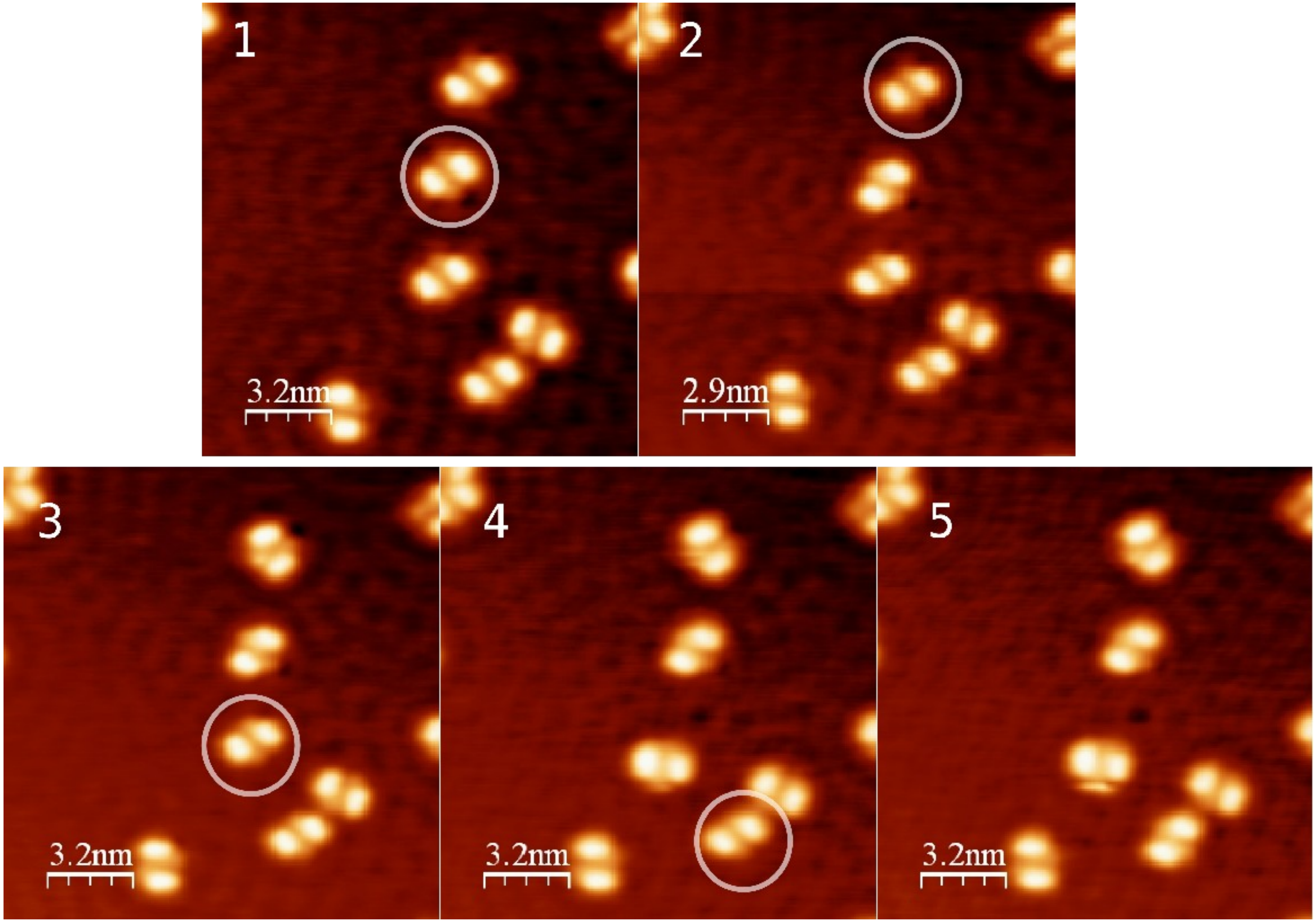
- **Rotation of 60° with respect to the initial conformation.**

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

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

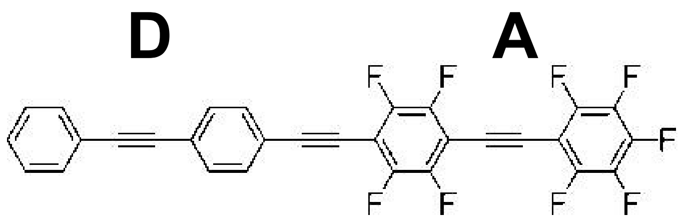


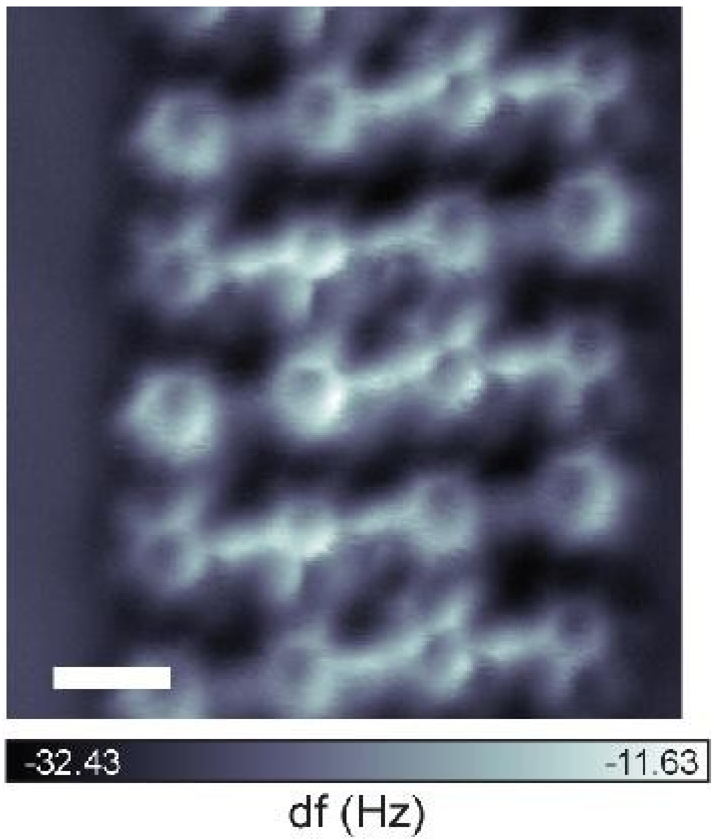
Rotation of molecules clockwise and anticlockwise



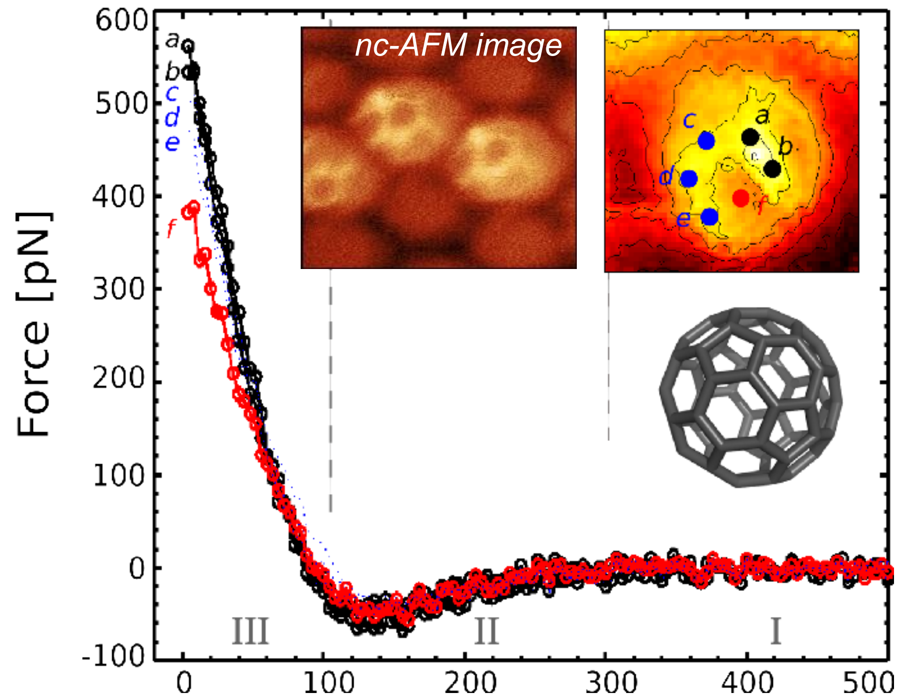
- Possibility to rotate molecules in both directions (clockwise and anticlockwise) without consideration to their symmetry

nc-AFM Messungen



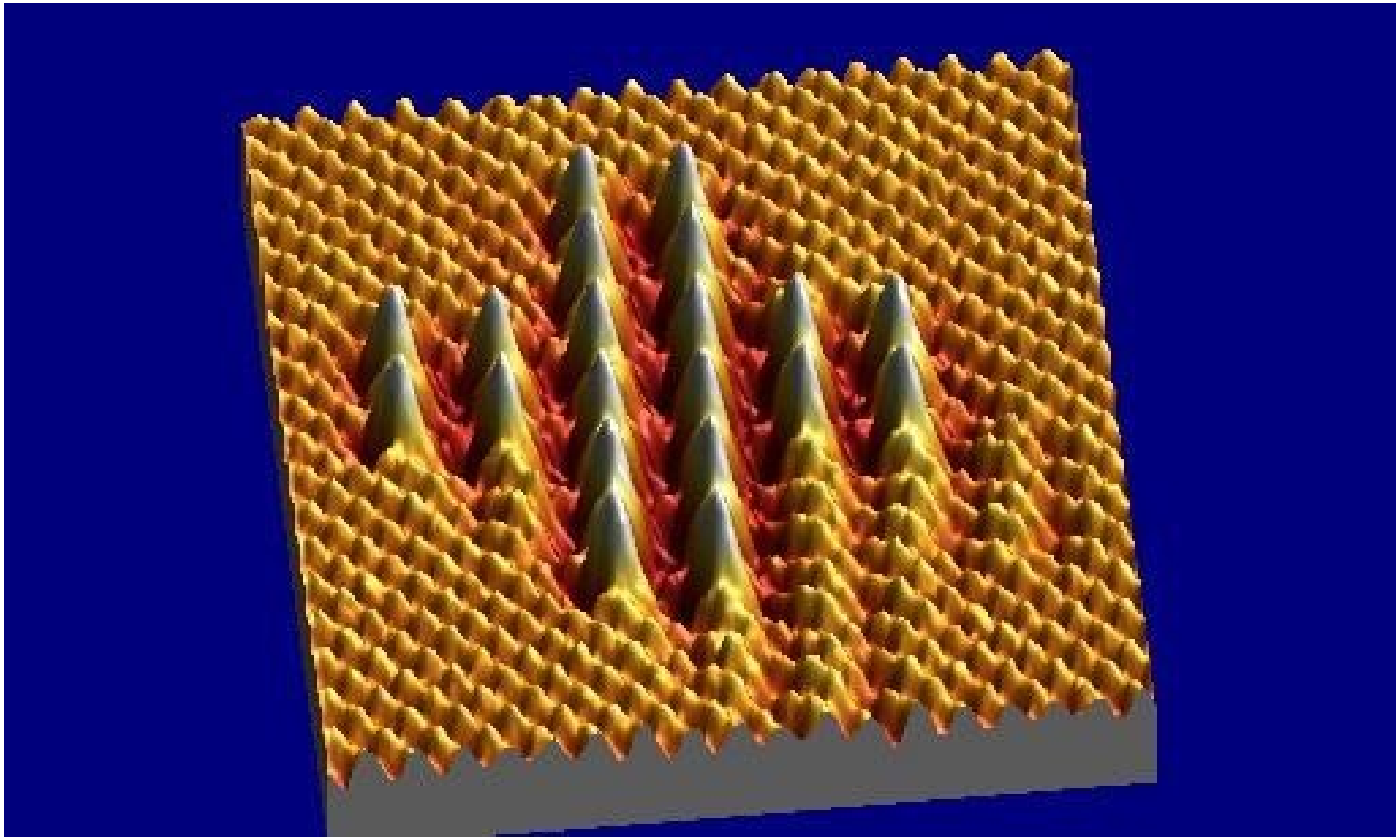


DA molecules on



C_{60} on Cu(111),
Kraftspektroskopie

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



S. Shigeki et al.