Wiederholung Diffusion

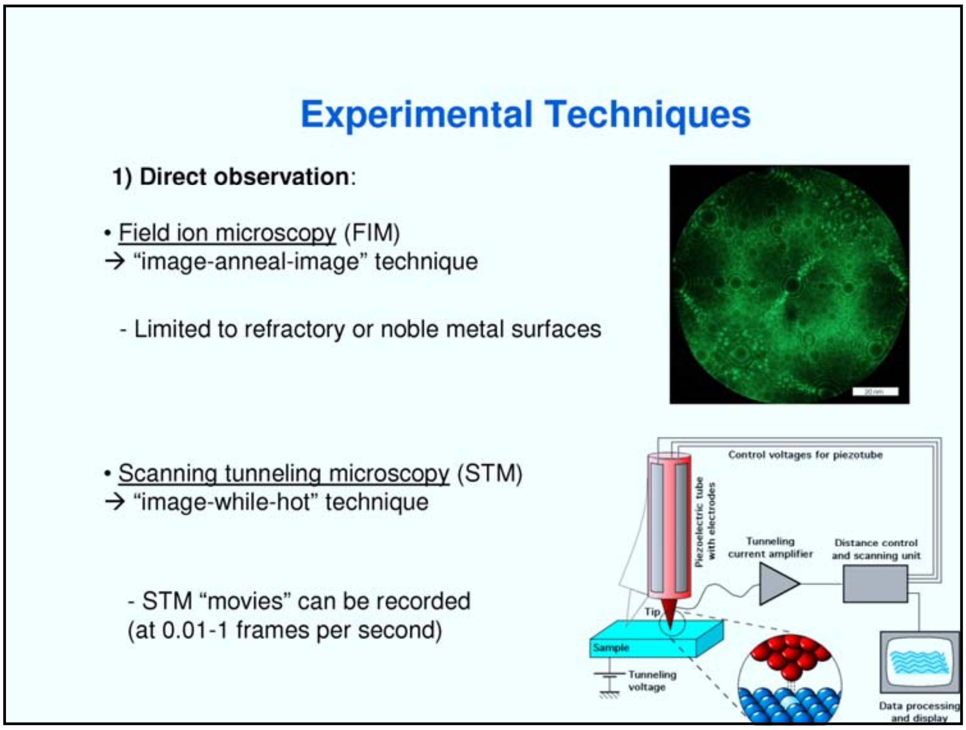
- kT (Arrhenius)
  → Random Walk / Lattice Gas / ‘on site’
- Fick’s laws
- Diffusion affected by cooperativity
- Atomistic Mechanisms
- Elektromigration / Stark Effect

Repetition PEEM / LEEM

- Magnetic domains
- Slow electrons (surface/interface sensitivity)
- PEEM with soft X-rays as source (XMCD image)
- Polarized X-ray source
- PEEM with slow electrons as source
- Research example nanocrystals

Repetition XAS, NEXAFS, XMCD

- Near Edge X-ray Absorption Fine Structure
- reflects density of unoccupied states
- Absorption processes and decay (soft X-rays)
- Sampling depths (total electron yield, secondary, Auger, Fluorescence)
- Multiplet structure (chemical, electronic sensitivity)
- XMCD (sum rules)
- XMLD
- Magnetism (spin and orbital moment, magnetocrystalline anisotropy)



Experimental Techniques

1) Direct observation:

- Field ion microscopy (FIM)
→ "image-anneal-image" technique

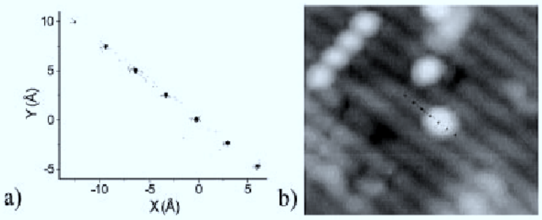
  - Limited to refractory or noble metal surfaces

- Scanning tunneling microscopy (STM)
→ "image-while-hot" technique

  - STM "movies" can be recorded
(at 0.01-1 frames per second)

Experimental Techniques

- Scanning tunneling microscopy (STM) → “atom-tracking” technique
  - STM tip locked onto an adparticle by 2D lateral feedback
  - Example: Si on Si(100) (Swartzentruber, PRL 1996)

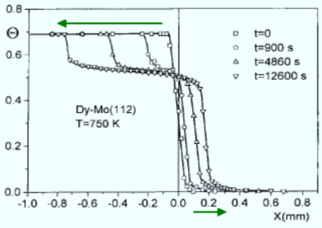


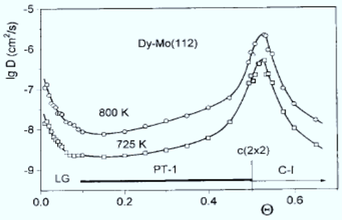
  - Electric fields from the STM tip influence surface diffusion!

Experimental Techniques

2) Profile evolution method:

- Smearing of a sharp initial concentration profile is monitored
  - Initial profile deposited using a mask
  - AES, SIMS, SEM or local work-function…
  - D(Θ) can be evaluated
- Example: Dy on Mo(112) (Loburets et al., SS 1998)





Experimental Techniques

3) “Capillarity” techniques:

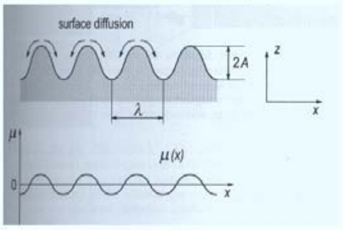
- A surface is perturbed from its lowest energy configuration…

… and allowed to relax via diffusion

- Relaxation rate → Coefficient of diffusion

- For a sinusoidal profile (Mullins, JAP 1999):

$$A(t) = A_0 \exp\left[-\frac{\gamma D n_0 V^2}{k_B T}\left(\frac{2\pi}{\lambda}\right)^4 t\right]$$



γ = surface tension; V = atomic volume; n_0 = surface density

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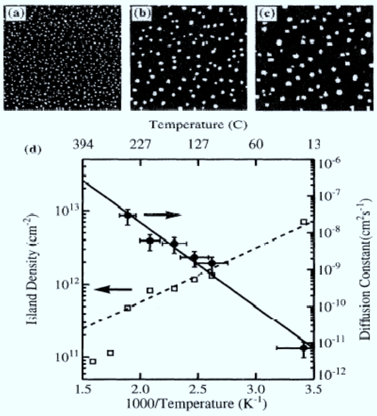
Experimental Techniques

4) Island growth techniques:

- Number density of islands after submonolayer deposition is monitored
- Example: Fe on Fe(100) (Stroscio et al., PRL 1993)



deposition rate

$$N \propto \left(\frac{R\Theta}{\nu}\right)^{1/3}$$

hopping rate

Further Reading

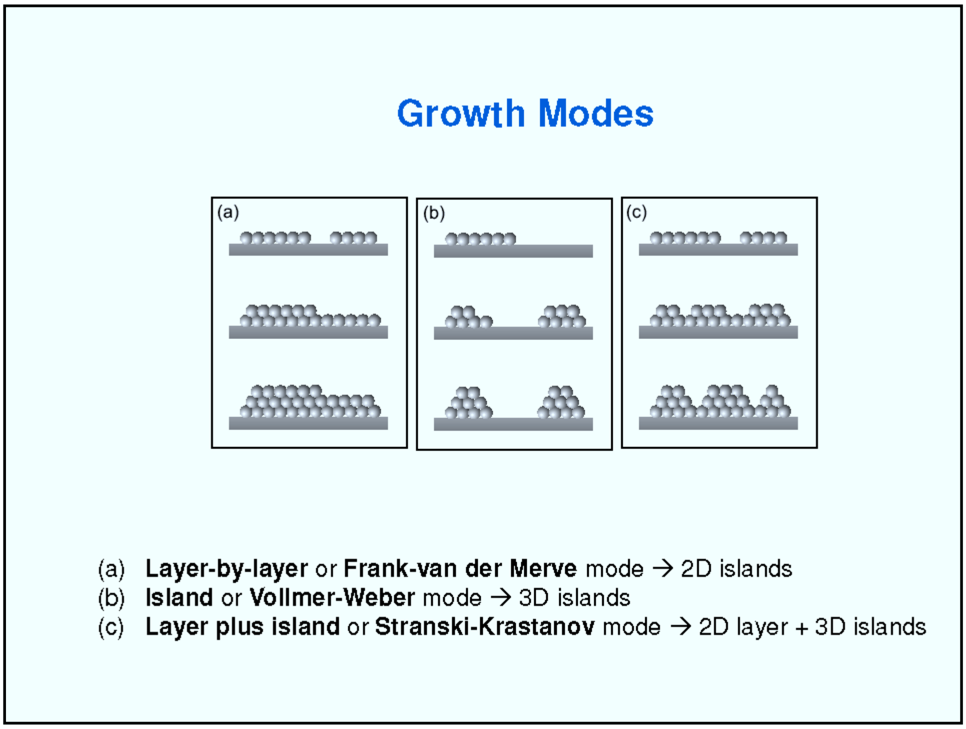
- K. Oura et al., Surface Science, Springer 2003, chapter 13
- A.G. Naumovets & Yu.S. Vedula, Surf. Sci. Rep. 4 (1985) 365
- R. Gomer, Rep. Prog. Phys. 53 (1990) 917
- G.L. Kellogg, Surf. Sci. Rep. 21 (1994) 1

Surface Physics 2010

Growth of Thin Films

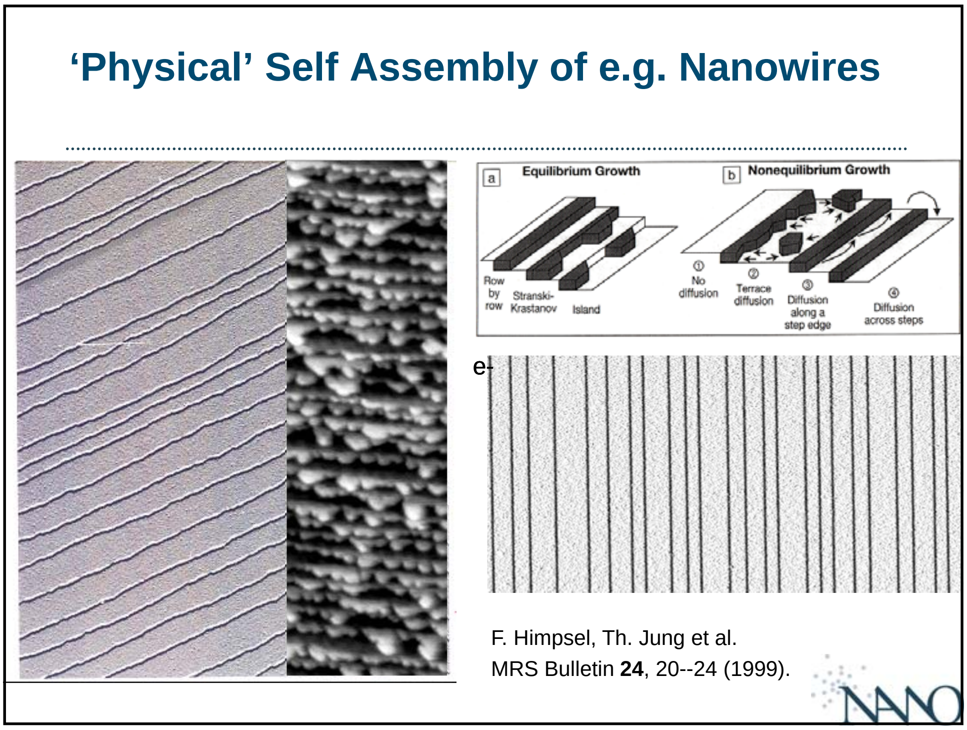
UNI
BASEL

Lecturer: Dr. Enrico Gnecco
NCCR Nanoscale Science



Growth Modes

(a) **Layer-by-layer** or **Frank-van der Merve** mode → 2D islands
(b) **Island** or **Vollmer-Weber** mode → 3D islands
(c) **Layer plus island** or **Stranski-Krastanov** mode → 2D layer + 3D islands



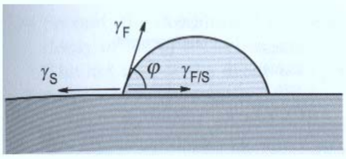
‘Physical’ Self Assembly of e.g. Nanowires

F. Himpsel, Th. Jung et al.
MRS Bulletin **24**, 20--24 (1999).

Growth Modes

- **Surface tension** (γ) = work required to build a surface of unit area

  (≡ force per unit length)

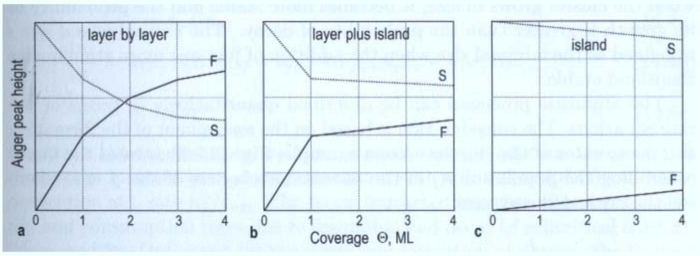


$$\gamma_S = \gamma_{SF} + \gamma_F \cos\varphi$$

- Island growth: $\varphi > 0$ → $\gamma_S < \gamma_{SF} + \gamma_F$
- Layer-by-layer growth: $\varphi = 0$ → $\gamma_S \geq \gamma_{SF} + \gamma_F$

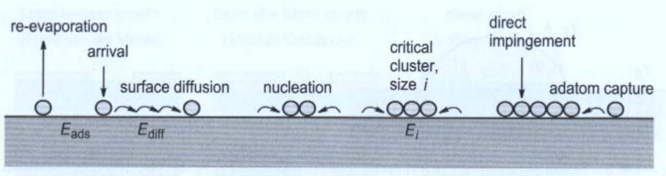
Growth Modes

- Exp: Monitor <u>Auger signals</u> from film and substrate while depositing...



Island Number Density

- Nucleation and growth on surfaces:



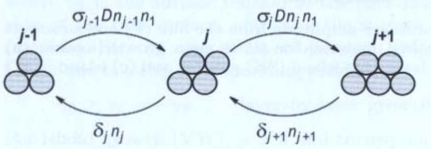
- Diffusion coefficient: $$D = \frac{\nu}{4n_0}\exp\left(-\frac{E_{diff}}{k_B T}\right)$$

- Residence time: $$\tau_{ads} = \frac{1}{\nu}\exp\left(\frac{E_{ads}}{k_B T}\right)$$

- **Critical island size i**: minimal size when the addition of one atom makes the island stable

Island Number Density

- Capture and decay processes → cluster size



- Rate equations:

adatom density

subcritical clusters

$$\frac{dn_1}{dt} = R - \frac{n_1}{\tau_{ads}} + \boxed{\left(2\delta_2 n_2 + \sum_{j=3}^{i}\delta_j n_j - 2\sigma_1 D n_1^2 - n_1\sum_{j=2}^{i}\sigma_j D n_j\right)} - \boxed{n_1\sigma_x D n_x}$$

stable clusters

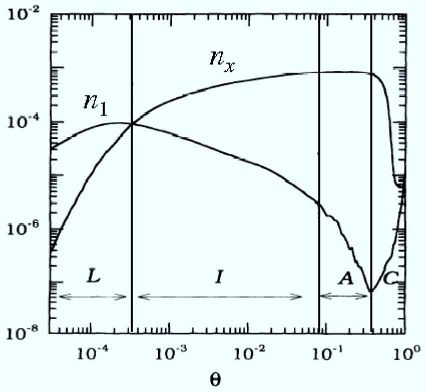
deposition rate

$$\frac{dn_j}{dt} = n_1\sigma_{j-1}Dn_{j-1} - \delta_j n_j + \delta_{j+1}n_{j+1} - n_1\sigma_j Dn_j$$ → metastable clusters

$$\frac{dn_x}{dt} = n_1\sigma_i Dn_i$$ → stable clusters

Island Number Density

- Numerical solution for $i = 1$ without re-evaporation (Amar, Family and Lam, PRB 1994):



- Four coverage regimes are found

Island Number Density

(1) Low-coverage nucleation regime: $n_1 >> n_x$

- In such case:

$$n_1 \propto \Theta \qquad n_x \propto \Theta^3$$

When $n_x \sim n_1$ → **(2) Intermediate-coverage regime**

- In such case:

$$n_1 \propto \Theta^{-1/3} \qquad n_x \propto \Theta^{1/3}$$

When mean island separation ~ mean free path of adatoms

→**(3) Aggregation regime** (Θ ~ 0.1-0.4 ML)

When the island join together

→**(4) Coalescence and percolation regime**

Island Number Density

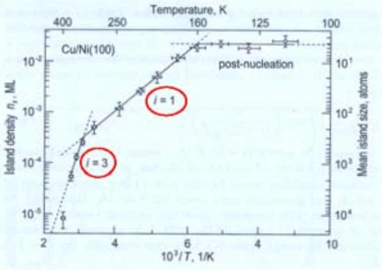
- <u>Saturation density</u> (Venables et al., 1984):

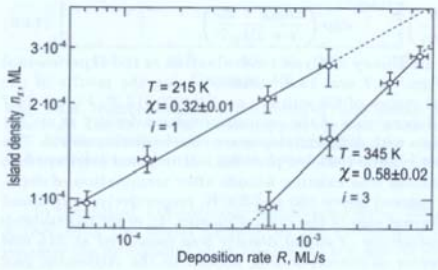
$$\boxed{n_x = n_0\eta(\Theta,i)\left(\frac{4R}{\nu_0 n_0}\right)^{\overset{\chi}{\frac{i}{i+2}}}\exp\left(\frac{iE_{diff}+E_i}{(i+2)k_BT}\right),}$$

binding energy
of critical cluster

$$\eta(\Theta,i)\sim 0.1-1$$

- Example: Cu on Ni(100) (Müller et al., PRB 1996)





Island Shape

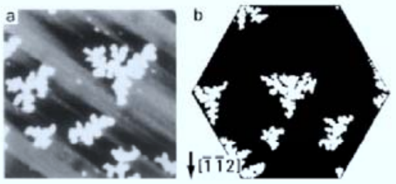
- At low T (slow edge diffusion): **ramified islands**
- **Diffusion-limited-aggregation (DLA) model** (Witten & Sander, PRL 1981):

- Adatoms stick at islands
- Fractal shape
- Branch thickness ~ 1 atom
- No influence of lattice geometry

- In real growth (STM experiments):
  - Fractal shape
  - Branch thickness > 1 atom
  - Influence of lattice geometry

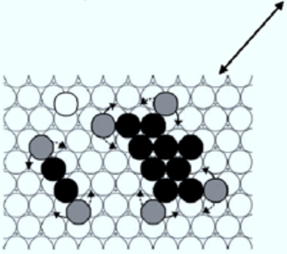
Island Shape

- Example: Pt/Pt(111) (Hohage et al., PRL 1996)



experiment simulation

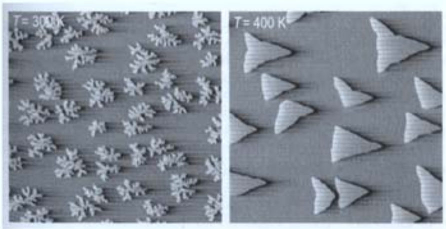
- Branch thickness ~ 4 atoms
- Trigonal symmetry



- Higher coordination is preferred

Island Shape

- At higher T: **compact islands**
- Example: Pt/Pt(111) (Bott et al., PRL 1992)

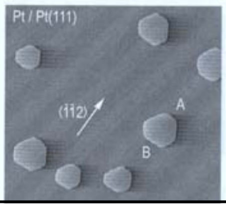


300 K

400 K

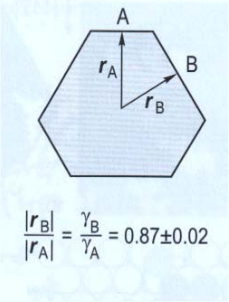
- The equilibrium shape is hexagonal:

(deposition at 425 K + annealing at 700 K)



Island Shape

- **2D Wulff theorem:** In a 2D crystal at equilibrium, the distances of the borders from the crystal center are proportional to their free energy per unit length



- For Pt(111): B/A ~ 0.87

Island Size Distribution

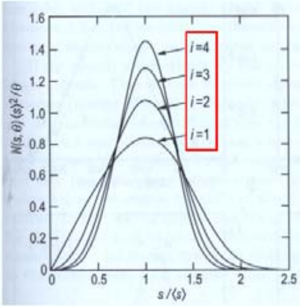
- **Island size distribution** depends on:
  - Critical island size
  - Coverage
  - Substrate structure
  - “Coarsening” (at high Θ)

- From **scaling theory** (Amar et al., PRB 1994):

$$N_s = \frac{\Theta}{\langle s \rangle^2} f_i\left(\frac{s}{\langle s \rangle}\right)$$

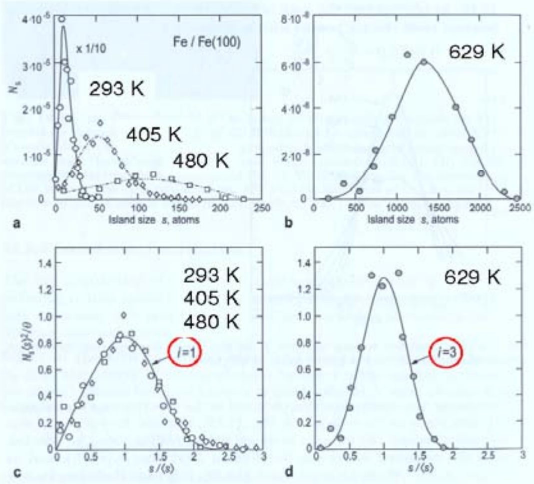
- Comparing with experimental results

→ critical island size



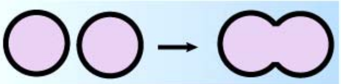
Island Size Distribution

- Example: Fe on Fe(100) (Stroscio et al., PRL1993, Amar et al., PRB 1994)



Coarsening Phenomena

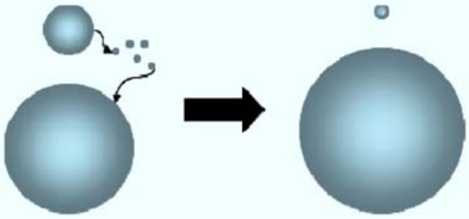
1) Coalescence:



- At 0.1 ML coverage: **dynamic coalescence** (**Smoluchowski ripening**)
- At 0.4-0.5 ML: **static coalescence**
- Higher coverages → **percolation** growth (→ change of physical properties!)

Coarsening Phenomena

2) (Ostwald) Ripening:



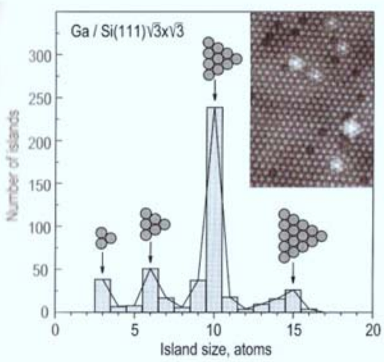
- Chemical potential of a circular island:

$$\mu(r) \propto \frac{\gamma}{r}$$

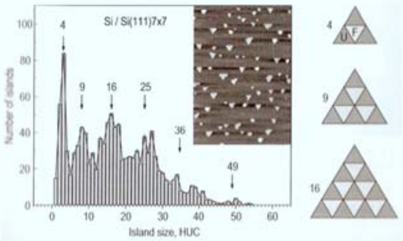
Reducing free energy → net flow from smaller to larger islands!

Magic Islands

- Ga on Si(111)√3x√3 (Lai & Wang, PRL 1998):



- Si on Si(111)7x7 (Voigtländer et al., PRL 199

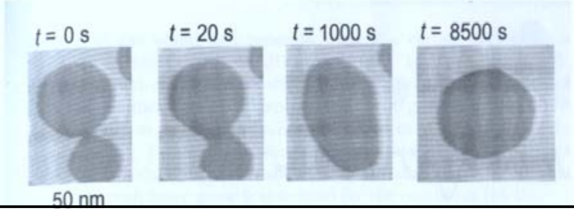


Formation of a new row → high energy cost!

Vacancy Islands

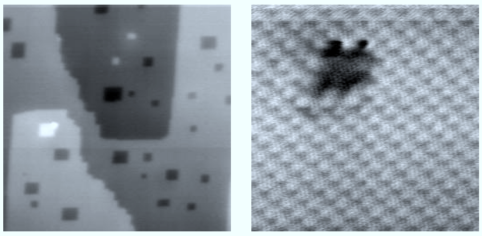
- Ion bombardment → formation of **vacancy islands**

- Analogies with adatom islands



Vacancy Islands

- Electron bombardment on insulating surfaces (Bennewitz et al., SS 2001):

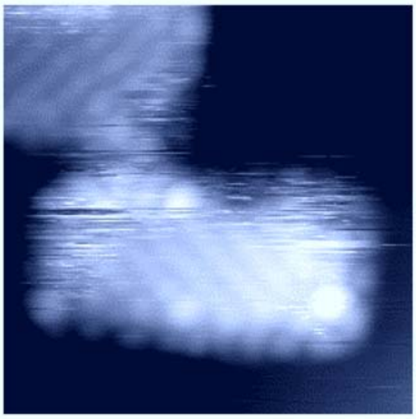


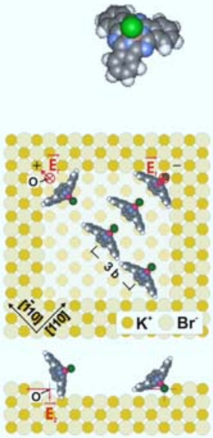
KBr(100)

- Irradiation with 1 keV electrons at 130 ºC
- Rectangular pits with area of 1x1 nm^2 up to 30x30 nm^2
- 1 ML deep (0.33 nm)

Vacancy Islands

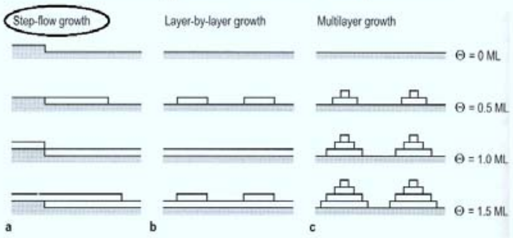
- Vacancy islands can be used as <u>molecular traps</u> (Nony et al., NL 2004)



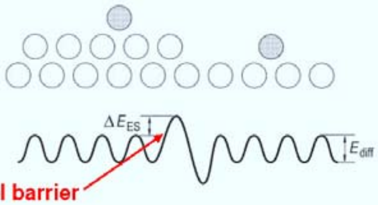


Kinetic Effects in Homoepitaxy

- Thermodynamics → Layer-by-layer growth but…
- Kinetic processes → Other growth modes are possible!



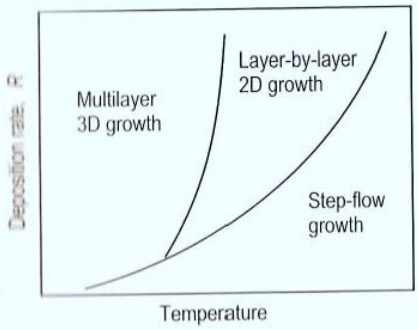
- **Interlayer** mass transport:



Ehrlich-Schwöbel barrier

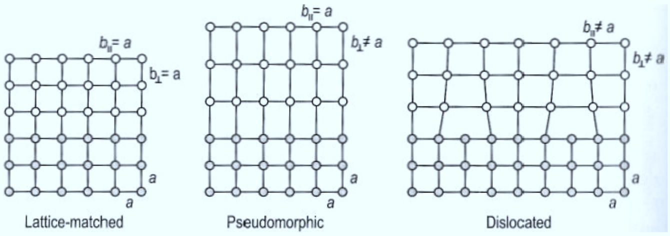
Kinetic Effects in Homoepitaxy

- Deposition rate and Temperature are important!
- Growth mode diagram (Rosenfeld et al., 1997):



Strain Effects in Heteroepitaxy

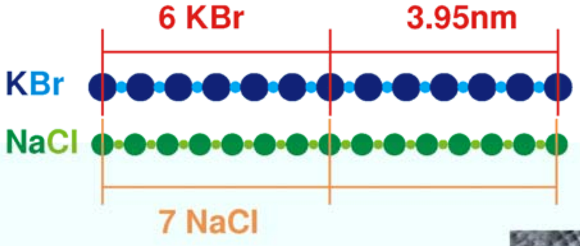
- Heteroepitaxy growth modes:



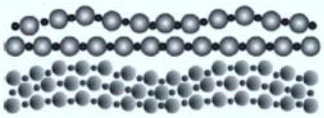
- Lattice **misfit** → elastic strain and dislocations
- Pseudomorphic growth below critical misfit and film thickness

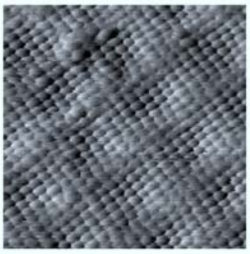
Strain Effects in Heteroepitaxy

- Heteropitaxy on insulating surfaces (Maier et al., PRB 2007):

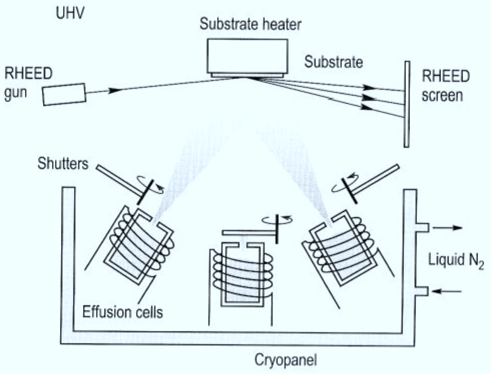


- A “Moiré pattern” appears (also in the substrate?)





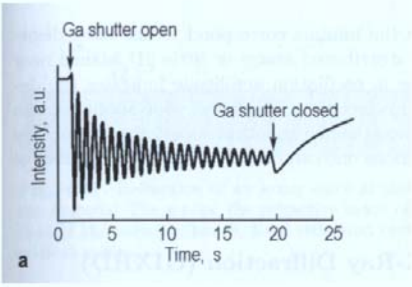
Molecular Beam Epitaxy

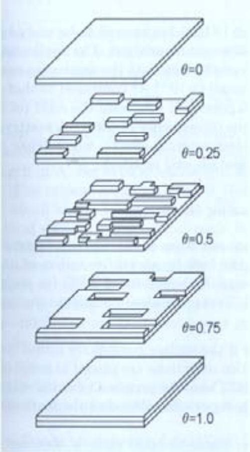


- Used both in research and in semiconductor device fabrications

Molecular Beam Epitaxy

- The growth process can be monitored by RHEED:





Solid Phase Epitaxy

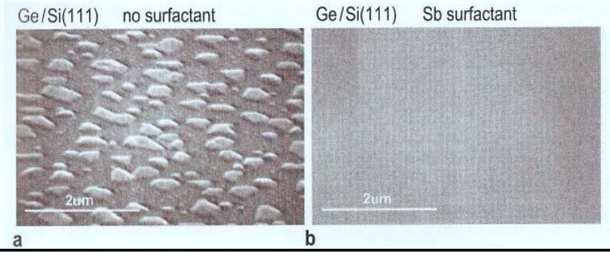
- Amorphous film deposited at low T and then crystallized upon heating at high T
- Lower crystallinity than MBE
- Used in semiconductor industry

Chemical Beam Epitaxy

- Growth by surface chemical reactions
- High temperature required
- High grow rate and cristallinity

Surfactant-Mediated Growth

- Impurity **(surfactant)** → different growth mode!
- Surfactant can be either segregated or trapped
- Example: Ge on Si(111) (Zahl et al., APA 1999)
  - Bare surface → Stranski-Krastanov mode
  - With surfactant (Sb) → Layer-by-layer mode



Further Reading

- K. Oura et al., Surface Science, Springer 2003, chapter 14
- J.A. Venables et al., Rep. Prog. Phys. 47 (1984) 399
- H. Brune, Surf. Sci. Rep. 31 (1998) 121

Oberflächenphysik

27/04/2010

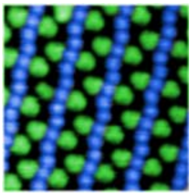
Local Probes and Experiments I:

Scanning Tunneling Microscopy (STM)
Inelastic Tunneling and
Scanning Tunneling Spectroscopy (STS)

Prof. Dr. Silvia Schintke & Prof. Dr. Thomas A. Jung

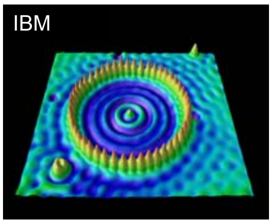
STM – local probe for surface science

surface analysis @ nanoscale
- scanning probe methods (STM/AFM)
  - working principle of STM
  - tunnel current
  - examples and image interpretation
- scanning tunneling spectroscopy (STS)
  - local electronic structure



STM image: self-assembled molecular layer
Nanolab, Uni Basel

surface modifications @ nanoscale
- manipulation of atoms or adsorbates
- nanoindentation

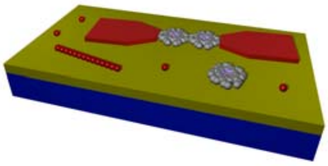


Nanotools for surface analysis and modifications

Motivation

- Miniaturization / Technology
- Study of material properties at small dimensions
  => **research on ultrathin insulator layers & organic molecules (building blocks for devices)**

- applications
  - OLED displays (Organic Light Emitting Diode)
  - future molecular electronics
  - catalysts
  - …

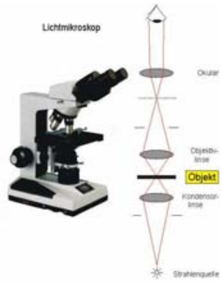


- fundamental interest
  - electronic structure
  - molecular interactions
  - chemical reactivities
  - …

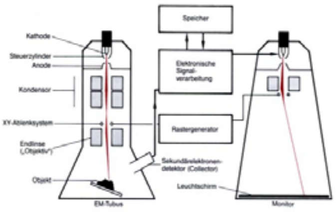
Microscopes

For the visualisation of millimeter to nanometer structures

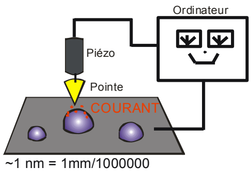
Light Microscope	Electron Microscope (SEM)	Scanning Probe Microscope (SPM)
since about 1750	since about 1955	since about 1981



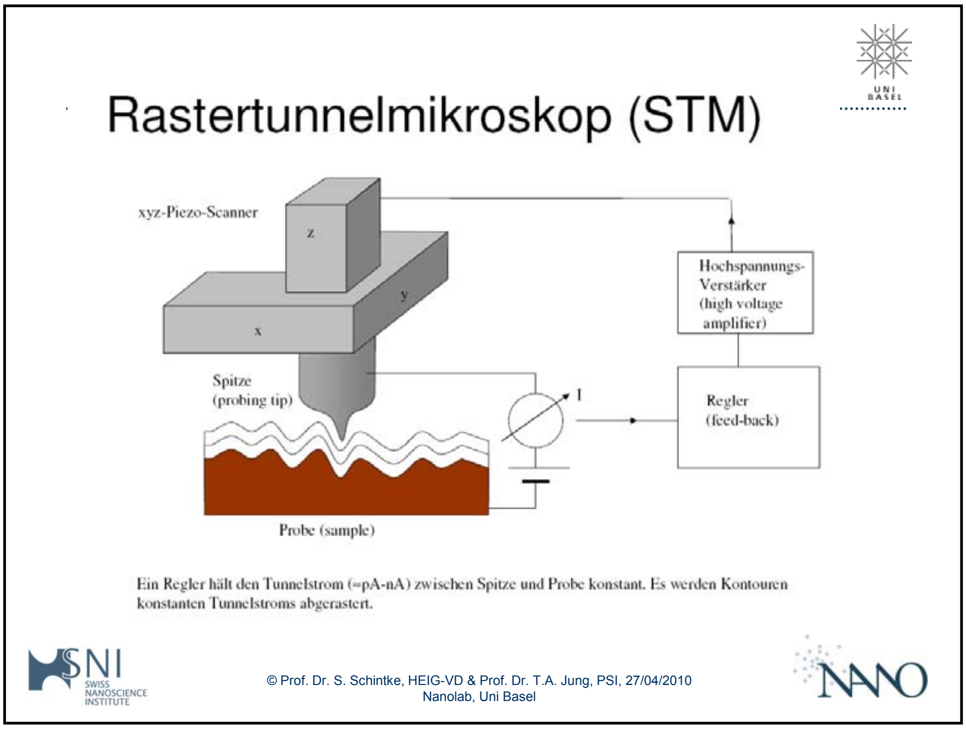
geometric optics
resolution about 500 nm
Light-Intensity contrast



e-beam raster-scan
resolution 5 nm
secondary electron counting
projection image



Local probe piezo-scan
resolution 0.1 nm
3D map of surface



Rastertunnelmikroskop (STM)

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

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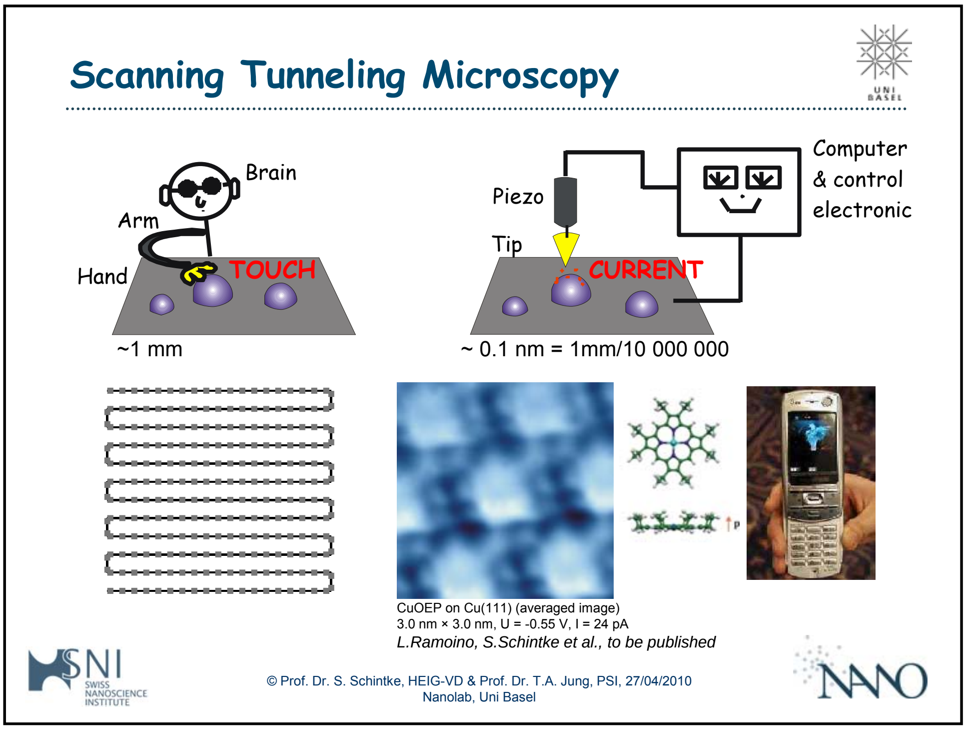
Nanolab, Uni Basel



Scanning Tunneling Microscopy

CuOEP on Cu(111) (averaged image)
3.0 nm × 3.0 nm, U = -0.55 V, I = 24 pA
L.Ramoino, S.Schintke et al., to be published

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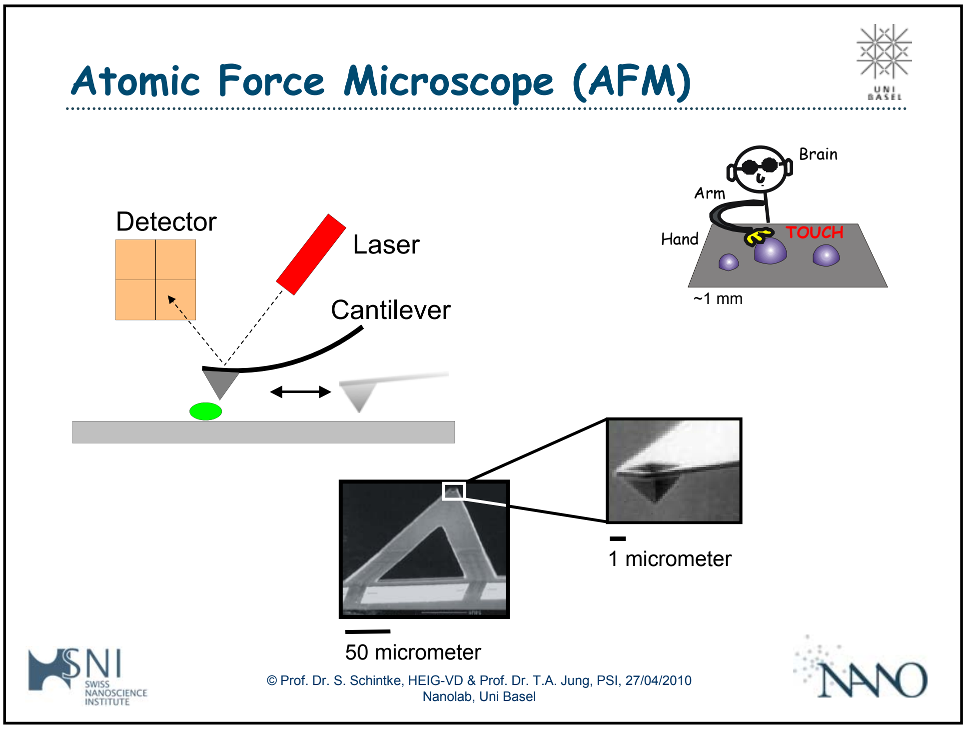

Atomic Force Microscope (AFM)

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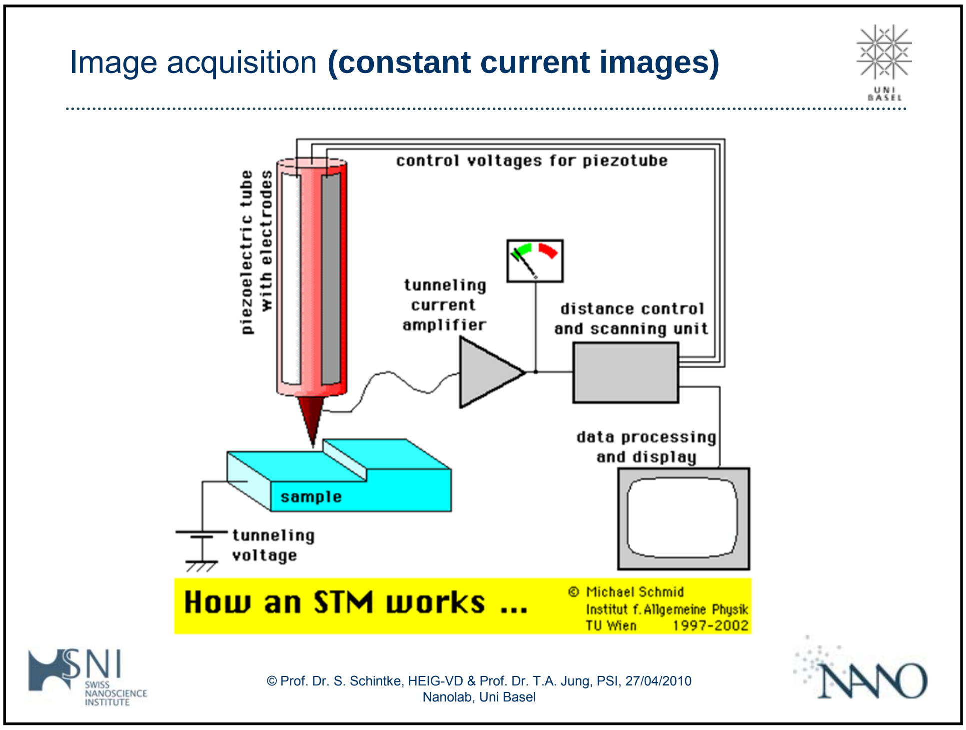

Image acquisition **(constant current images)**

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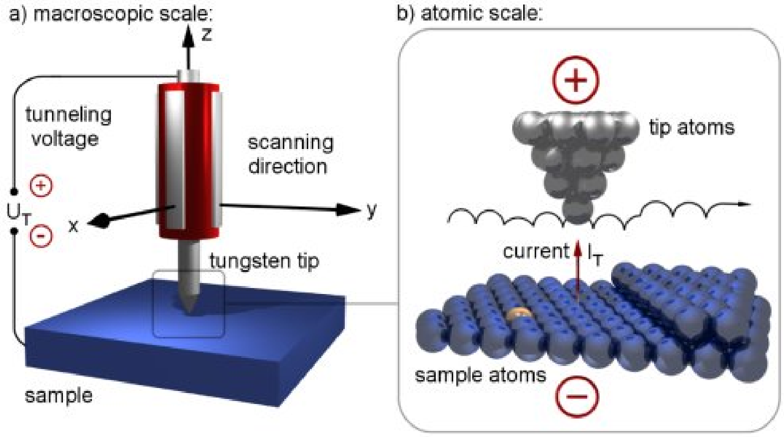
Piezo unit and tip displacement



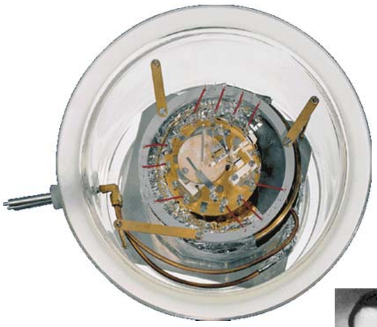
History of Scanning Tunneling Microscopy

- **1979-1981 Development at IBM Zürich**
  G. Binnig, H. Rohrer, Ch. Gerber, E. Weibel,
  Appl. Phys. Lett 40 (1982), Phys. Rev. Lett. 49, 57 (1982)
- **1986** **Nobel prize of Physics** for Gerd Binnig and Heinrich Rohrer

The soccer ball team of the IBM research lab; 15 October 1986
C. Julian Chen: Introduction to Scanning Tunneling Microscopy;
Original photo: Blick

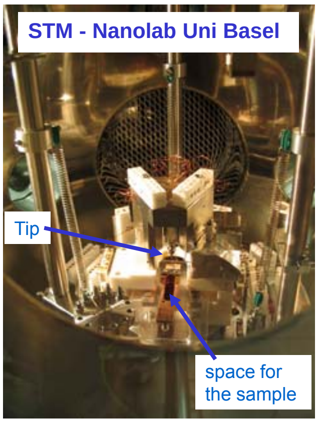
The first Scanning Tunneling Microscope

1981 development at
IBM Rüschlikon, Switzerland

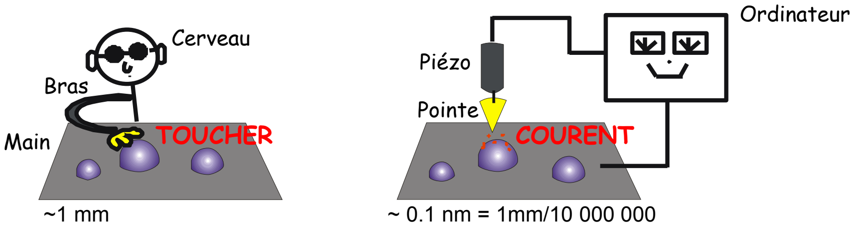


G. Binnig and H. Rohrer
Nobelprize for physics 1986

The « Nanolab » at the University of Basel



Les composants principaux d'un STM



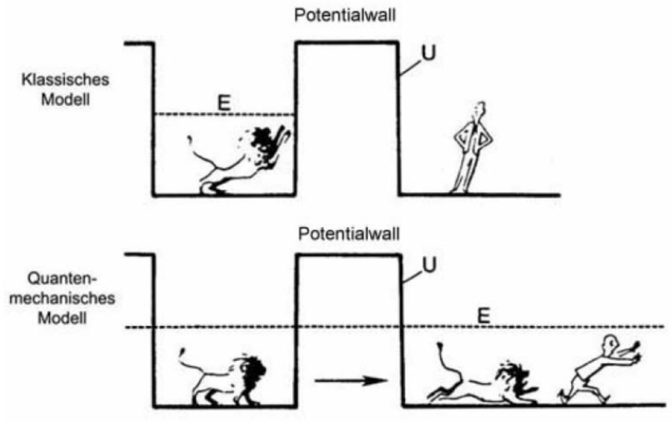
Composants principaux:

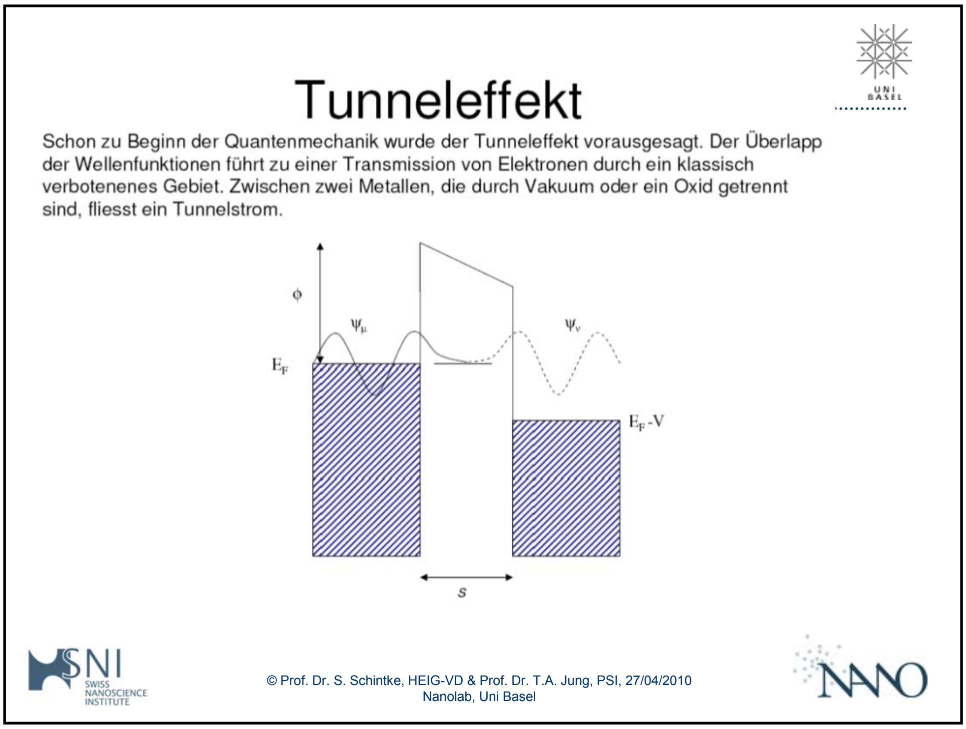
Main: sonde locale => **pointe métallique, fine**

Bras: balayage => **actuateur piézoelectrique**

Cerveau: régulation & enrégistrement => **électronique de régulation & ordinateur**

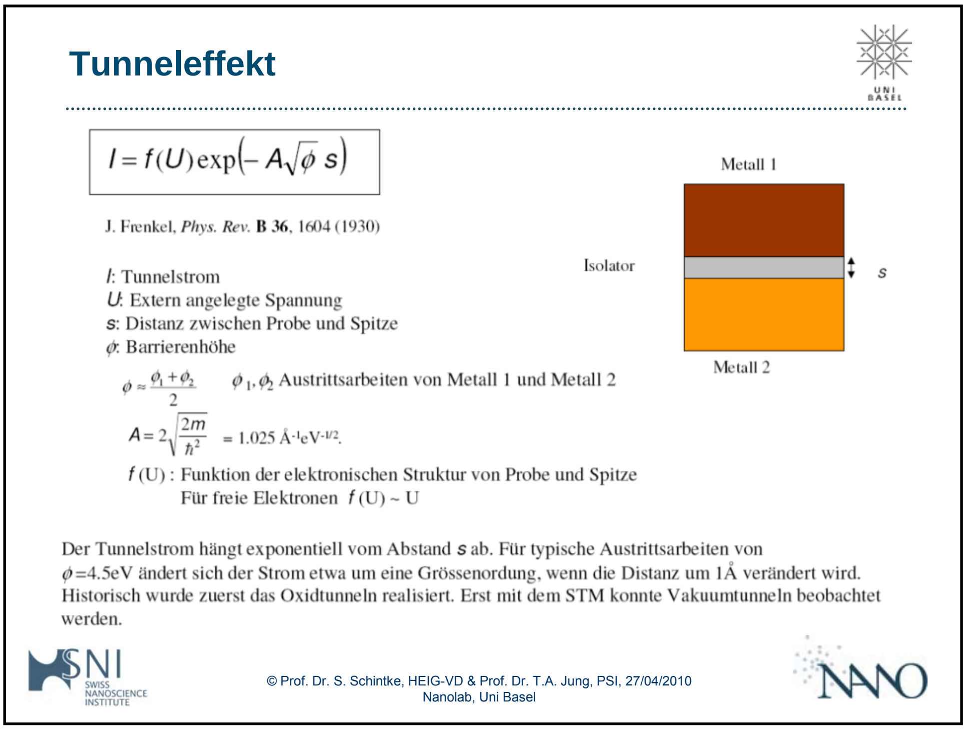
Quantum Mechanic Tunneling





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.



Tunneleffekt

$$\boxed{I = f(U)\exp\left(-A\sqrt{\phi}\, s\right)}$$

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

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

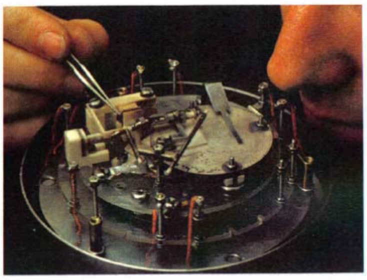
$\phi \approx \frac{\phi_1 + \phi_2}{2}$ ϕ_1, ϕ_2 Austrittsarbeiten von Metall 1 und Metall 2

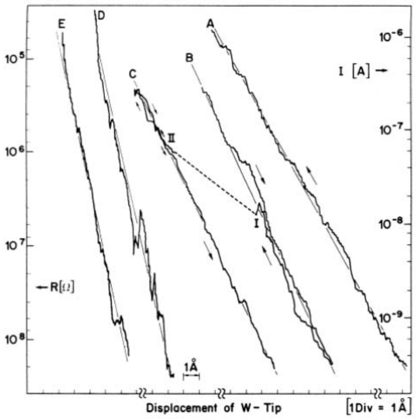
$A = 2\sqrt{\frac{2m}{\hbar^2}}$ = 1.025 $Å^{-1}eV^{-1/2}$.

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

Der Tunnelstrom hängt exponentiell vom Abstand s ab. Für typische Austrittsarbeiten von ϕ=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 beobachtet werden.

Tunnelstrom

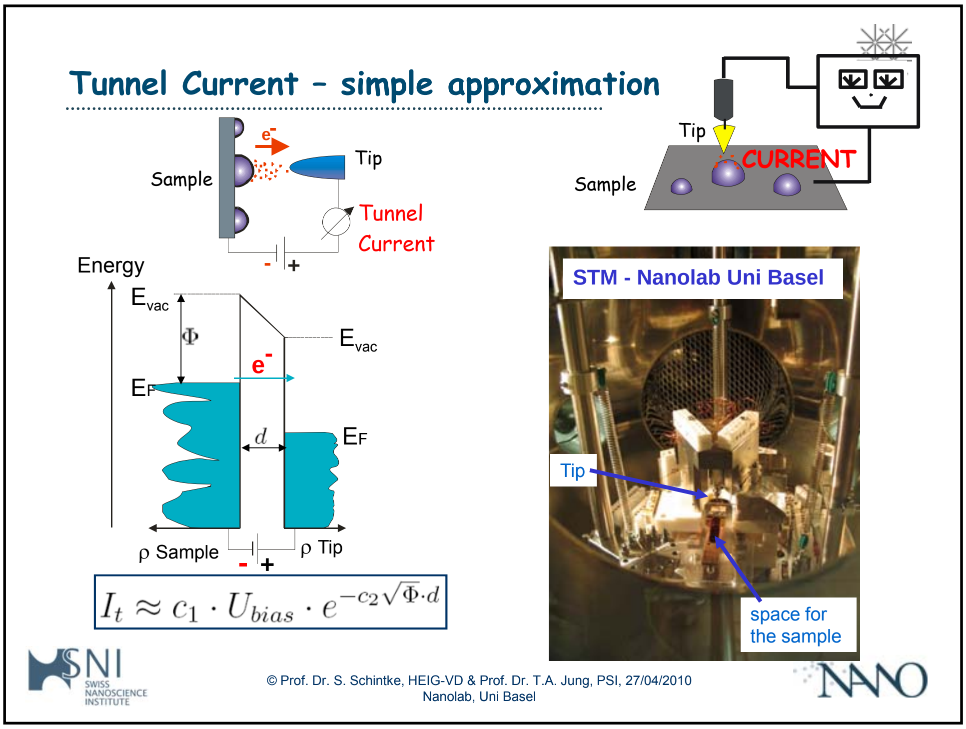




Exponentieller Abfall des Tunnelstromes mit dem Abstand

STM

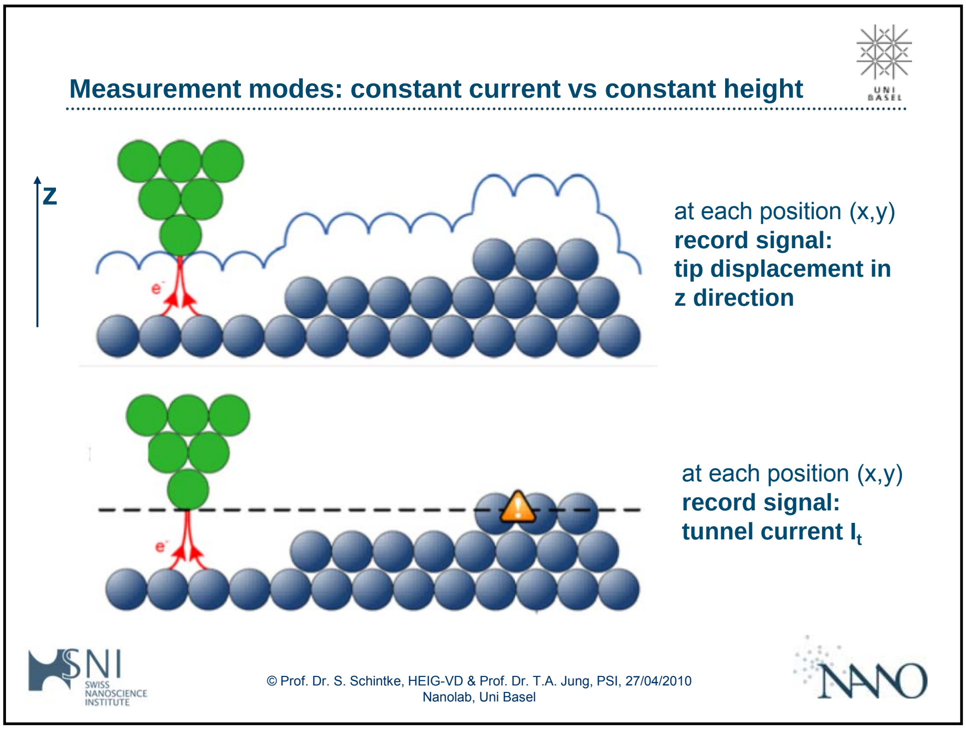
Nanosurf AG, Liestal



Tunnel Current – simple approximation

$$I_t \approx c_1 \cdot U_{bias} \cdot e^{-c_2\sqrt{\Phi}\cdot d}$$

STM - Nanolab Uni Basel



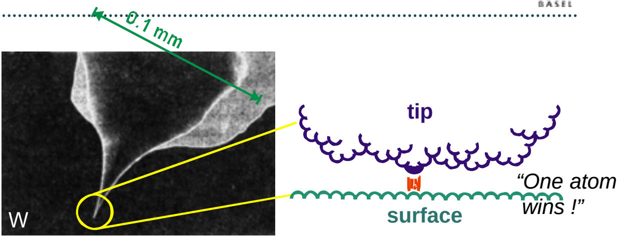
Measurement modes: constant current vs constant height

at each position (x,y)
record signal:
tip displacement in z direction

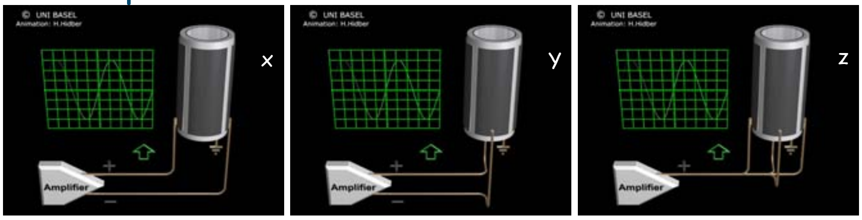
at each position (x,y)
record signal:
tunnel current I_t

The « finger » and the « arm »

"Finger" = tip



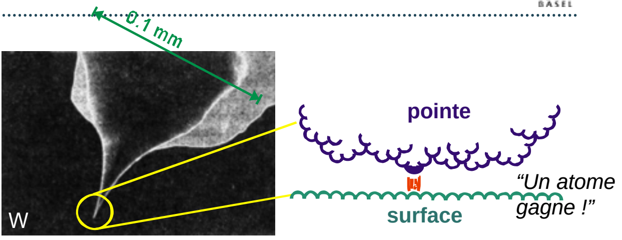
"Arm" = piezoelectric actuator



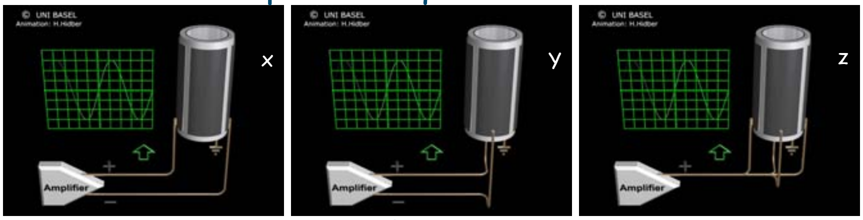
Animations: H. Hidber, University of Basel

La « main » et le « bras »

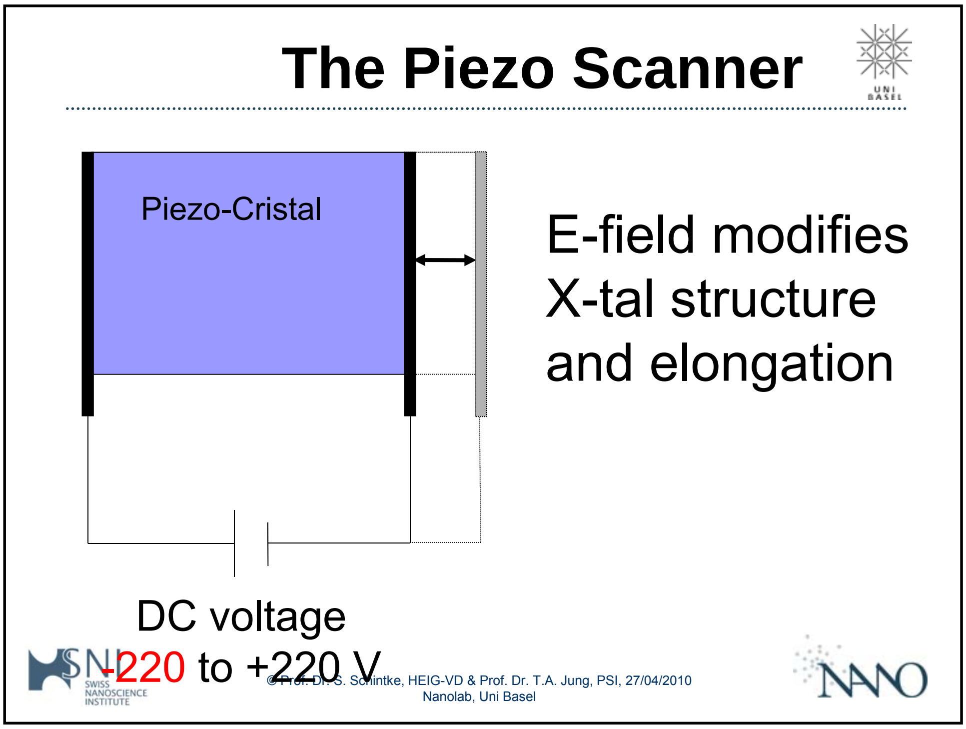
"Main" = pointe



"Bras" = actuateur piézoélectrique



Animations: H. Hidber, Université de Bâle



The Piezo Scanner

Piezo-Cristal

E-field modifies
X-tal structure
and elongation

DC voltage
-220 to +220 V

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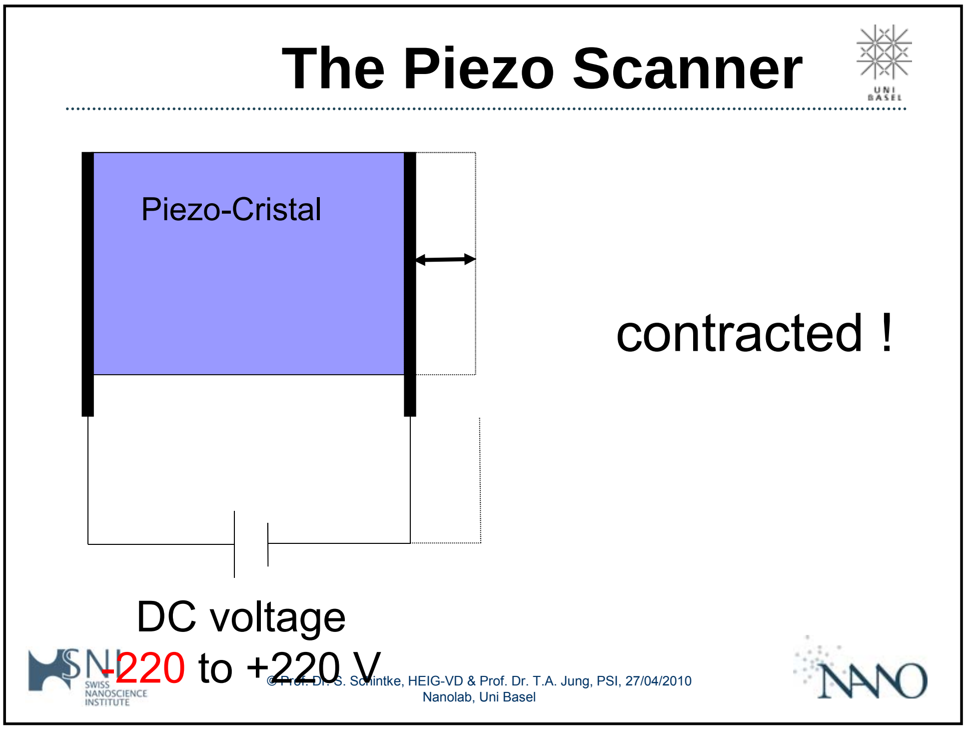
Nanolab, Uni Basel



The Piezo Scanner

Piezo-Cristal

contracted !

DC voltage
-220 to +220 V

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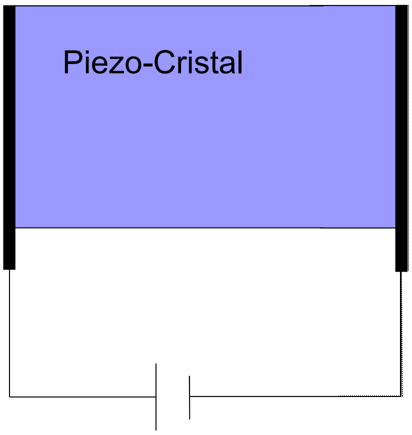
The Piezo Scanner

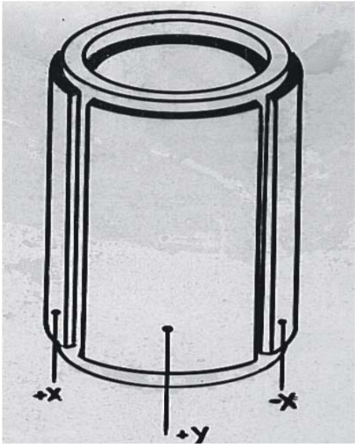


extended !

DC voltage
-220 to +220 Volt

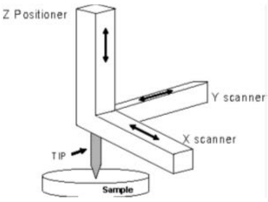
XYZ – scan unit

'precision at your fingertips'

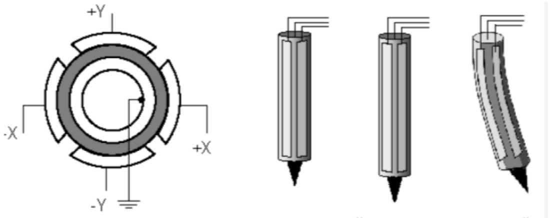


Precision: 1 pm

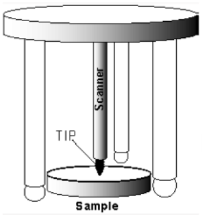
Piezo scan unit



tripod scanner



tube scanner

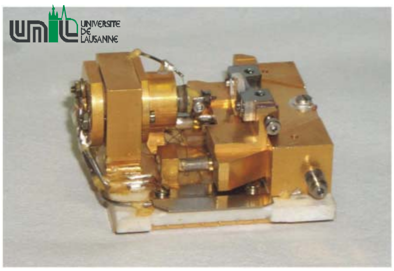


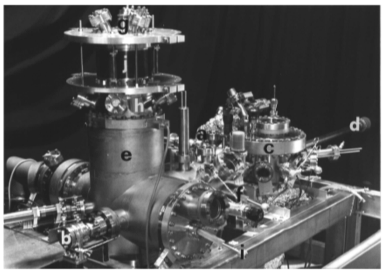
beetle type STM

Principe d’un microscope à effet tunnel

Animation: IBM

Advantages of UHV and low temperature



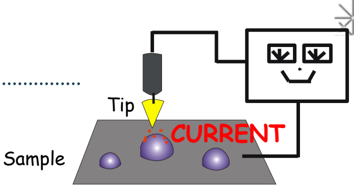


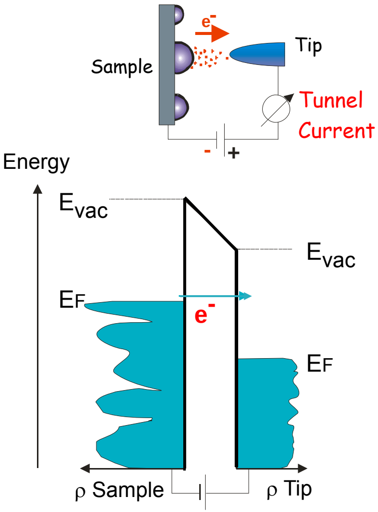
Reinheit der Probenoberflächen
Präparation der Kristalloberfläche und Messung
im Ultrahochvakuum (UHV) ($p<10^{-10}$ mbar)

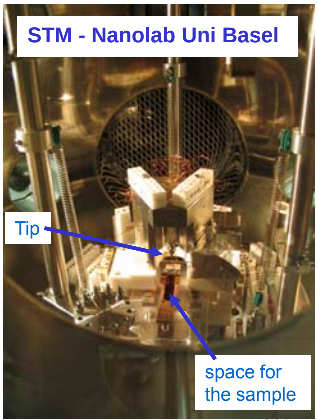
Schwingungsdämpfung
- STM auf pneumatisch gelagertem massiven Rahmen
- STM Mess-Station mit Faltenbalg schwingungsisoliert
- Schallschutzkammer um Gesamtanlage während der Messungen

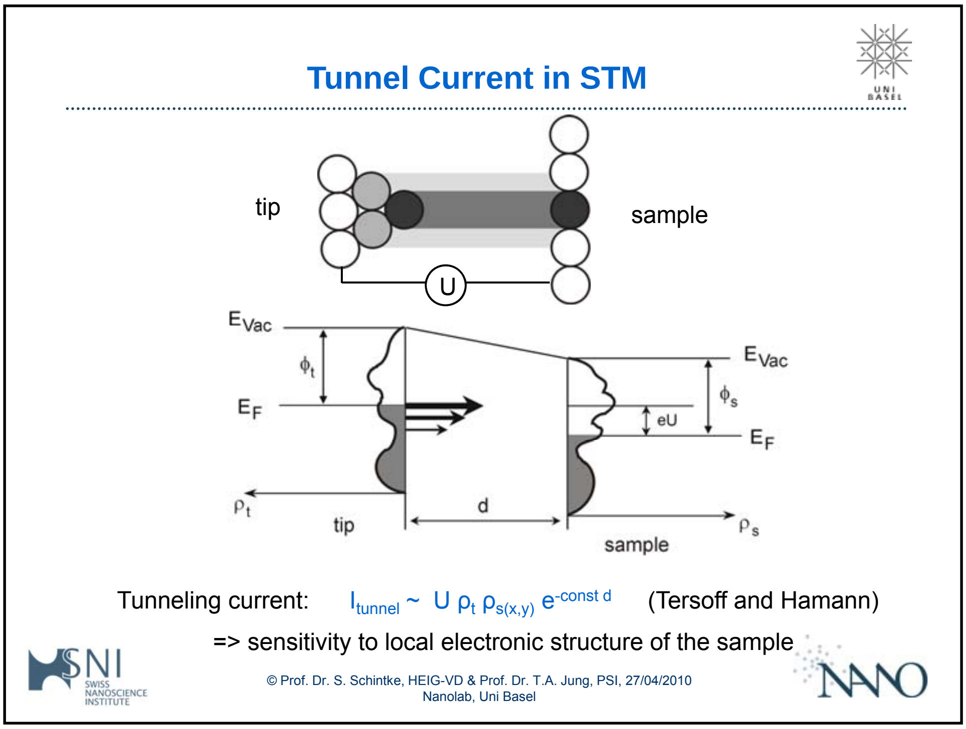
Stabilität atomarer Strukturen
Messung bei Tieftemperatur
=> reduzierte Beweglichkeit von Atomen und Molekülen auf der Oberfläche
T=50K (fester Stickstoff)
T=5K (flüssiges Helium)

Tunnel Current





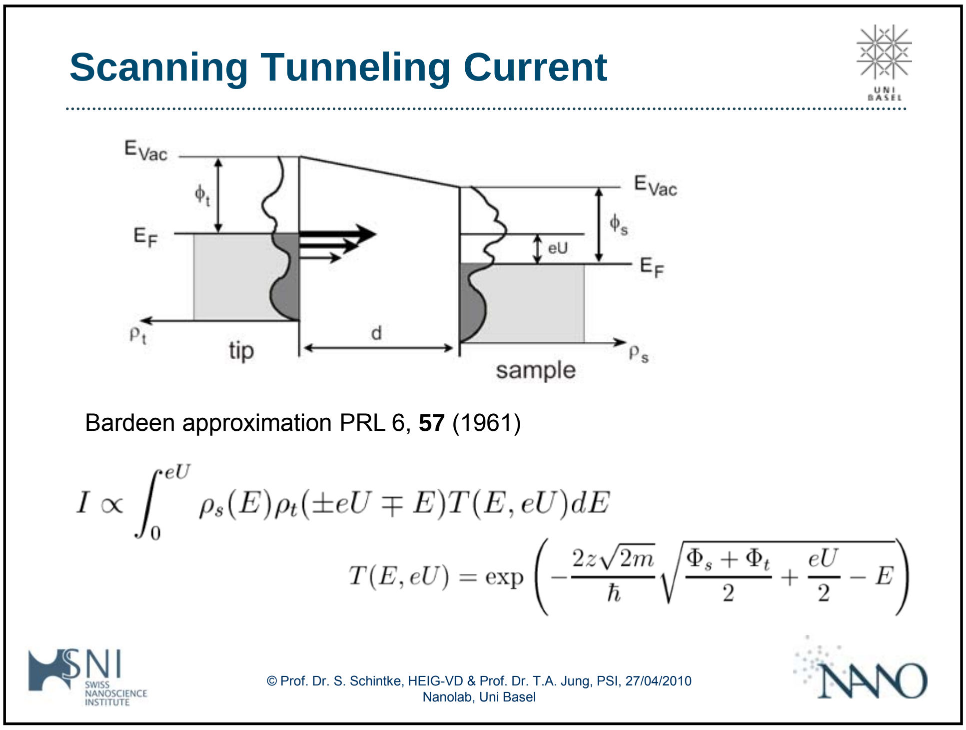




Tunnel Current in STM

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



Scanning Tunneling Current

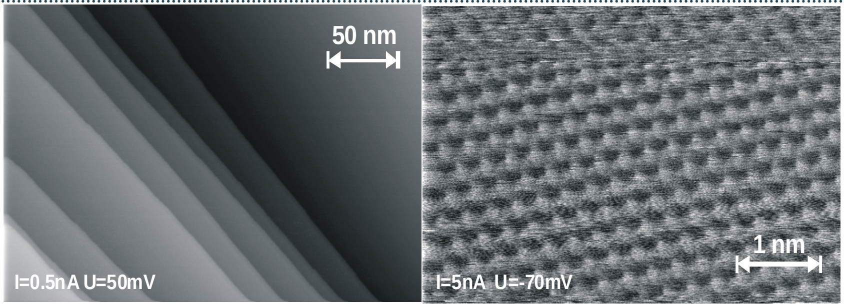
Bardeen approximation PRL 6, **57** (1961)

$$I \propto \int_0^{eU} \rho_s(E)\rho_t(\pm eU \mp E)T(E,eU)dE$$

$$T(E,eU) = \exp\left(-\frac{2z\sqrt{2m}}{\hbar}\sqrt{\frac{\Phi_s+\Phi_t}{2}+\frac{eU}{2}-E}\right)$$

STM Application
for
Surface Analysis
and
Surface Material Science & Engineering

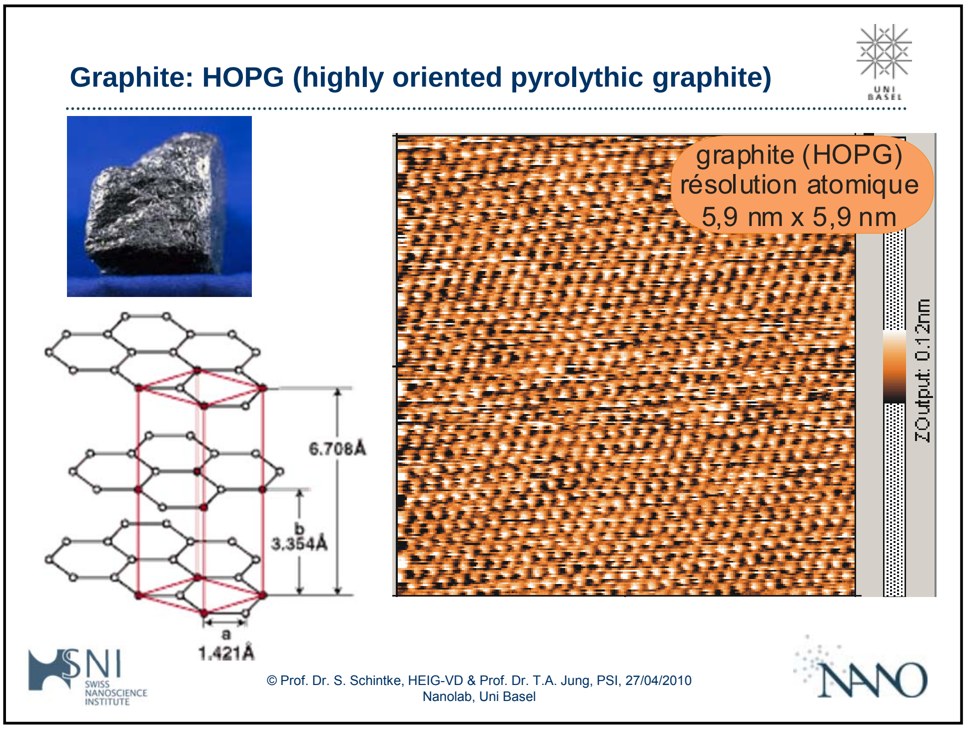
Atomic resolution
Metals



steps of monatomic height atomic resolution
(raw data on Ag(111))

$$I \propto \int_0^{eU} \rho_s(E)\rho_t(\pm eU \mp E)T(E, eU)dE$$

$$T(E, eU) = \exp\left(-\frac{2z\sqrt{2m}}{\hbar}\sqrt{\frac{\Phi_s + \Phi_t}{2} + \frac{eU}{2} - E}\right)$$



Graphite: HOPG (highly oriented pyrolythic graphite)

graphite (HOPG)
résolution atomique
5,9 nm x 5,9 nm

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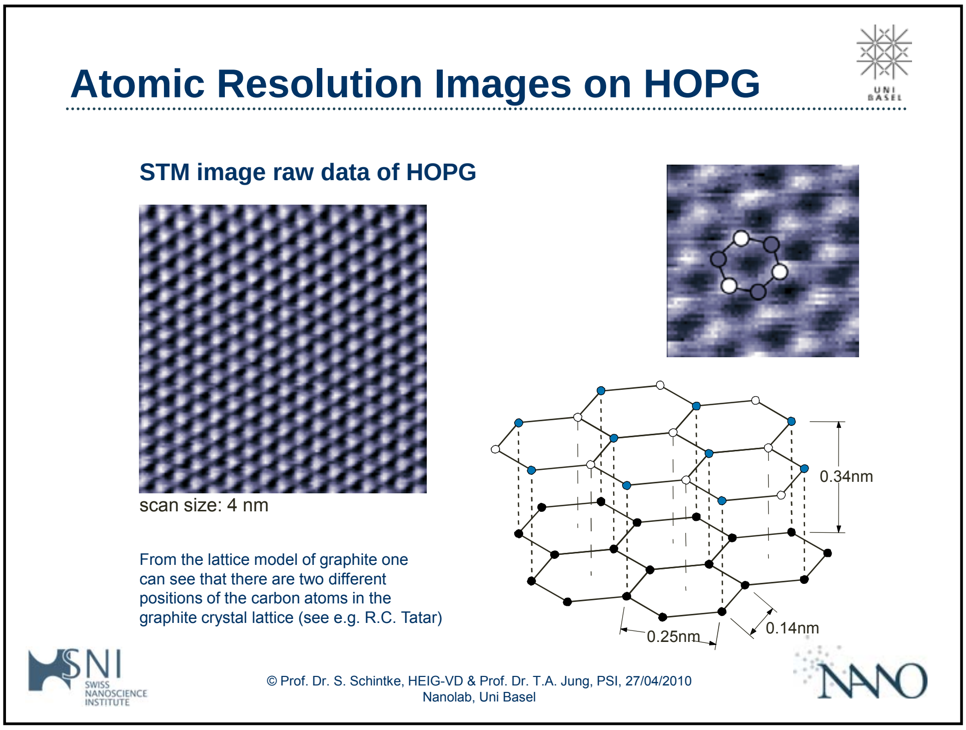
Nanolab, Uni Basel



Atomic Resolution Images on HOPG

STM image raw data of HOPG

scan size: 4 nm

From the lattice model of graphite one can see that there are two different positions of the carbon atoms in the graphite crystal lattice (see e.g. R.C. Tatar)

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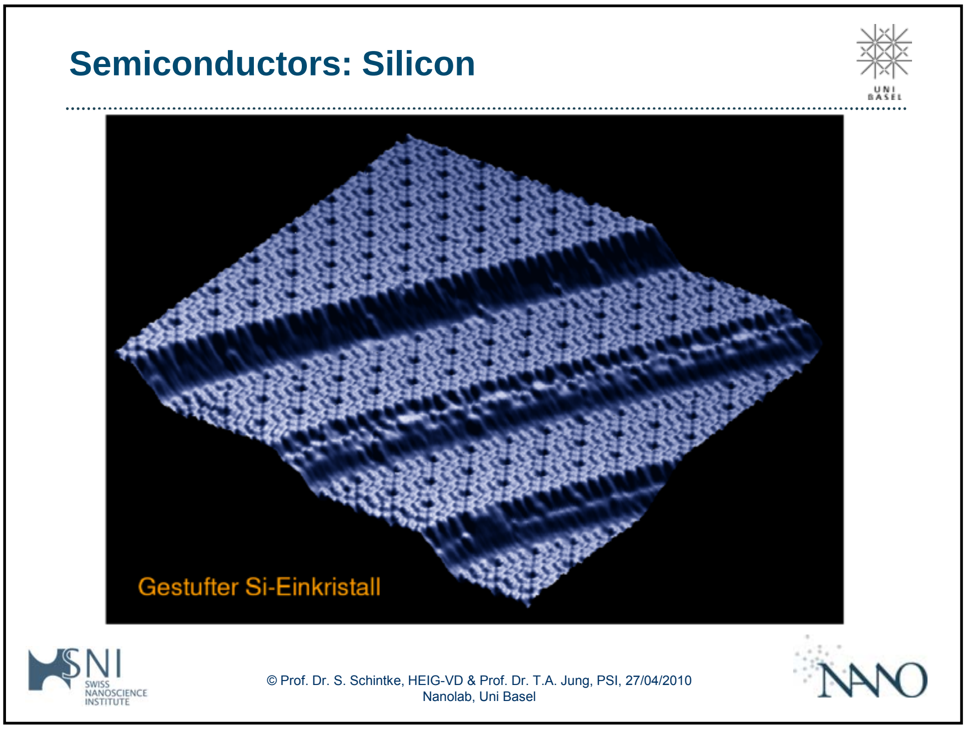

Semiconductors: Silicon

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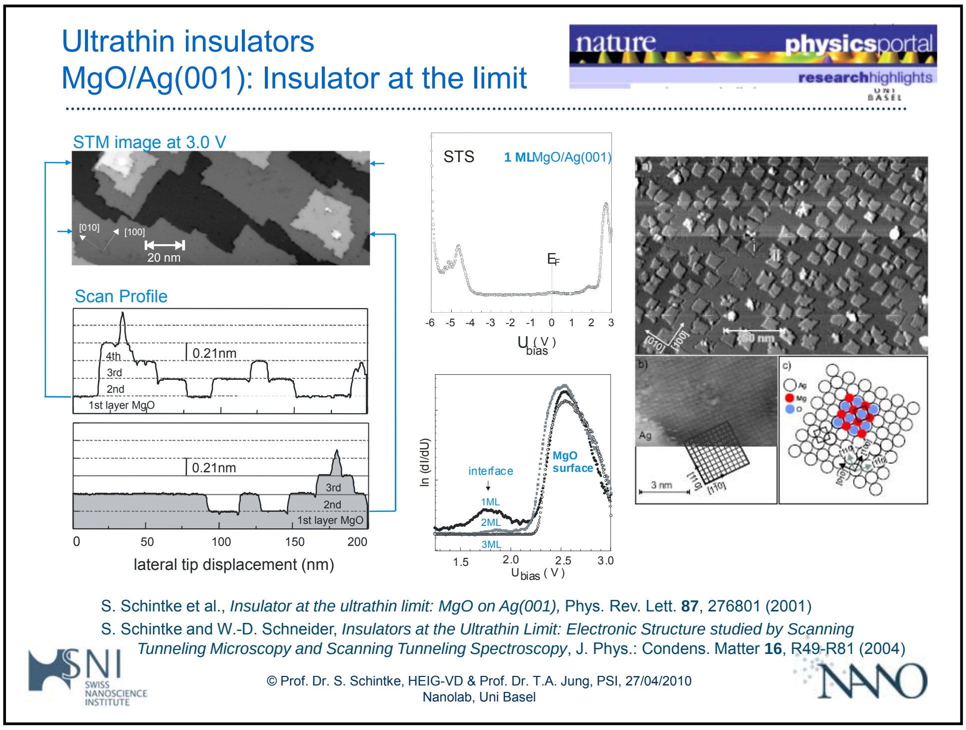

Ultrathin insulators
MgO/Ag(001): Insulator at the limit

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)

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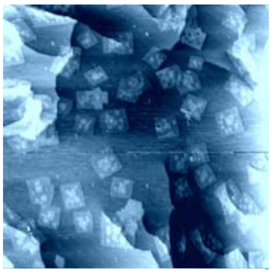
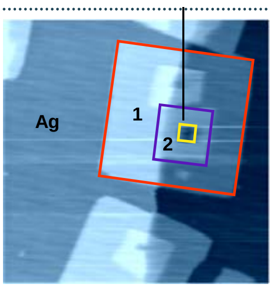
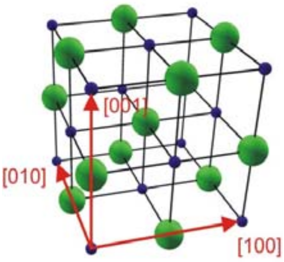
Ultrathin insulators: NaCl layers

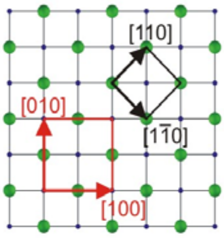


NaCl on Ag(111)
1.25 μm x 1.25 μm

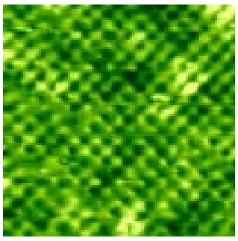


NaCl on Ag(111) 200 nm x 200 nm
U = 4.0 V, I = 15 pA





atomic resolution: one type of the ions is imaged



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

$a_0 = 5.65$ Å

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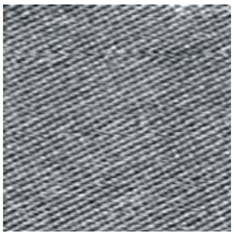
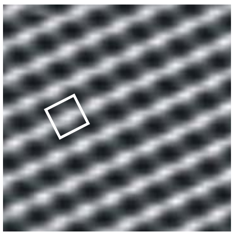
Nanolab, Uni Basel

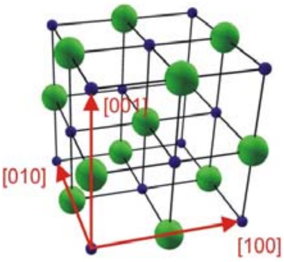
NaCl/metal Atomic Resolution

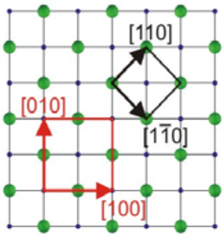


NaCl on Ag(001)
14.5 × 14.5 nm
U = 1.24 V, 40 pA



Average
3.4 × 3.4 nm





	surface periodicity	corresponding 3D lattice constant	relaxation
Cu(111)	3.88 Å	5.49 Å	−3%
Ag(111)	3.91 Å	5.53 Å	−2%
Ag(001)	3.76 Å	5.32 Å	−6%

$a_0 = 5.65$ Å

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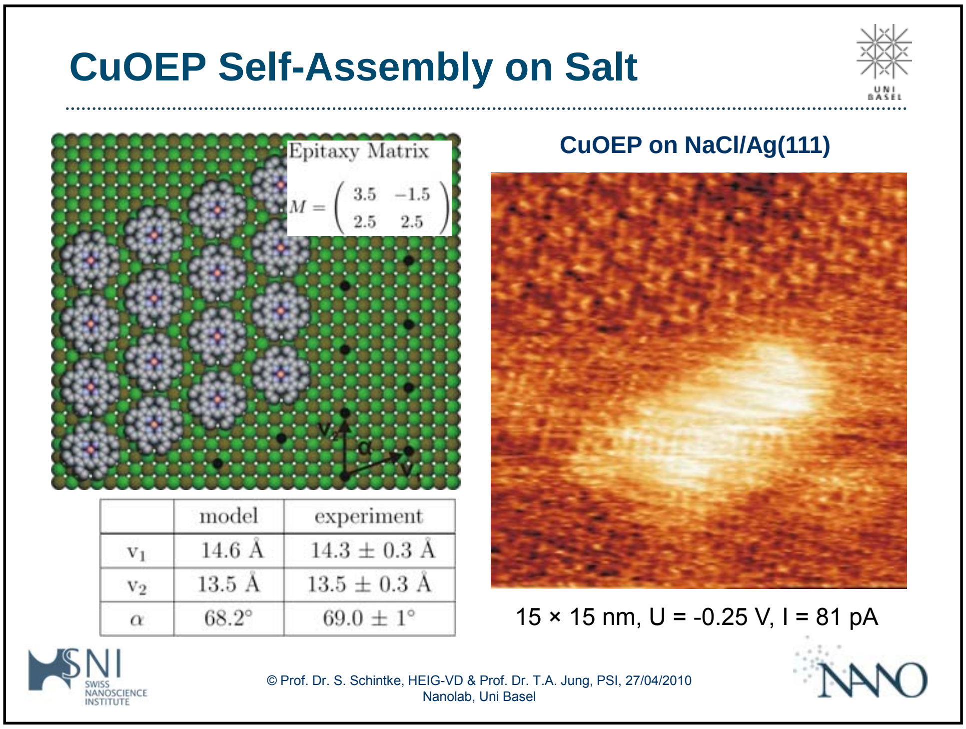
Nanolab, Uni Basel

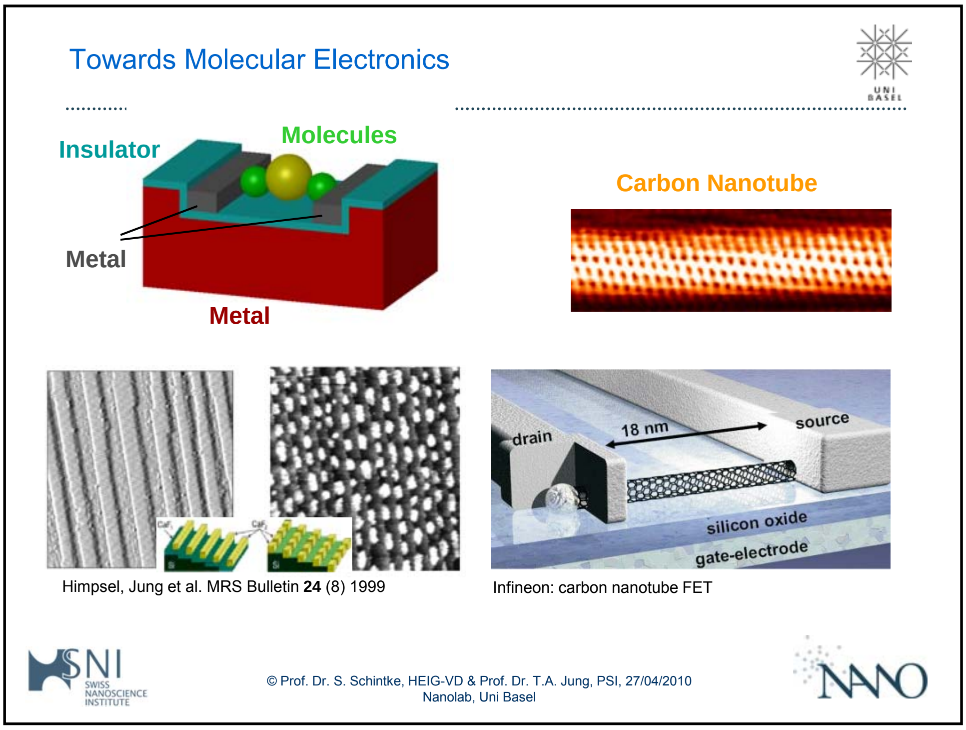


CuOEP Self-Assembly on Salt

	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°

CuOEP on NaCl/Ag(111)

15 × 15 nm, U = -0.25 V, I = 81 pA



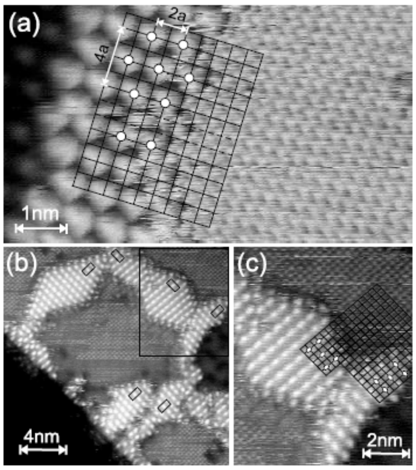
Towards Molecular Electronics

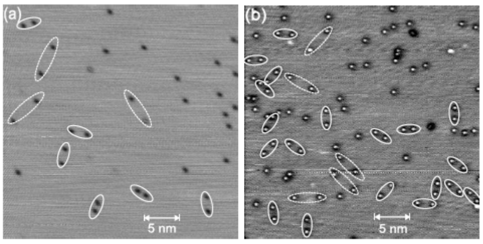
Himpsel, Jung et al. MRS Bulletin **24** (8) 1999

Infineon: carbon nanotube FET

Oxygen on Ag(001): molecular superstructures; far- ranged dissociation

Atoms





Atoms:
S. Schintke, S. Messerli et al., J. Chem. Phys. 114, 4206 (2001)
Molecules:
S. Messerli, S. Schintke et al., Chem. Phys. Lett. 328, 330 (2000).

Oxygen/Ag(001)

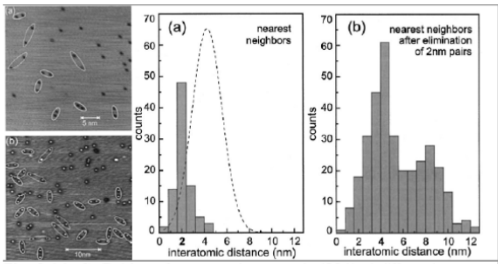


Fig. 3.1 Left: Pairing of oxygen atoms on Ag(001) at different coverages observed in STM images (50 K).
Right: Distribution of interatomic distances analysed from STM data.

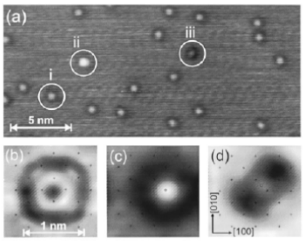
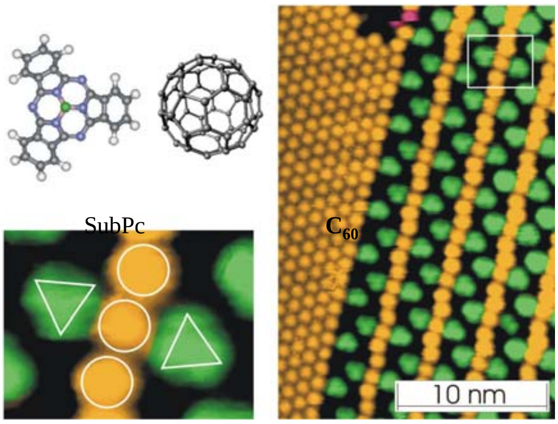


Fig. 3.2: Binding sites of oxygen atoms. Top: experimental STM data (50 K). Bottom: Calculated STM images a) hollow site, b) on-top site, c) bridge site.

S. Schintke, S. Messerli, K. Morgenstern, J. Nieminen, and W.-D. Schneider, Journal of Chemical Physics **114**, 4206-4209 (2001)

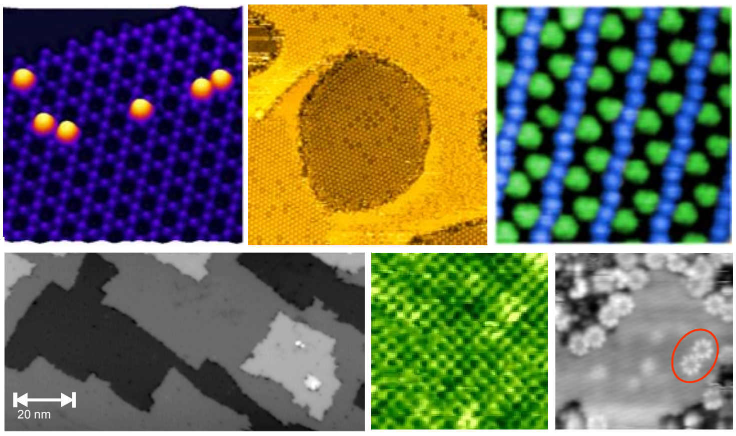
Self-intermixed monolayer



Scan range 4.3nm x 3.2nm. V_{bias}=1.3V, I_t=20pA. Scan range 17nm x 25nm. V_{bias}=1.3V, I_t=20pA.

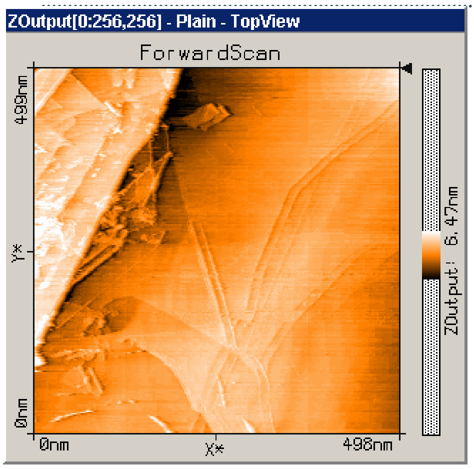
M. de Wild *et al., ChemPhysChem* **10**, 181 (2002)
M. de Wild *et al., Chimia* **10,** 56 (2002)

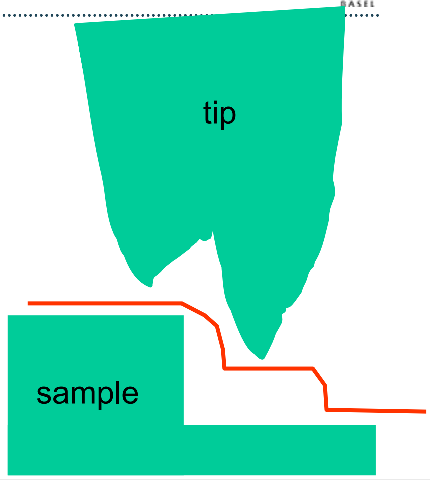
Further STM images from research



www.nccr-nano.ch (Uni Basel)

Artefact: Double Tip Effect





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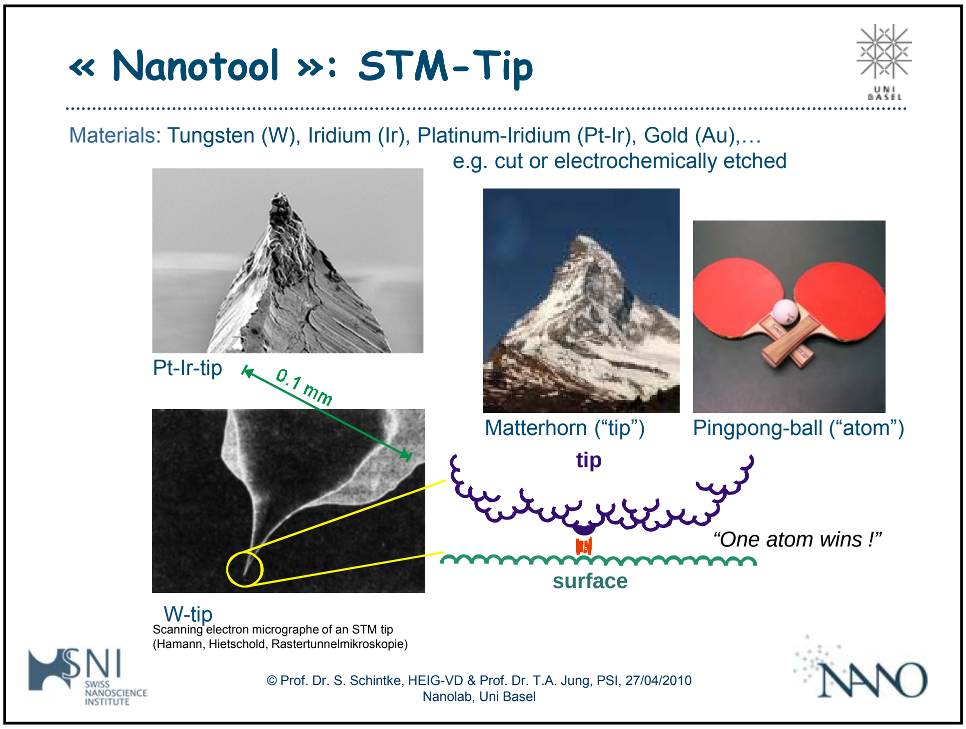
2. STM beyond imaging

- STM a tool for nanofabrication:
    - Adsorbate manipulation

- STM a local spectroscopy tool:
    - Scanning Tunneling Spectroscopy (STS)
    - Inelastic Tunneling Spectroscopy (IETS)
    - Local Photonemission spectroscopy



« Nanotool »: STM-Tip

Materials: Tungsten (W), Iridium (Ir), Platinum-Iridium (Pt-Ir), Gold (Au),…

e.g. cut or electrochemically etched

Scanning electron micrographe of an STM tip
(Hamann, Hietschold, Rastertunnelmikroskopie)

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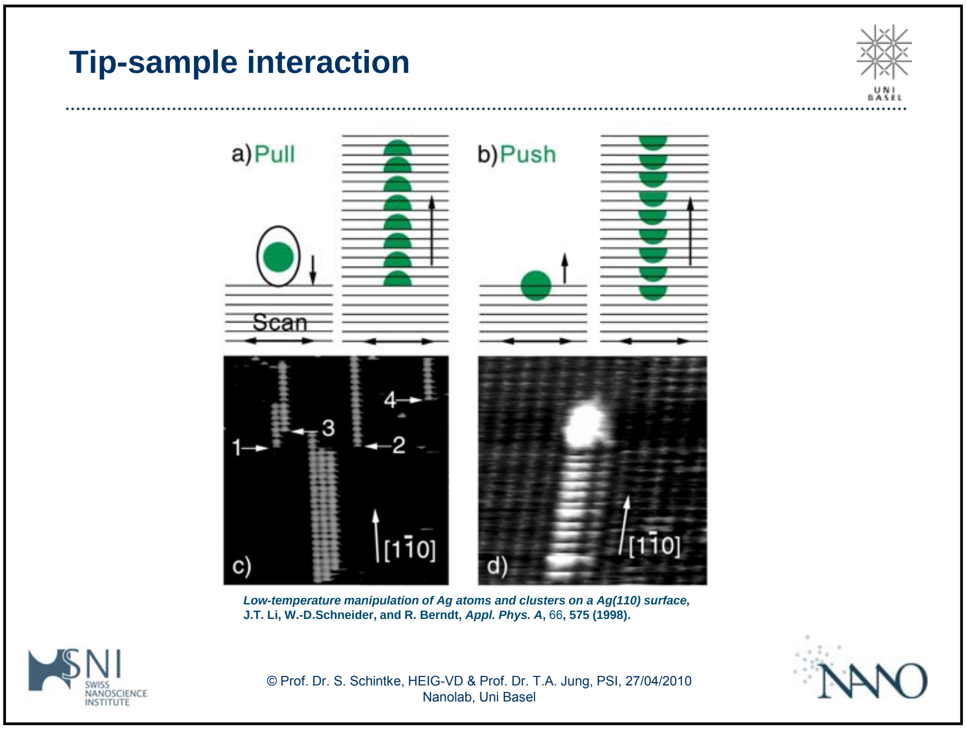

Tip-sample interaction

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).

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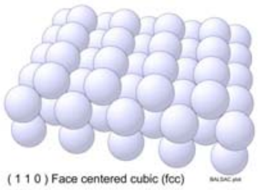
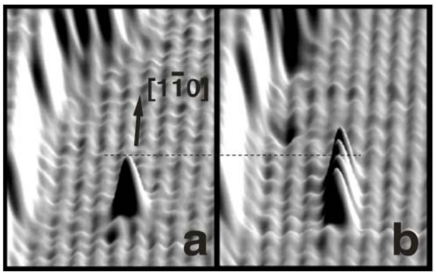
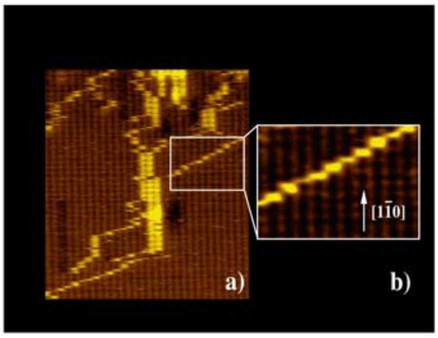
Tip-sample interaction





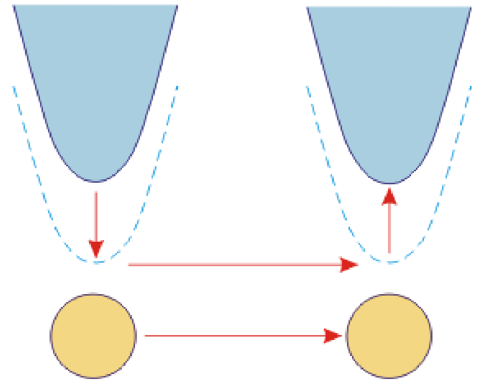
Low-temperature manipulation of Ag atoms and clusters on a Ag(110) surface,
J.T. Li, W.-D.Schneider, and R. Berndt, *Appl. Phys. A*, 66, 575 (1998).

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



Adsorbate manipulation by STM

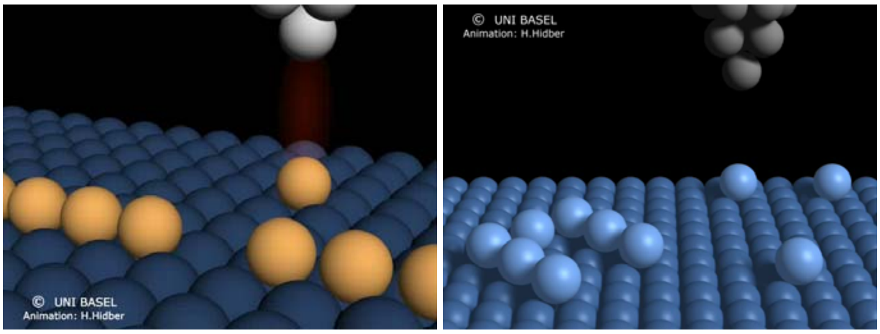
Bewegen eines Atoms



Aufnehmen des Atoms

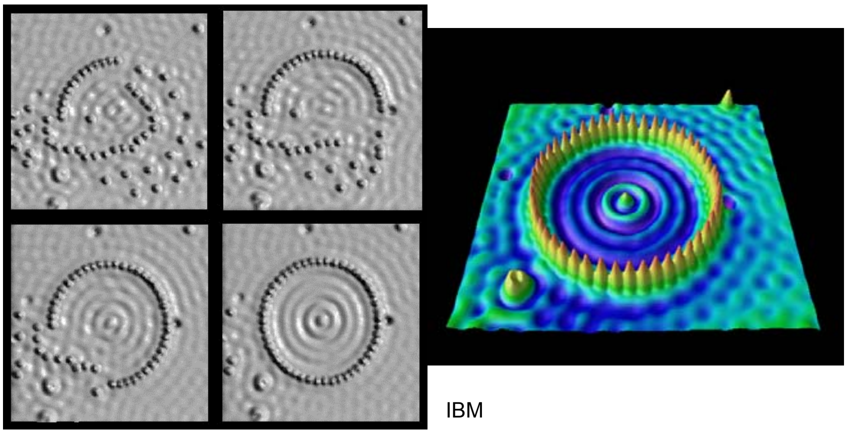
Absetzen des Atoms

Déplacer des atomes ou molécules

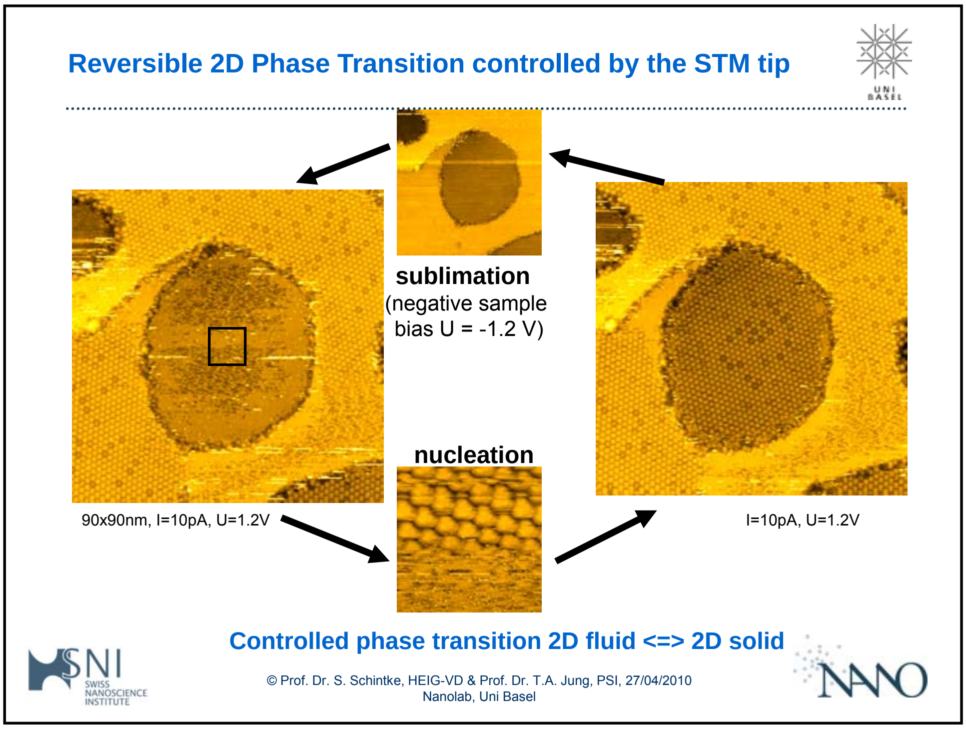


Animations: H. Hidber, Université de Bâle

Quantum Corral



IBM



Reversible 2D Phase Transition controlled by the STM tip

sublimation
(negative sample
bias U = -1.2 V)

nucleation

90x90nm, I=10pA, U=1.2V

I=10pA, U=1.2V

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

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