Repetition II

- Kristallographie / Oberflaechenkristallographie
- Bragg, Laue: Beugung am Kristallgitter
- XRD, surface XRD, LEED, RHEED
- Ewald Kugel / Konstruktion
- Wood Notation und
  Oberflaechenrekonstruktion (weitere Beispiele)

Repetition III

- What can we learn from Diffraction?
  - -- statistical average
  - -- lattice constants, size and structure of unit cell
  - -- position of atoms within cell (rocking curves, I/V)
  - -- spot profiles: defect structure
  - only RHEED: growth velocity
  - -- inelastic processes modify diffraction
    (phonons, plasmons)

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

heig-vd
Haute Ecole d'Ingénierie et de Gestion du Canton de Vaud

PAUL SCHERRER INSTITUT PSI

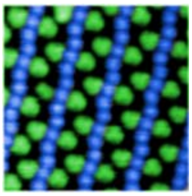
UNI BASEL

SNI SWISS NANOSCIENCE INSTITUTE

NANO

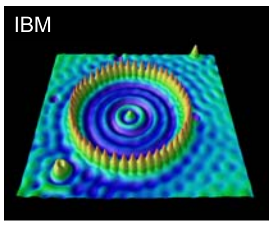
STM – local probe for surface science

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



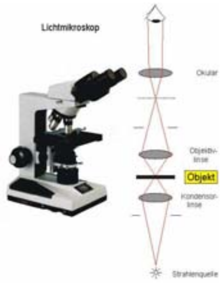
SNI SWISS NANOSCIENCE INSTITUTE

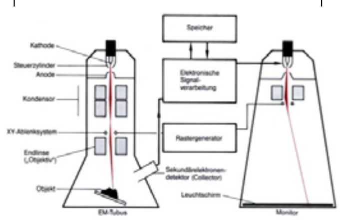
NANO

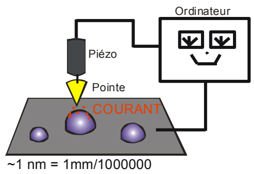
Microscopes

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





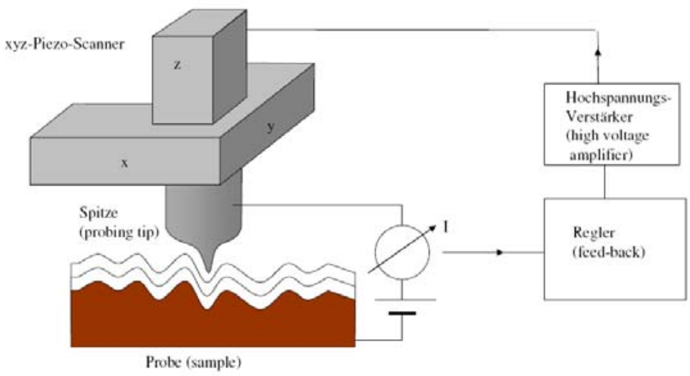


Light Microscope	Electron Microscope (SEM)	Scanning Probe Microscope (SPM)
geometric optics resolution about 500 nm *Light-Intensity contrast*	e-beam raster-scan resolution 5 nm *secondary electron counting* *projection image*	Local probe piezo-scan resolution 0.1 nm *3D map of surface*

SNI SWISS NANOSCIENCE INSTITUTE

NANO

Rastertunnelmikroskop (STM)



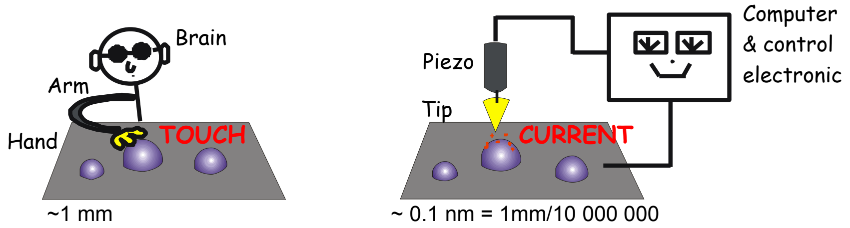
Ein Regler hält den Tunnelstrom (≈pA-nA) zwischen Spitze und Probe konstant. Es werden Konturen konstanten Tunnelstroms abgerastert.

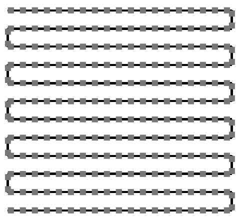
SNI SWISS NANOSCIENCE INSTITUTE

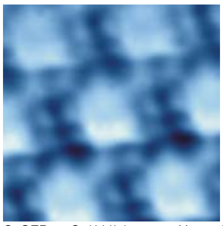
© Prof. Dr. S. Schintke, HEIG-VD & Prof. Dr. T.A. Jung, PSI, 27/04/2010
Nanolab, Uni Basel

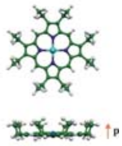
NANO

Scanning Tunneling Microscopy



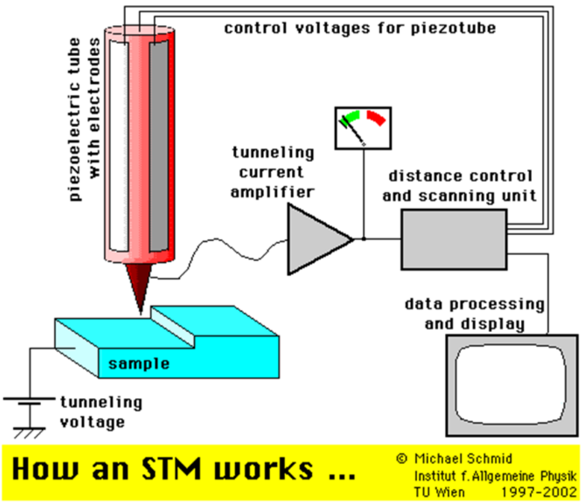




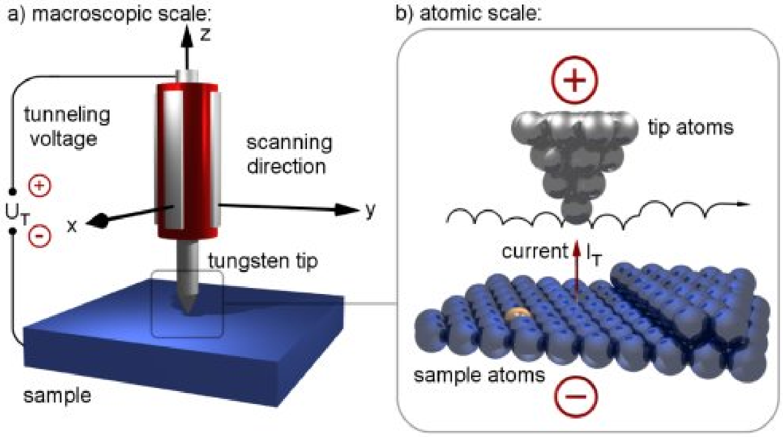


CuOEP on Cu(111) (averaged image)
3.0 nm × 3.0 nm, U = -0.55 V, I = 24 pA
L.Ramoino, S.Schintke et al., to be published

Image acquisition **(constant current images)**



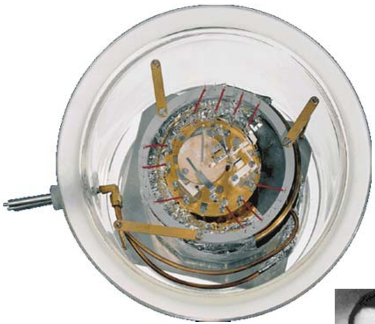
Piezo unit and tip displacement



© Prof. Dr. S. Schintke, HEIG-VD & Prof. Dr. T.A. Jung, PSI, 27/04/2010
Nanolab, Uni Basel

The first Scanning Tunneling Microscope

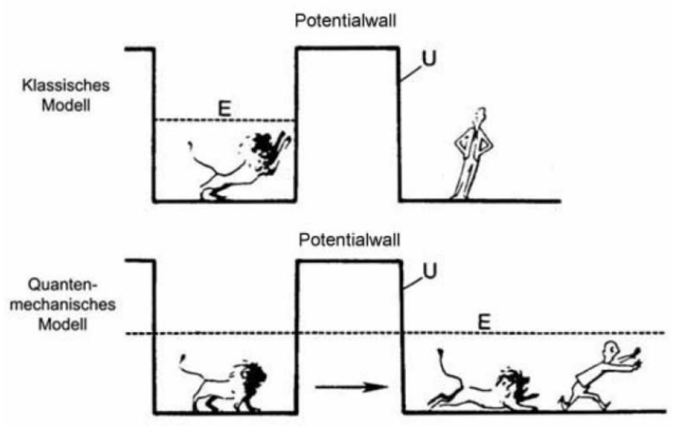
1981 development at
IBM Rüschlikon, Switzerland



G. Binnig and H. Rohrer
Nobelprize for physics 1986

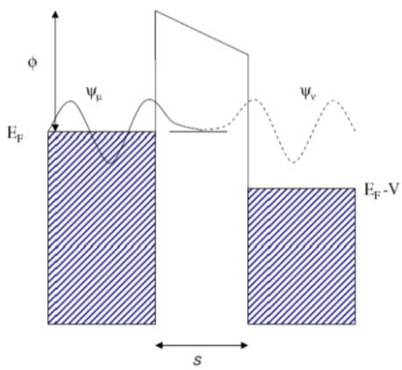
© Prof. Dr. S. Schintke, HEIG-VD & Prof. Dr. T.A. Jung, PSI, 27/04/2010
Nanolab, Uni Basel

Quantum Mechanic Tunneling



Tunneleffekt

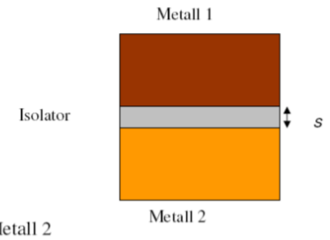
Schon zu Beginn der Quantenmechanik wurde der Tunneleffekt vorausgesagt. Der Überlapp der Wellenfunktionen führt zu einer Transmission von Elektronen durch ein klassisch verbotenenes Gebiet. Zwischen zwei Metallen, die durch Vakuum oder ein Oxid getrennt sind, fliesst ein Tunnelstrom.



Tunneleffekt

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

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



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

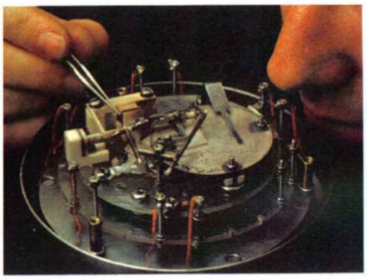
$\phi \approx \frac{\phi_1 + \phi_2}{2}$ ϕ_1, ϕ_2 Austrittsarbeiten von Metall 1 und Metall 2

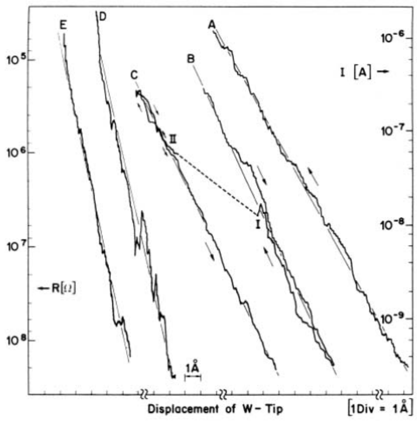
$A = 2\sqrt{\frac{2m}{\hbar^2}}$ = 1.025 Å^{-1}eV$^{-1/2}$.

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

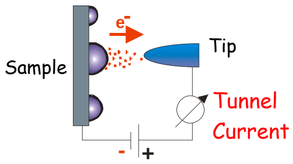
© Prof. Dr. S. Schintke, HEIG-VD & Prof. Dr. T.A. Jung, PSI, 27/04/2010
Nanolab, Uni Basel

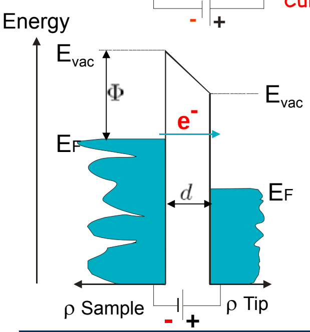
STM

Nanosurf AG, Liestal

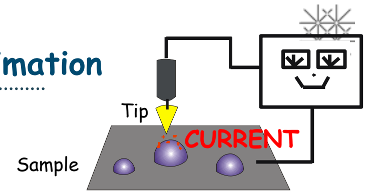
© Prof. Dr. S. Schintke, HEIG-VD & Prof. Dr. T.A. Jung, PSI, 27/04/2010
Nanolab, Uni Basel

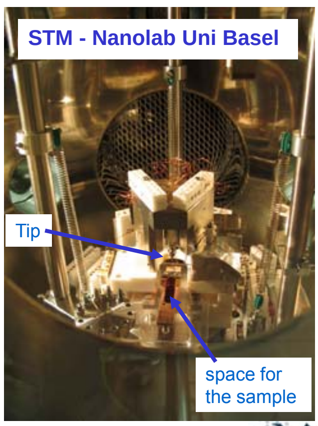
Tunnel Current – simple approximation





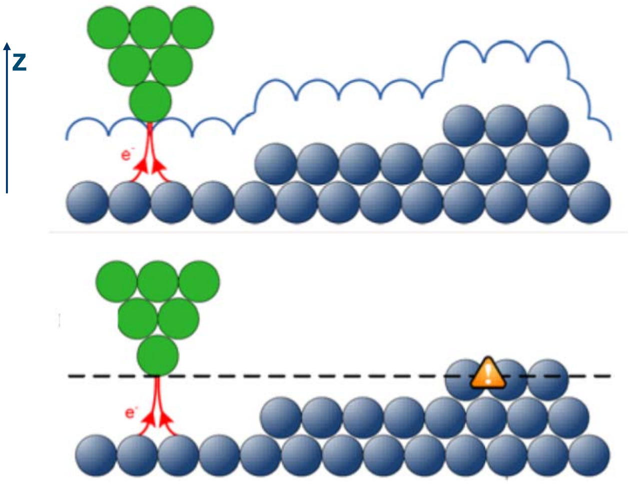
$$I_t \approx c_1 \cdot U_{bias} \cdot e^{-c_2\sqrt{\Phi}\cdot d}$$





© Prof. Dr. S. Schintke, HEIG-VD & Prof. Dr. T.A. Jung, PSI, 27/04/2010
Nanolab, Uni Basel

Measurement modes: constant current vs constant height

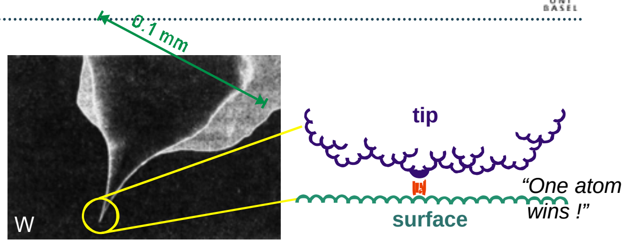


at each position (x,y)
record signal:
tip displacement in z direction

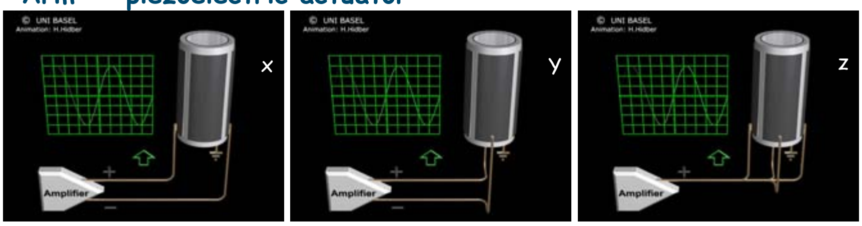
at each position (x,y)
record signal:
tunnel current I_t

The « finger » and the « arm »

"Finger" = tip

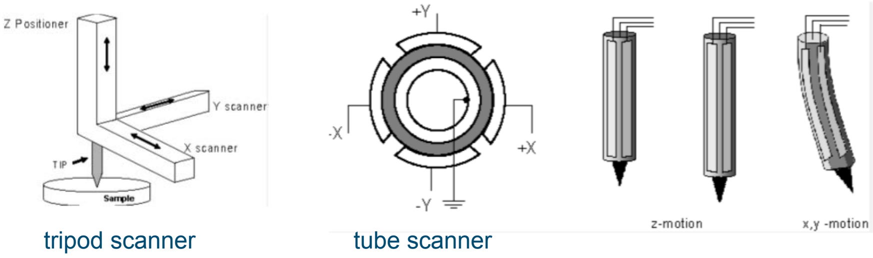


"Arm" = piezoelectric actuator



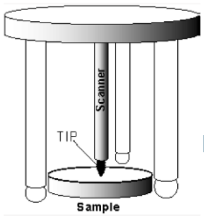
Animations: H. Hidber, University of Basel

Piezo scan unit



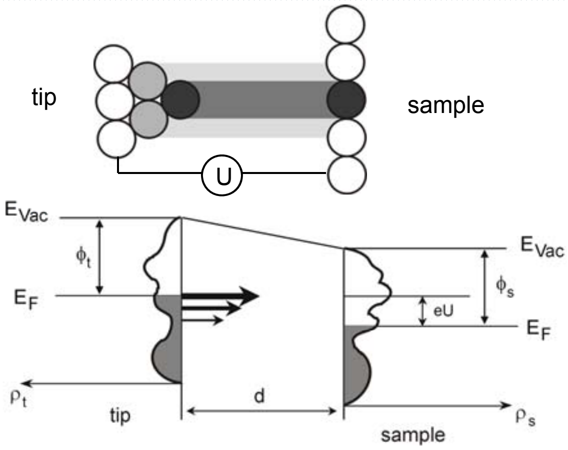
tripod scanner

tube scanner



beetle type STM

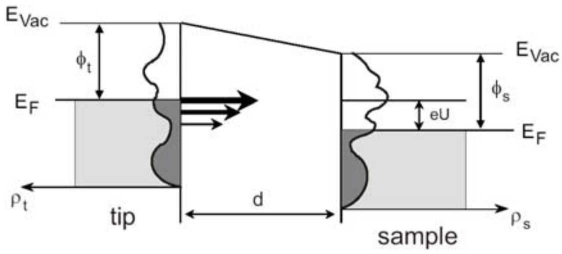
Tunnel Current in STM



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)

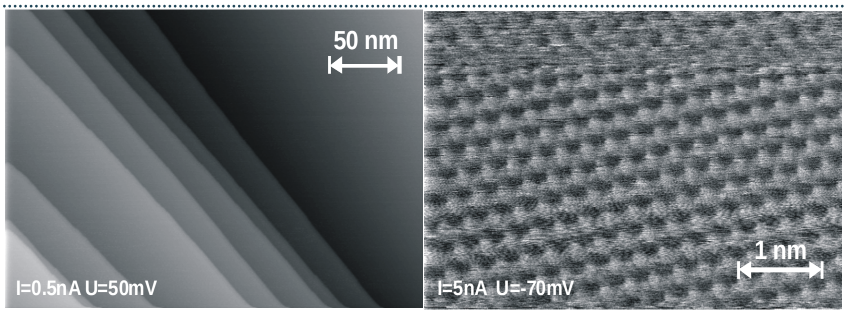
$$I \propto \int_0^{eU} \rho_s(E)\rho_t(\pm eU \mp E)T(E,eU)dE$$

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

STM Application for Surface Analysis and Surface Material Science & Engineering

© Prof. Dr. S. Schintke, HEIG-VD & Prof. Dr. T.A. Jung, PSI, 27/04/2010
Nanolab, Uni Basel

Atomic resolution
Metals



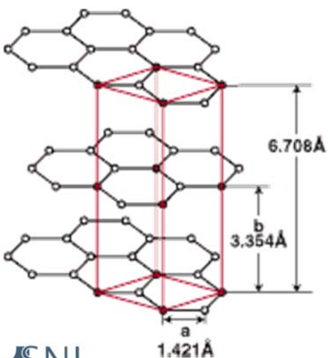
steps of monatomic height　　　　　atomic resolution

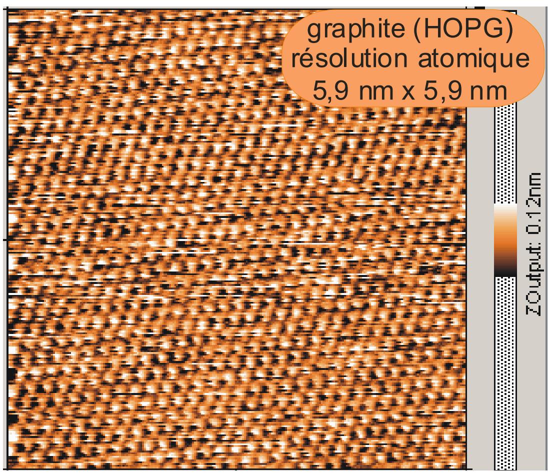
(raw data on Ag(111))

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

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

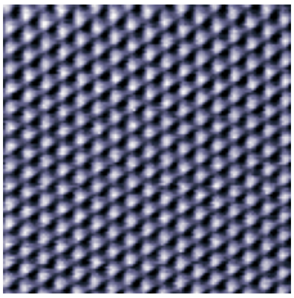
Graphite: HOPG (highly oriented pyrolythic graphite)



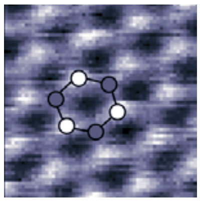


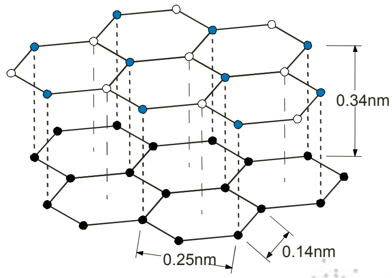
Atomic Resolution Images on HOPG

STM image raw data of HOPG



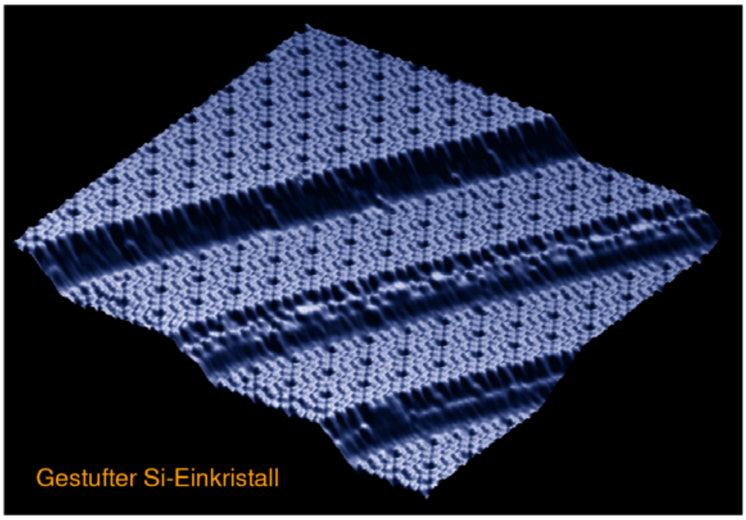
scan size: 4 nm



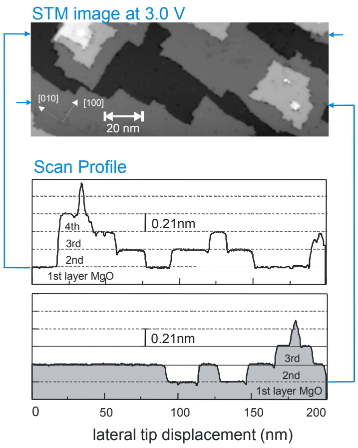


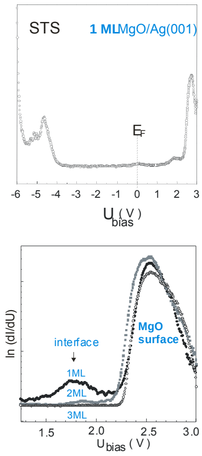
From the lattice model of graphite one can see that there are two different positions of the carbon atoms in the graphite crystal lattice (see e.g. R.C. Tatar)

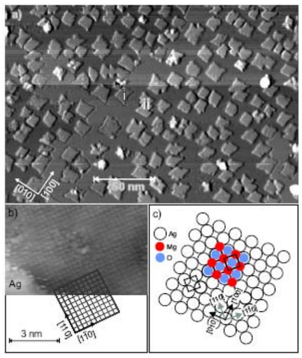
Semiconductors: Silicon



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



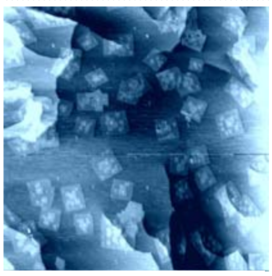




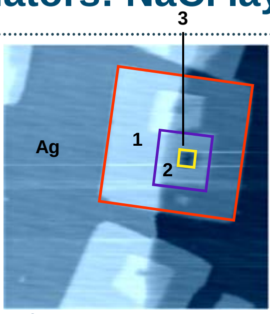
S. Schintke et al., *Insulator at the ultrathin limit: MgO on Ag(001),* Phys. Rev. Lett. **87**, 276801 (2001)

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)

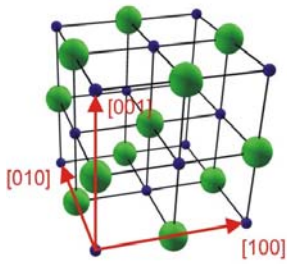
Ultrathin insulators: NaCl layers



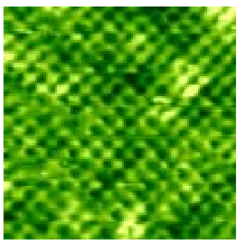
NaCl on Ag(111)
1.25 μm x 1.25 μm



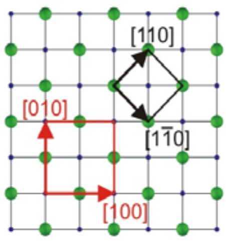
NaCl on Ag(111) 200 nm x 200 nm
U = 4.0 V, I = 15 pA



atomic resolution: one type of the ions is imaged

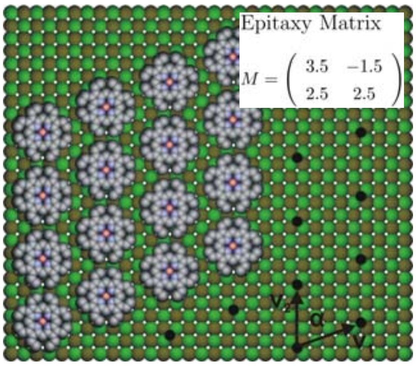


NaCl on Cu(111)
5 nm × 5 nm
U = -1.5 V, 50 pA



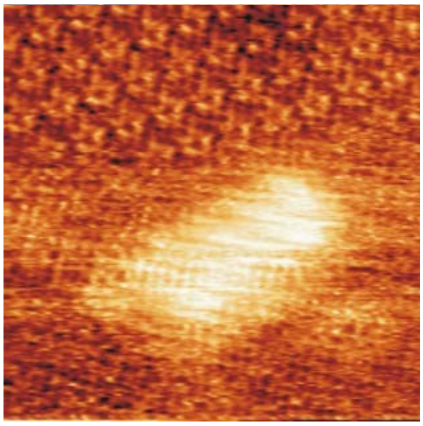
a_0 = 5.65 Å

CuOEP Self-Assembly on Salt



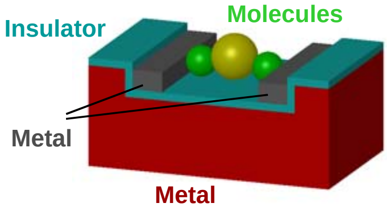
	model	experiment
v_1	14.6 Å	14.3 ± 0.3 Å
v_2	13.5 Å	13.5 ± 0.3 Å
α	68.2°	69.0 ± 1°

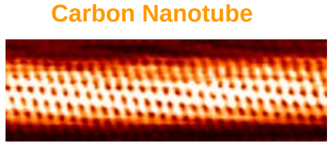
CuOEP on NaCl/Ag(111)

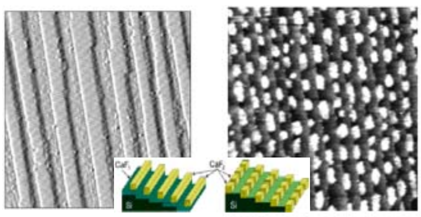


15 × 15 nm, U = -0.25 V, I = 81 pA

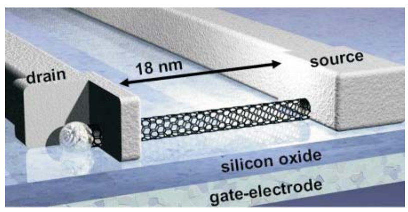
Towards Molecular Electronics





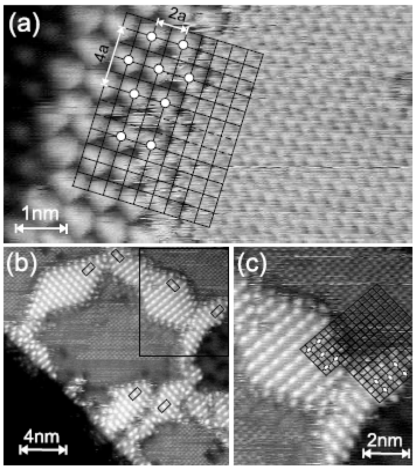


Himpsel, Jung et al. MRS Bulletin **24** (8) 1999

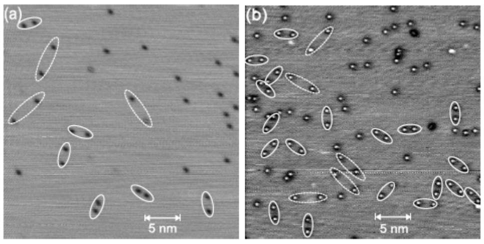


Infineon: carbon nanotube FET

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)

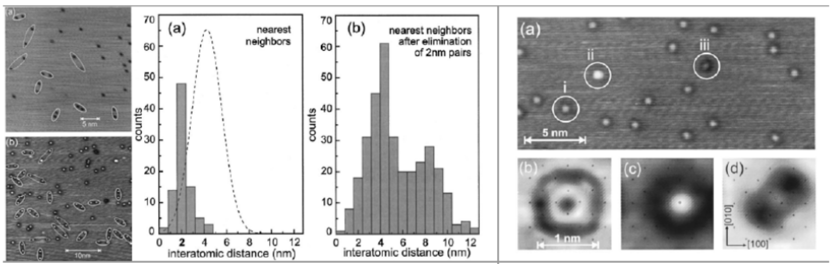
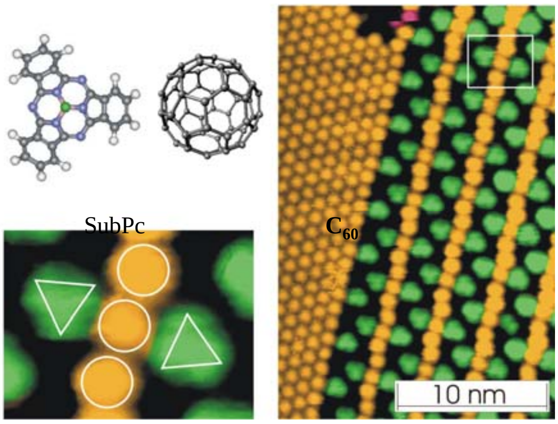


Fig. 3.1 Left: Pairing of oxygen atoms on Ag(001) at different coverages observed in STM images (50 K).
Right: Distribution of interatomic distances analysed from STM data.

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)

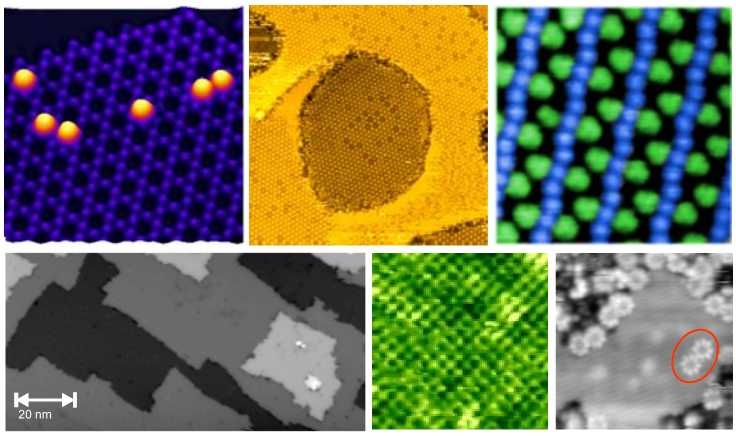
Self-intermixed monolayer



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)

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

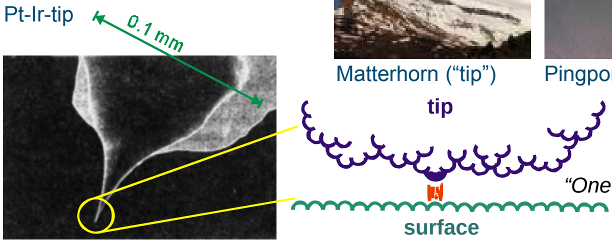
« Nanotool »: STM-Tip

Materials: Tungsten (W), Iridium (Ir), Platinum-Iridium (Pt-Ir), Gold (Au),…
e.g. cut or electrochemically etched

Pt-Ir-tip

Matterhorn (“tip”)

Pingpong-ball (“atom”)

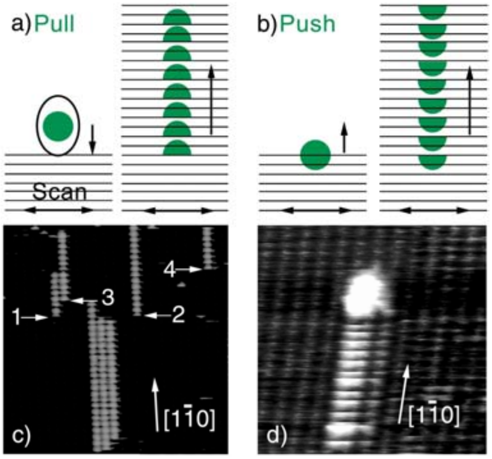


“One atom wins !”

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

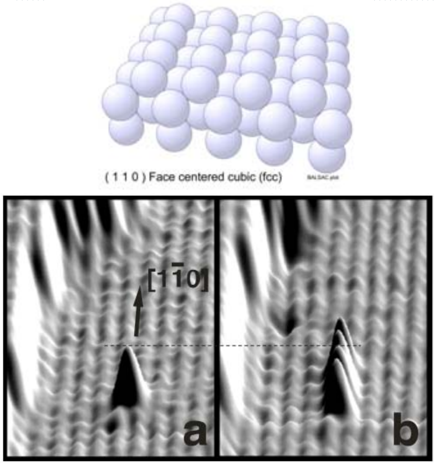
© Prof. Dr. S. Schintke, HEIG-VD & Prof. Dr. T.A. Jung, PSI, 27/04/2010
Nanolab, Uni Basel

Tip-sample interaction

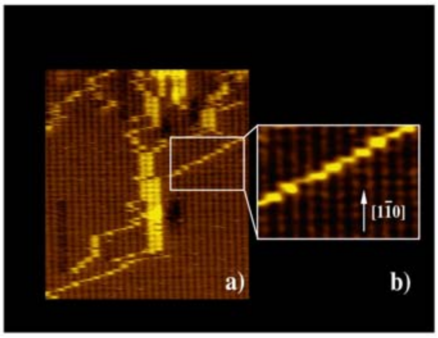


Low-temperature manipulation of Ag atoms and clusters on a Ag(110) surface,
J.T. Li, W.-D.Schneider, and R. Berndt, *Appl. Phys. A*, 66, 575 (1998).

Tip-sample interaction

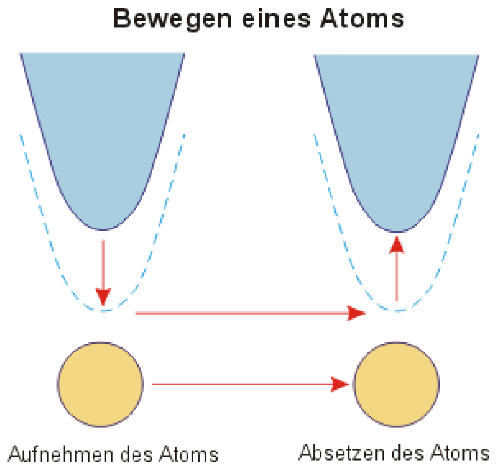


Diagonal Ag adatom motion along [1-11] direction (atom exchange)

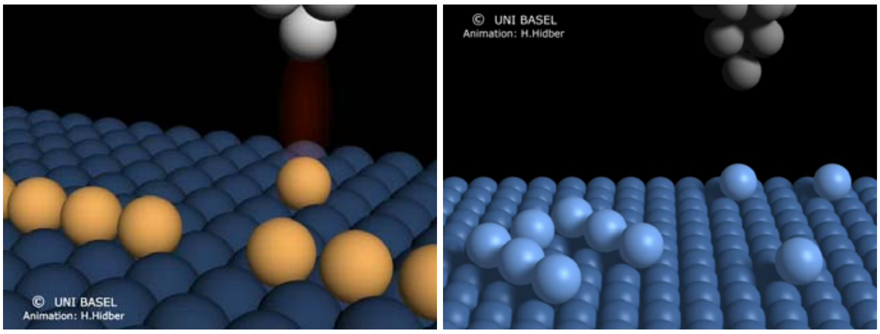


Low-temperature manipulation of Ag atoms and clusters on a Ag(110) surface,
J.T. Li, W.-D.Schneider, and R. Berndt, *Appl. Phys. A*, 66, 575 (1998).

Adsorbate manipulation by STM

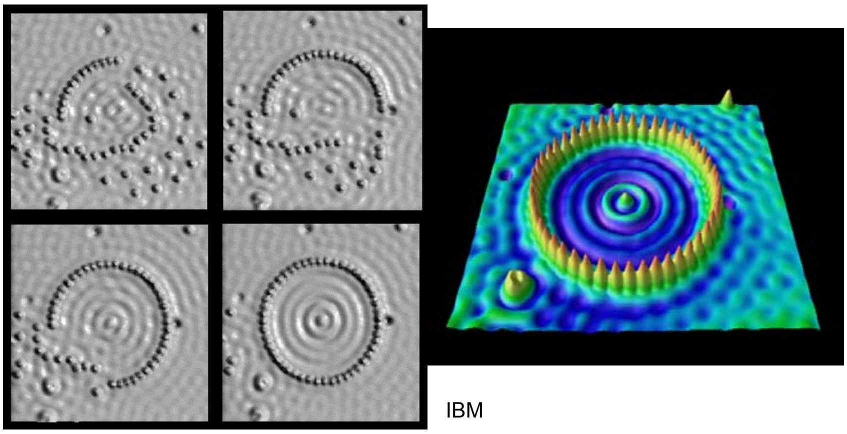


Déplacer des atomes ou molécules

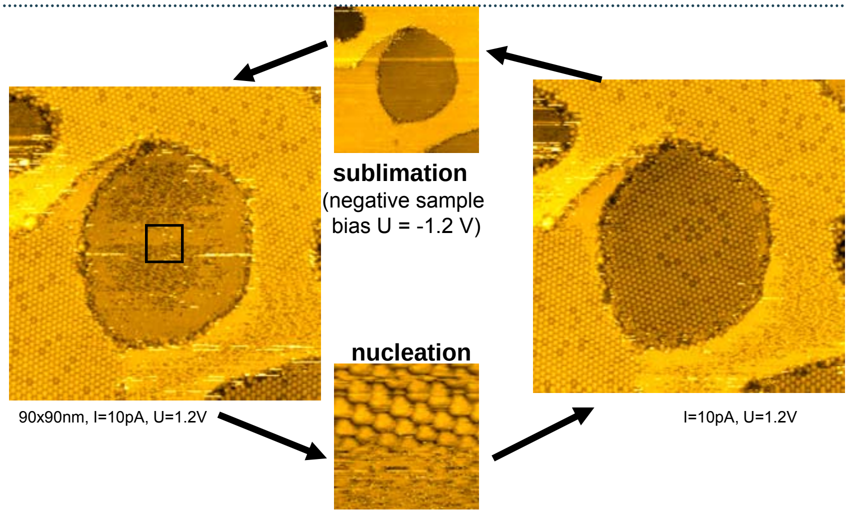


Animations: H. Hidber, Université de Bâle

Quantum Corral



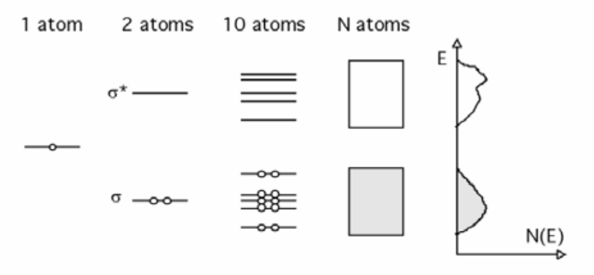
Reversible 2D Phase Transition controlled by the STM tip



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

STS (scanning tunneling spectroscopy)

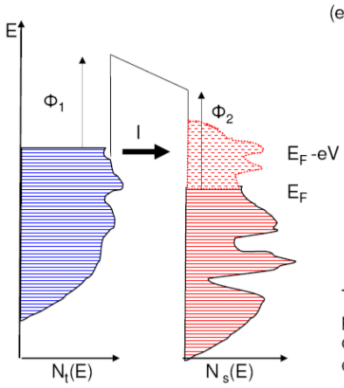
Density of States (DOS)



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

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

Voltage dependence of tunneling current



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

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

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

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

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

Spektroskopie

Spektroskopie

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

Information über lokale elektronische Zustandsdichten N(E) enthalten in

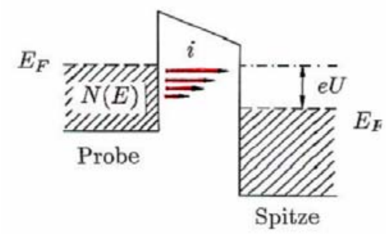
$$I/U$$

$$dI/dU$$

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

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

Stabilisierungsspannung U_0 und U sind Parameter

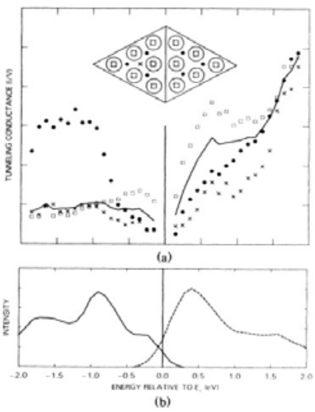


Zustandsdichte der Wolframdichte im Bereich der Fermienergie ändert Sich wenig, d.h. es wird primär die Zustandsdichte der Probe beobachtet (+; unbesetzte Zustände, -, besetzte Zustände)

Tunnelspektroskopie von Si(111)7x7

I(V)/V

UPS/IPS



R. Hamers,
Phys. Rev. Lett. 56, 1972 (1986)

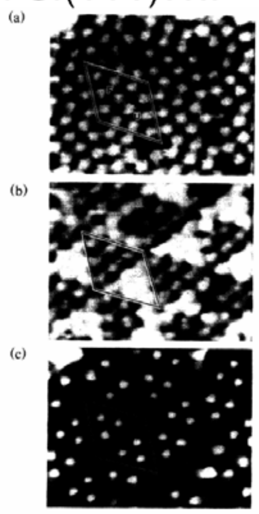


FIG. 1. Simultaneously acquired topograph and current images: (a) STM topograph with +2 V applied to the sample, and current images with (b) +1.45 V and (c) −1.45 V applied to the sample.

Tunnelspektroskopie von GaAs(110)

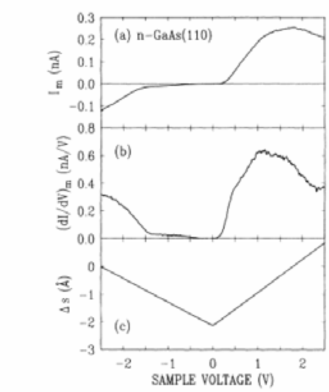


FIG. 1. Raw data from an *n*-type GaAs(110) surface, showing the (a) measured tunnel current and (b) measured conductance, as a function of sample voltage. The applied variation in tip-sample separation is shown in (c).

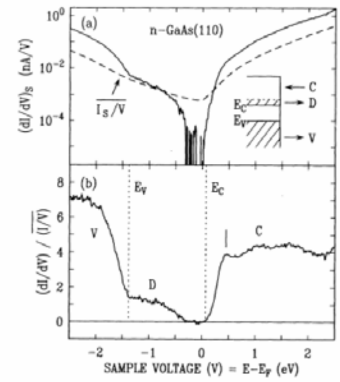


FIG. 3. Analyzed spectral data for *n*-type GaAs(110), showing (a) the differential conductance at constant tip-sample separation, and (b) the ratio of differential to total conductance. The dashed line in (a) shows the total conductance, broadened over a voltage width of 1.5 V. The components of the spectrum are indicated in the inset: *C*—conduction band, *V*—valence band, and *D*—dopant induced. Valence- and conduction-band edges are indicated by dotted lines, labeled E_V and E_C, respectively. The thin vertical line at 0.45 V marks a surface-state feature.

R. Feenstra et al., Phys. Rev. B 50, 4561 (94)

Tunnelspektroskopie auf Supraleitern

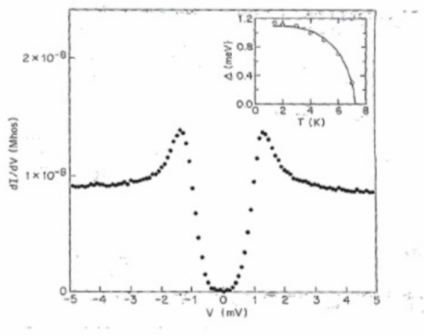


Fig. 2.7. dI/dV vs. bias voltage V for $NbSe_2$ at 0T applied magnetic field used to determine the gap at 1.45K. Inset: The gap vs. temperature and the corresponding BCS-fit. From [35].

H.Hess et al., Phys.Rev. Lett. 62(2), 214(1989)

Inelastic Tunneling Spectroscopy

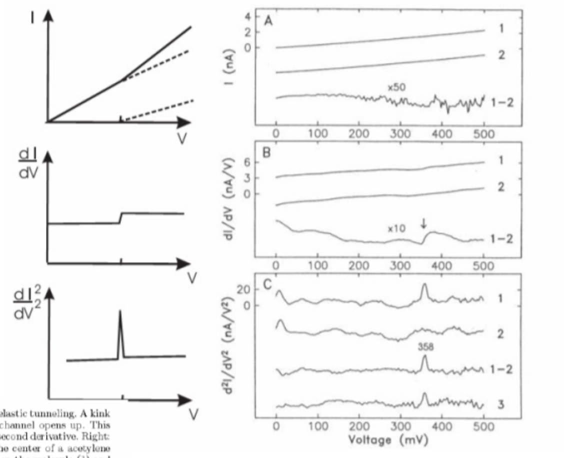


Fig. 2.8. Left: Current vs. voltage curves with elastic and inelastic tunneling. A kink is observed when the inelastic electron tunneling current channel opens up. This kink becomes a step in the first derivative and a peak in the second derivative. Right: (A) I-V-curves recorded with the STM tip directly over the center of a acetylene molecule (1) and over the bare Cu(100) surface. (B) dI/dV on the molecule (1) and on the substrate (2). (C) dI^2/dV^2 on the molecule (1) and on the substrate (2). The difference spectrum (1-2) shows a peak at 358mV. (3) is an average of 279 scans. From [41].

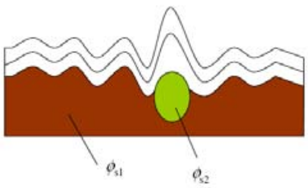
B.Stipe,M.Rezaei,W.Ho:Science 280, 1732 (1998)

Constant current mode

$$\ln(I) = \text{konst.} \quad \Rightarrow \quad \sqrt{\phi}\, s = \text{konst.}$$

If barrier height constant ⇨ **s=constant**

If barrier height varies ⇨ **ϕ(x,y), s(x,y) affect topography z(x,y)**



Contour z(x,y)
at constant current

© Prof. Dr. S. Schintke, HEIG-VD & Prof. Dr. T.A. Jung, PSI, 27/04/2010
Nanolab, Uni Basel

Chemical contrast in an alloy

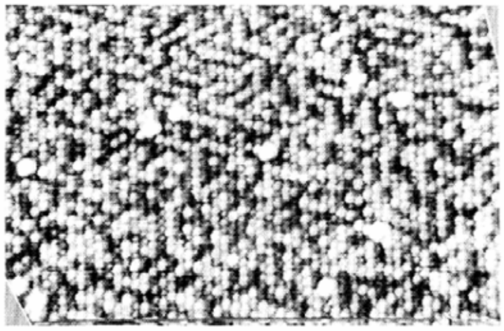


Fig. 2.14. STM image of the (111) surface of a $Pt_{25}Ni_{75}$ single crystal. A voltage of 5mV and current of 16nA were applied. A rather strong "chemical" contrast is observed, where the dark species is attributed to Pt und the bright features to Ni. The contrast is related to the interaction between tip adsorbates and the surface. Image size is 125Åx 100Å. From [50].

Oberflächenzustände auf Cu(111)

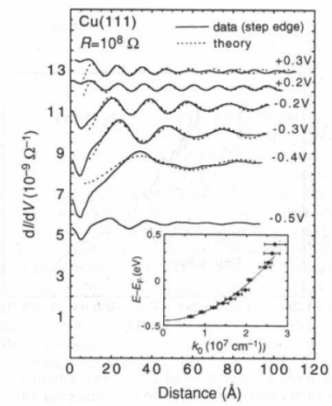
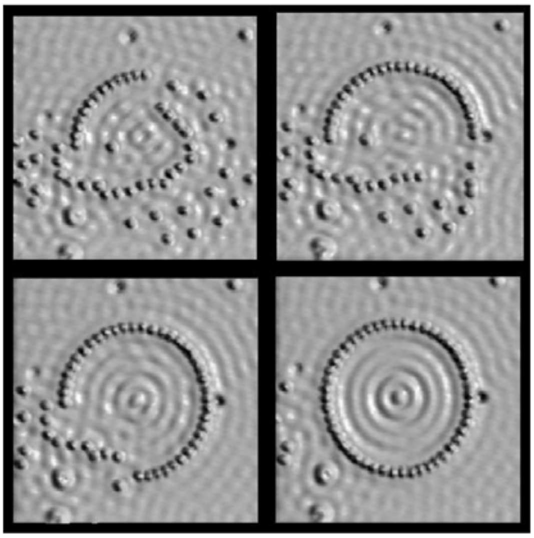


Fig. 2.16. Spatial dependence of dI/dV across a step edge on Cu(111) at 4K. For details see text. From [80].

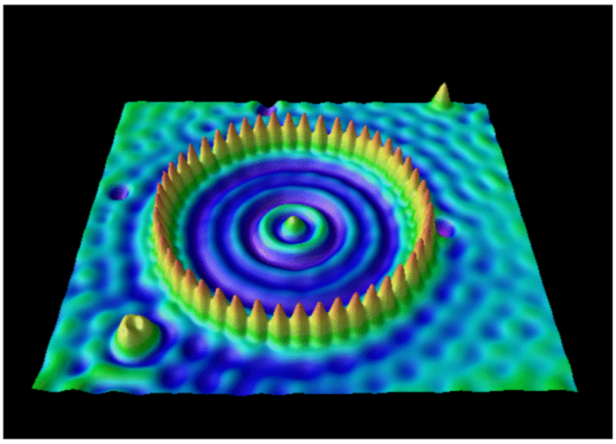
© Prof. Dr. S. Schintke, HEIG-VD & Prof. Dr. T.A. Jung, PSI, 27/04/2010
Nanolab, Uni Basel

Surface state scattering



M.F. Crommie, C.P. Lutz and D.M. Eigler, *Nature* 363 (1993)

Quantum corral



M.F. Crommie, C.P. Lutz and D.M. Eigler, *Nature* 363 (1993)

„Confined electrons“

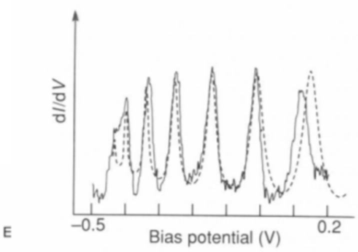
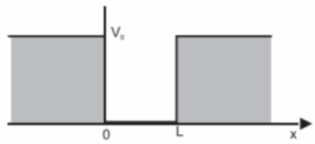


Fig. 2.18. The experimental (solid line) and theoretical (dashed line) voltage dependence of dI/dV, with the top of a STM located at the center of a 88.7Å diameter, 60-atom circle of Fe atoms on a Cu(111) surface. From [84].



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

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

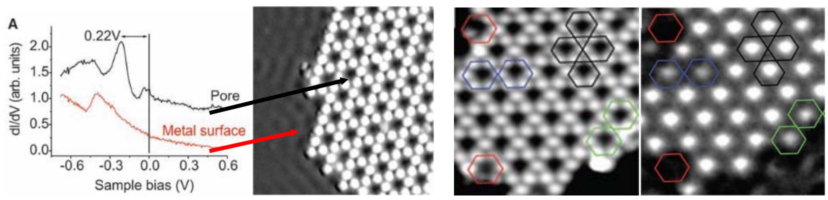
2D bandstructure

Detection of confined states in a porous supramolecula network

STS is a powerful tool to probe the local electronic density of states (LDOS) of a quantum entity.

STS performed inside the hexagonal DPDI pores shows, in the corresponding dI/dV curve, a confined electronic state at -0.22V (black curve).

No peak is seen on the metal surface for the same voltage (red curve).



J.Lobo-Checa et al, Science, 325,300 (2009).

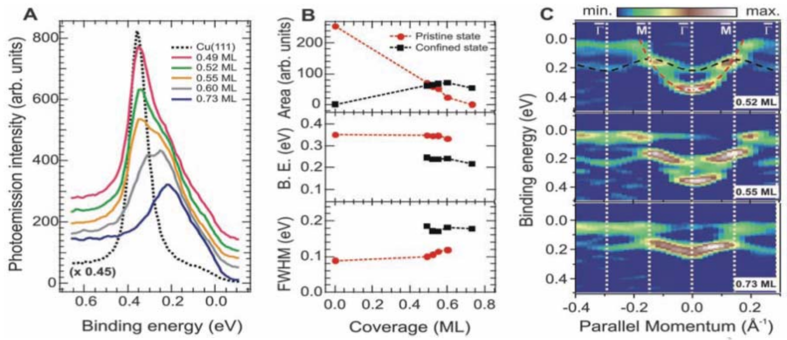
2D bandstructure (STS+ARPES)

ARPES is a surface analytical technique that helps us to identify the binding energy of the confined electrons with respect to their momentum.

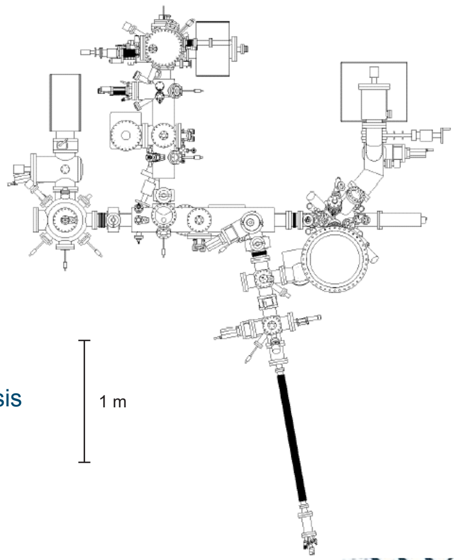
The red dotted line in fig c shows the E(k) relation of the free surface electrons and the black line (first sub-band) corresponds to the first confined state.

The energy gap between the sub-bands is ~90 eV.

With increasing molecular coverage, the number of the confined states increases and the surface state forms a continuous band in 2D supramolecular structure.



Come an study more: STM/STS - Nanolab Uni Basel



- UHV 10^{-10} mbar
- *in situ* sample preparation and analysis
- multiple evaporation facilities
- STM (home-built RT, Omicron LT)
- XPS, UPS, AES, LEED