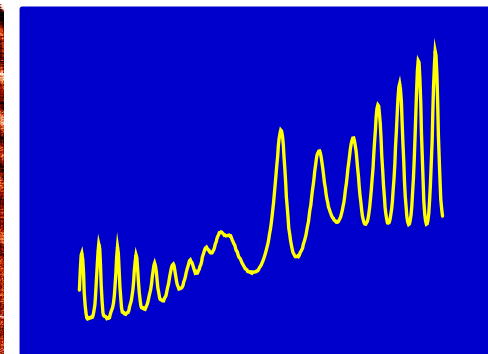
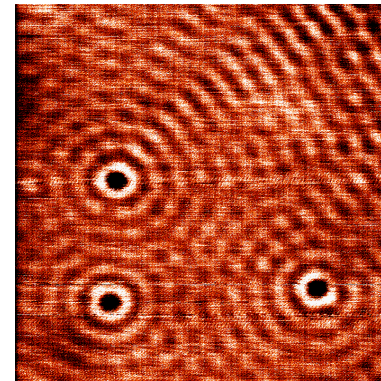
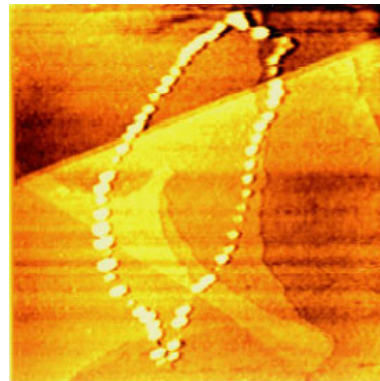
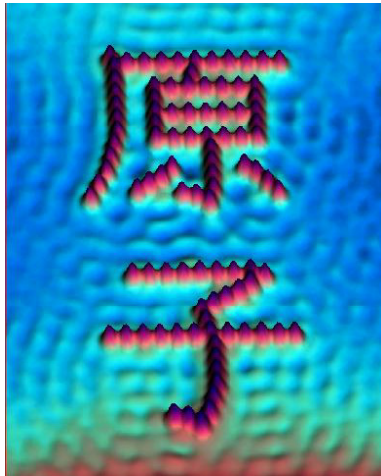
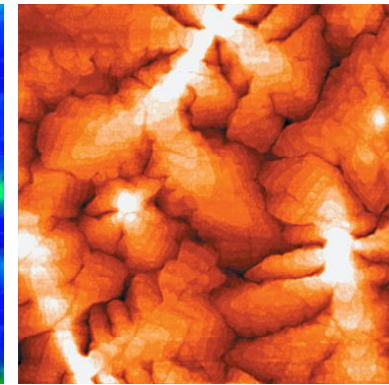
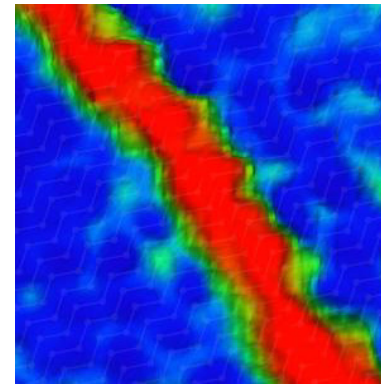
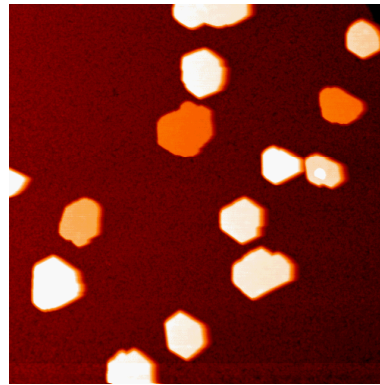
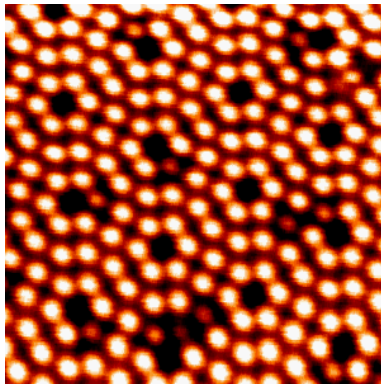


Scanning Tunneling Microscopy

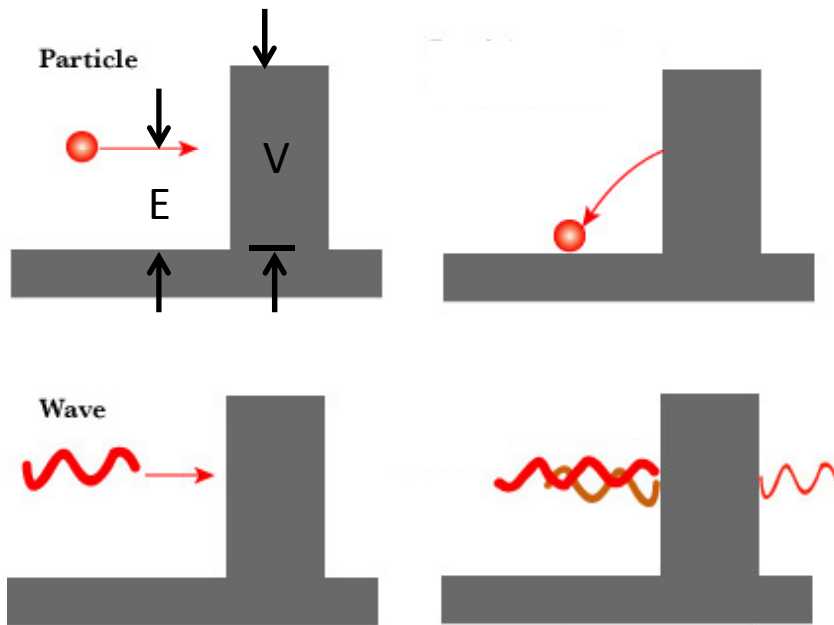
Wei-Bin Su, Institute of Physics, Academia Sinica



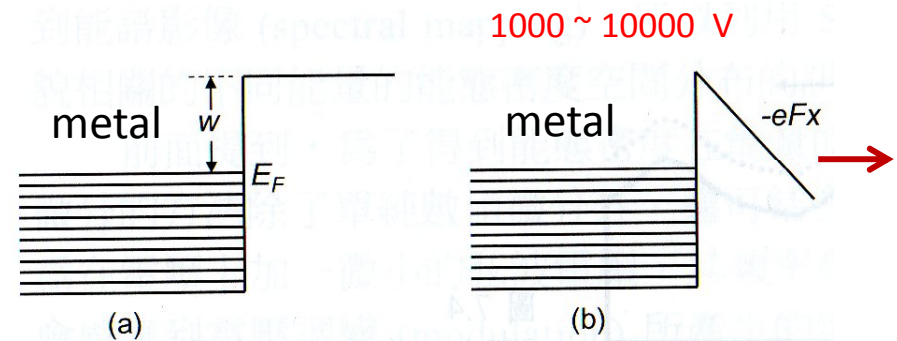
The Nobel Prize in Physics 1986



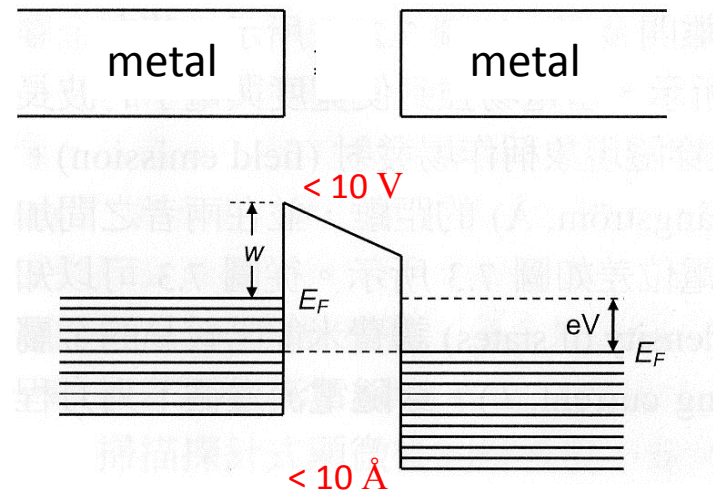
Tunneling effect



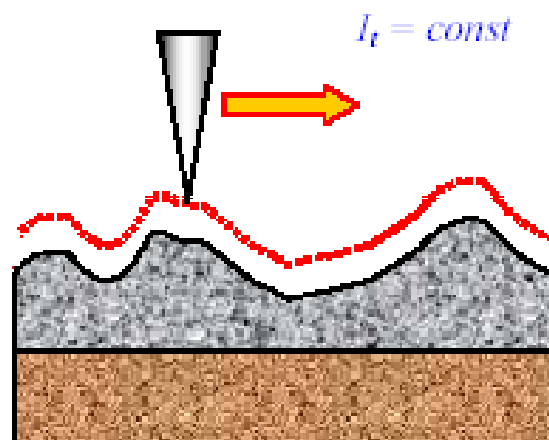
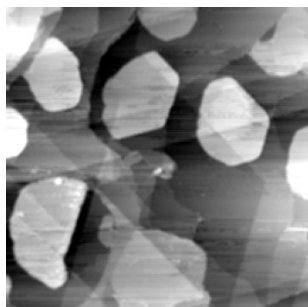
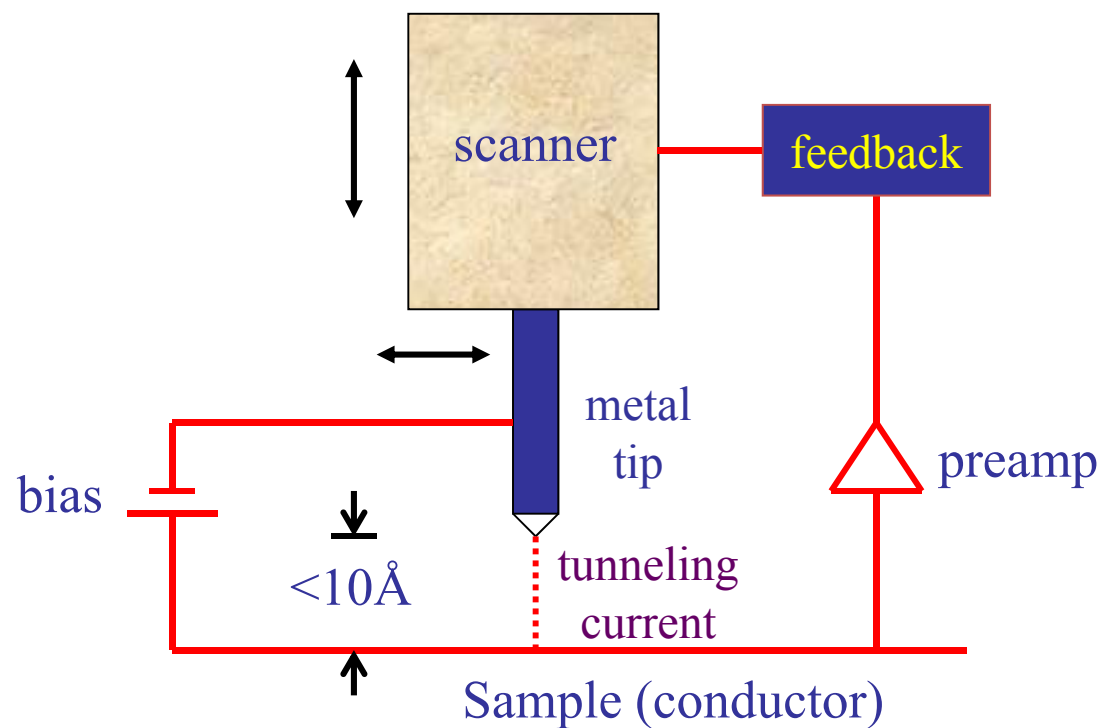
Field emission



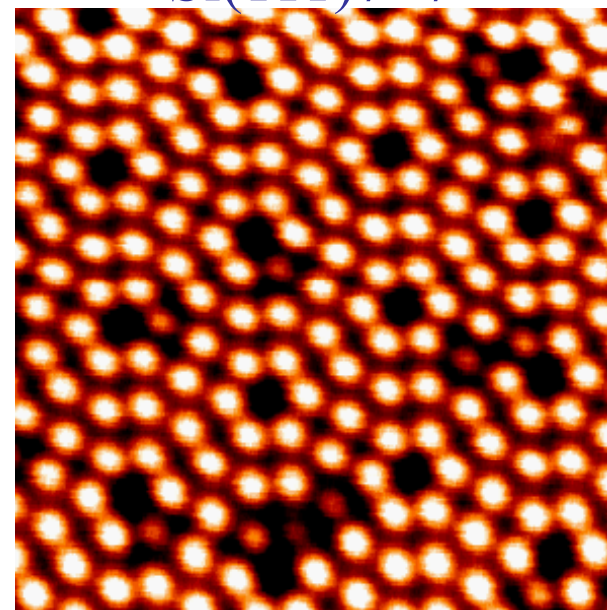
metal-vacuum-metal tunneling



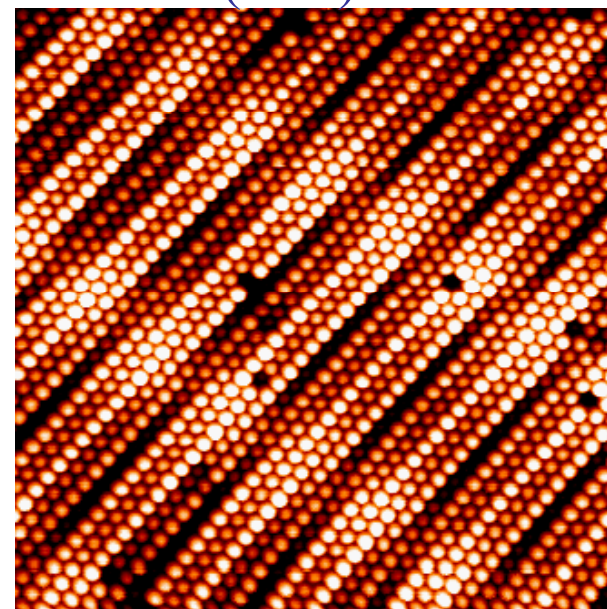
Scanning Tunneling Microscopy (STM)

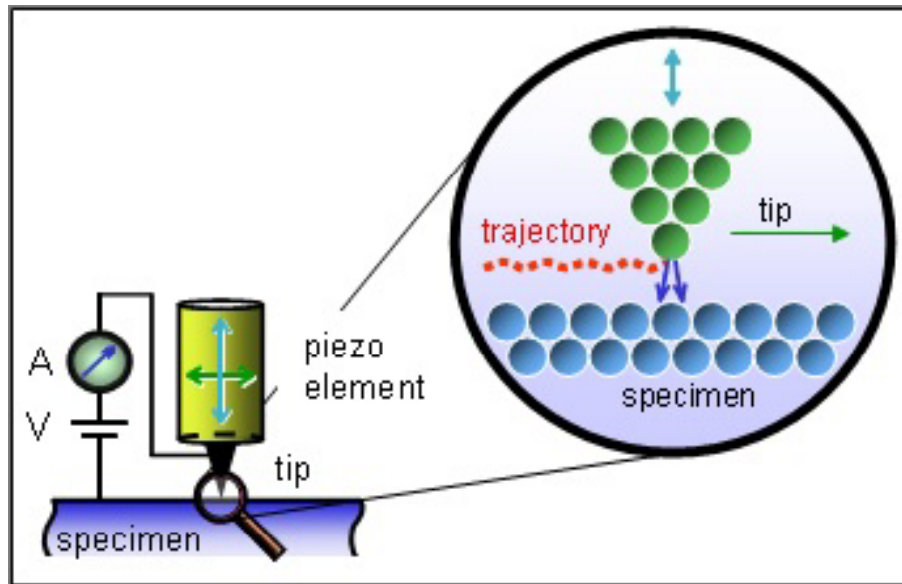


Si(111)7×7

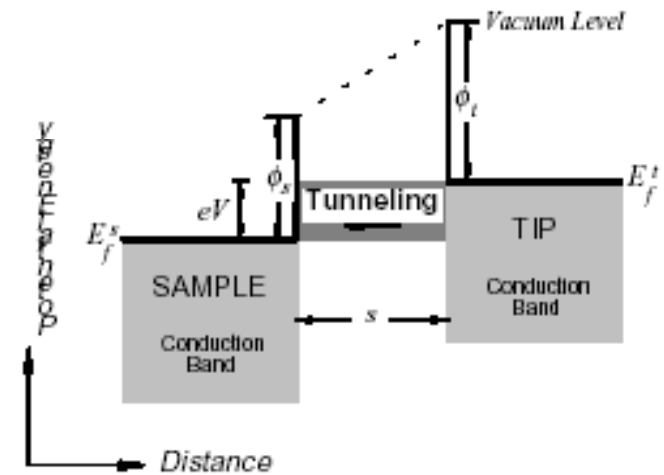


Pt(100)-R0.7°





(a)



tunneling
probability

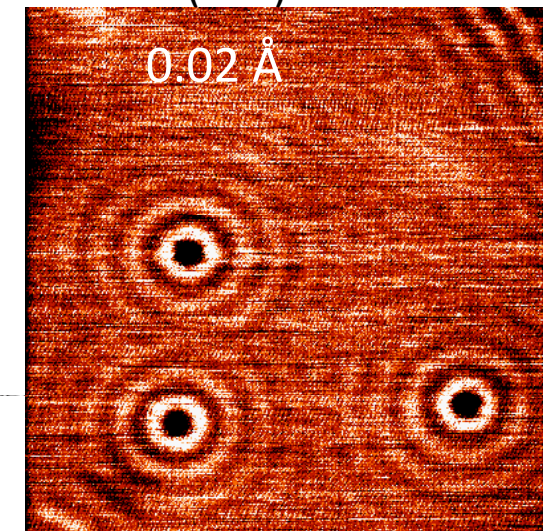
$$T(s) \sim \exp(-2\kappa s) ; \kappa = (2m\phi/\hbar^2)^{1/2} ; \phi = (\phi_t + \phi_s)/2$$

average work function

$\kappa \sim 1 \text{ \AA}^{-1} \rightarrow$ the current decays about $e \approx 7.4$ times
when s increases by $1 \text{ \AA}$

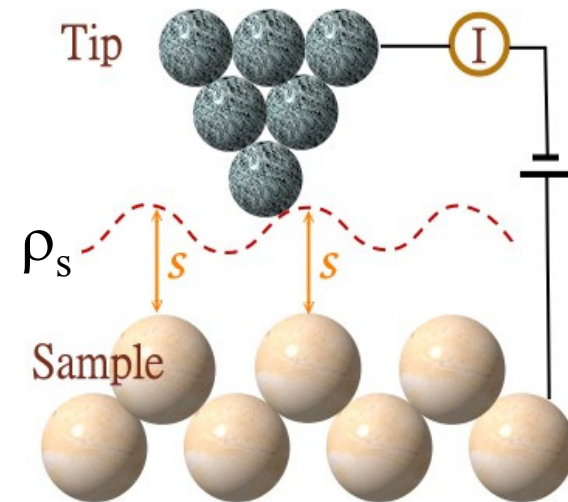
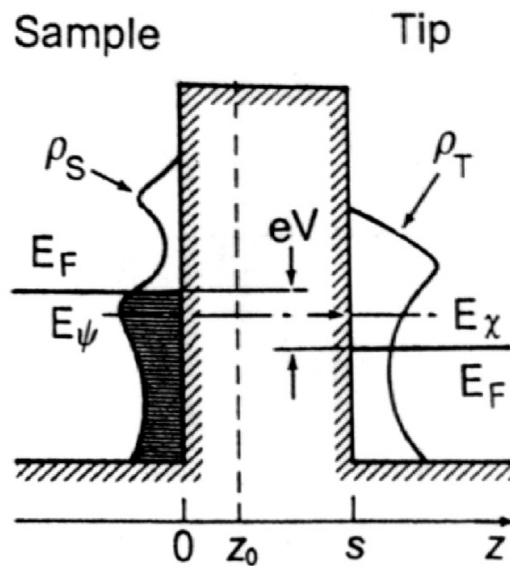
(b)

Cu(111) surface



Tunneling current

$$I \propto \int_0^{eV} \rho_s(E_F - eV + \varepsilon) \rho_T(E_F + \varepsilon) d\varepsilon \exp(-2\kappa s)$$

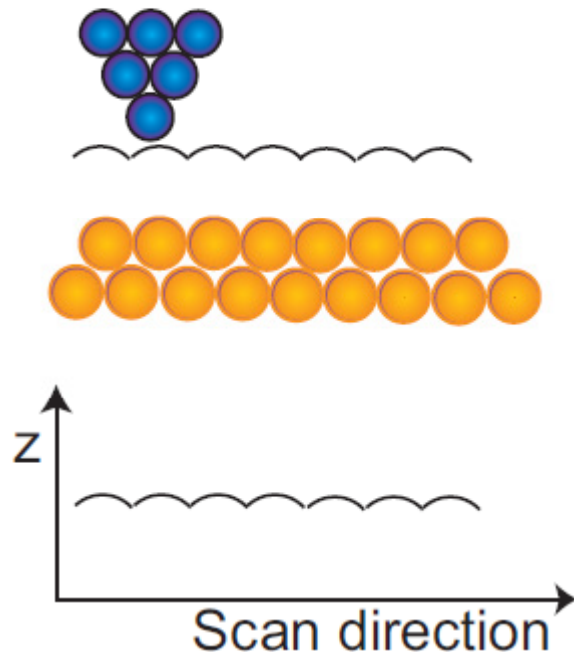


Modes of Operation

1. Constant Current Mode

By using a feedback loop the tip is vertically adjusted in such a way that the current always stays constant.

Constant current mode



constant

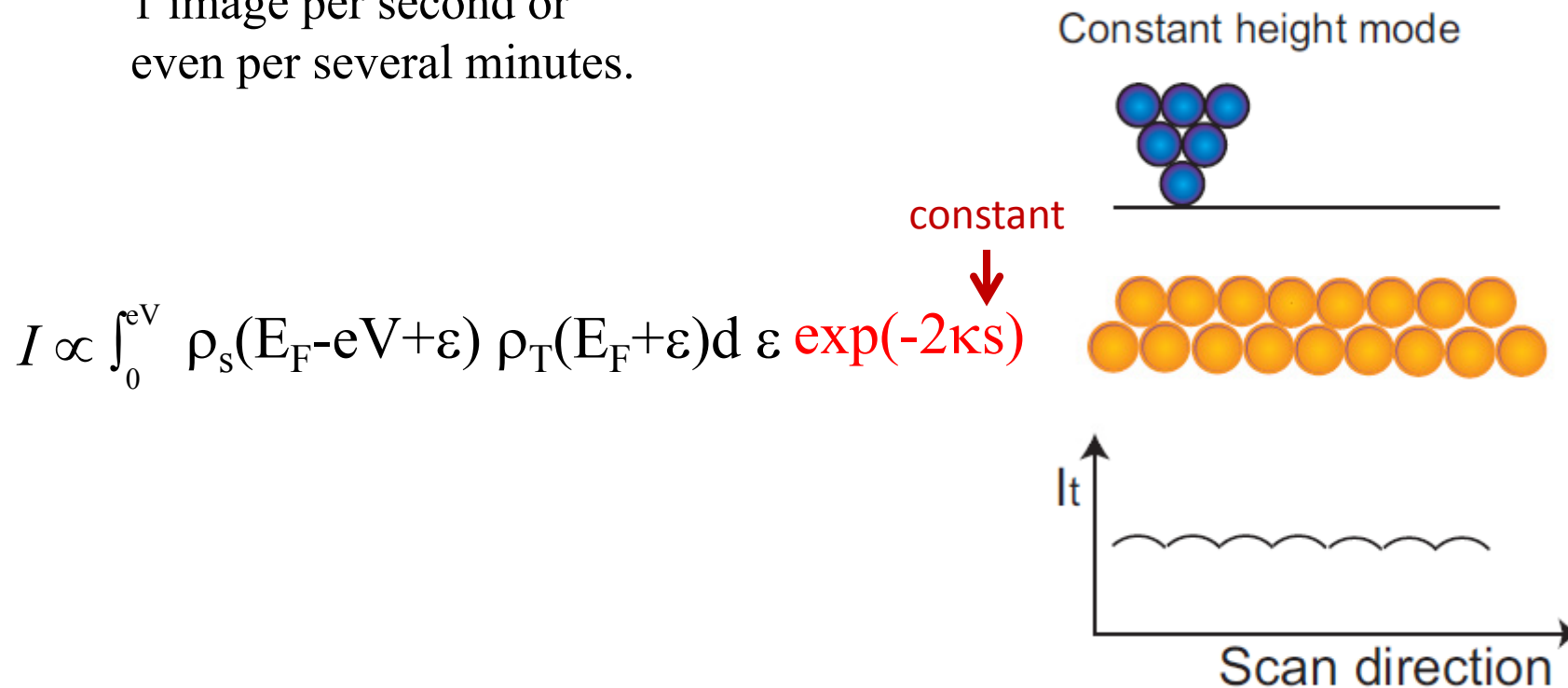
$$I \propto \int_0^{eV} \rho_s(E_F - eV + \varepsilon) \rho_T(E_F + \varepsilon) d\varepsilon \exp(-2\kappa s)$$

$\rho_s \uparrow$

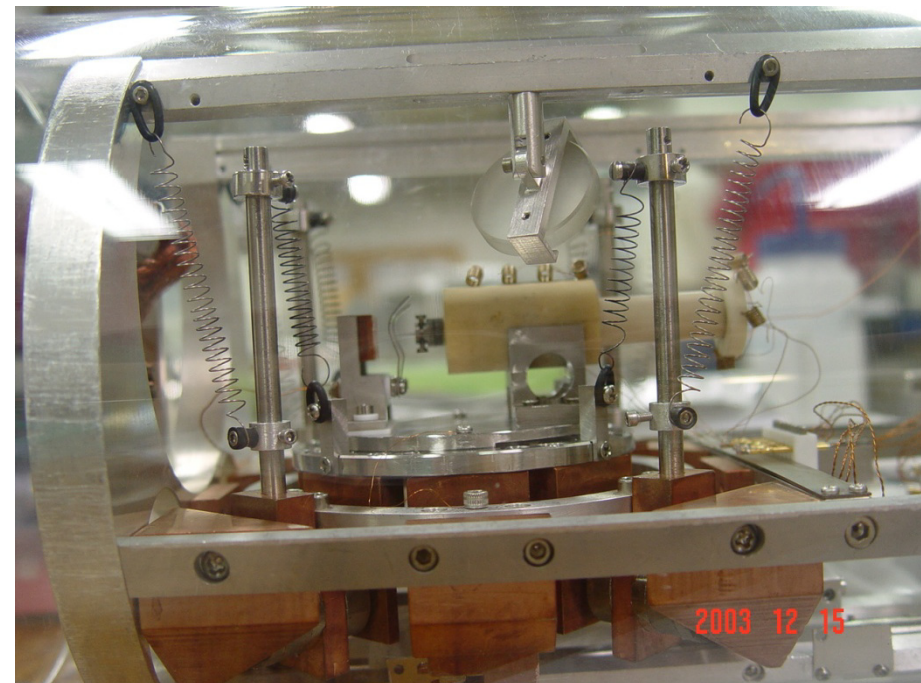
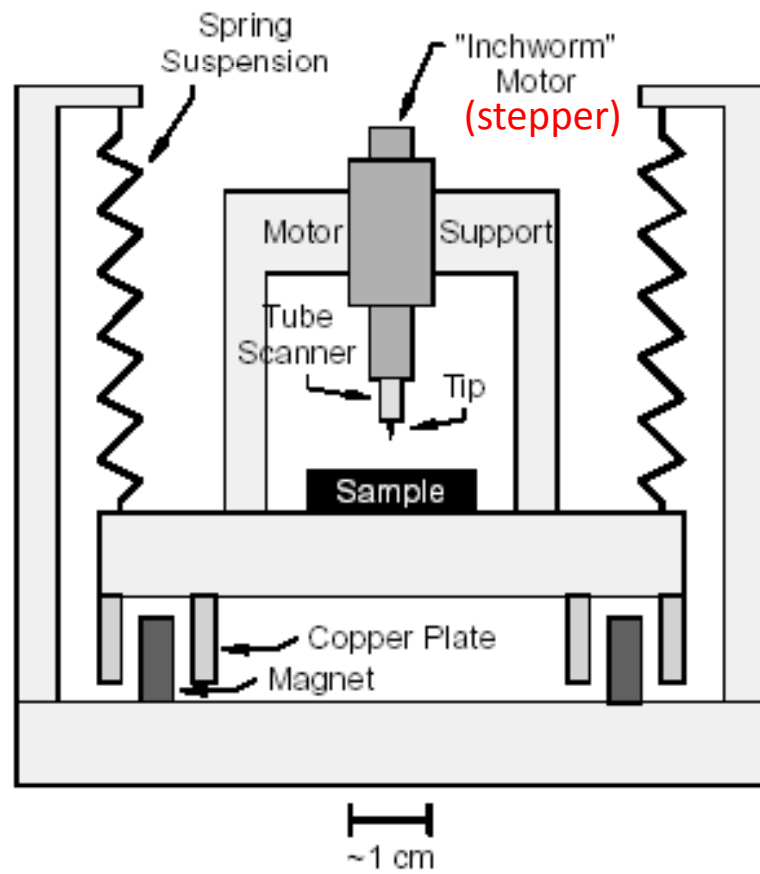
$s \downarrow$

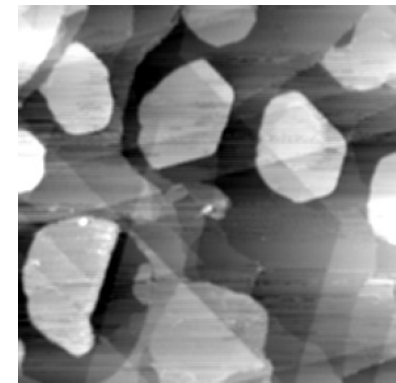
2. Constant Height Mode

In this mode the vertical position of the tip is not changed, equivalent to a slow or disabled feedback. The current as a function of lateral position represents the surface image. This mode is only appropriate for atomically flat surfaces as otherwise a tip crash would be inevitable. One of its advantages is that it can be used at high scanning frequencies (up to 10 kHz). In comparison, the scanning frequency in the constant current mode is about 1 image per second or even per several minutes.



Structure of STM





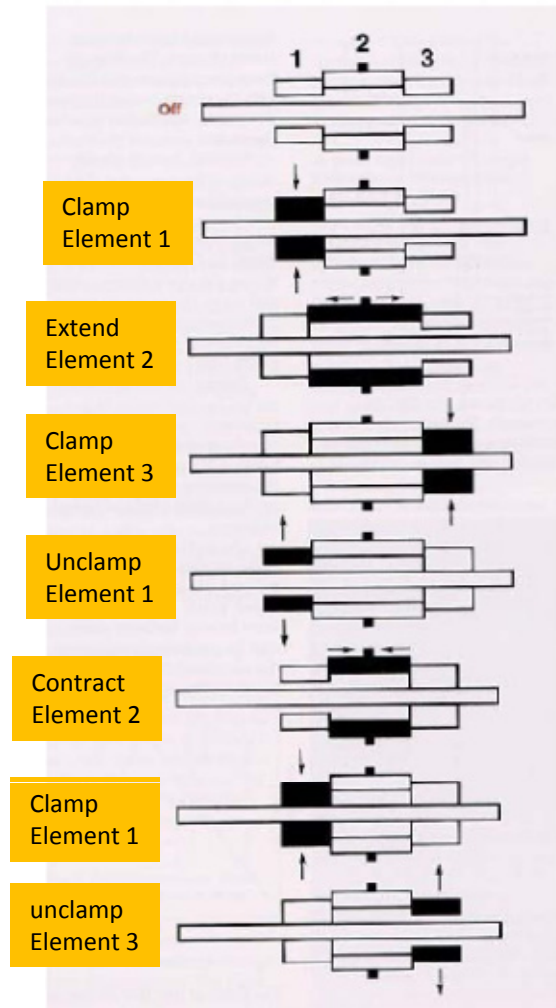
The contrast in STM image is the variation of voltage on z electrode.

(piezo)

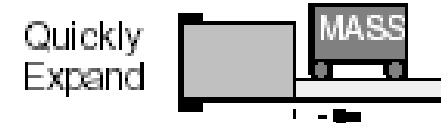
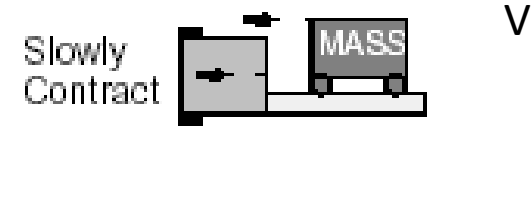
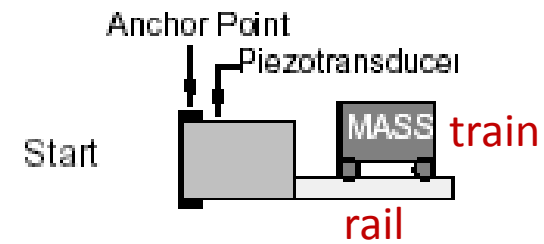
can be deformed by applying voltage

Stepper

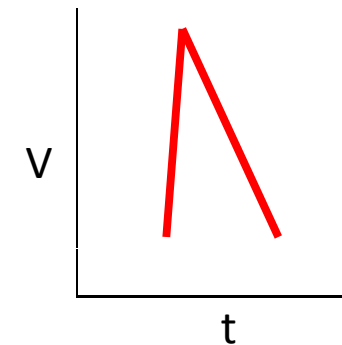
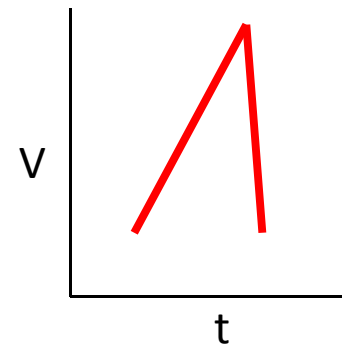
(a) "INCHWORM"



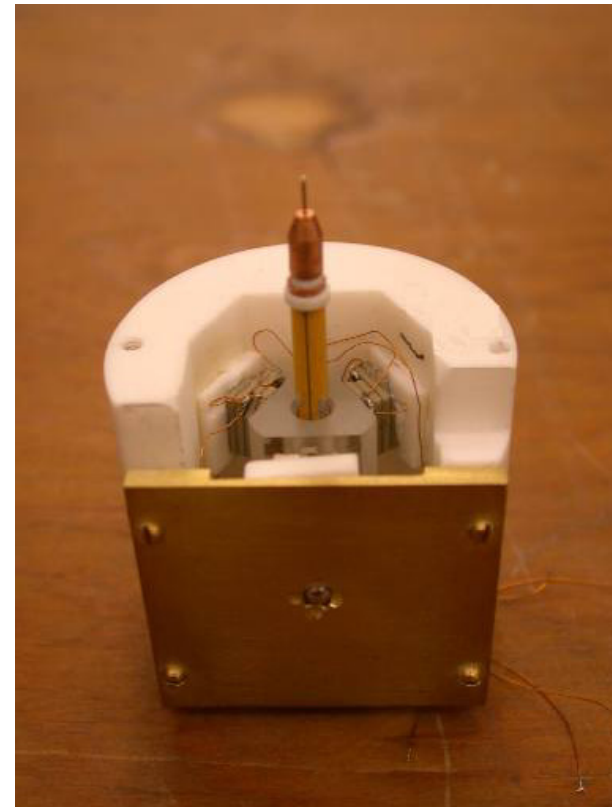
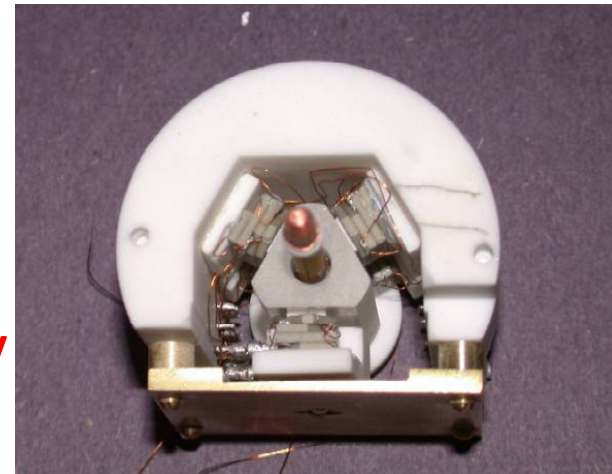
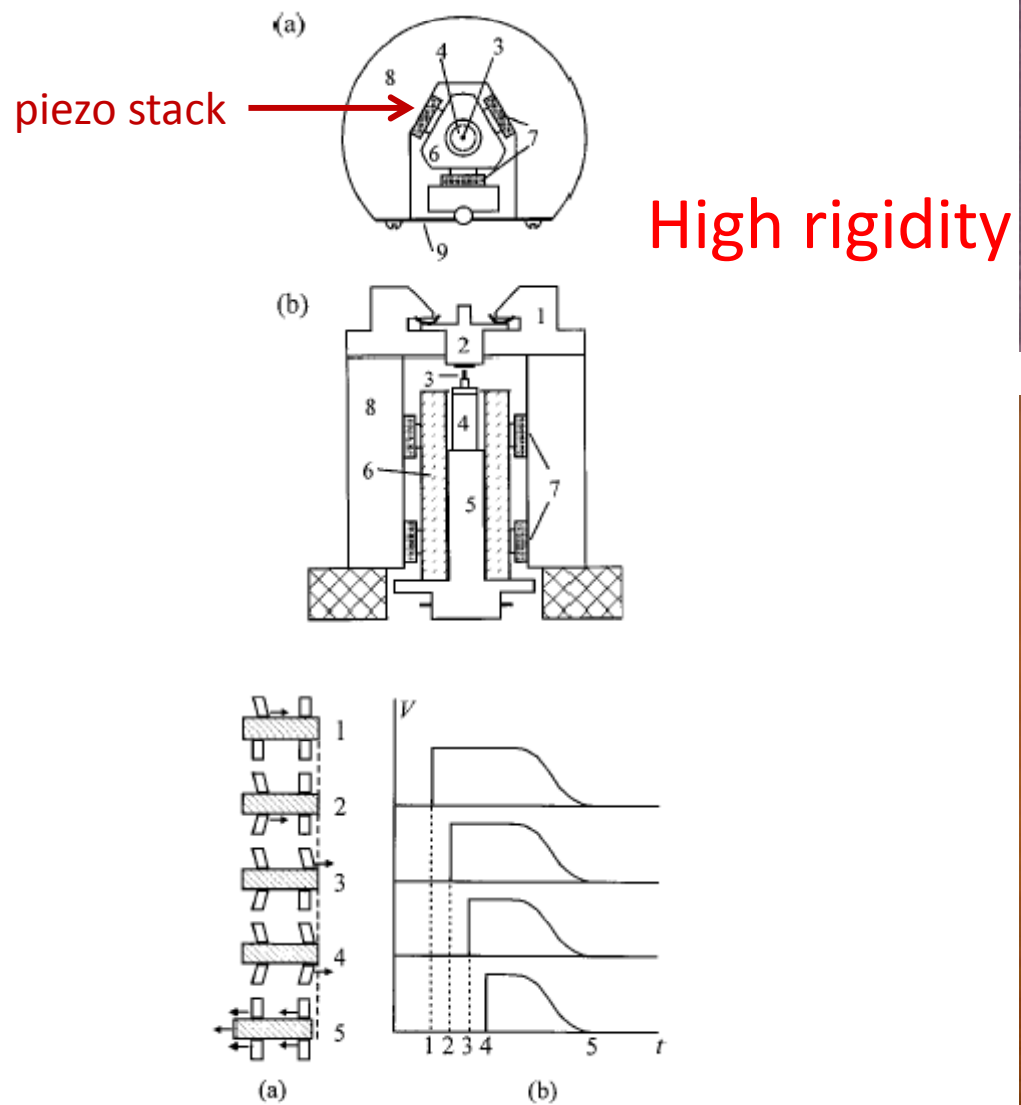
(b) INERTIAL SLIDER



Reverse direction



Pan-style Stepper invented by S. H. Pan



Rev. Sci. Instrum., 70, 1459

Vibration Isolation

The tip-sample distance must be kept constant within $0.01\text{\AA}$ to get good atomic resolution. Therefore it is absolutely necessary to reduce inner vibrations and to isolate the system from external vibrations.

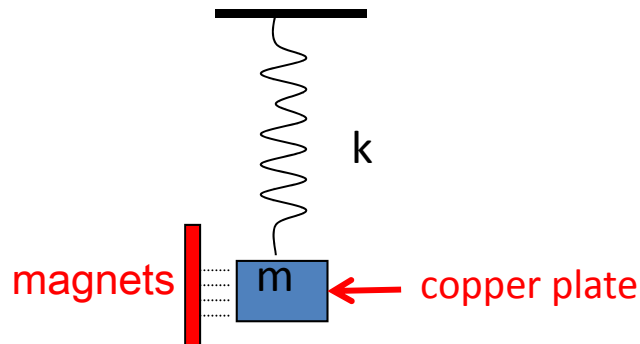
Environmental vibrations are caused by:

- Vibration of the building 15 - 20 Hz
- Running people 2 - 4 Hz
- Vacuum pumps
- Sound

Vibration damping can be done by

- Suspension with springs (including additional eddy current dampers)
- Pneumatic systems

magnets and copper plates



Pneumatic systems

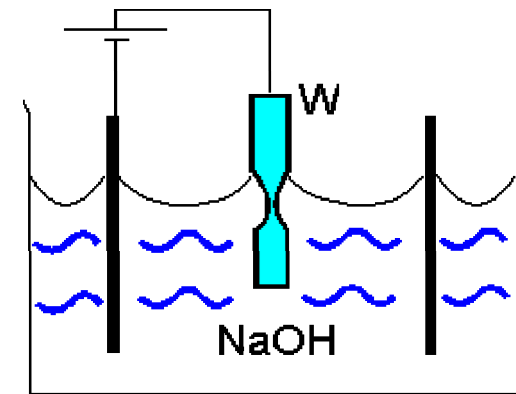


Tip

The tip is the trickiest part in the STM experiment. It needs a small curvature to resolve coarse structures. For atomic resolution a minitip with a one atomic end is necessary. Tips typically are made out of tungsten, platinum or a Pt-Ir wire.

A sharp tip can be produced by:

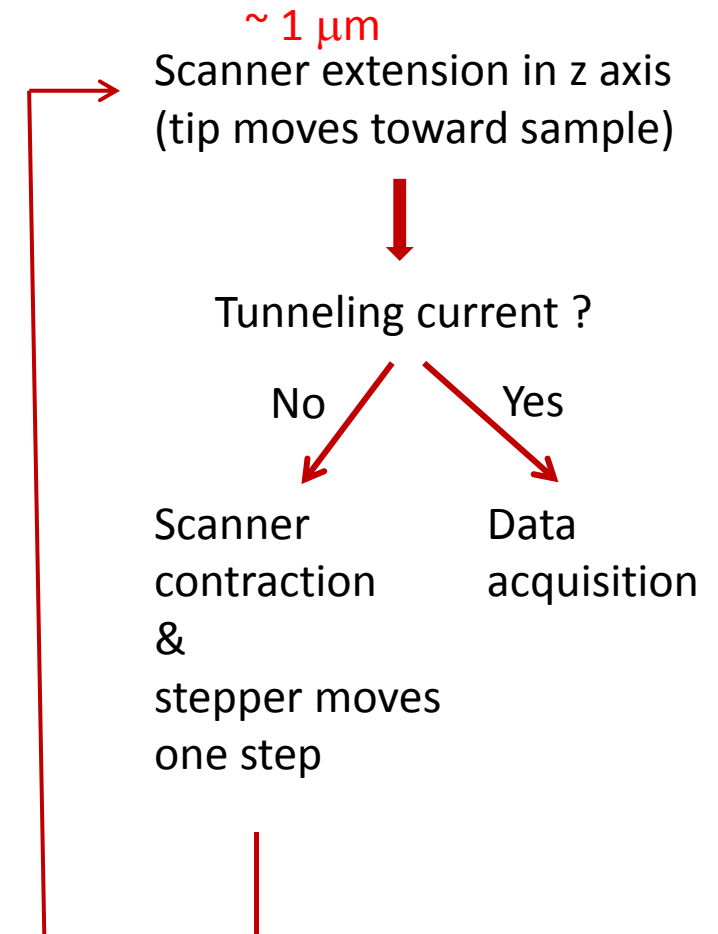
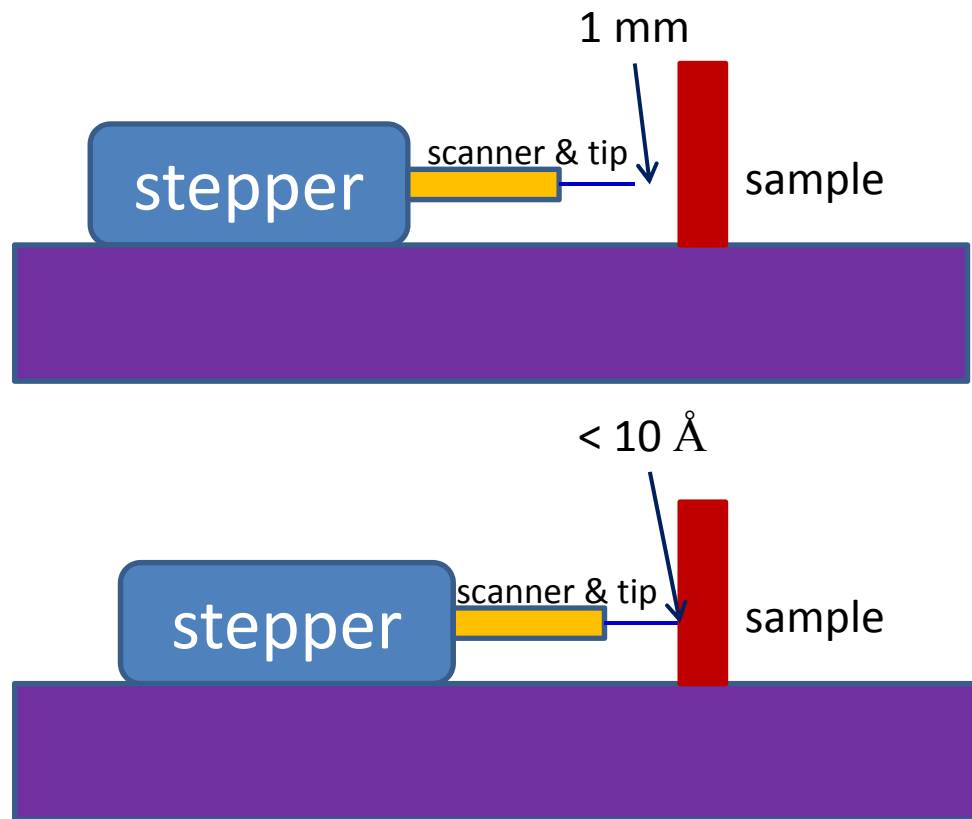
- Cutting and grinding
- Electrochemical etching



Most often the tip is covered with an oxide layer and contaminations from the etchant and is also not sharp enough. Thus other treatments to the tip, like annealing or field evaporation are necessary.

STM electronics and control

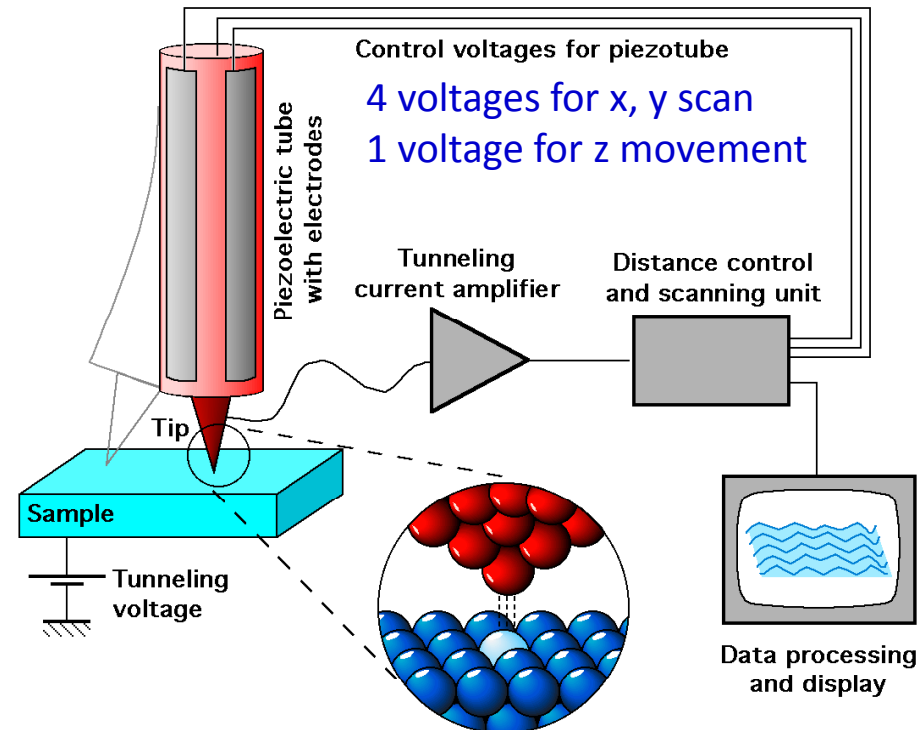
1. Auto approach



Extension in z axis > one step of stepper

STM electronics and control

2. Data acquisition

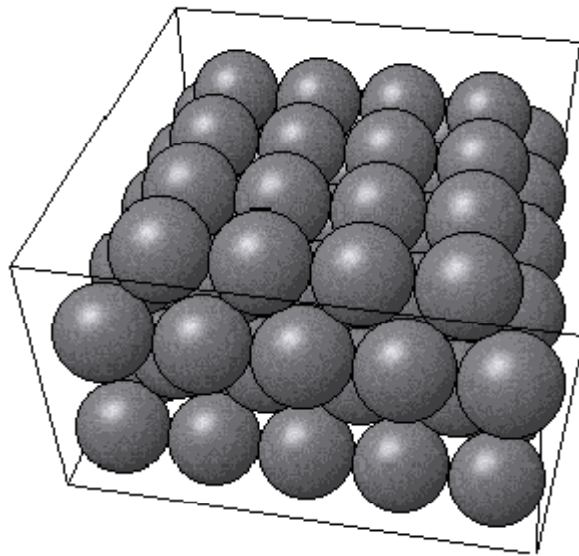


The tunneling current (0.01nA-50nA) is converted into a voltage by a current amplifier. To get a linear response with respect to the tunneling gap (the current is exponentially dependant on the tip-sample distance) the signal is processed by a logarithmic amplifier. The output of the logarithmic amplifier is compared with a predetermined voltage which is used as a reference current. The error signal is passed to feedback electronics, which applies a voltage to the z piezo to keep the difference between the current set point and the tunneling current small. Care has to be taken to keep the noise signal ratio on a low level. Also the response time of the feedback has to be minimized without loosing accuracy.

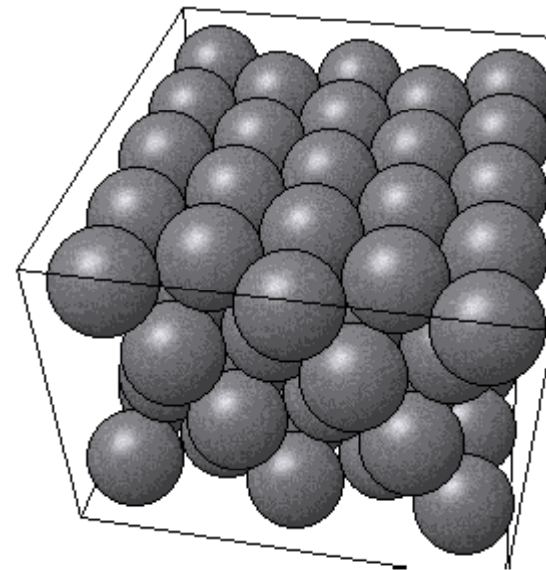
Applications of scanning tunneling microscopy

Surface reconstruction

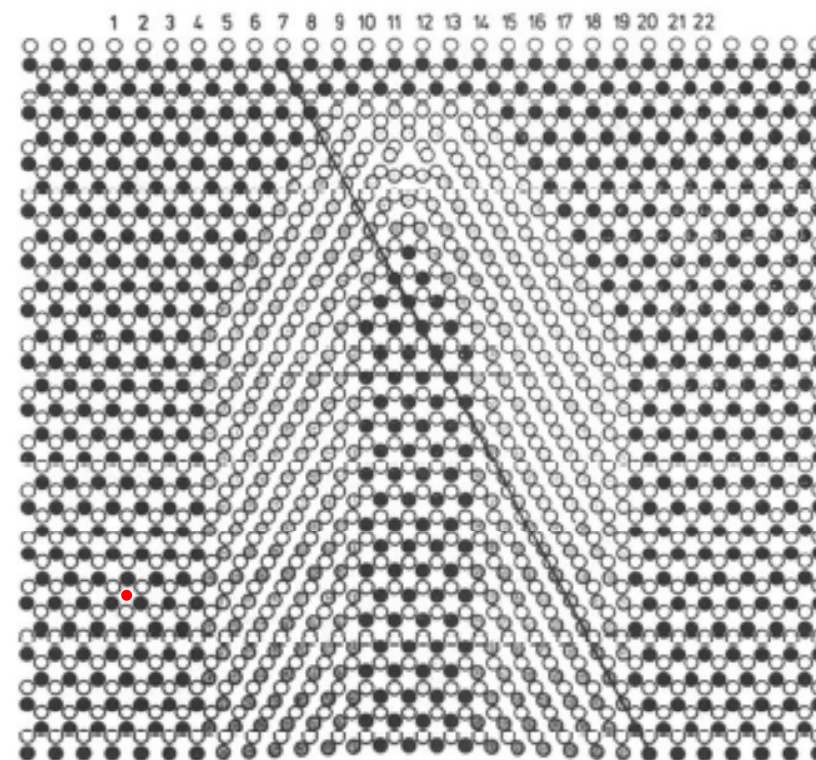
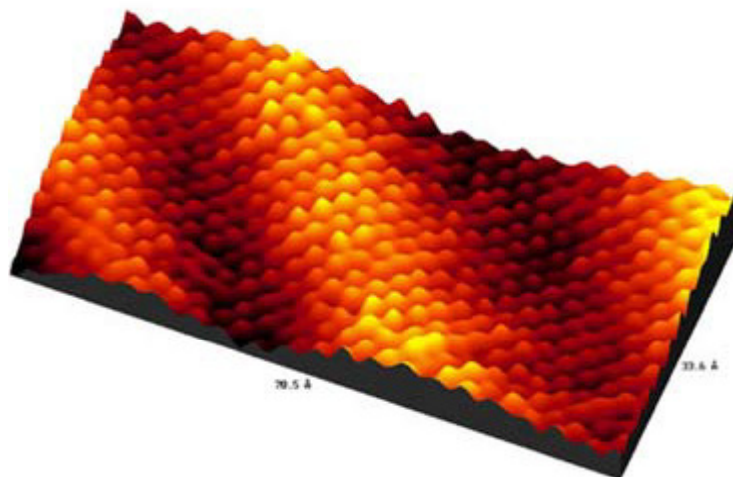
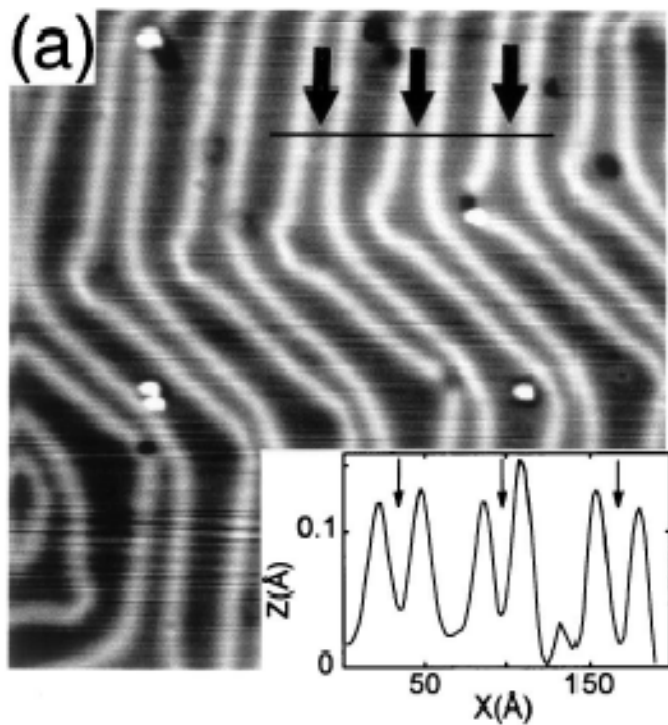
FCC(100)



FCC(111)

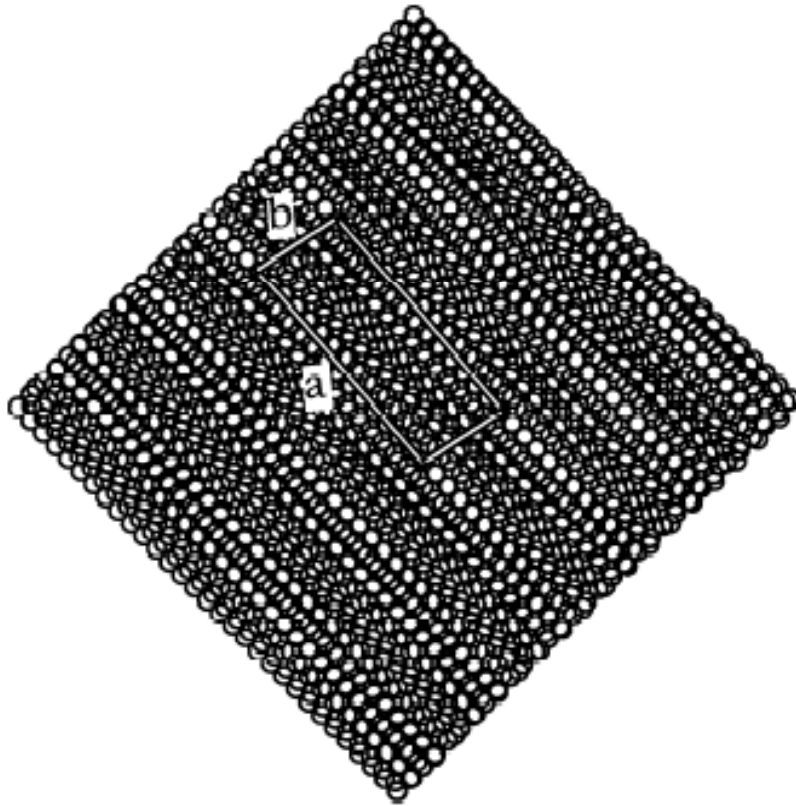


22x3 Reconstruction of Au(111) surface

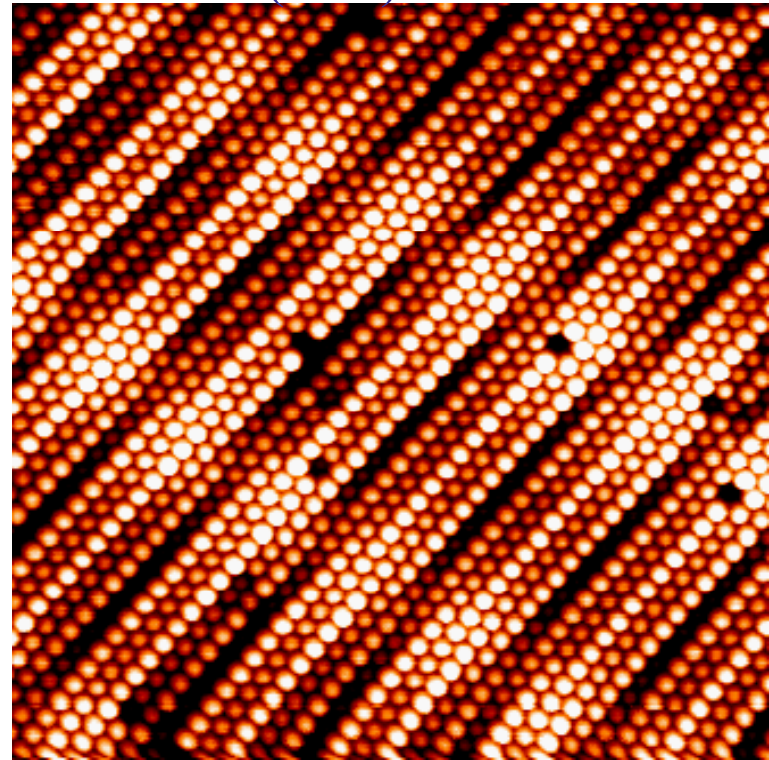


FCC ridge HCP FCC
(ABC) (ABA)

Reconstruction on Pt(100)



Pt(100)-R0.7⁰



Close packed lattice (0.965 Å) / square lattice (Å)
A=lattice constant

Surface Diffusion

Einstein Equation : $D = \langle x^2 \rangle / 2\alpha\gamma$

D : diffusion coefficient,

$\langle x^2 \rangle$: mean square displacement of atom

$\alpha=1$ for one dimensional diffusion

$\alpha=2$ for two dimensional diffusion ($\langle x^2 \rangle + \langle y^2 \rangle$)

γ : time interval

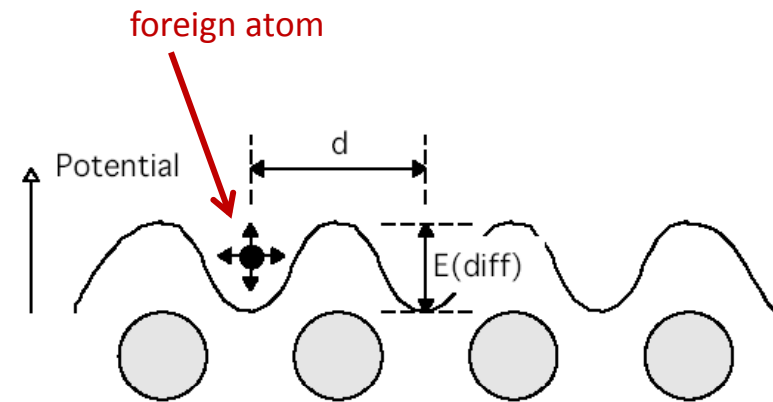
$\langle x^2 \rangle$ can be related to the number of jumps N

According to random walk theory $\langle x^2 \rangle = Nd^2$

d : mean jump distance

Γ is defined as the number of atom jumps per time interval $= N/\gamma$

$$\ln (\langle x^2 \rangle / 2\alpha\gamma) = \ln(D_0) - E_d/kT$$



$$D = d^2 \Gamma / 2$$

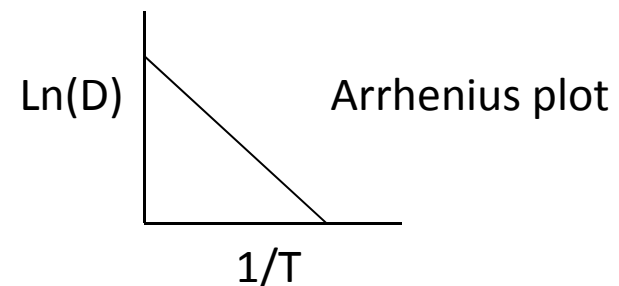
$$\Gamma = v_0 \exp(-E_d/kT)$$

v_0 is vibration frequency,

E_d is activation energy

$D = D_0 \exp(-E_d/kT)$ D : diffusion coefficient

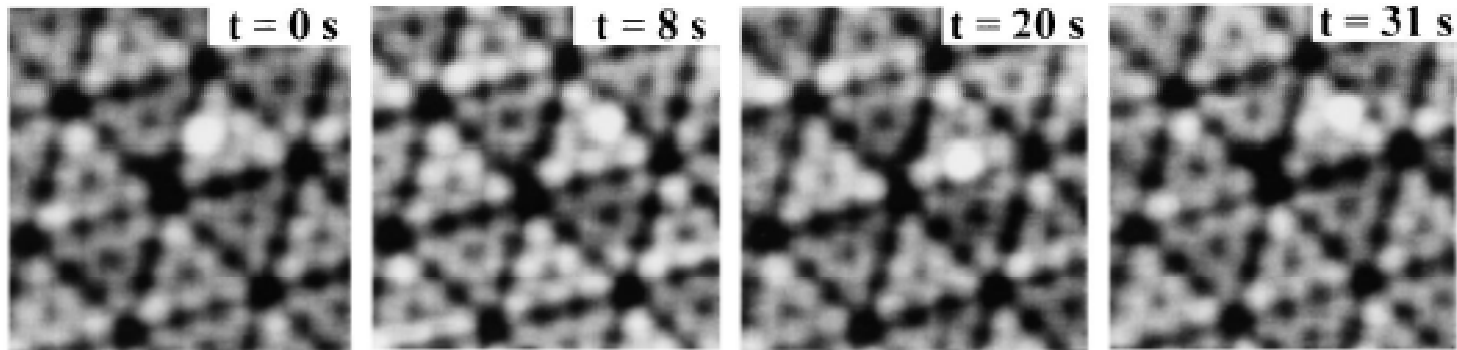
D_0 is the diffusivity $= v_0 d^2 / 2$



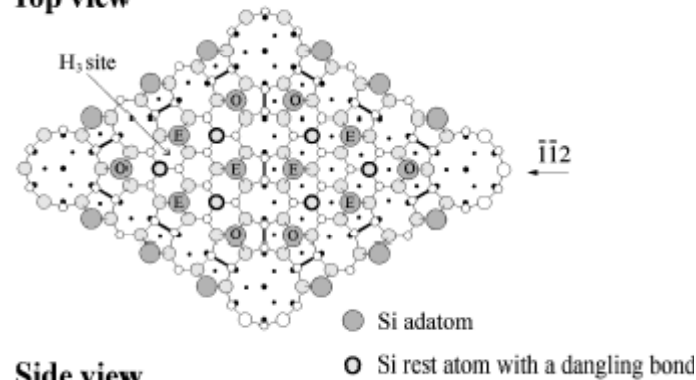
Surface Diffusion

Site Hopping of Single Chemisorbed O_2 Molecule on Si(111)7×7

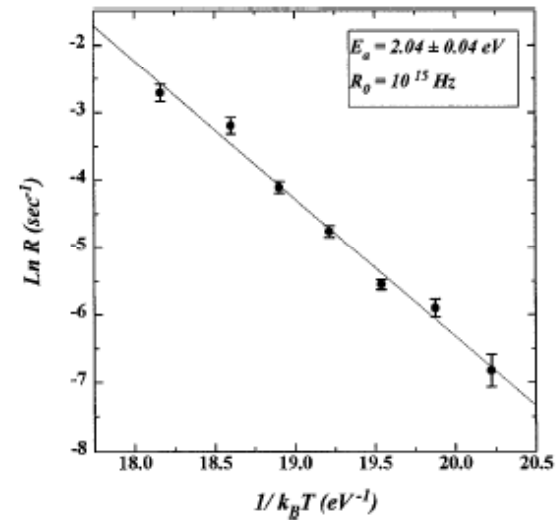
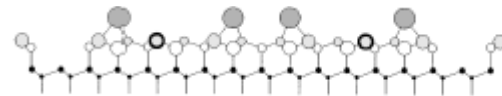
350°C



Top view



Side view



Phys. Rev. Lett. 78, 4797 (1997)

Nucleation and Epitaxial Growth

Fe/Fe(100)

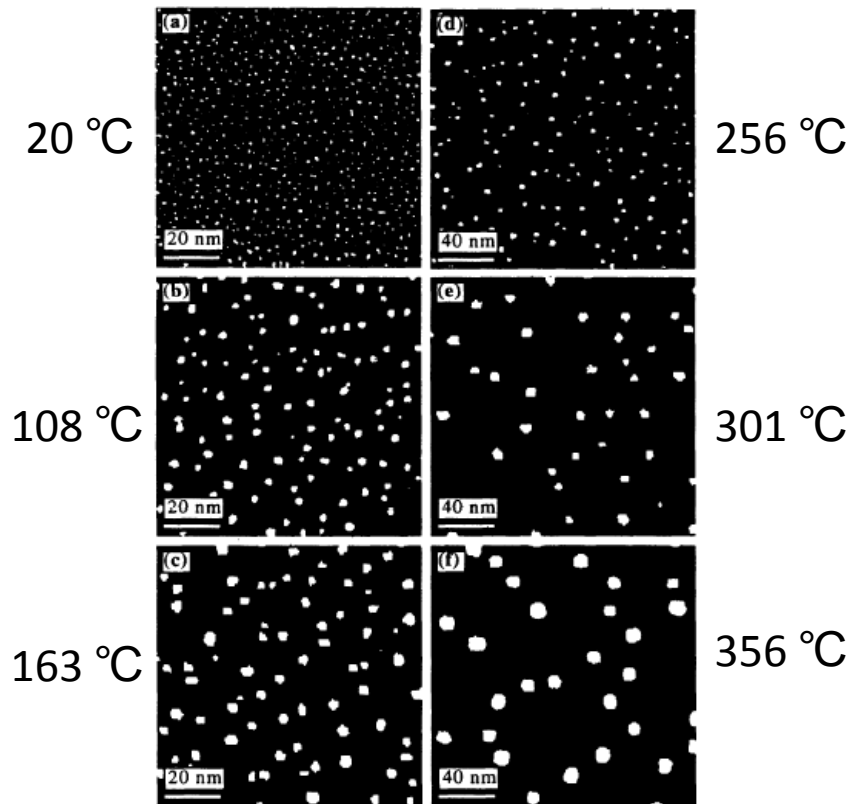


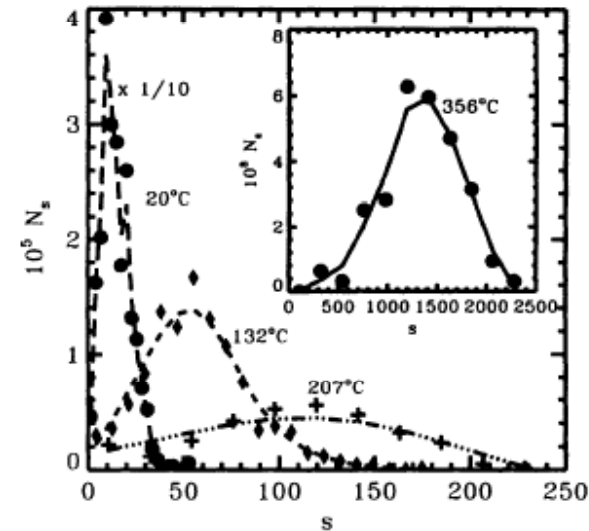
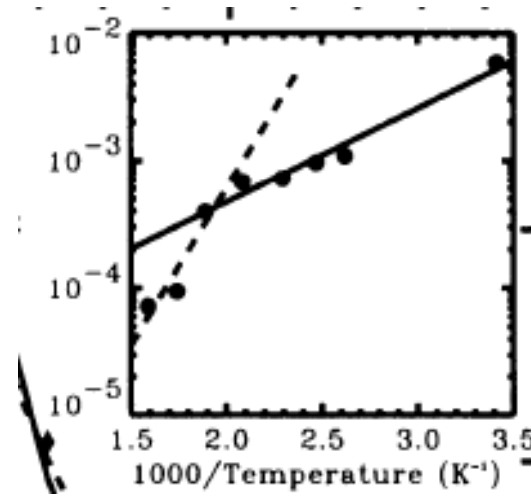
FIG. 1. STM images, $100 \times 100 \text{ nm}^2$, of single-layer Fe islands (white) on the Fe(001) surface (black). Sample temperatures during growth are (a) 20°C , (b) 108°C , (c) 163°C , (d) 256°C , (e) 301°C , and (f) 356°C . Fe was deposited for a fixed time for all measurements with a flux of $1.4 \pm 0.3 \times 10^{13} \text{ atoms cm}^{-2} \text{ s}^{-1}$, yielding a coverage of $0.07 \pm 0.016 \text{ ML}$ ($1 \text{ ML} = 1.214 \times 10^{15} \text{ atoms cm}^{-2}$).

Phys. Rev. B 49, 8522 (1994)

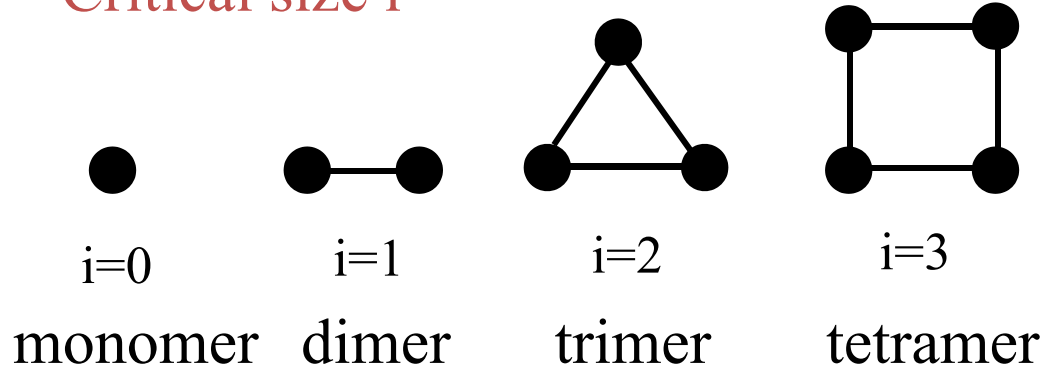
$$N \sim \eta(\Theta)(r/\nu)^{\chi} \exp[\chi(E_d + E_i/i)/k_B T],$$

E_d : activation energy

E_i : binding energy of critical size i



Critical size i



Scaling theory

$$N_s = \theta S^{-2} f_i(s/S)$$

N_s : island density at size s

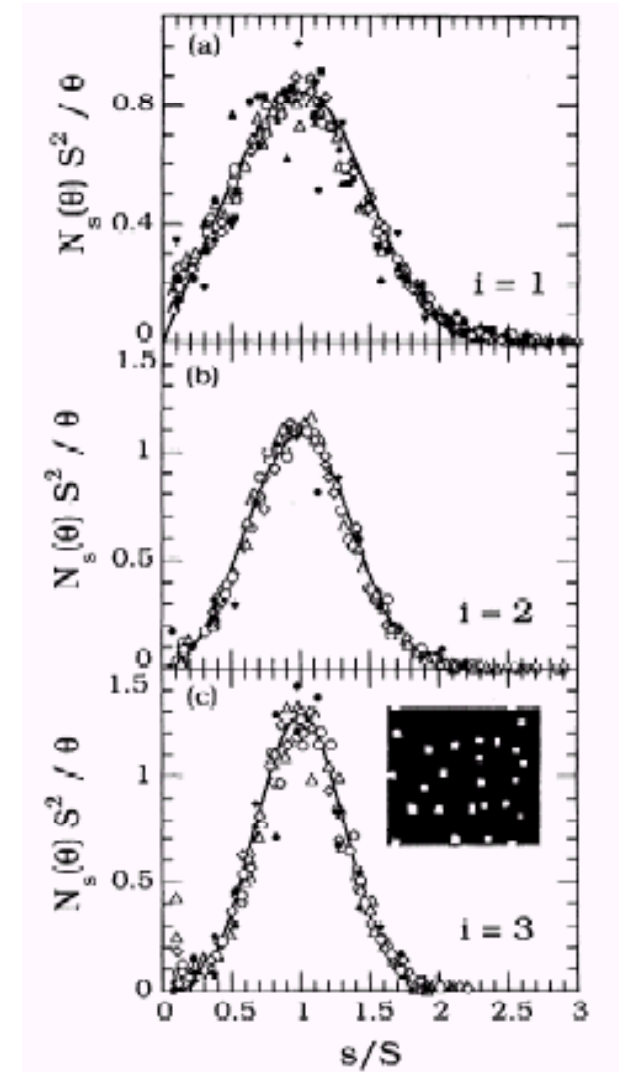
θ : coverage

S : average island size

$$N_s S^2 / \theta = f_i(s/S)$$

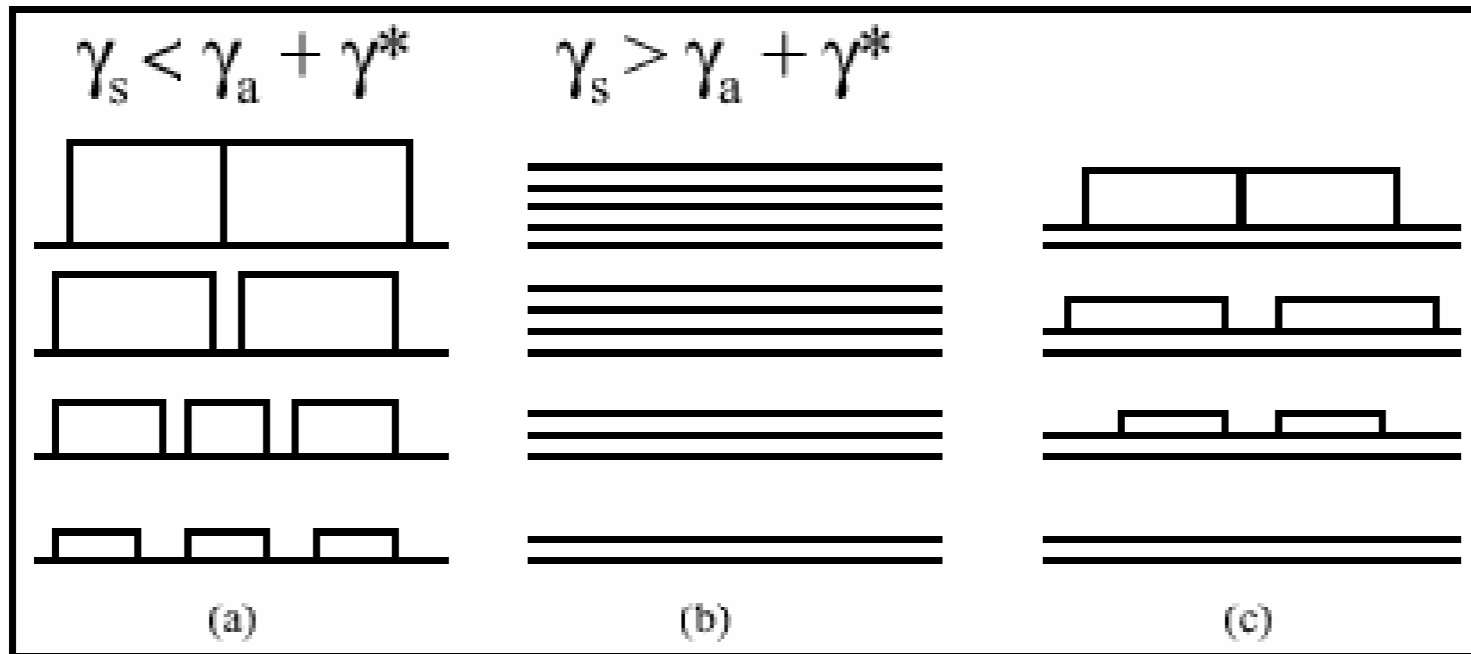
$f_i(s/S)$ is an universal

Scaling function at critical
size i



J. G. Amar and F. Family
Phys. Rev. Lett. **74**, 2066 (1995)

Hetero Epitaxial Growth Mode



Volmer-Weber
(VW)

Frank-van-der-Merwe
(FM)

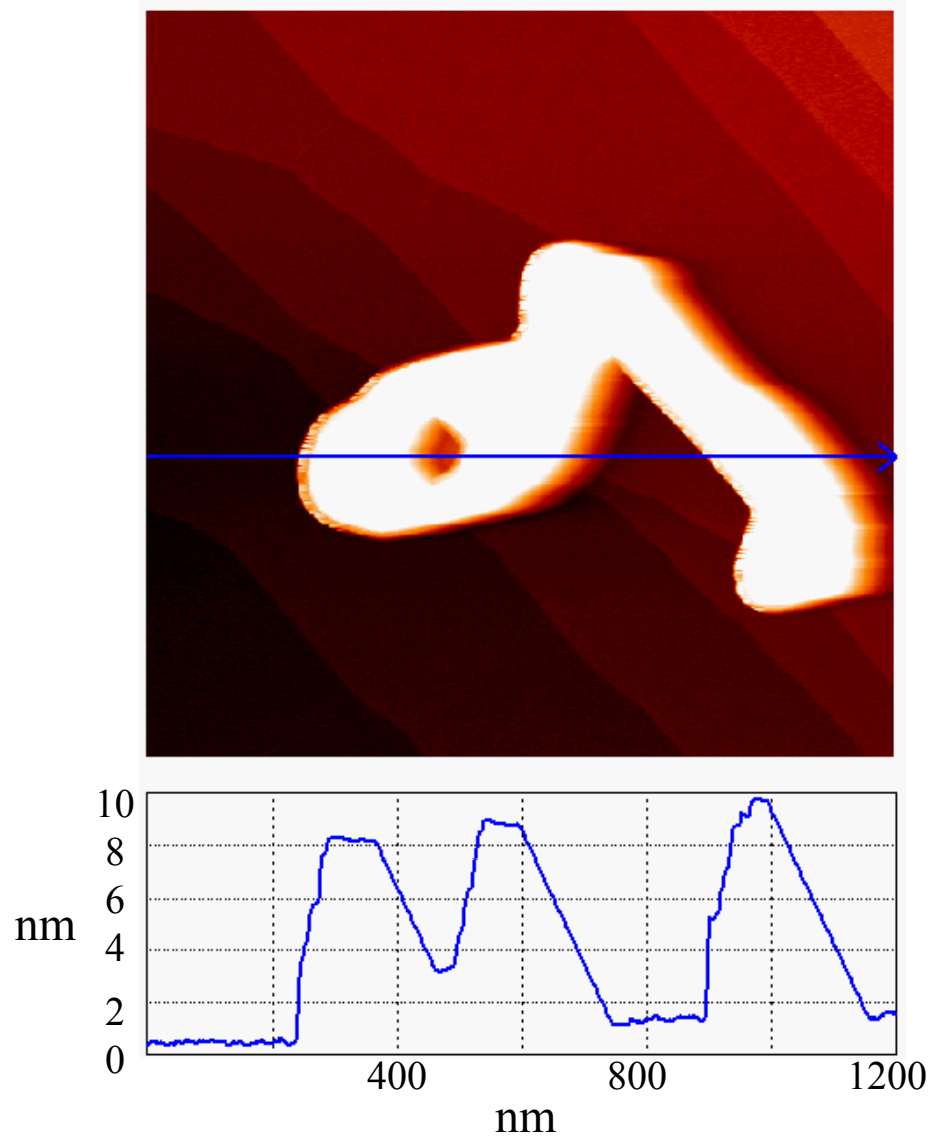
Stranski-Krastonov
(SK)

γ_s : surface free energy of substrate

γ_a : surface free energy of adsorbate

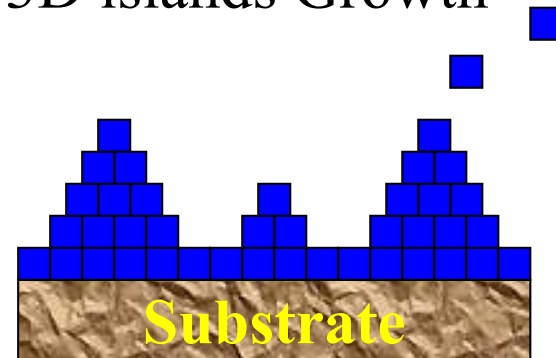
γ^* : interfacial free energy

Pb/Si(111) at RT



Stranski-Krastanov
growth mode

3D islands Growth

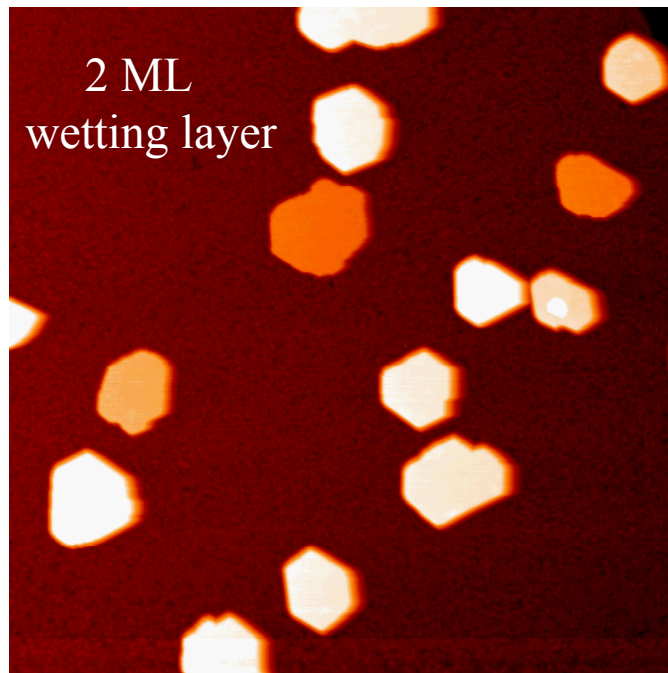


Layer + Island (SK) Growth

The Growth of 2D Pb islands on Si(111)7×7 surfaces at Low Temperature

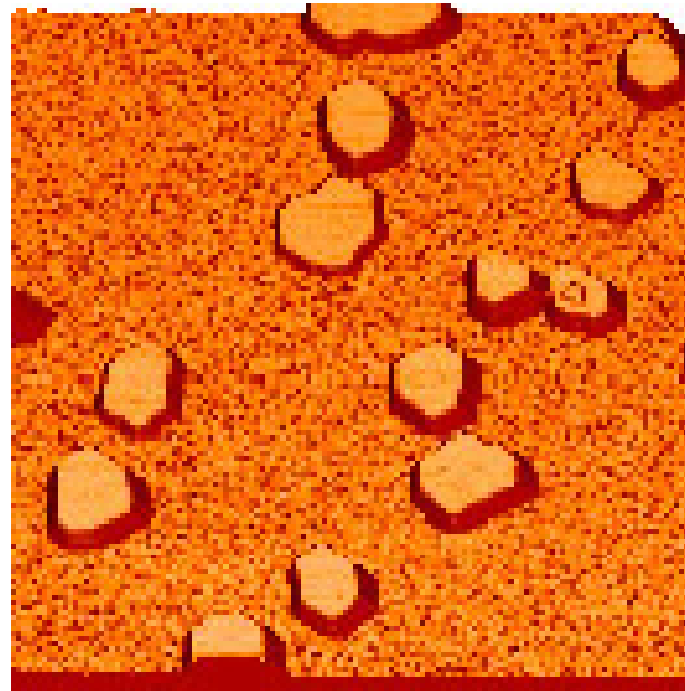
T=208K, $\theta = 3.2$ ML Pb

Topography

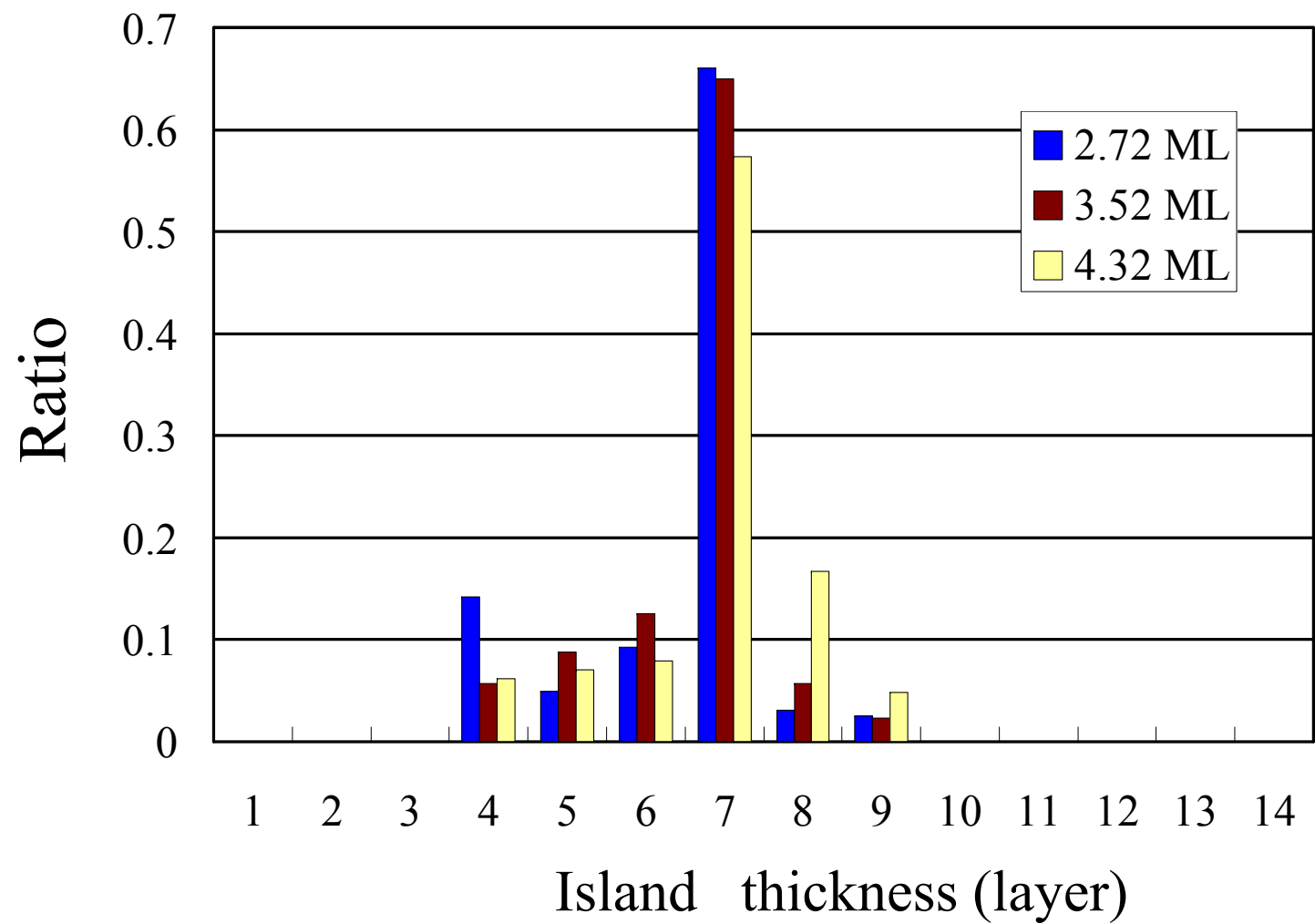


100 nm

3D image of topography



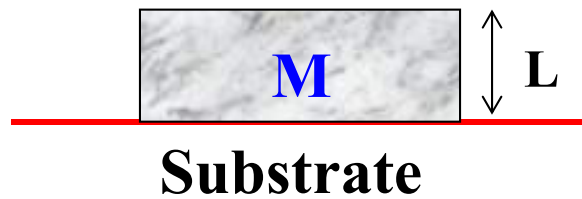
Phys. Rev. Lett. 86, 5116 (2001)



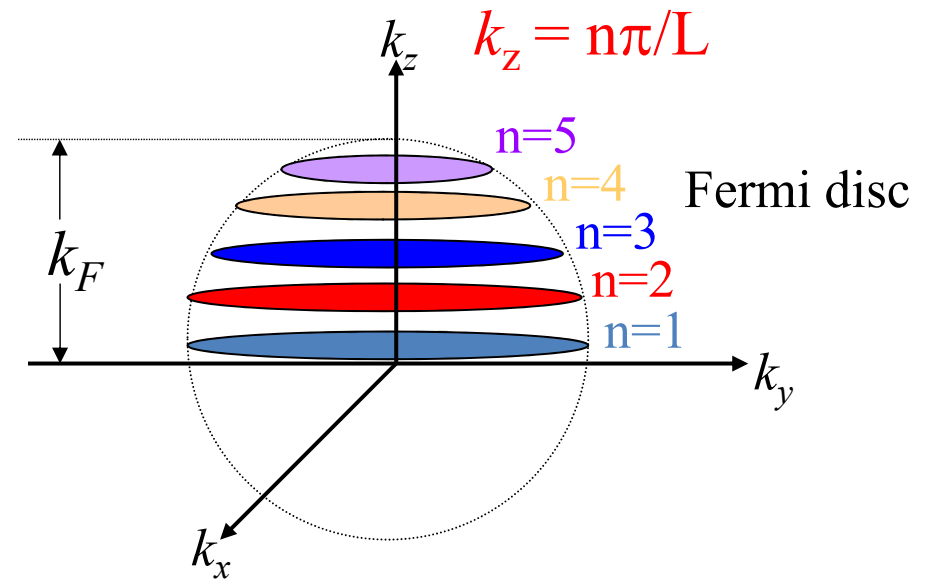
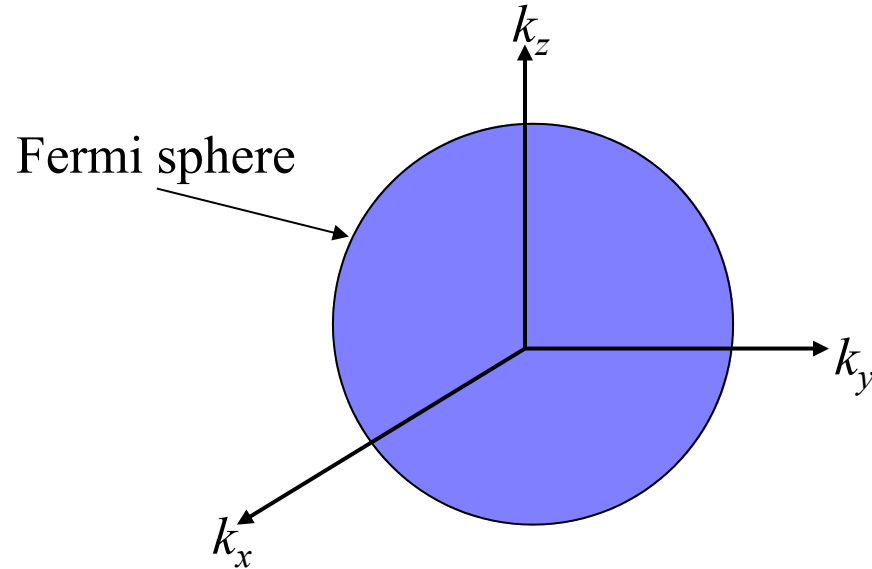
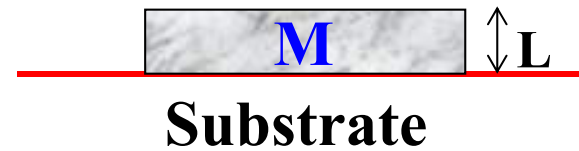
Quantum Size Effect-Driven Epitaxial Growth

λ = de Broglie wavelength of electron

$$L \gg \lambda$$

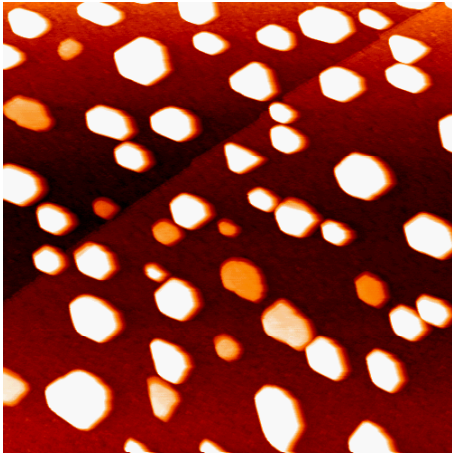


$$L \approx \lambda$$

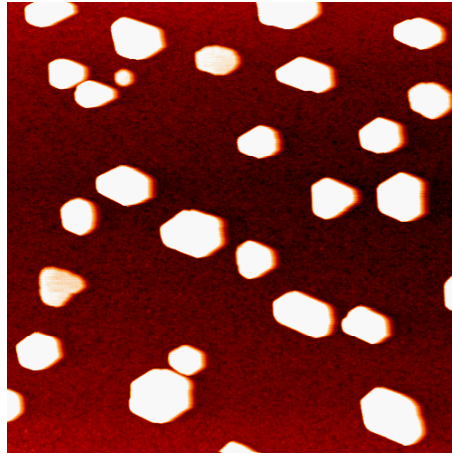


Phys. Rev. Lett. 80, 5381 (1998)

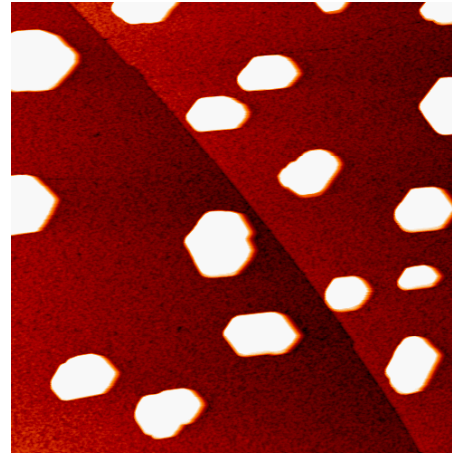
189K



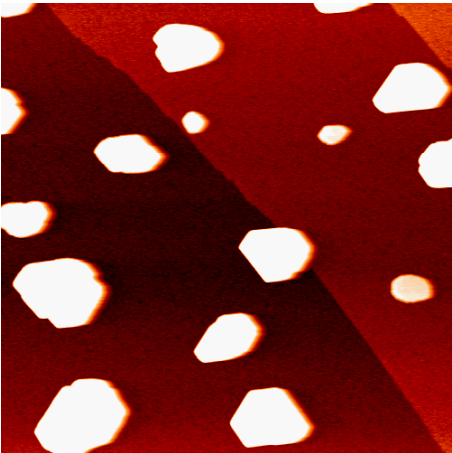
198K



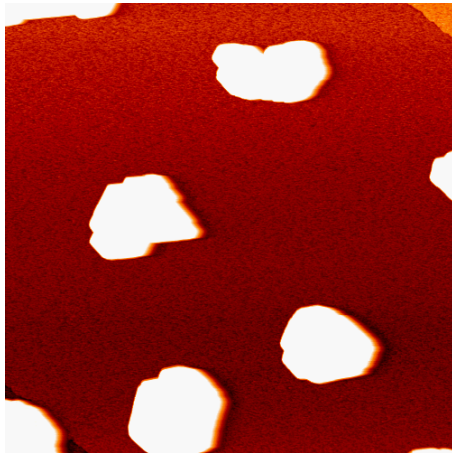
207K



216K



225K



254K



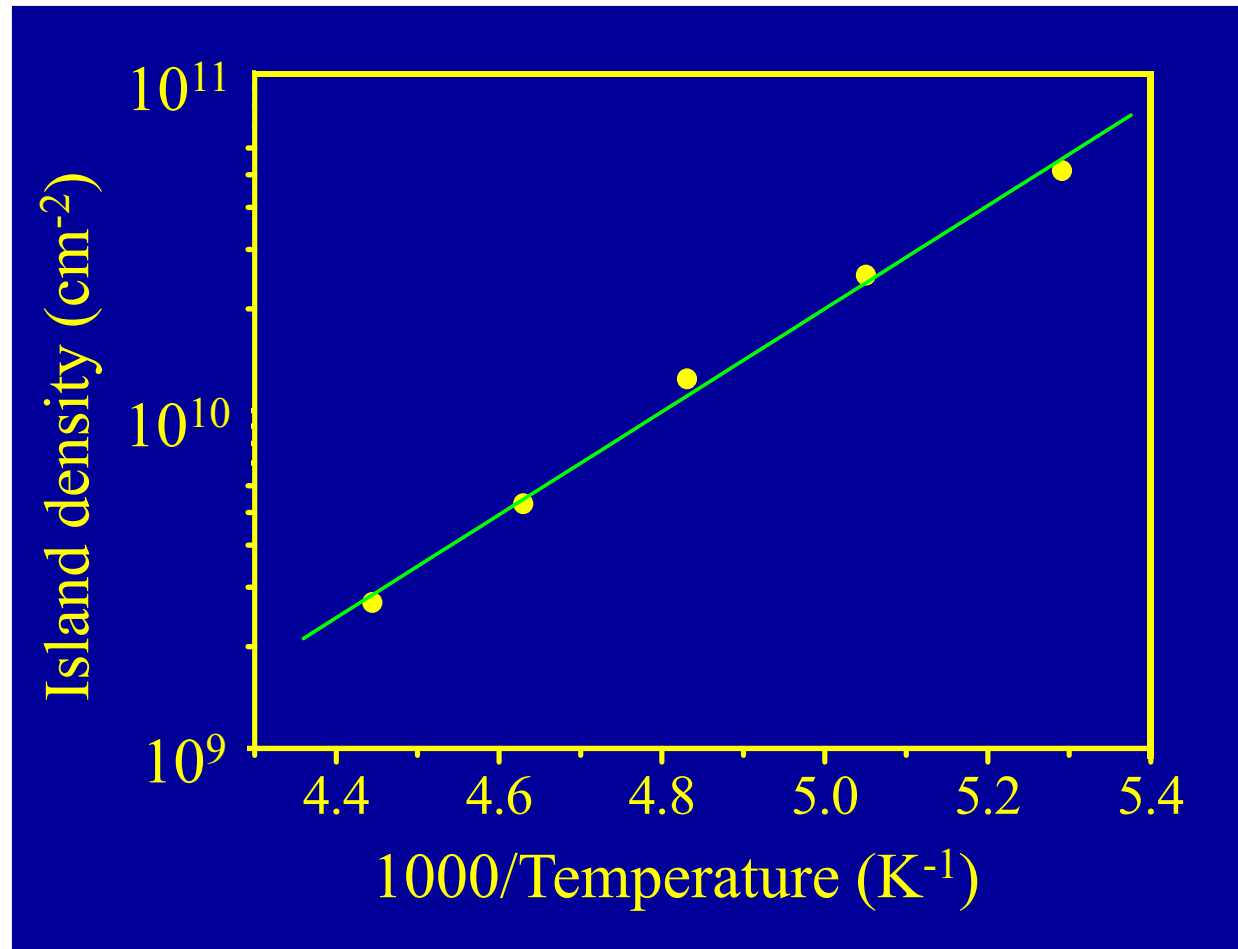
$$N \sim \exp[(iE_d + E_i)/(i+2)k_B T]$$

E_d : the activation for diffusion

E_i : the binding energy for the critical size i

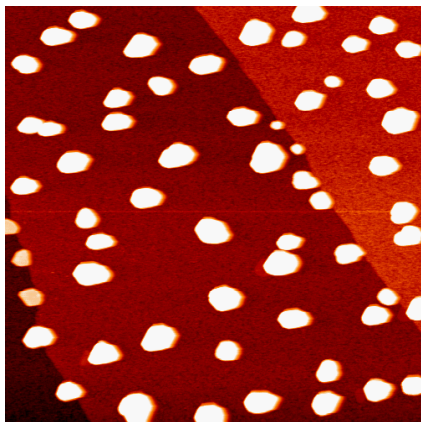
Phys. Rev. B 65, 245401 (2002)

Arrhenius Plot : Island density vs. $1/\text{Temperature}$

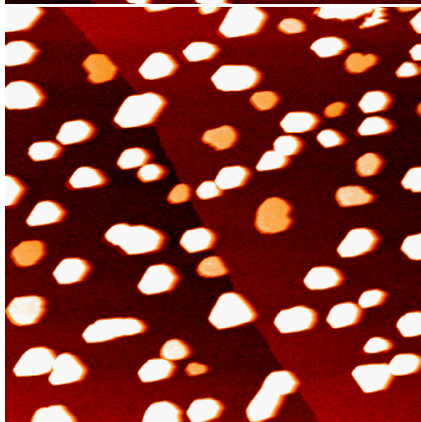


- The nucleation and the quantum size effect are two independent factors in the formation of an island, the former results in the creation of an island and the latter determines the thickness of the created island.

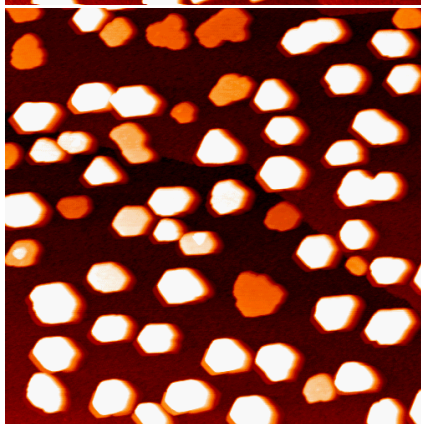
2.72 ML



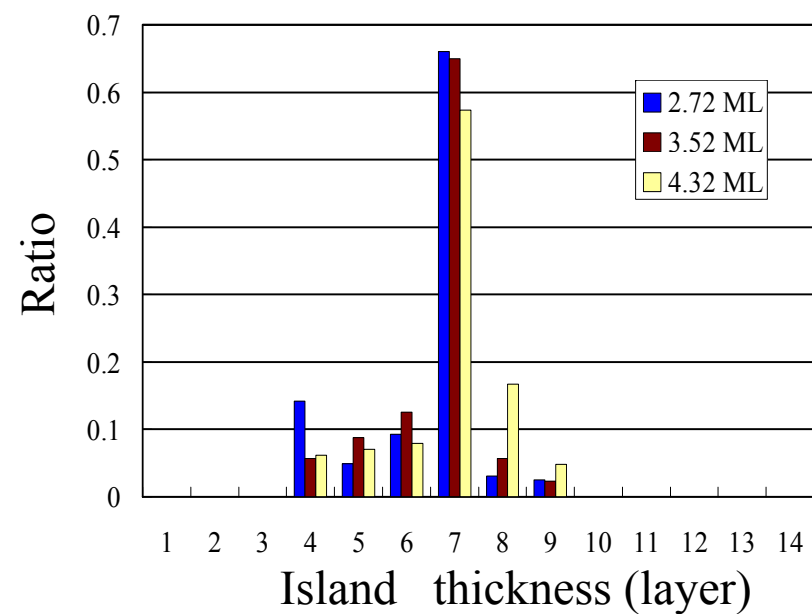
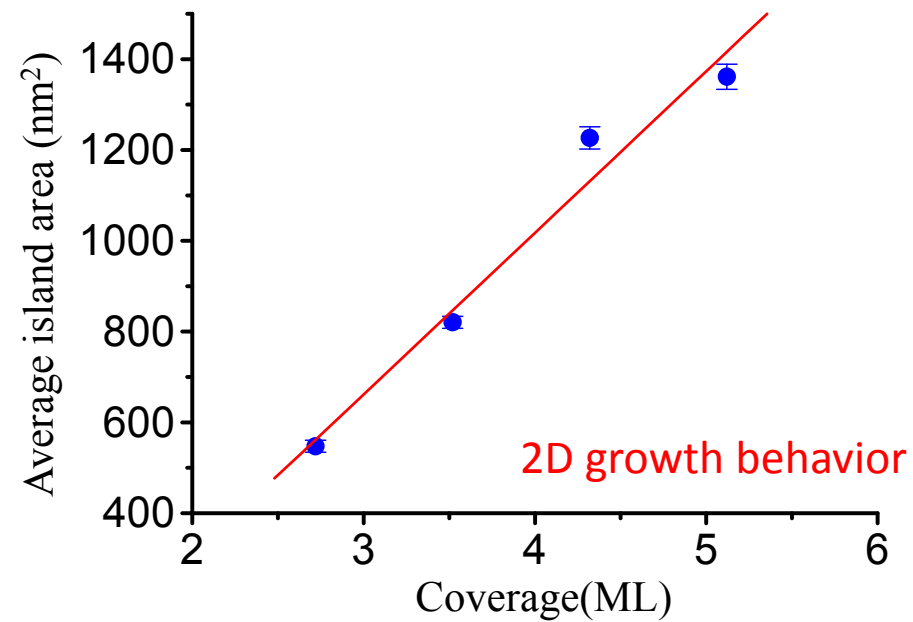
3.52 ML



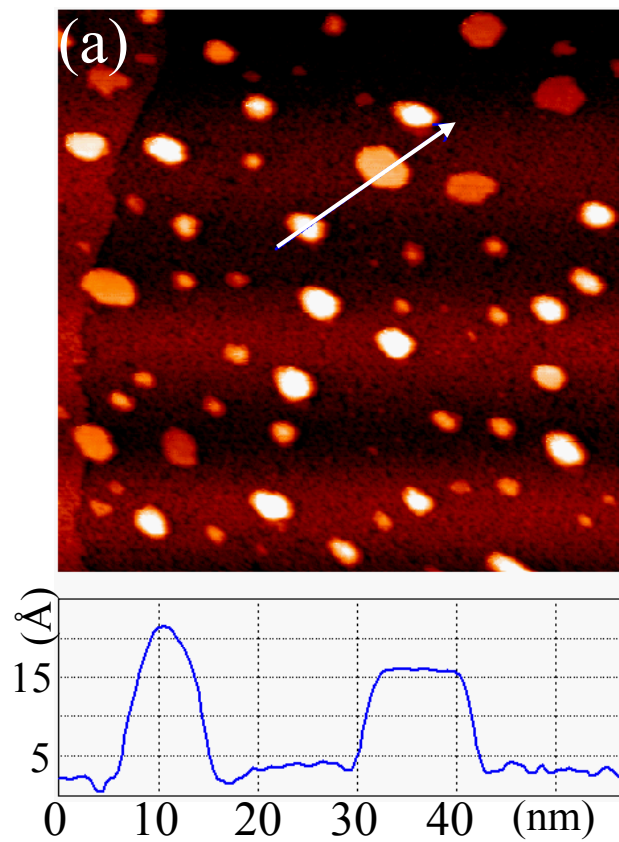
4.32 ML



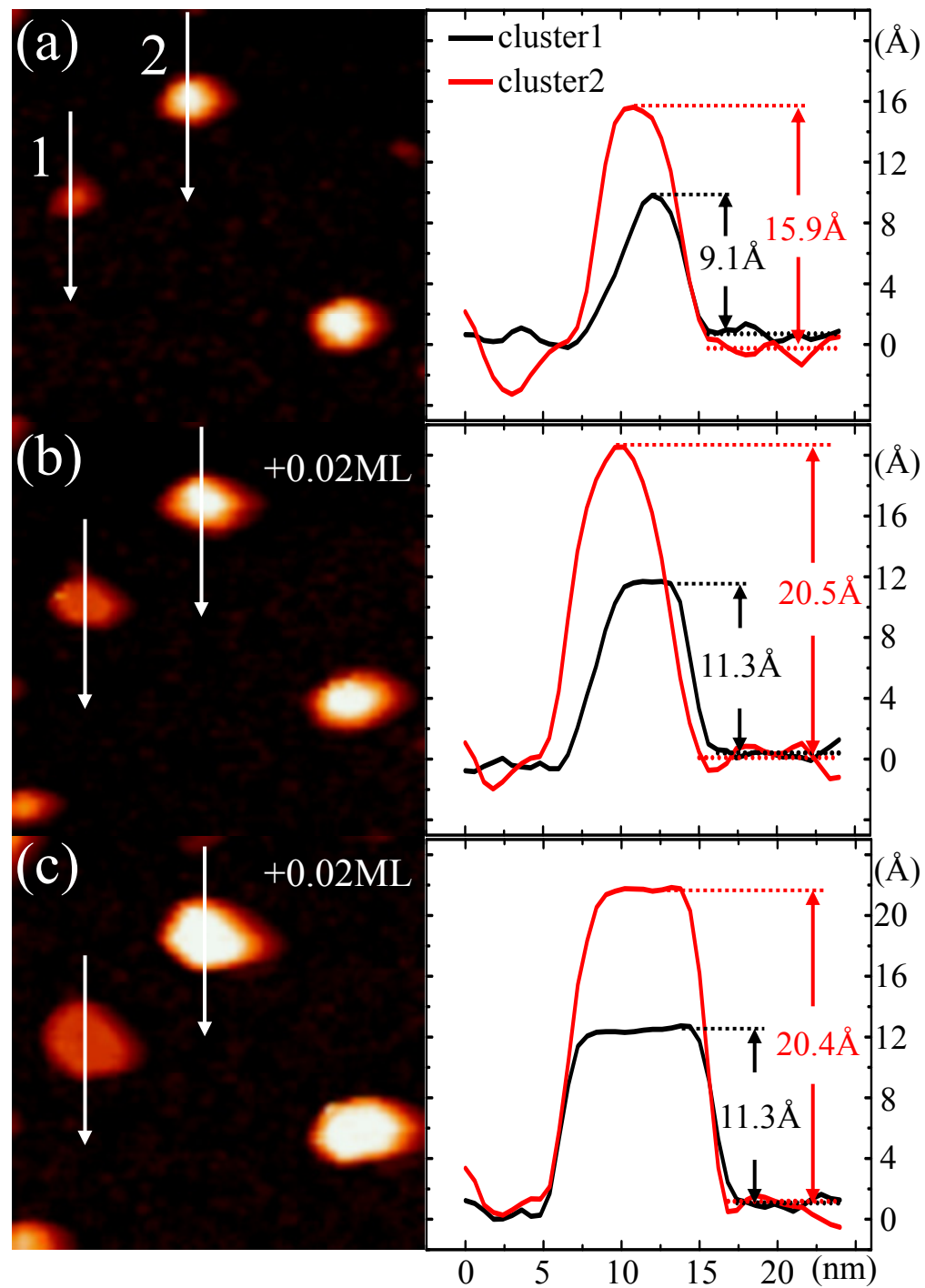
(500×500 nm²)

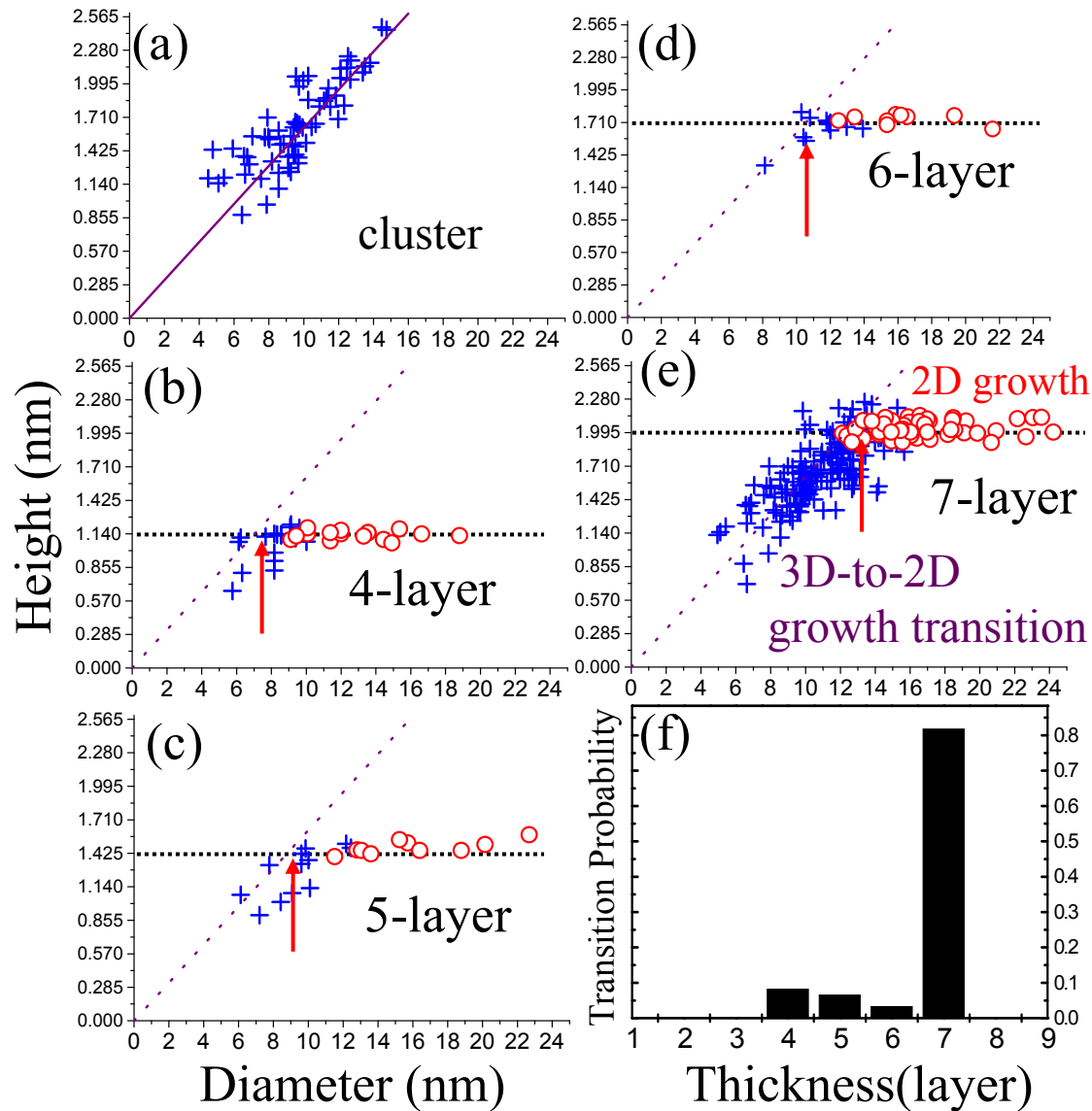


2.3 ML, 170 K



Phys. Rev. B 68, 033405 (2003)

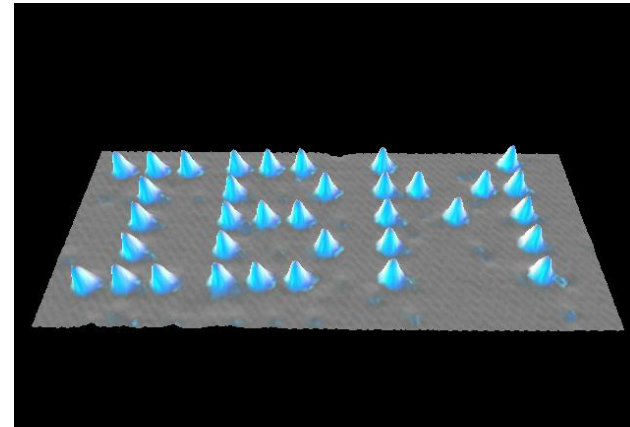
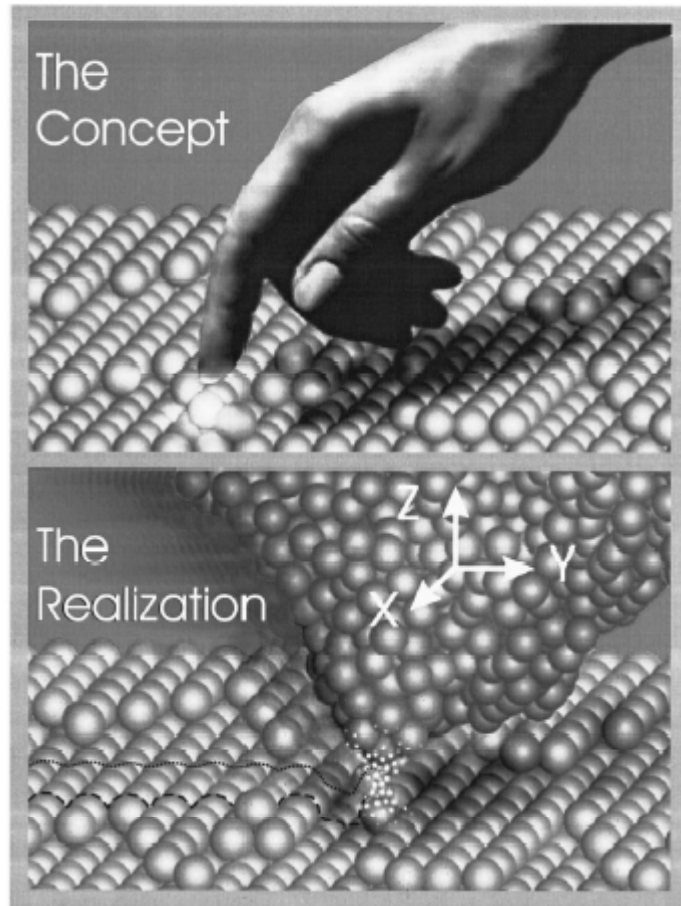




- Growth transition induced by the quantum size effect
- Independent transition pathway:
N-layer thickness island
is transformed from
N-layer height cluster
- Identical cluster can be of
different electronic structure
(quantum size effect).

Phys. Rev. B 71, 073304 (2005)

Atomic Manipulation

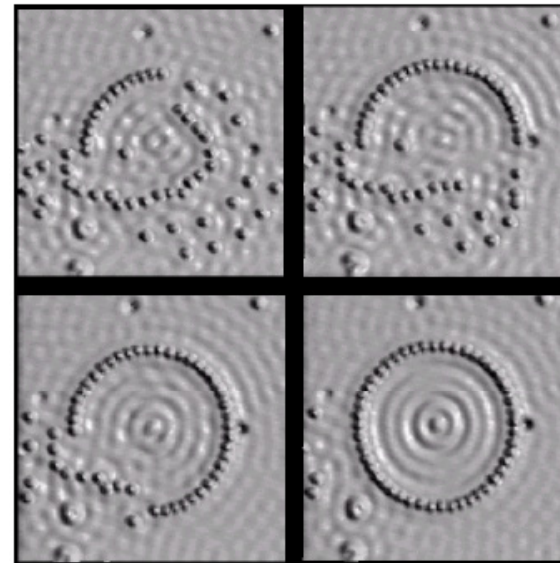
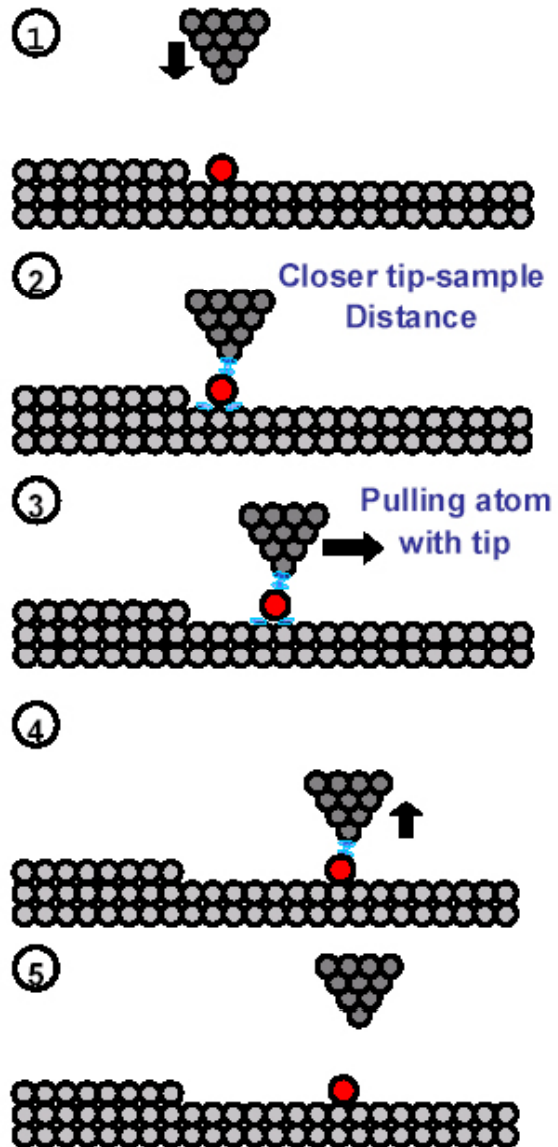


By Eigler et al.

[Nature 344, 524 \(1990\)](#)

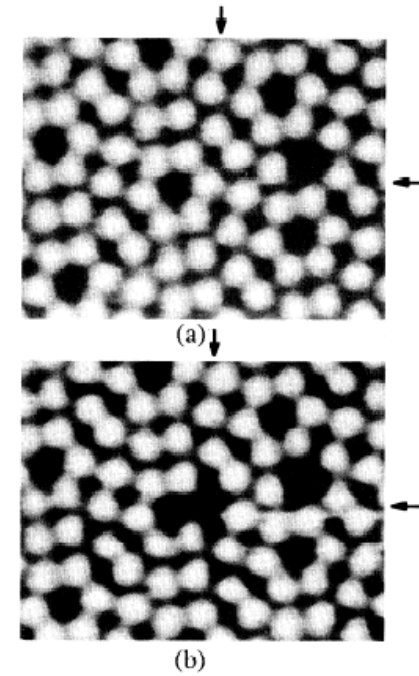
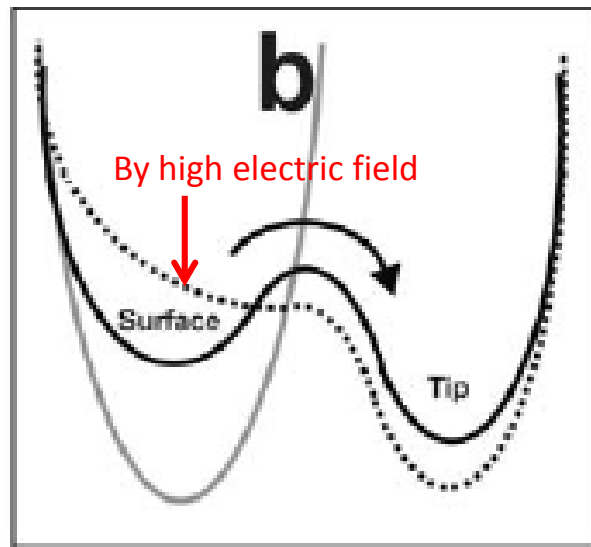
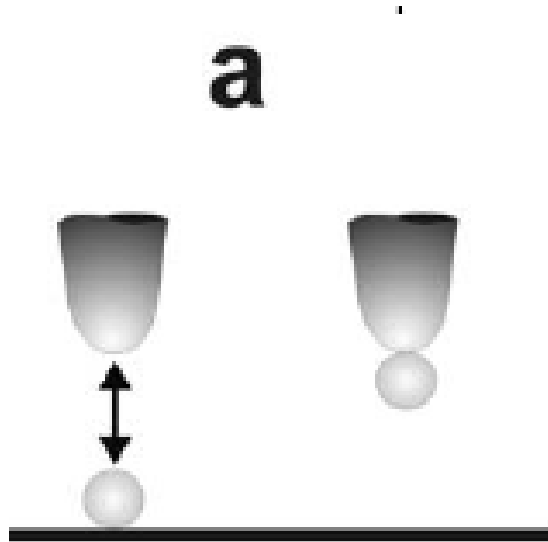
Atomic Manipulation

Lateral Manipulation



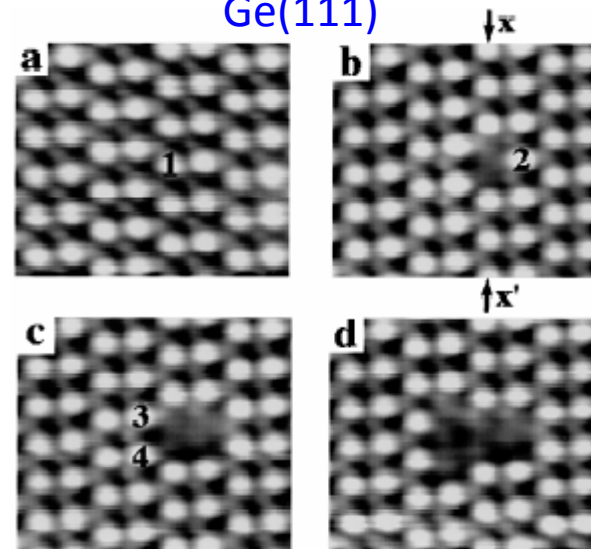
Science 262, 218 (1993)

Vertical Manipulation



Phys. Rev. Lett. 70, 2040 (1993)

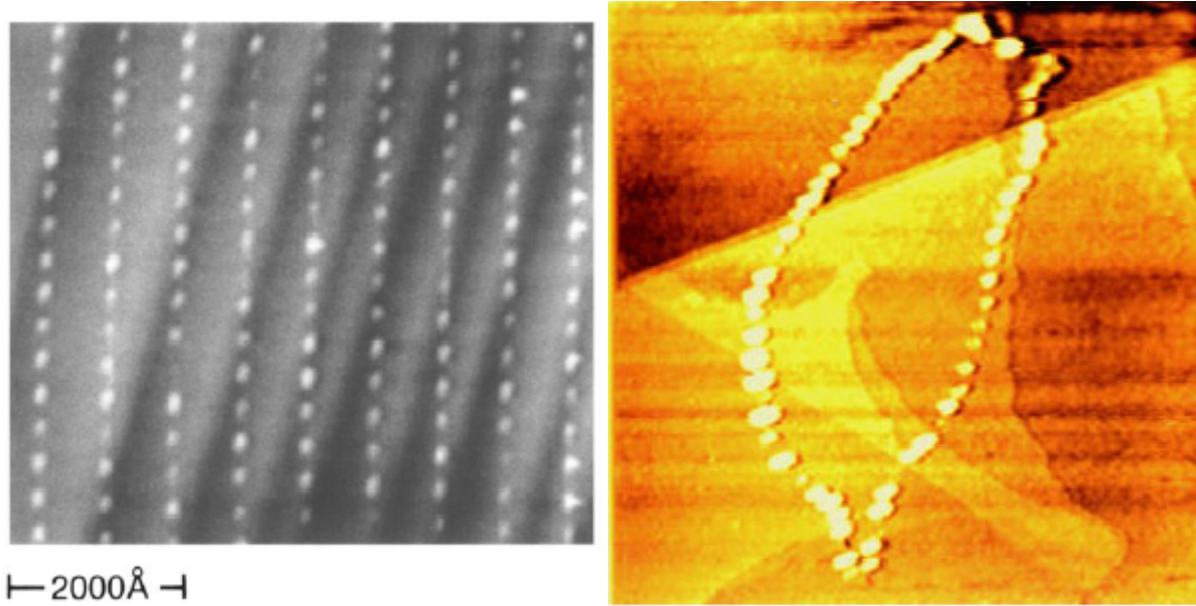
Ge(111)



Phys. Rev. Lett. 80, 3085 (1998)

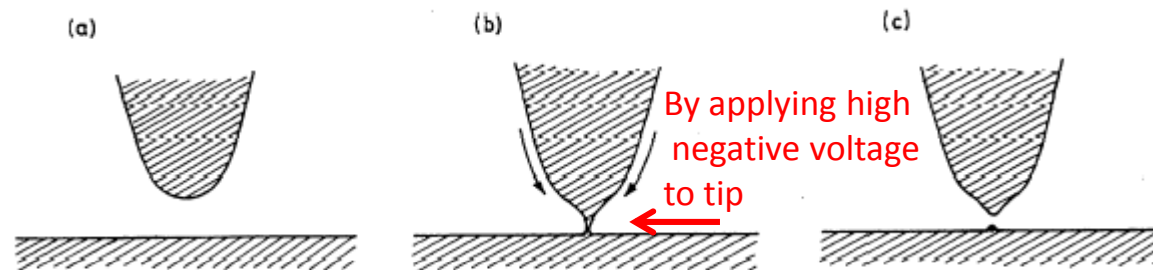
Nanolithography

Nano Au cluster/Au (in air)



— 2000Å —

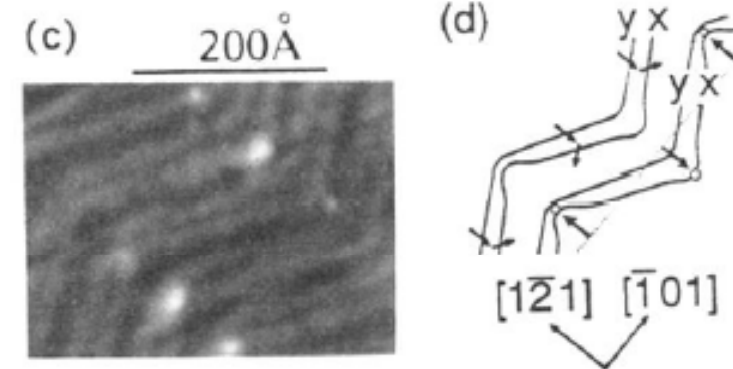
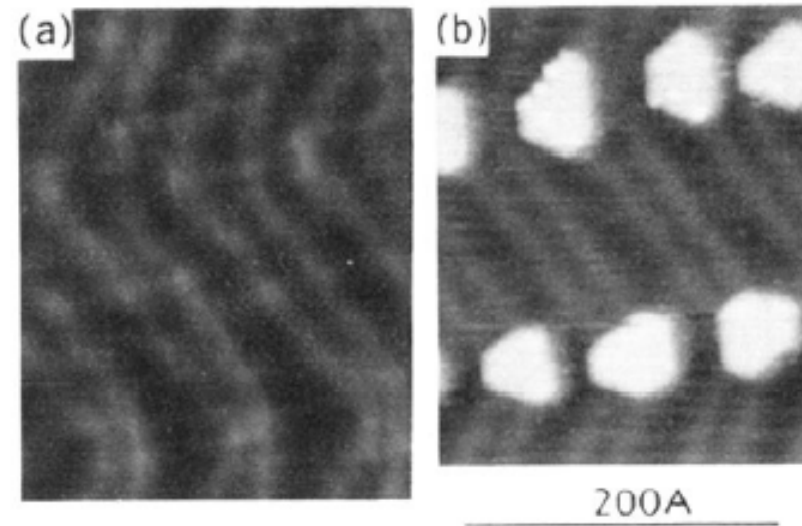
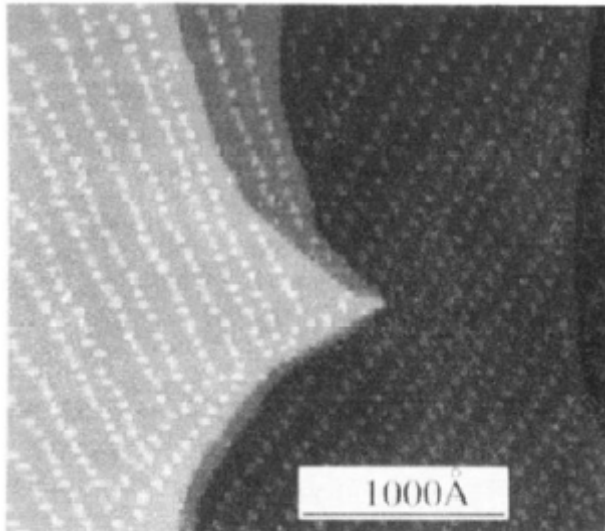
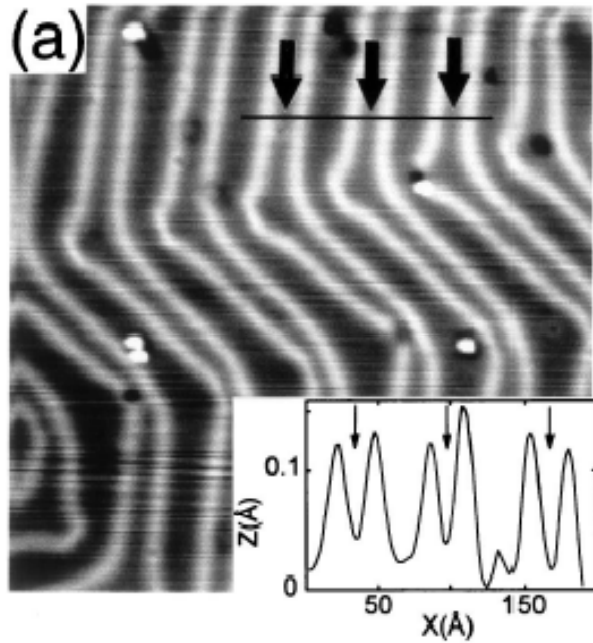
Phys. Rev. Lett. 65,
2418 (1990)



Melt-then-contact Mechanism

Self-Assembly

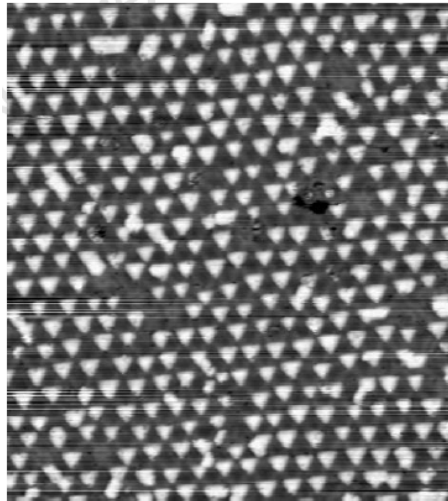
Ni cluster on reconstructed Au(111)



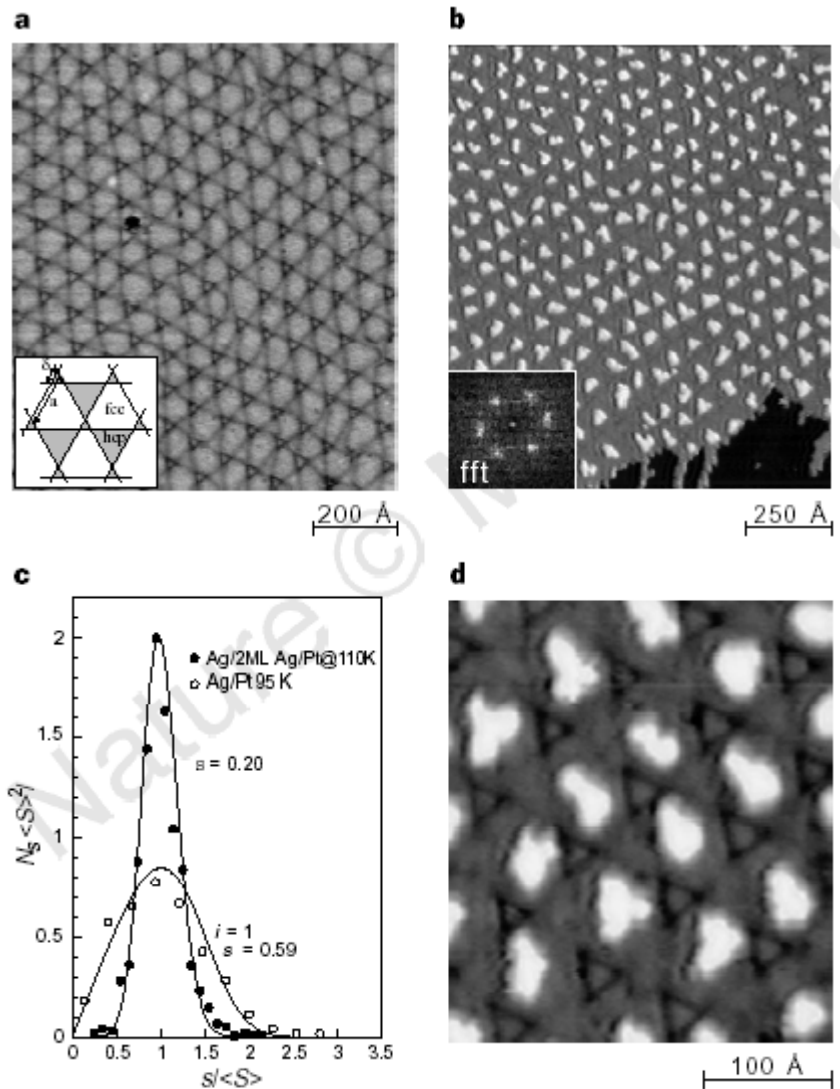
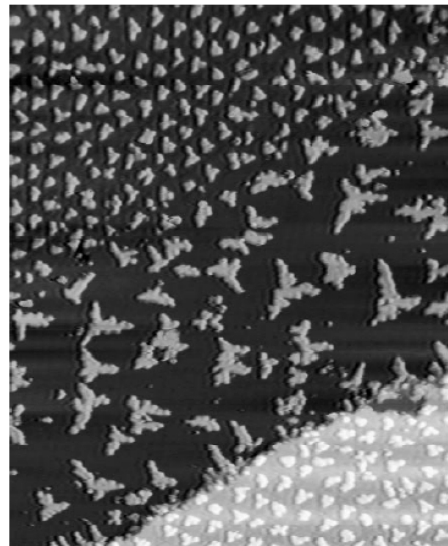
Phys. Rev. Lett. 66, 1721 (1991).

Self-organized growth of nanostructure arrays on strain-relief patterns

Fe islands/Cu/Pt(111)

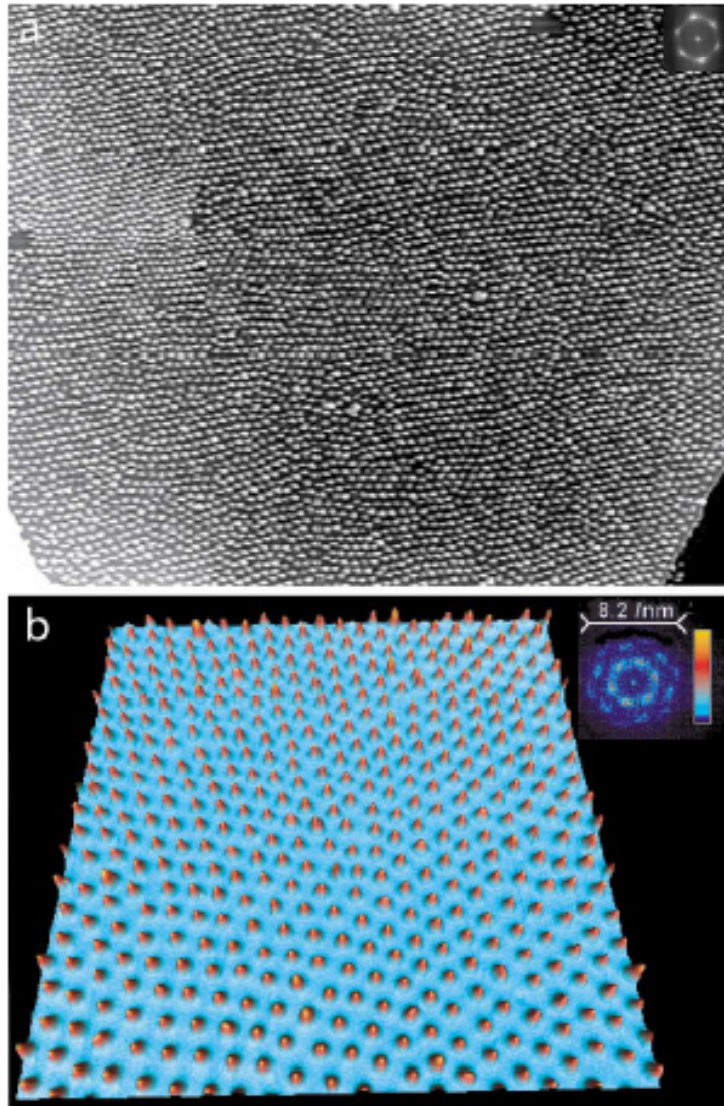


Ag island/Ag/Pt(111)



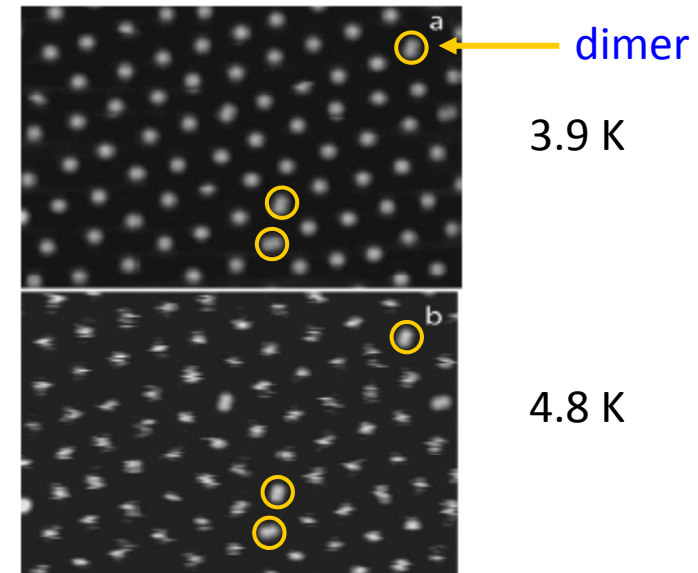
Nature 394, 451 (1998)

Ce atomic superlattice on Ag(111) at 3.9 K

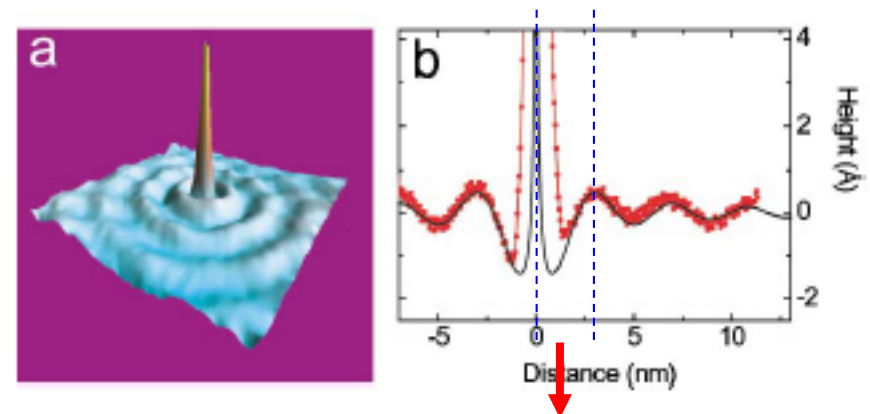


Lattice constant=32 Å

Ce: Cerium (鈰), 稀土族, 原子序:58



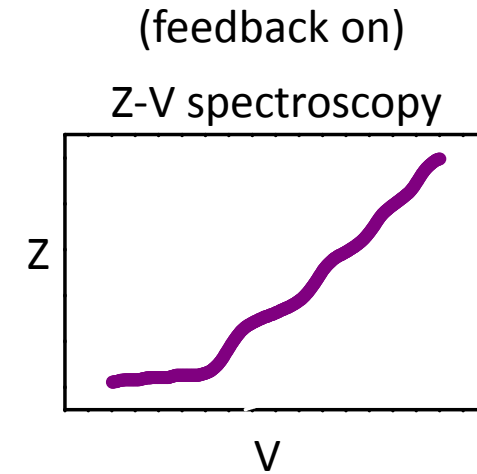
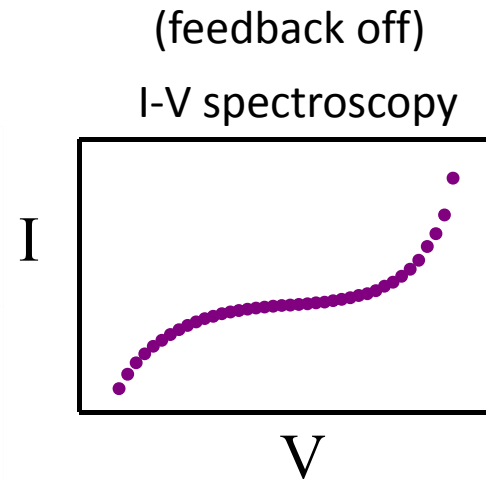
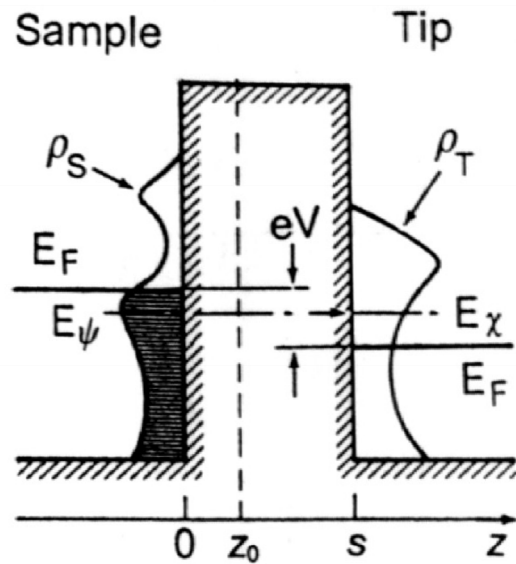
lattice disappear at 10 K



32 Å
Ce superlattice is created by standing wave formed around Ce atoms.

Phys. Rev. Lett. 92, 016101 (2004).

Scanning Tunneling Spectroscopy (STS)



$$I \propto \int_0^{eV} \rho_S(E_F - eV + \varepsilon) \rho_T(E_F + \varepsilon) d\varepsilon$$

ρ_T is constant

$$\Rightarrow dI/dV \propto \rho_S(E_F - eV)$$

Numerical differentiation

Lock-in technique

Lock-in technique

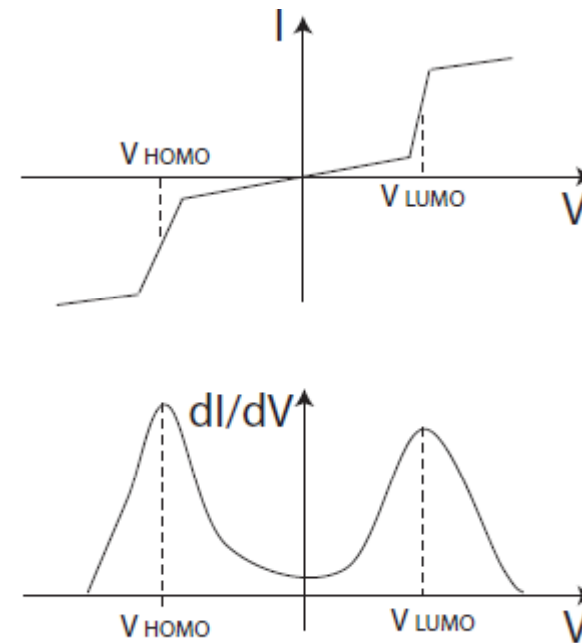
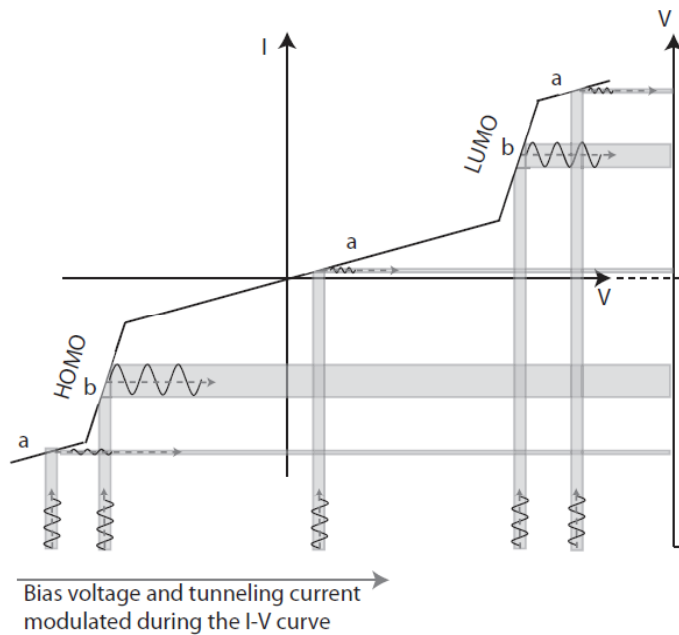
$$V_{\text{bias}} + V_{\text{mod}} \sin(\omega t) \quad \omega: 500-5000 \text{ Hz}$$

$$I(V_{\text{bias}} + V_{\text{mod}} \sin(\omega t)) \sim I(V_{\text{bias}}) + \frac{dI(V_{\text{bias}})}{dV} \cdot V_{\text{mod}} \sin(\omega t)$$

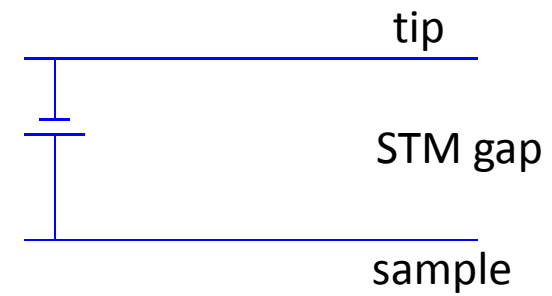
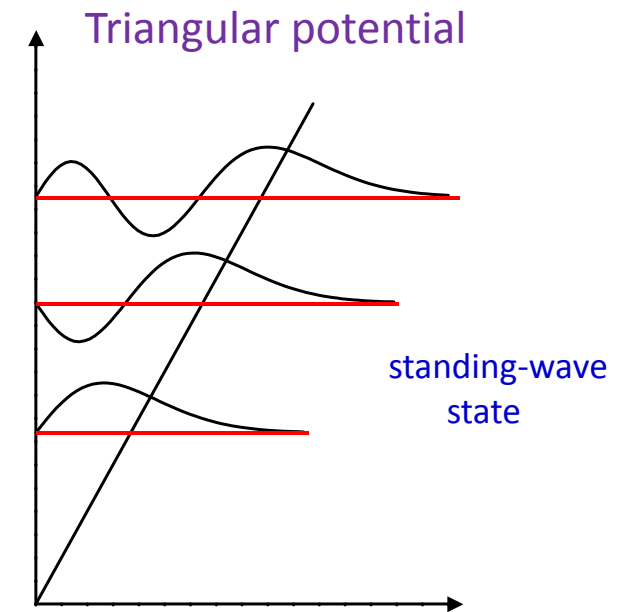
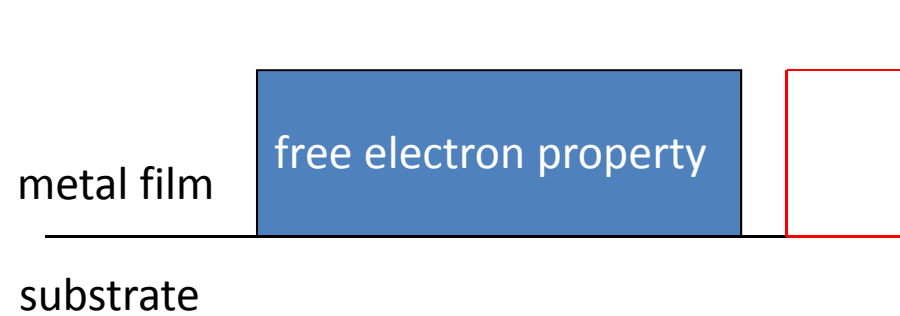
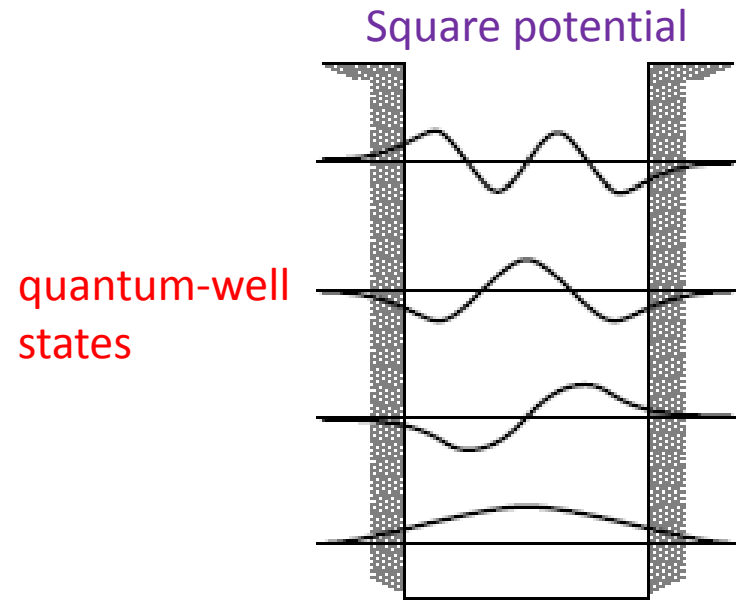
modulation of current

detected by

lock in amplifier

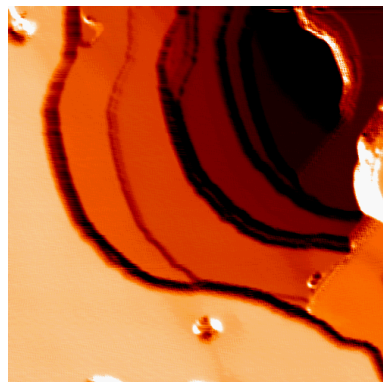


Quantum Confinement Effect

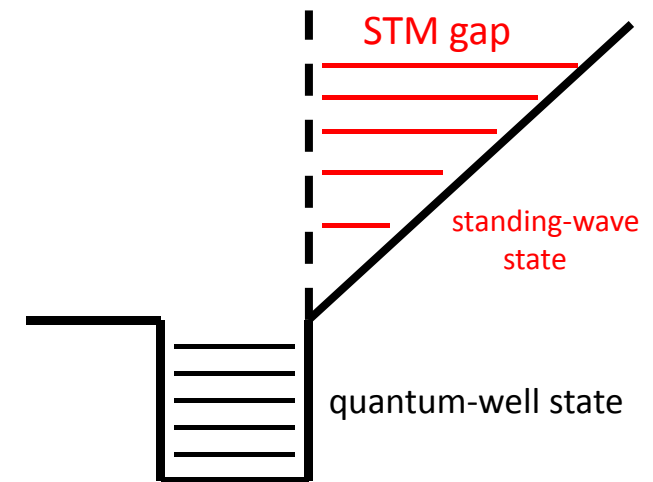
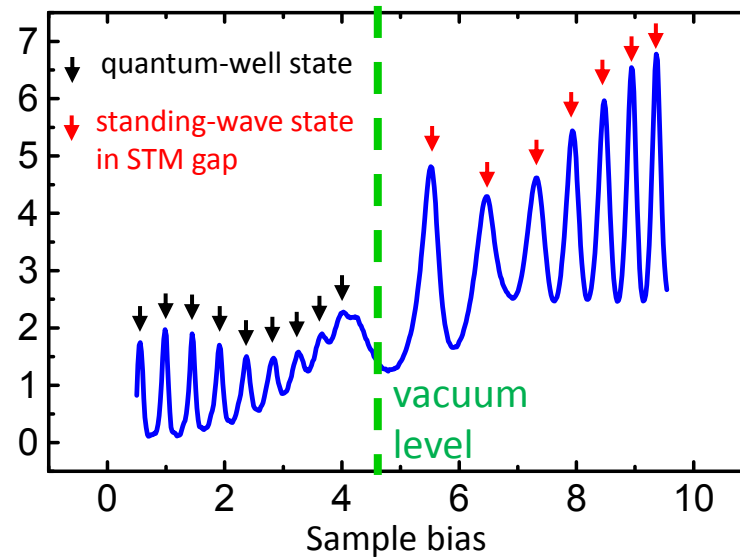


Visualization of quantum confinement effect by STS

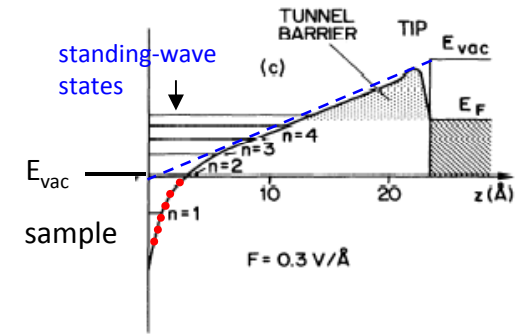
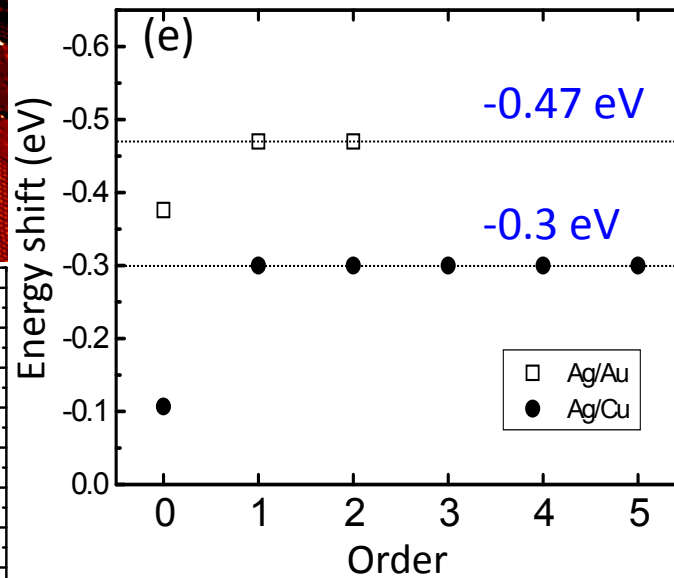
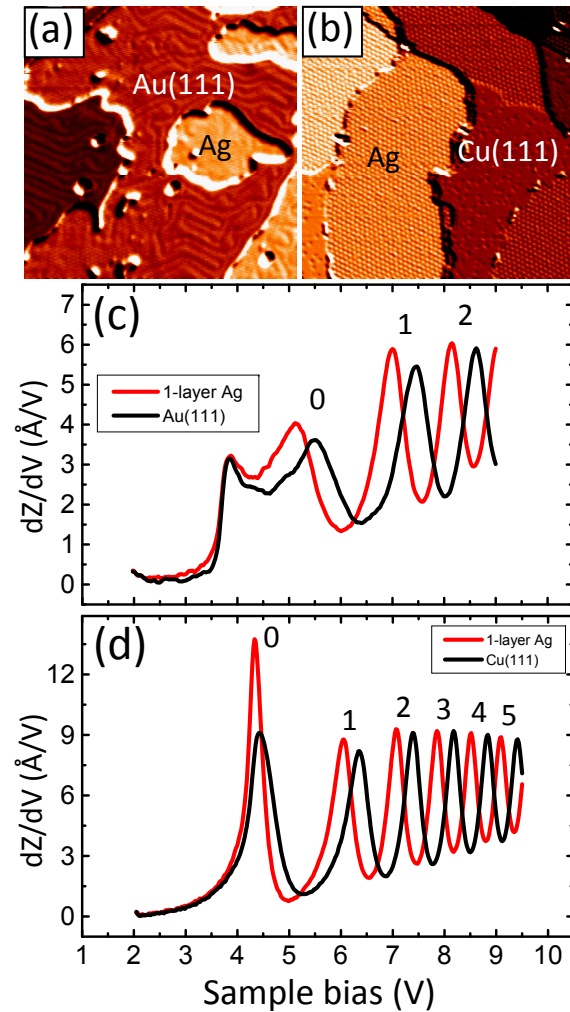
Pb/Cu(111)



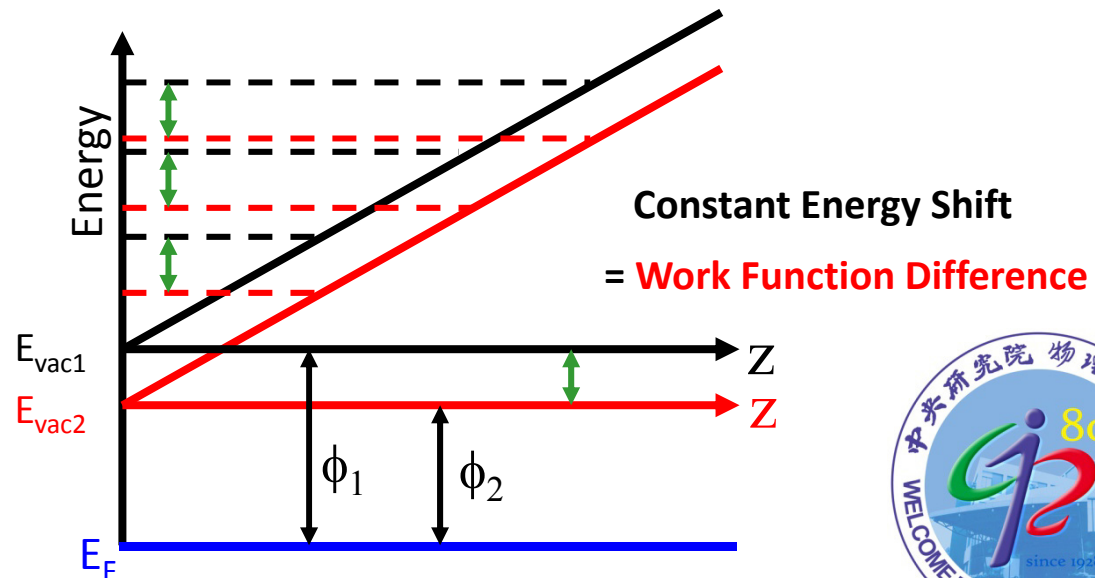
dz/dV - V spectrum



Application of standing-wave state in STM gap on work function measurement of thin metallic film

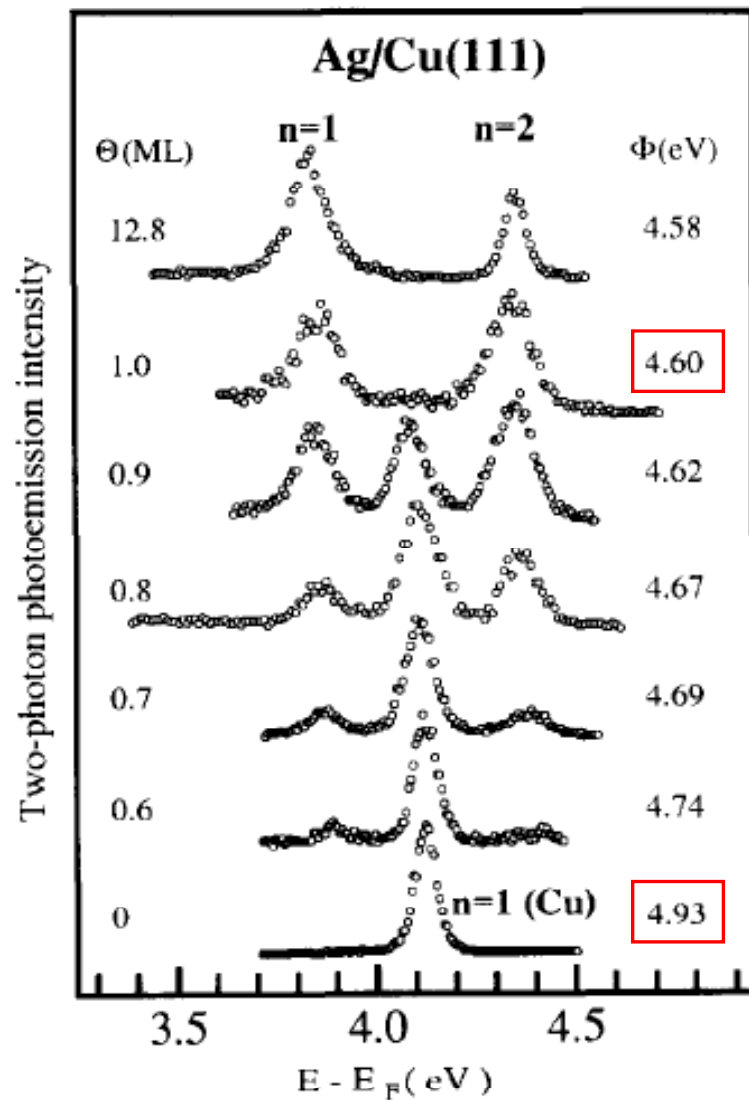


Superposition of image potential and applied potential

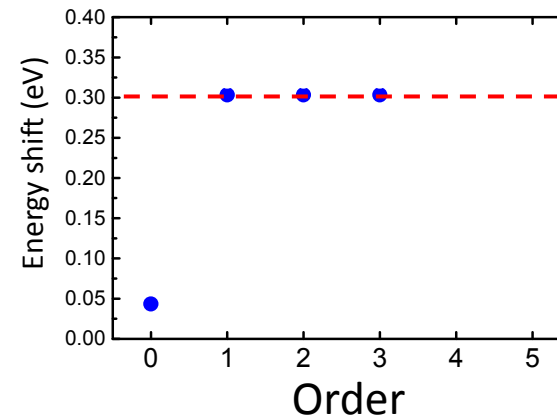
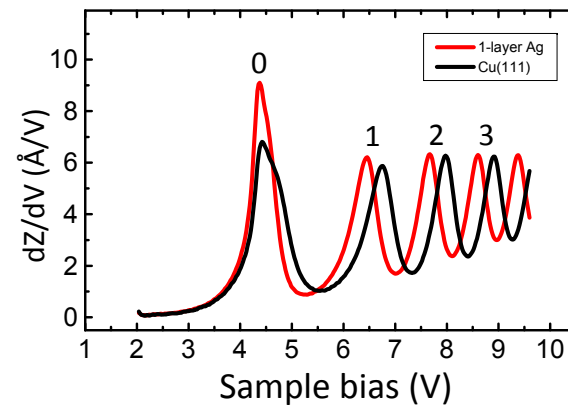


Phys. Rev. Lett. 99, 216103 (2007)

Photoemission (-0.33 eV)



Standing-wave states (-0.3 eV)



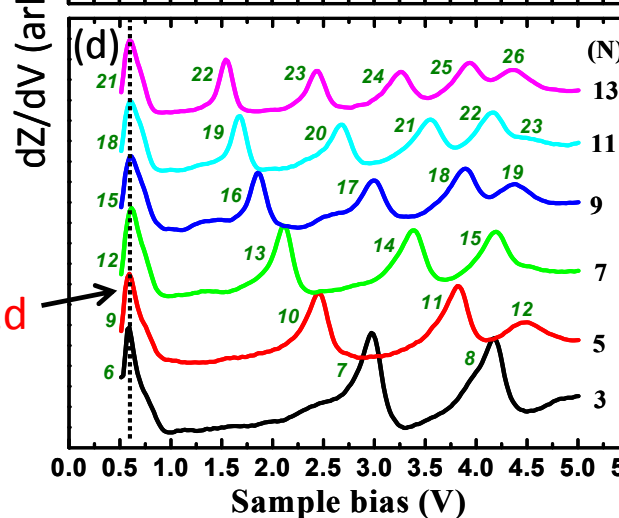
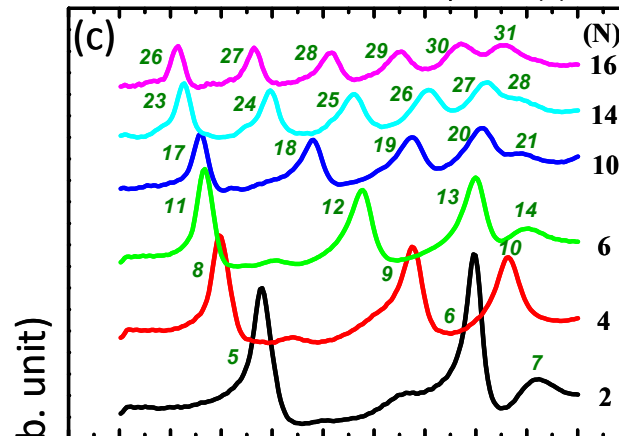
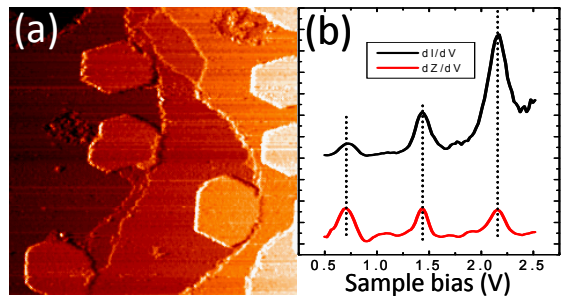
Both techniques are consistent.

Precision can be better than 20 meV.

Wallauer et al., Surf. Sci 331, 731 (1995)

Influence of image potential in vacuum on empty quantum well states

Pb island/Cu(111)



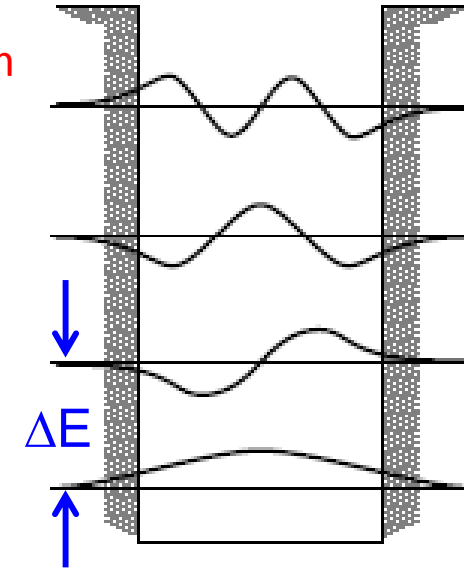
thickness

quantum number

$$2k(N+1)d = 2n\pi$$

wave vector

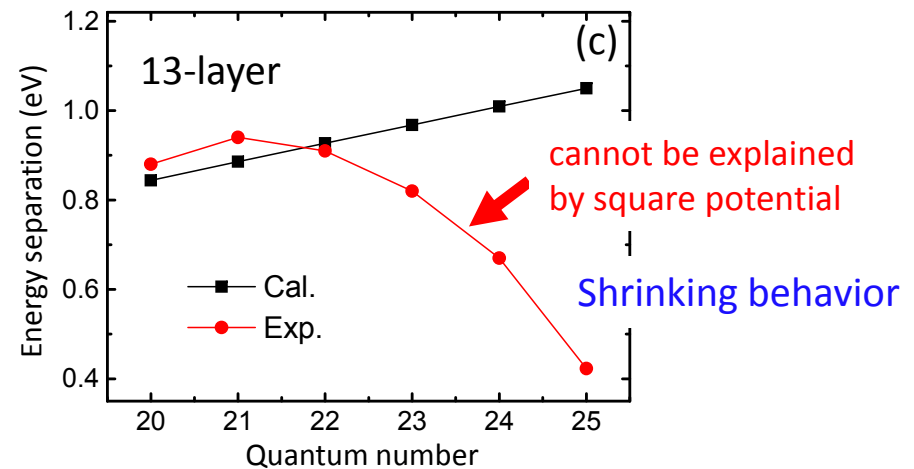
Interlayer spacing



$$\Delta E = \hbar^2(2n+1)\pi^2/2m^*(N+1)^2d^2$$

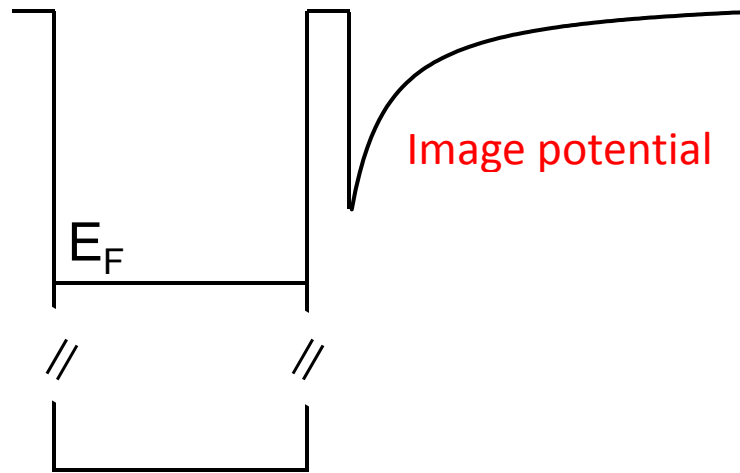
even

odd



Phys. Rev. Lett. 102, 196102 (2009)

Phase contribution of image potential on empty quantum well States



For simple square well:

$$2k(N+1)d = 2n\pi$$

Including phase ϕ_B contributed from image potential

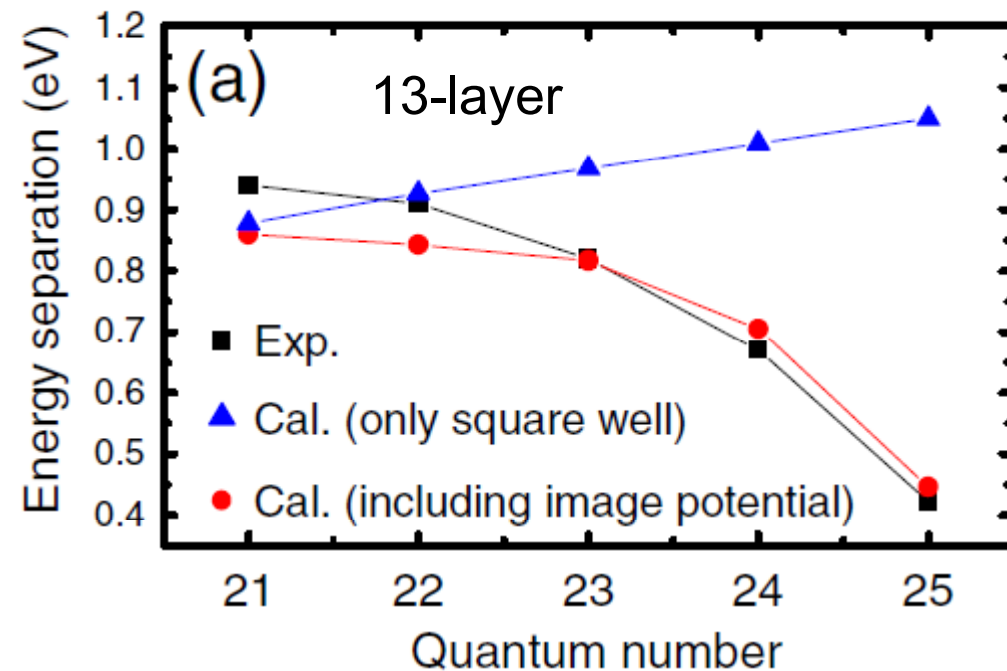
$$2k(N+1)d + \phi_B = 2n\pi$$

$$\phi_B / \pi = [3.4 \text{ eV} / (E_V - E)]^{1/2} - 1$$

Echenique et al.
J. Phys. C 11, 2065 (1978).

E: energy of quantum well state

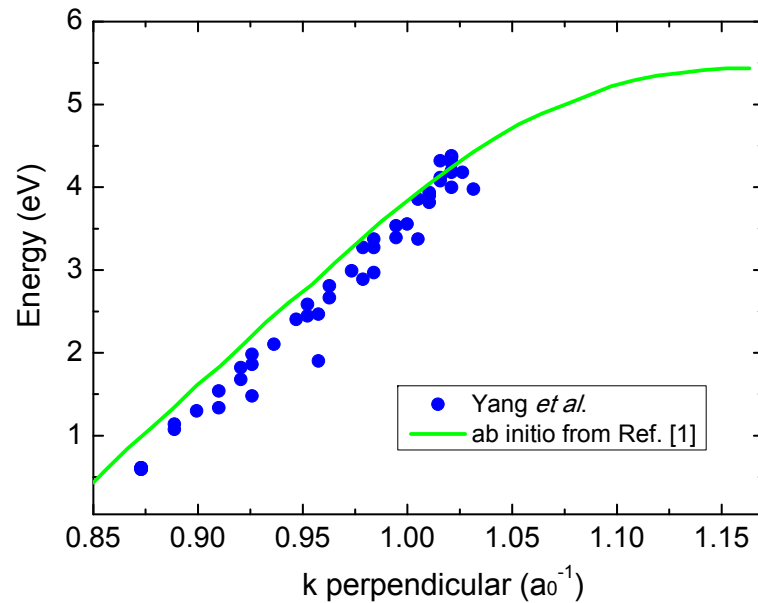
E_V : vacuum level



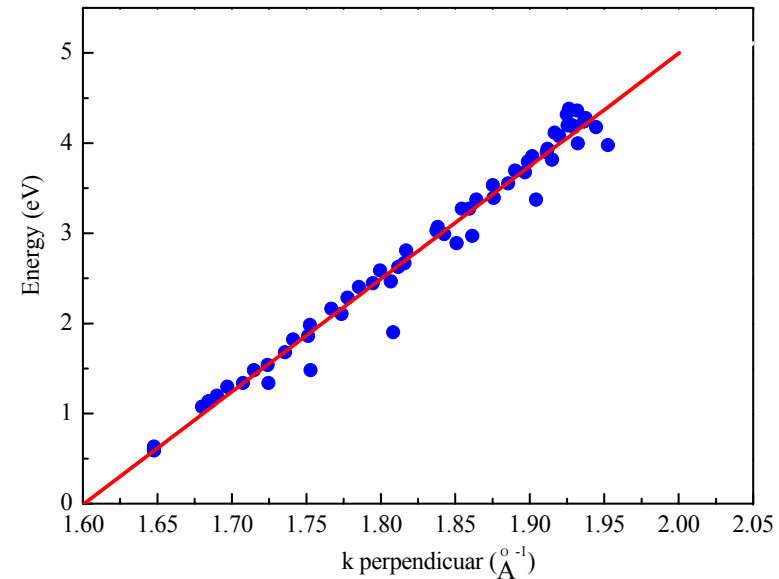
Pb band structure along Γ -L direction: detect with quantum-well states

$$2k(N+1)d + \phi_B = 2n\pi$$

$$\phi_B/\pi = [3.4 \text{ eV}/(E_V - E)]^{1/2} - 1$$



Phys. Rev. Lett. 106, 249602 (2011)



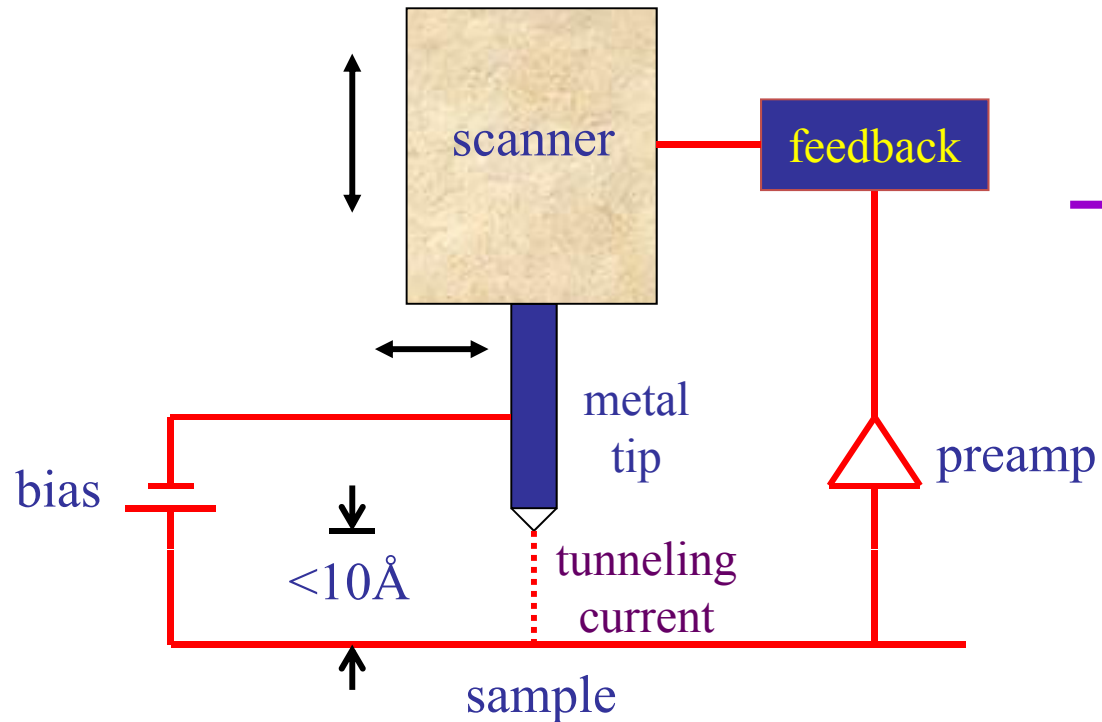
$$k_F = 1.6 \text{ \AA}^{-1}$$

angle-resolved photoemission
spectroscopy, $k_F = 1.598 \text{ \AA}^{-1}$ (bulk)

Scanning Probe Microscopy

Scanning Tunneling Microscopy (STM)

Gerd Binnig, Heinrich Rohrer
1986 Nobel Prize in Physics



Detecting the interaction
between probe and sample:

Atomic force (AFM)
Magnetic force (MFM)
Electrostatic force (EFM)
Near field optics (NSOM)
⋮