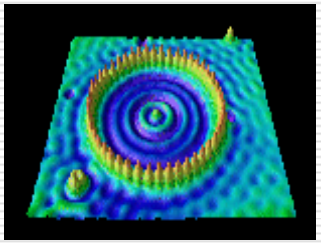
Scanning Tunneling Microscopy



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Advanced Solid State Physics II

April 16, 2009

Outline

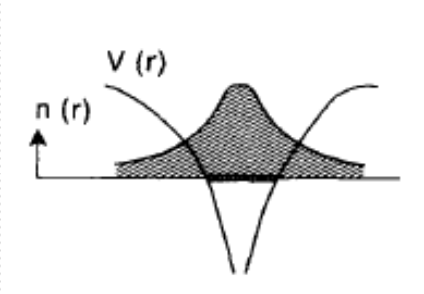
- Introduction
- Theory of STM
- Working principle
  - Modes of operation
  - Instrument
- Application

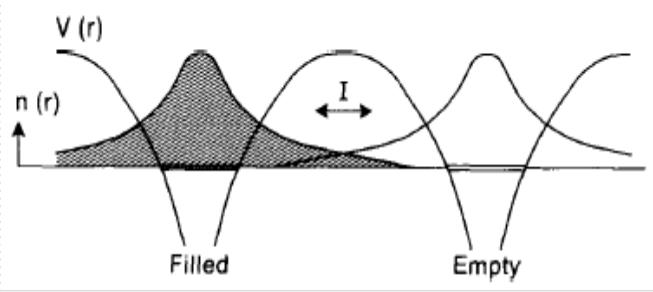
Scanning Tunneling Microscopy

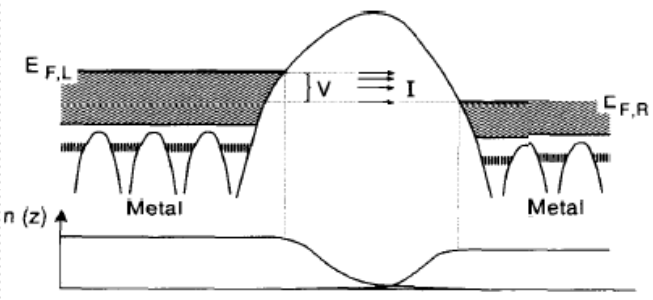
- First developed in 1981 by Gerd Binnig and Heinrich Rohrer. It won them the Nobel Prize in 1986.

The scanning tunneling microscope (STM) is a type of electron microscope that shows three-dimensional images of a sample

Tunneling current







- Tunneling into vacuum
- Electron Tunneling through potential barrier between Atom to Atom
- Electron tunneling in a metal

Tunneling current

1-dimensional , Schrödinger's equation:

$$-\frac{\hbar^2}{2m}\frac{\partial^2\psi_n(z)}{\partial z^2}+U(z)\psi_n(z)=E\psi_n(z)$$

If an electron of energy *E* is incident upon an energy barrier of height *U*(*z*), Inside a barrier, such as between tip and sample, *E* < *U*(*z*)

$$\psi_n(z)=\psi_n(0)e^{\pm\kappa z}$$

$$\kappa=\frac{\sqrt{2m(U-E)}}{\hbar}$$

Tunneling current

Assume the bias is *V* and the barrier width is *W.* The probability, *P*, that an electron at *z*=0 (left edge of barrier) can be found at *z*=*W* (right edge of barrier) is proportional to the wave function squared.

$$P \propto |\psi_n(0)|^2 e^{-2\kappa W}$$

Only electronic states very near the Fermi level are excited.

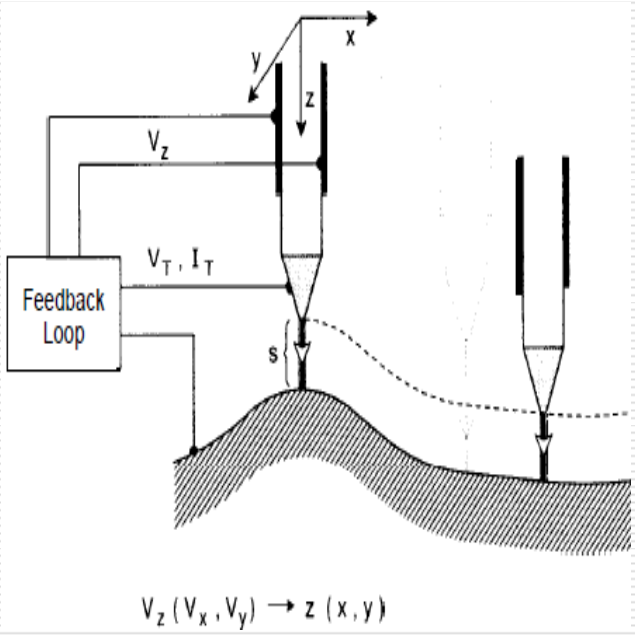
$$I \propto \sum_{E_f - eV}^{Ef} |\psi_n(0)|^2 e^{-2\kappa W}$$

The tunnel current is proportional to the local density of states(LDOS) near the Fermi level

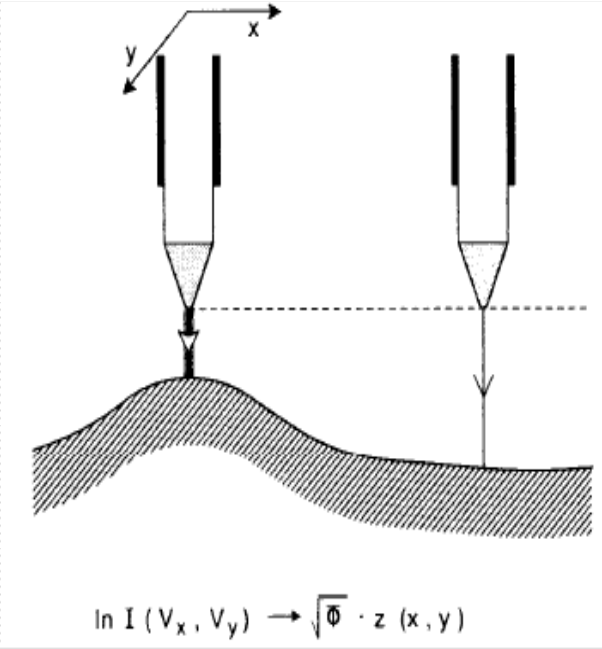
$$\rho_s(z, E) = \frac{1}{\epsilon} \sum_{E-\epsilon}^{E} |\psi_n(z)|^2,$$

$$I \propto V \rho_s(0, E_f) e^{-2\kappa W}$$

Modes of operation

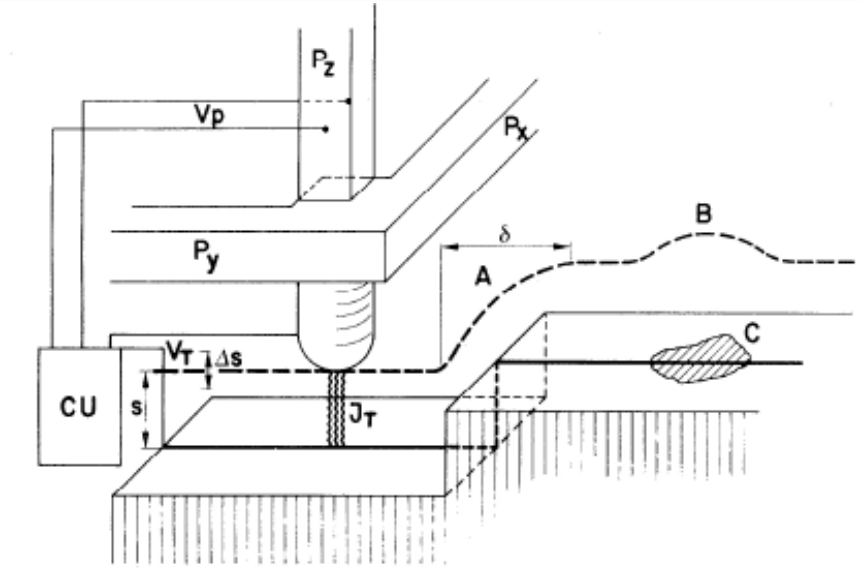


Tip is scanned across the surface at constant tunnel current, vertical tip position will be continuously changed to keep the tunnel current as a constant.



Change the current to make sure both the voltage and height are held as a constant

Instrument



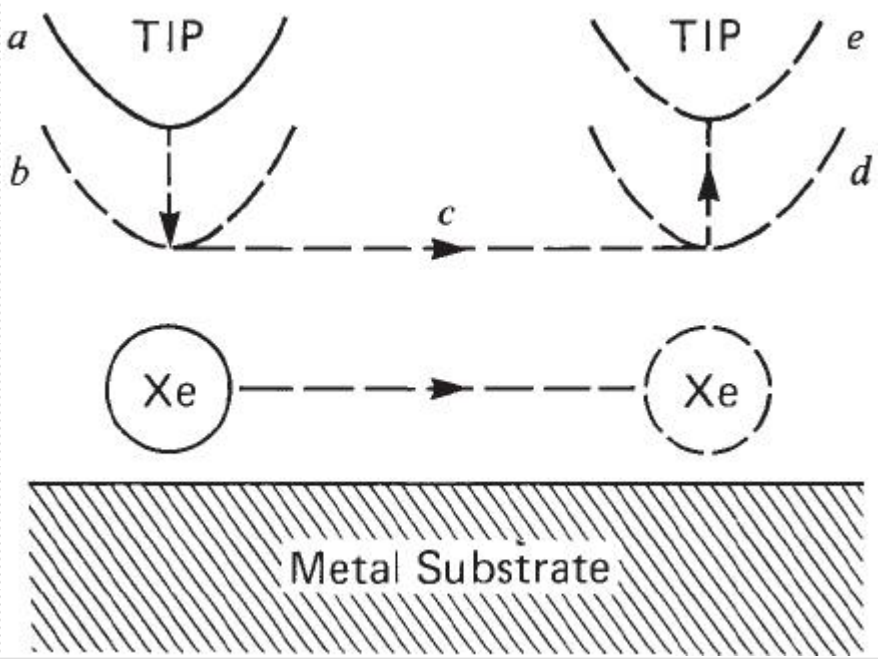
- Three frictionless x-y-z piezodrive control the movement of the tip
- A little change on the surface will lead a dramatic current change

$$I \propto \exp(-A\varphi^{\frac{1}{2}}w)$$

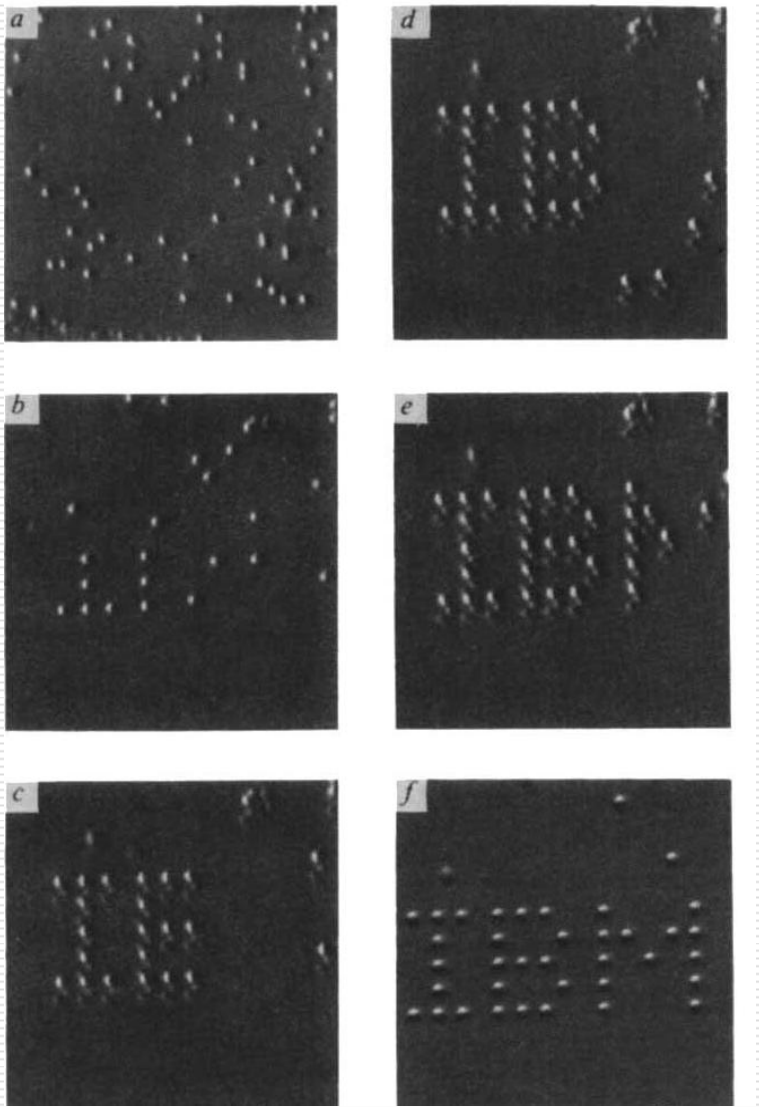
Application

- Positioning single atoms with a STM
- Fabricate metallic nanostructures on clean substrate
  - High-density information storage
  - High-resolution lithography
  - Nanoscale integrated chemical systems
  - Electronic devices

Positioning single atoms



- At low temperature, position individual xenon atoms on a single-crystal nickel surface
- The STM tip can pull an atom across a surface while the atom remains bound to the surface



Each letter is 50Å from top to bottom.

Positioning single atoms with a scanning tunnelling microscope

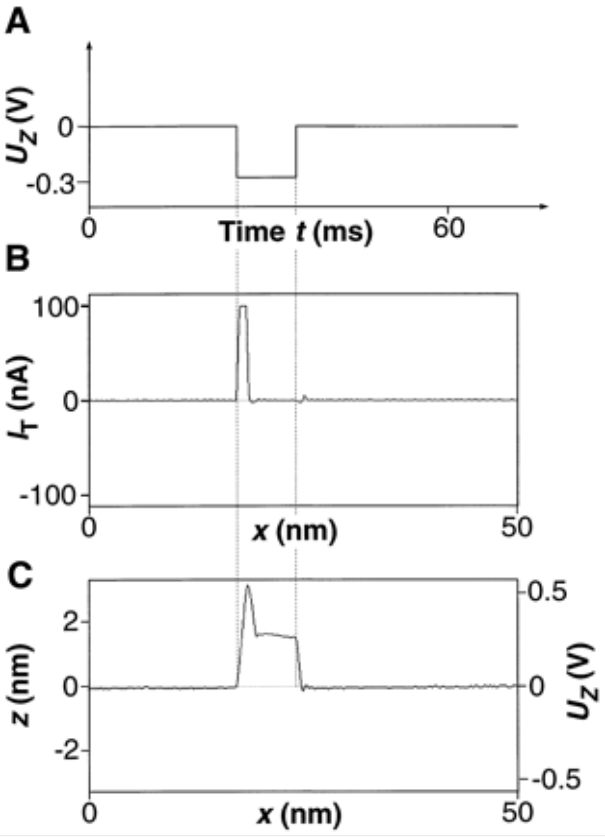
D. M. Eigler & E. K. Schweizer*

IBM Research Division, Almaden Research Center, 650 Harry Rd, San Jose, California 95120, USA

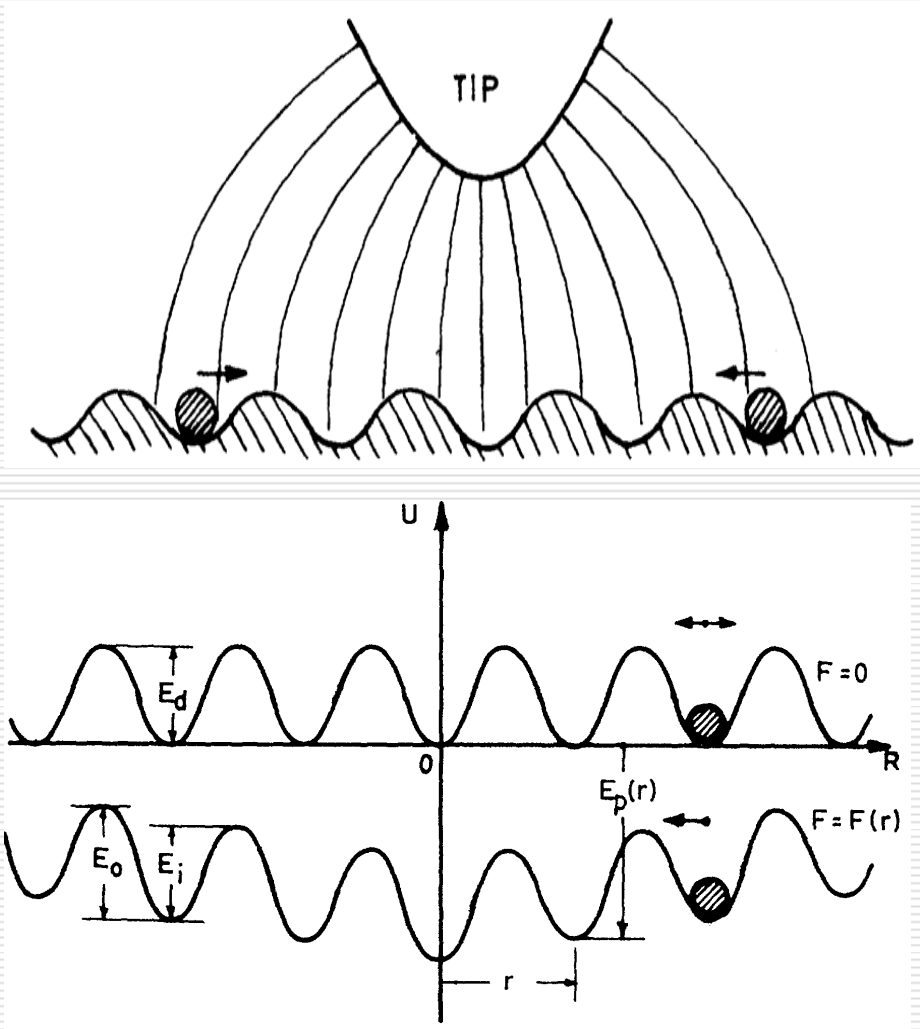
Fabricate nanodots on surface

- Z-piezo voltage pulse
- Process
- Mechanical of nanodots deposition
  - Field evaporation model
  - Mechanical point-contact model
    - I-z curve
    - Field-induced diffusion
    - Formation of a chemical bond

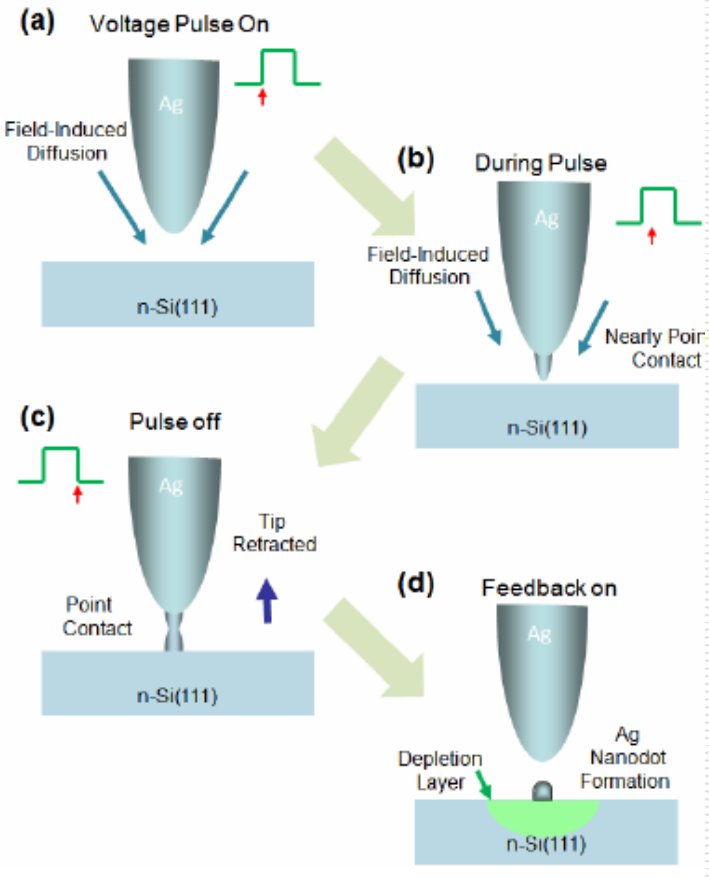
Z-piezo voltage pulse



- The imposition of an external voltage pulse *Uz* on the *z*-piezo Pulse duration was t = 10 ms
- Both tip height and the tunnel current will show simultaneous responses to this voltage pulse.
- After about 3 ms the feedback circuit causes the tip to retract in order that the tunneling current regain its predetermined value, (constant-current mode). The reverse step of the *z* pulse causes the STM tip to retract from the surface by 1.2 nm.

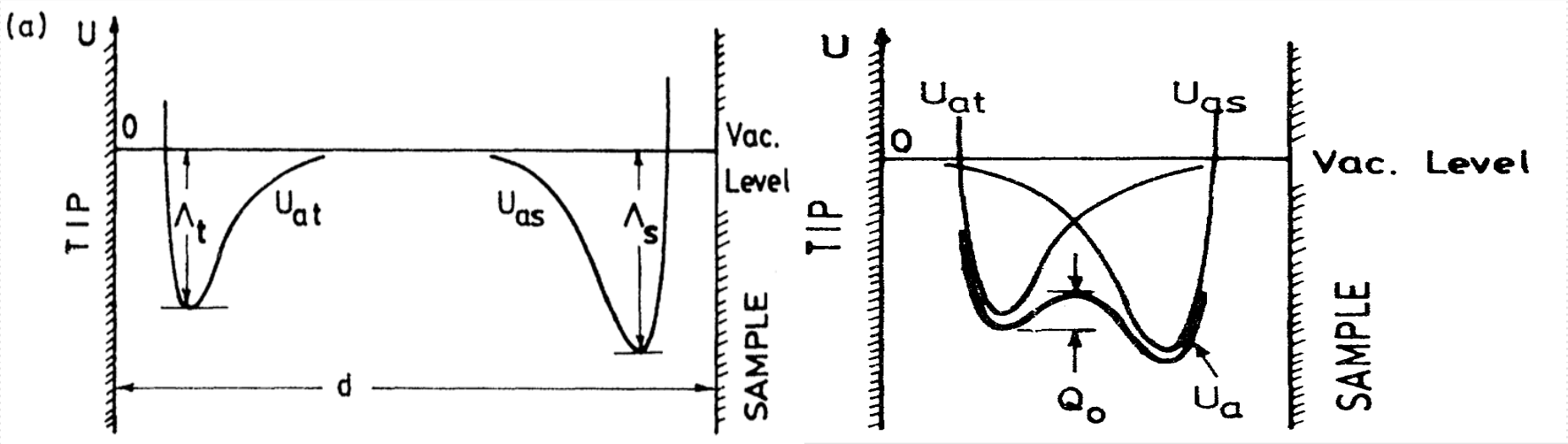


- Adsorbed atoms will always migrate toward the center where the field is the highest.
- In the absence of a high voltage pulse, surface potential is periodic, surface diffusion is in random directions.
- When a voltage pulse is applied due to the no uniformity of the field, the polarization energy is larger near the tip because of the higher field, the surface potential is inclined toward the center, migration of adatoms is always toward the center.



- Tip is stay at a certain height
- Apply external voltage pulse on the z-piezo, STM tip approached the surface, atom on the apex of the tip will transfer to the sample surface , the nanodot is formed
- Feedback circuit causes the tip to retract in order that the tunneling current regains its predetermined value.

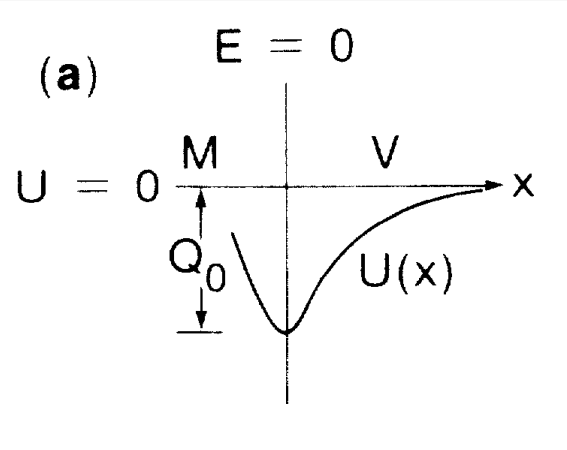
Field evaporation model



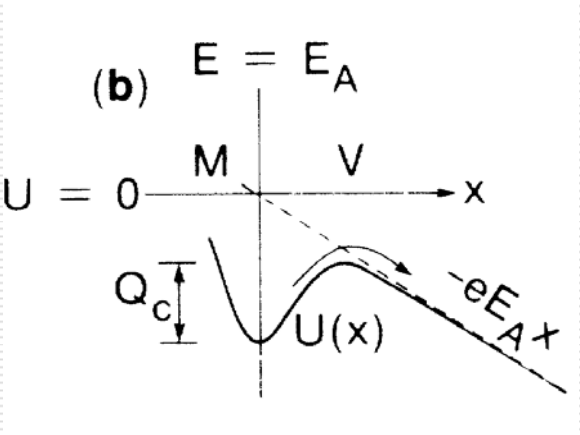
When the distance between tip and sample is large, the atom-tip and atom-sample interaction Uat and Uas don't overlap

When distance is small, the two start to overlap, there will form a small activation barrier. Atom can transfer between the tip and sample

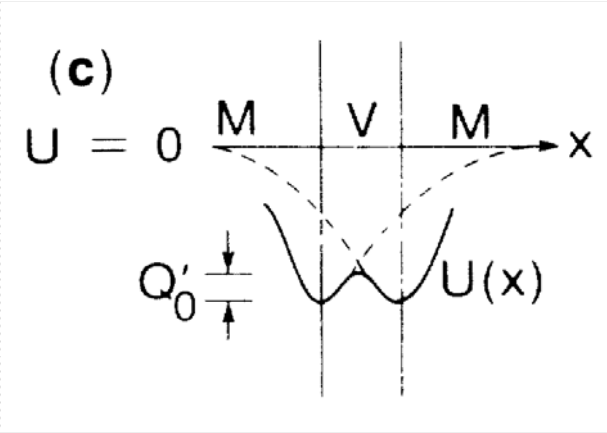
Energy diagrams---an ion at a metal-vacuum interface



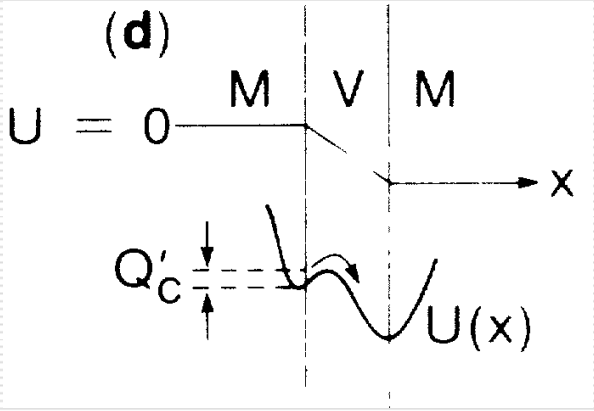
Single metal vacuum interface with no applied field



Interface with applied field, the ion can lower its energy by leaving the metal

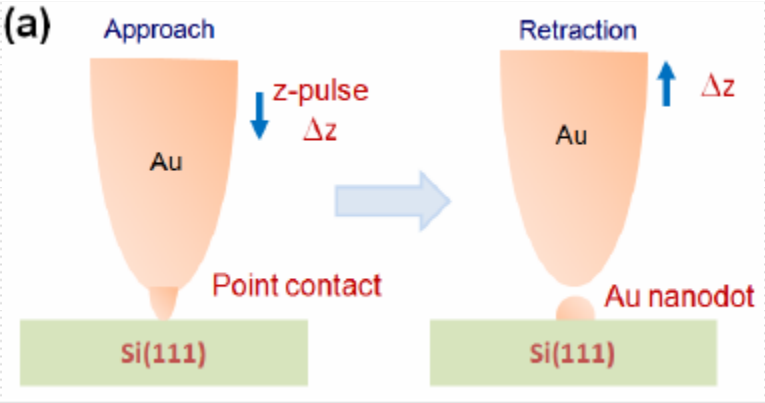


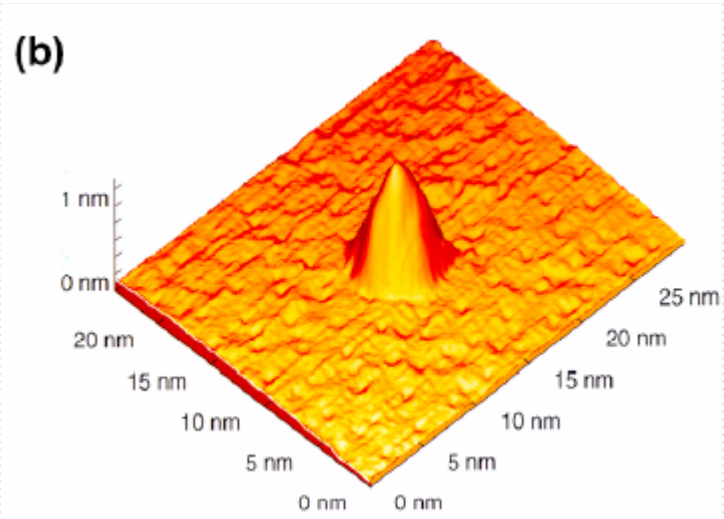
Metal-vacuum-matal structure with two like metals and no applied field



With applied field, Qc reduced

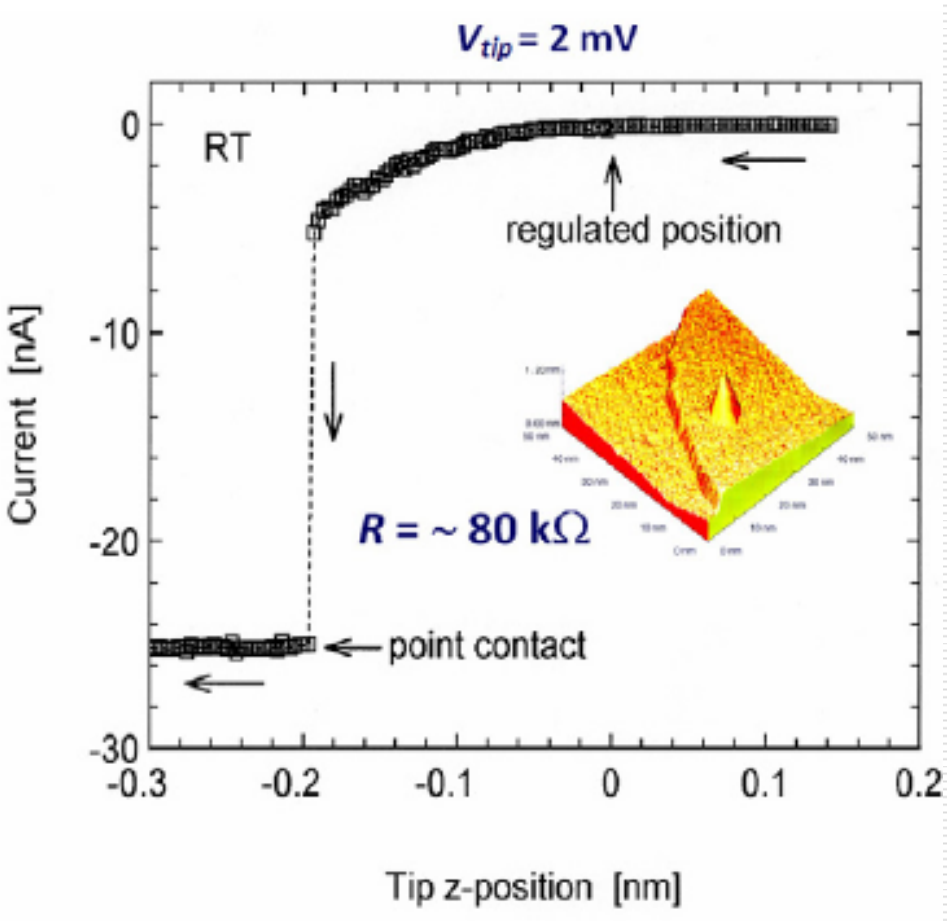
Spontaneous point-contact formation





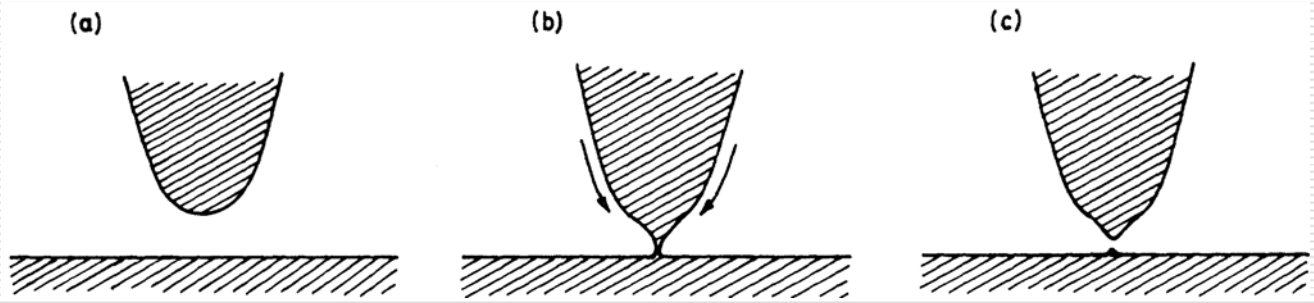
- (a)Schematic representation of tip-material transfer from a gold tip to a Si(111) surface by the spontaneous formation of a point contact
- (b) STM image of a gold nanodot formed on a Si(111)

I-z curve



- At first the observed current showed an exponential increase because the tip was still in the tunneling Regime
- At approximately −0.2 nm closer to the surface than the regulated position, the current suddenly jumped to a much higher value, the current was almost constant up to−0.3 nm
- This discrete change in current clearly suggests the formation of a point contact between the gold tip and the Si(111) surface

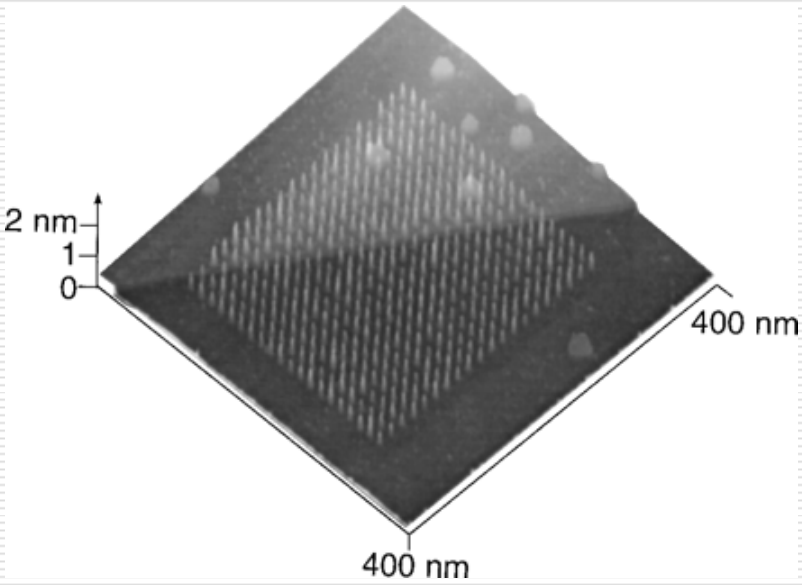
Field-induced diffusion



- A high voltage pulse is applied, field electrons are emitted either from the tip or the sample according to the polarity of the pulse.
- The electron current will heat up or even melt the tip. Because of the field gradient existing at the tip surface, atoms will migrate from the tip shank to the tip apex either by a directional surface diffusion or by a hydrodynamic flow of atoms, it will form a liquidlike-metal cone and touch the sample.
- When the pulse is over and the liquidlike-metal cone cools down, the neck is broken by surface tension leaving a mount of tip atoms on the sample surface

Formation of a chemical bond

- The Si(111) surface contains lots of adatoms, those adatoms have dangling bonds protruding into the vacuum.
- When the gap distance is become very small, the dangling bonds will extracting the tip.
- Nanoscale dot will left on the surface of the silicon because the chemical bonding between the atoms
- After this, the feedback circuit causes the tip to retract in order that the tunneling current regains its predetermined value



- 20*20=400 single Cu clusters array which is fabricated on an area 245 nm by 275 nm , the time of this fabricate is less than 90 s

In the near future the STM:

- will help computer designers as they shrink the features on integrated circuits.
- will yield scientific insights into the behavior of very small structures.
- will pave the way for circuits made from atomic or molecular components.
- could lead to smaller, faster, lower-power and even more portable computers.

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