M5052-Characterization of Materials and Nanomaterials

Graduate Program in Nanotechnology

Scanning Probe Microscopy 1

Scanning Tunneling Microscopy

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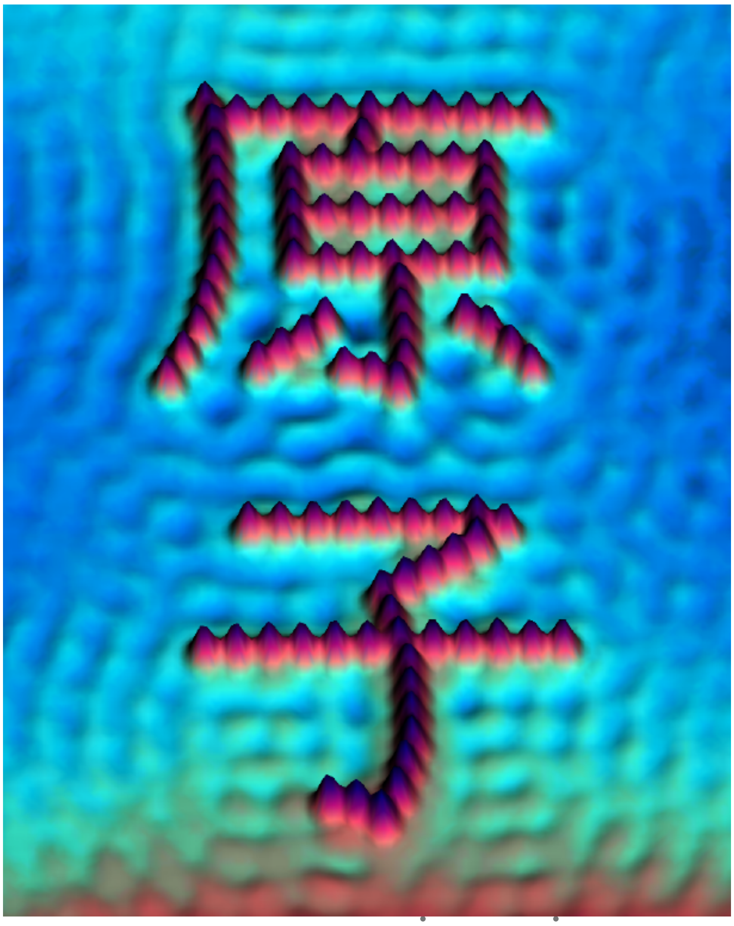

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Resolutions of Different Microscopies

- This figure from 1982 shows how different microscopy techniques are suitable for different observation scales
- Conventional Optical microscopy is quite limited compared to scanning probe and electron microscopies
  - *In the three decades since then, advanced optical microscopy techniques have broken the resolution limit shown here*

Image taken from: Roland Wiesendanger (Ed.) Scanning Probe Microscopy and Spectroscopy : Methods and Applications, Cambridge University Press, Cambridge, (1994).

84 *Scanning tunneling microscopy (STM)*

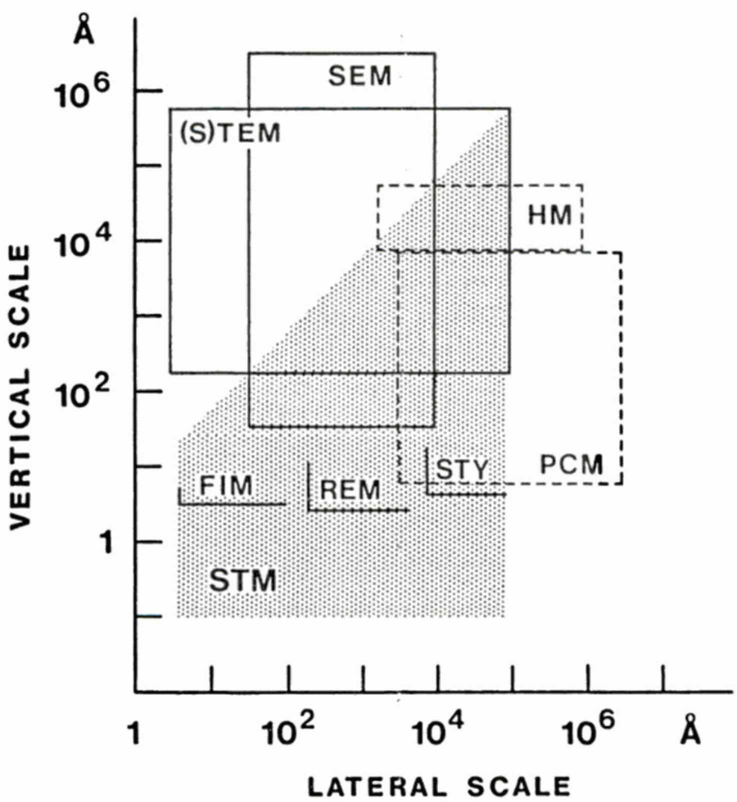
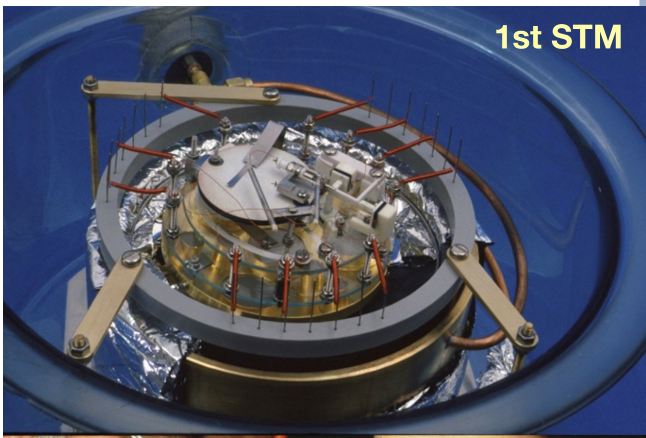
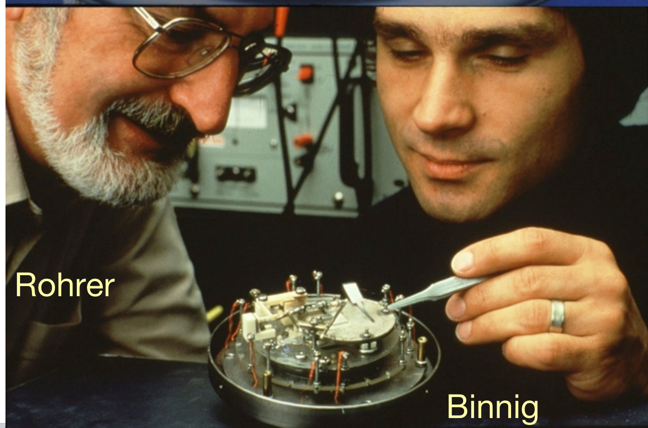


Fig. 1.43. Comparison of resolutions of different microscopes. STM: shaded area. HM: high-resolution optical microscope, PCM: phase-contrast microscope, (S)TEM: (scanning) transmission electron microscope, SEM: scanning electron microscope, REM: reflection electron microscope, and FIM: field ion microscope (Binnig and Rohrer, 1982).

Scanning Tunneling Microscopy Introduction

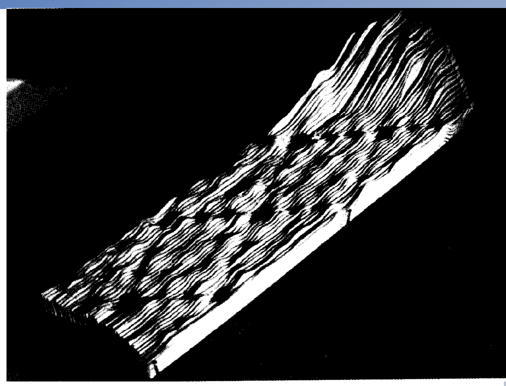
- Developed by Gerd Binnig & Heinrich Rohrer at IBM's Research Labs in Zurich
  - Development started in 1979
  - First experimental observation in March 1981
  - Observation of the (7x7) reconstruction of the atomic surface of Si(111) in the autumn of 1982
  - Nobel Prize in Physics in 1986
    - Shared with Ernst Ruska, inventor of TEM
- Scanning Tunneling Microscopy can achieve atomic resolution



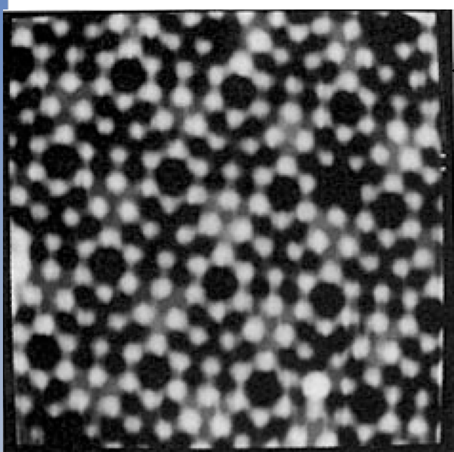


Si(111)-(7x7) Reconstruction

- First defining application of STM to surface science.
- Atomic structure of this reconstruction was unknown
  - In surface reconstructions when a material is provided enough energy surface atoms rearrange to reduce number of dangling bonds
  - STM evidence allowed to discard various models for this reconstruction
  - The right theoretical model was found in 1985

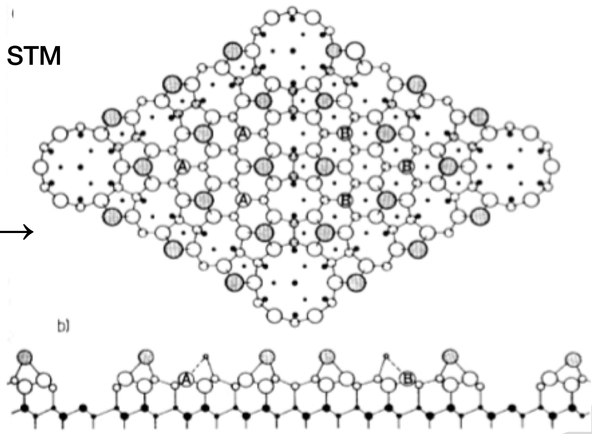


Relief model of original recorder traces of the STM, from: Gerd Binnig and Heinrich Rohrer "Scanning Tunneling Microscopy: From Birth to Adolescence" Nobel Lecture, December 8, 1986



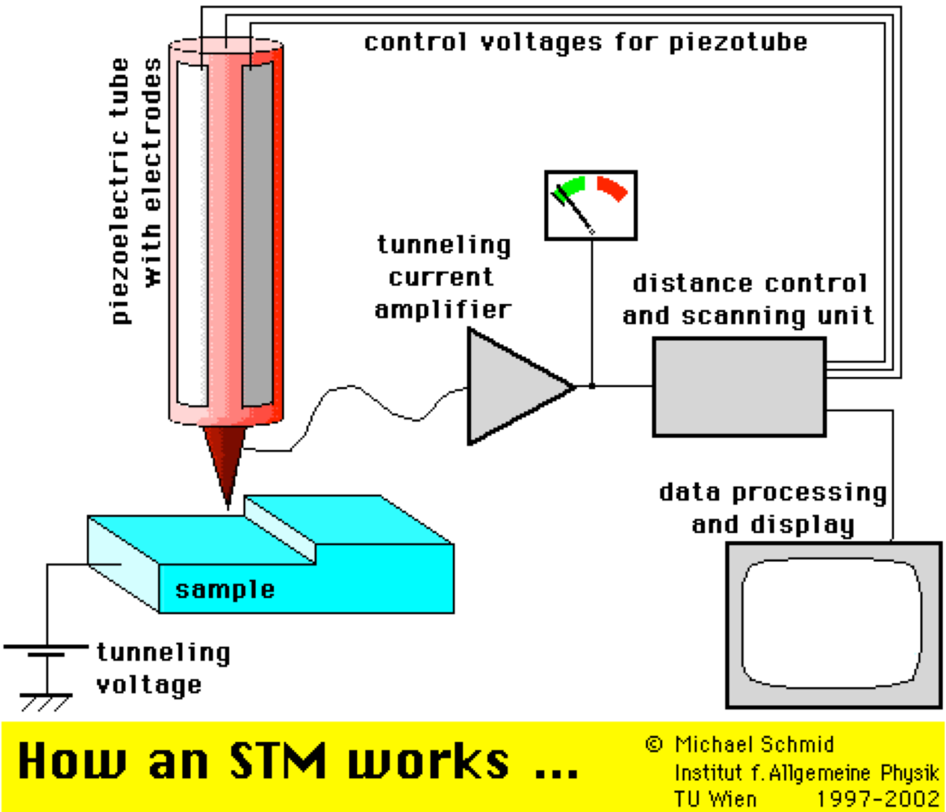
← High resolution STM

Atomic model →



STM

- Based in tunneling effect
  - Apply a potential difference between sample and probe (fine metallic tip)
  - Electrons “jump” between the two materials
    - Not an actual jump: the electron never exists in the gap between the two materials, it moves from one material directly to the other through quantum mechanical effects
  - Tunneling current is extremely sensible to distance between sample and probe, and to density of electronic states
- Capable of atomic resolution in real space
  - It is possible to characterize and control surface structures (natural or artificial) at the atomic scale
  - It allows to position the tip over a pre-selected atomic site and carry out a local experiment
    - Scanning Probe Spectroscopy: direct measurements of density of states
  - Capability of direct and controlled manipulation at the atomic level
    - Combining capabilities of surface structure characterization and positioning tip with atomic scale precision over specific surface sites
    - Offers the capability of atomic scale devices



Animated GIF image taken from http://www.iap.tuwien.ac.at/www/surface/stm_gallery/animated_stm

Tunneling through a Barrier

- An electron finds a potential energy barrier (U) higher than its kinetic energy
- Classical Physics: the electron (particle) can not go through the barrier, regions II and III are forbidden
- Modern Physics: there is a probability that the electron (particle-wave) may appear on the other side of the barrier
  - Electronic wave function extends through the barrier
    - But the electron cannot be found inside the barrier (region II forbidden)
  - Applications of tunnel effect:
    - Tunnel Effect Diodes
    - Alpha Decay
      - Gamow explained this radioactivity process in 1928 through tunneling effects
    - Scanning *Tunneling* Microscopy

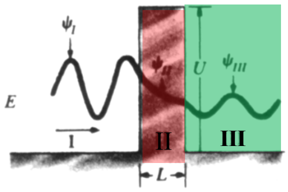


Figura 41.19 Función de onda para una partícula que incide desde la izquierda sobre una barrera de altura *U*. Nótese que la función de onda es senoidal en las regiones I y III pero decae exponencialmente en la región II.

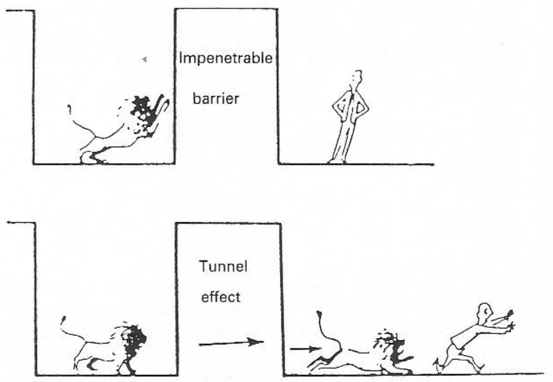
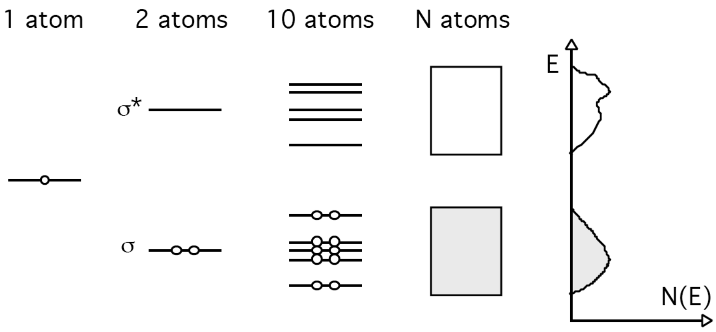
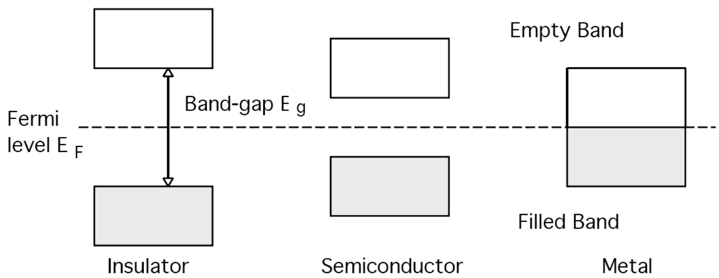


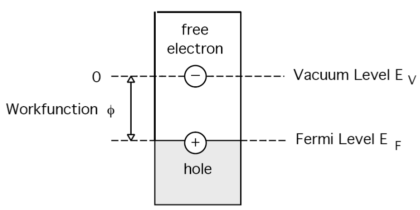
Fig. 1.1. The difference between classical theory and quantum theory, illustrating tunneling through a potential barrier (Bleaney, 1984).

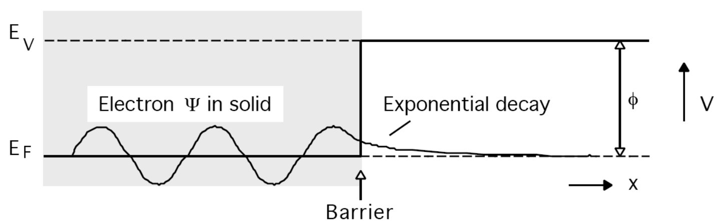
Tunneling and Electronic Structure of Solids

- In solids, electrons from molecular orbitals form energy bands
  - Bands can be separated by a gap
- Fermi level, E_F, marks separation between filled and empty bands
- Vacuum level energy, E_V, minimum energy that an electron needs to break free
- Work function: ϕ_W energy required to move an electron on the surface from E_F to E_V
  - ϕ_W is equivalent to an energy barrier
- **Density of States,** $N(E)$: number of levels with energy between E and $E + dE$



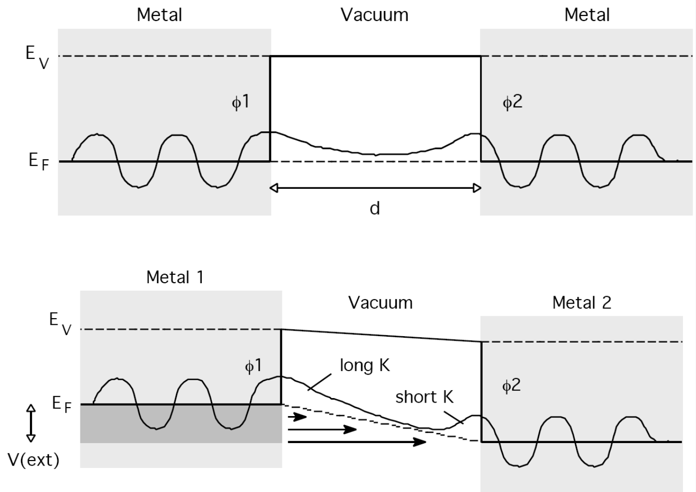




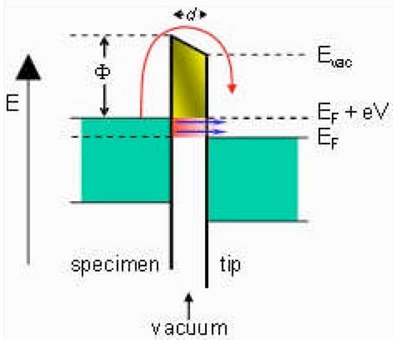


Tunneling Effect: STM

- Near the surface an electron behaves like a particle in a box
- Electron density decays exponentially away from the surface
- When two conductors are very close their wavefunctions overlap
  - On both sides electron fill bands up to the Fermi level
- If there is a voltage difference (V_{ext}) a current will flow between both metals



- Metal 1 with negative bias with respect to Metal 2:
  - Tunneling from filled states of M1 [with energy in the range of V_{ext} to empty states of M2 [with energy $E_{F,2} + eV$]
- Metal 1 at positive bias with respect to Metal 2:
  - Tunneling from filled states of M2 to empty states in M1
- Tunneling is sensitive to electronic structure
  - Convolution of density of filled states of M1 (-) and density of filled states of M2 (+)



Q. What Are Those Lines on the Edge of the Steps?

A. Electron Waves

- Imaging of electron waves can be acquired using STM at the highest resolution
  - Electron waves are the square of the wavefunction that represents the probability density
- Example: Copper (111)
  - Waves correspond to electrons reflected by the barrier formed by atomic steps
    - NOTE: scale of atomic steps largely exaggerated with respect to atom sizes in X-Y

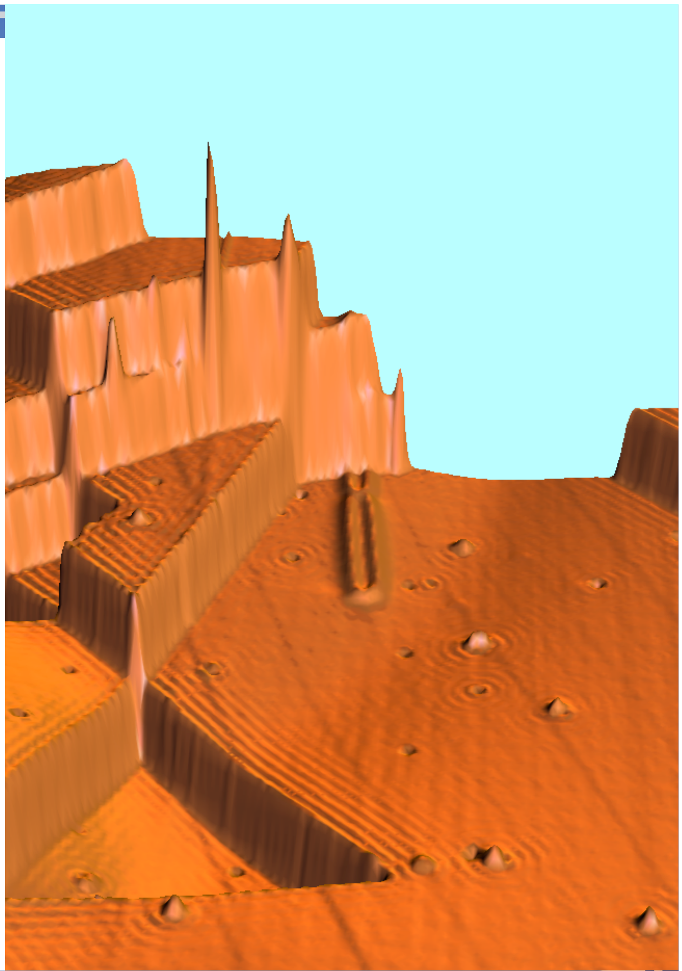
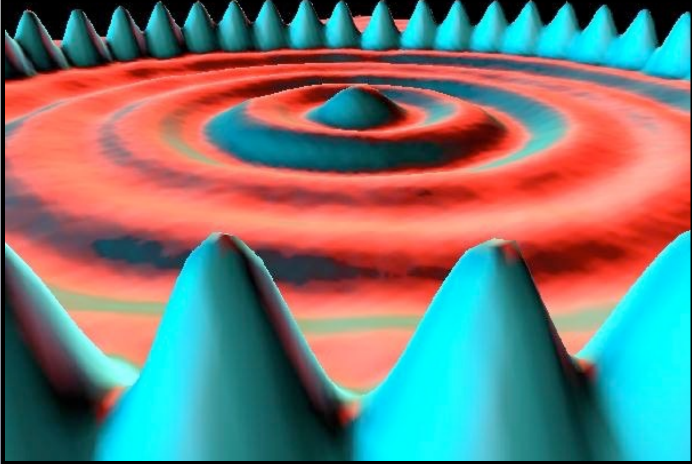
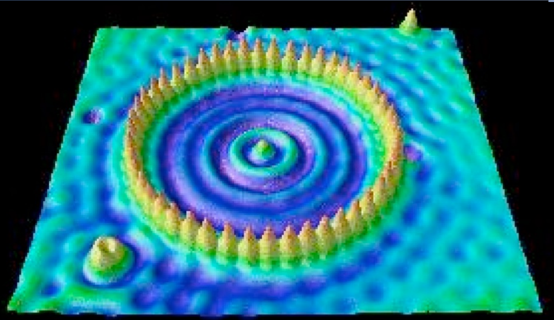
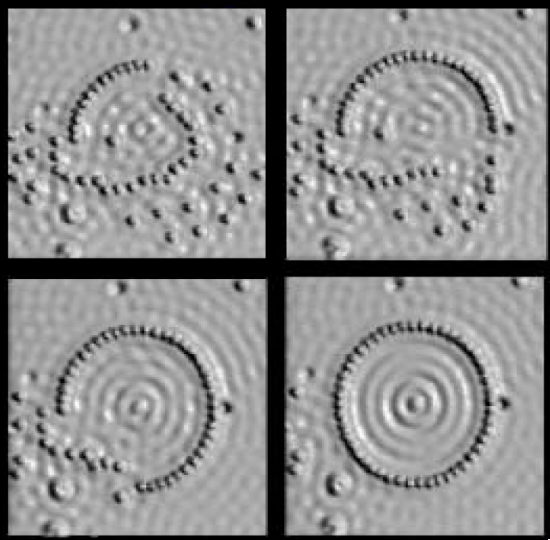


Image source: http://researcher.watson.ibm.com/researcher/view_project_subpage.php?id=4249

STM: Quantum Corral



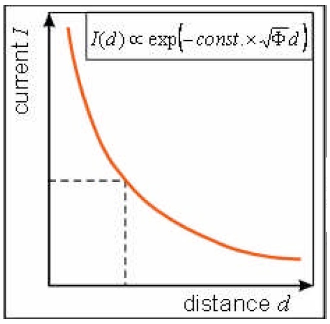




- Fe on Cu(111)
  - STM tip used to move Fe atoms
  - Stationary electron waves can be visualized inside the “quantum corral”

http://researcher.watson.ibm.com/researcher/view_project_subpage.php?id=4252

Tunneling Current

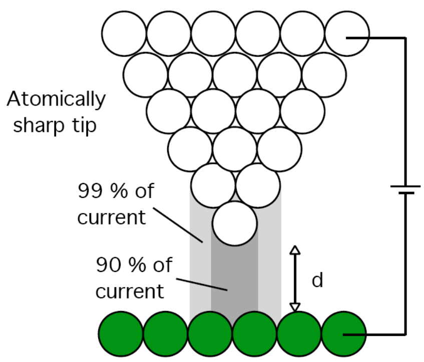


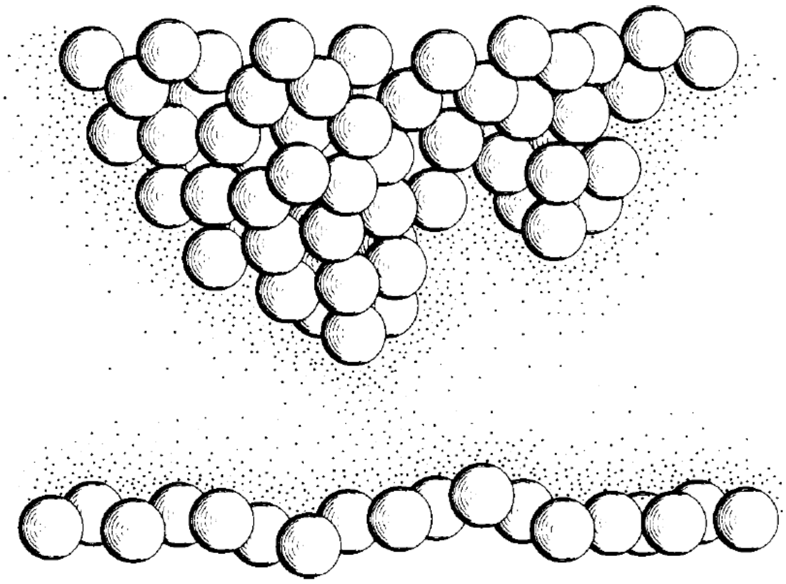
$$I_T \propto V e^{-Cd\sqrt{\phi}}$$

I_T = tunneling current
φ = work function
d = distance between tip and sample
V = voltage bias

$$C = 4\pi\sqrt{2m}/h = 10.25 eV^{-1/2} nm^{-1}$$

- Equation gives an approximation of tunneling current as a function of distance and the work function
- Strong exponential dependence of IT to distance between sample and tip
  - V only changes IT linearly
  - Relation satisfies Ohm’s Law (I α V)
- For a work function ϕ =4 (typical value for metals) tunneling current decreases by a factor of 10 with an increase of 0.1 nm in d
  - For a typical atomic diameter of 0.3 nm IT is reduced by a factor of 1000





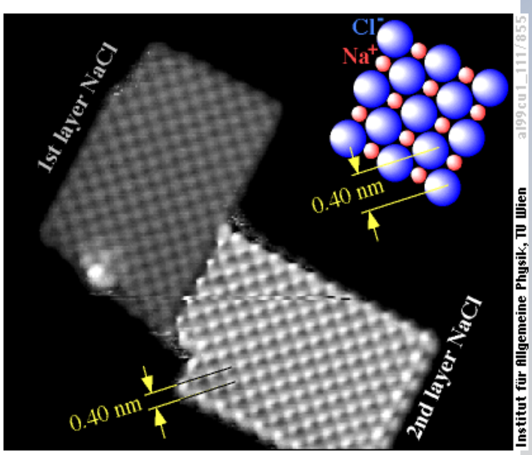
Due to the strong **exponential dependence** of **tunneling current** with **distance** even if STM tip doesn't end in a single atom ***most of the tunneling happens through one single atom***

Fig. 2. The principle. The tunneling transmittivity decreases exponentially with the tunneling distance, in vacuum about a factor 10 for every Å. In an oxide tunnel junction, most of the current flows through narrow channels of small electrode separation. With one electrode shaped into a tip, the current flows practically only from the front atoms of the tip, in the best case from a specific orbital of the apex atom. This gives a tunnel-current filament width and thus a lateral resolution of atomic dimensions. The second tip shown is recessed by about two atoms and carries about a million times less current.

Image from: Gerd Binnig and Heinrich Rohrer, "Scanning Tunneling Microscopy – From Birth to Adolescence" Nobel Lecture, December 8, 1986
http://www.nobelprize.org/nobel_prizes/physics/laureates/1986/binnig-lecture.html

Some Operational Aspects of STM

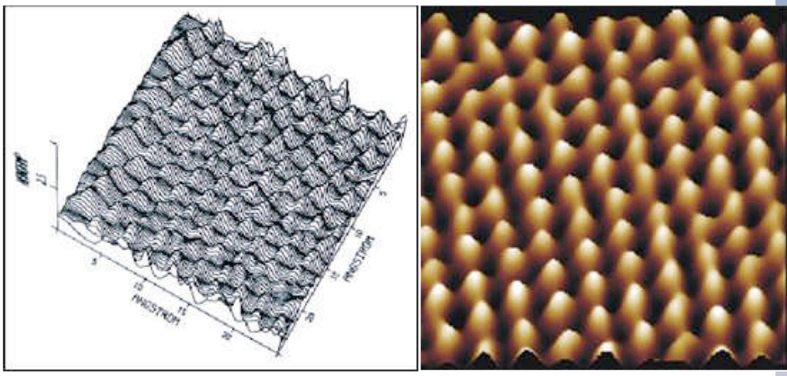
- STM does not require a vacuum to operate, but for some experiments ultra-high vacuum operation is desirable to avoid sample contamination
- In addition to under air STM can operate under liquids
  - Water is an ionic conductor, for electrons water is equivalent to a vacuum
- Two operation modes
  - Constant Height
  - Constant Current
    - More common
- Sample must be conducting
  - Very few exceptions, e.g. a very thin film over a conductor
- Atomic resolution can be hard to achieve
- Images are entirely digital, and contain tridimensional information (x, y, z coordinates for each point)
  - Visualization parameters such as angle for a 3D representation can usually be adjusted easily
  - Representation of height as a color scale on a 2D image is relatively common



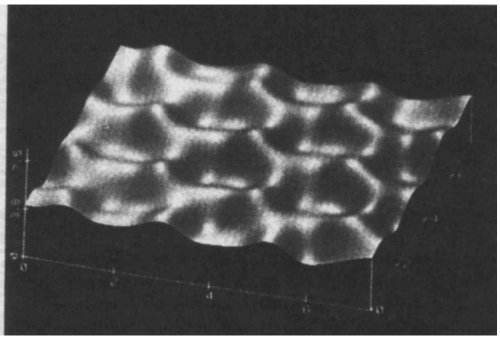
http://www.iap.tuwien.ac.at/www/surface/stm_gallery/nonmetals

Additional Remarks on STM

- STM signal is a series of lines
  - False color used to represent height visually
  - Z-axis scale usually exaggerated to facilitate visualization
  - Image is not directly of atoms, but of their density of states
    - By changing the voltage sign images of either filled or empty states can be acquired
- Tunneling current is extremely sensitive to distance between tip and sample



Example: **Graphite, with atomic resolution**



In each hexagon 3 atoms stand out

This is considered to be an effect of the stacking of graphene layers in graphite

Example: Single Walled Carbon Nanotubes

- Appl. Phys. A, 66, S153–S155 (1998)
- SWCNT (produced by laser ablation) ~1.4 nm diam. over Au
  - Atomic resolution identifies chiral angle unequivocally
  - Carbon atoms appears to be in a triangular not hexagonal network

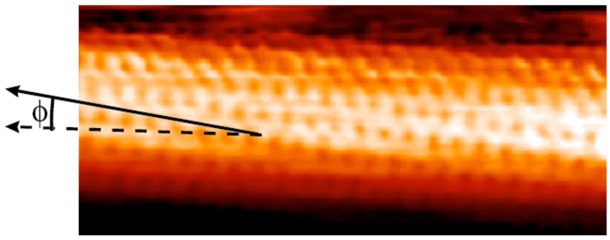


Fig. 1. Atomically resolved image of an individual carbon nanotube. The image size is $6 \times 3\,\mathrm{nm}^2$. The dashed arrow indicates the direction of the tube axis and the solid arrow denotes the direction of the nearest neighbor hexagon rows. The angle between these two arrows is the chiral angle $\varphi = 9 \pm 1°$

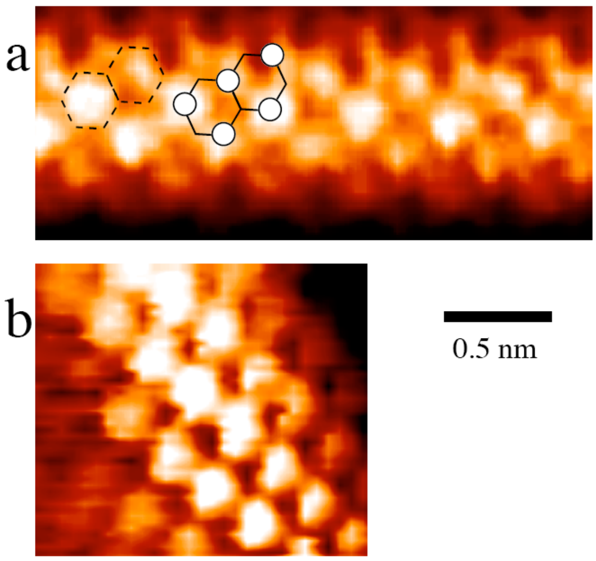


Fig. 2a,b. Zoomed images of two different nanotubes. The carbon lattice is observed to be triangular in most cases. In **a**, two hexagon configurations are drawn to indicate possible interpretations of the apparent contrast. The dashed configuration follows the idea of high contrast in the centers of the hexagons. The solid configuration illustrates the interpretation that every other atom is imaged. The filled black circles indicate the imaged carbon atoms

Example: fluorinated SWCNT

- Chem. Phys. Lett., 313, 445-450 (1999)

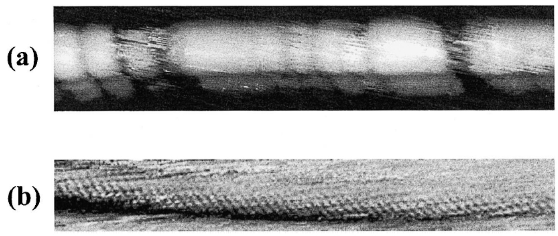


Fig. 1. (a) An image (860 Å by 180 Å) of a carbon nanotube fluorinated at 250°C for 12 h. The bright regions correspond to areas on the tube covered by fluorine atoms. Scan parameters: 0.7 nA tunneling current and +500 mV sample bias voltage. (b) A high-pass filtered image (170 Å by 25 Å, 1 nA, +100 mV) of a bare single-walled carbon nanotube deposited on an Au(111) on mica surface and imaged using a C_{60}-functionalized STM tip.

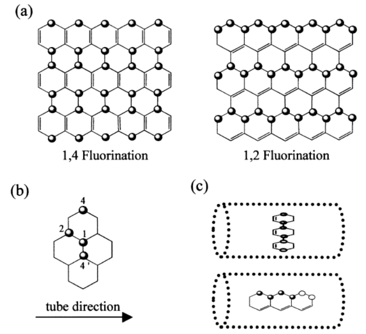


Fig. 3. (a) Proposed 1,4 (left) and 1,2 (right) 2C:1F fluorination isomers. Tube axis for (10,10) tube is horizontal in both cases. (b) Geometry denoting possible secondary fluorination sites (2,4,4′) relative to an initial fluorine addition site (1). (c) Illustration of energetically favorable multiple addition scenarios for the 1,4 circumferential (top) and the 1,2 axial (bottom) fluorination isomers.

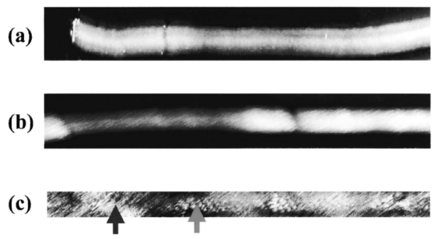


Fig. 2. (a) An image (1500 Å by 200 Å, 0.3 nA, +400 mV) of a carbon nanotube fluorinated at 250°C for 12 h. The approximat fluorine ratio by microprobe analysis is 2:1. (b) An image (1250 Å by 175 Å, 0.5 nA, +500 mV) of a carbon nanotube fluorinate for 5 h (3.7:1, C:F). The darker area on the left side of the image appears to be a less fluorinated area. (c) A high resolution im by 20 Å, 1 nA, +300 mV) of a carbon nanotube fluorinated at 250°C for 1 h. This image was also obtained using a C_{60}-functiona tip. Between the fluorinated areas (e.g., at left-hand arrow), small regions of atomic resolution can be observed (e.g., at right-ha

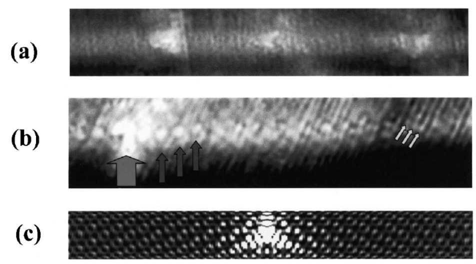
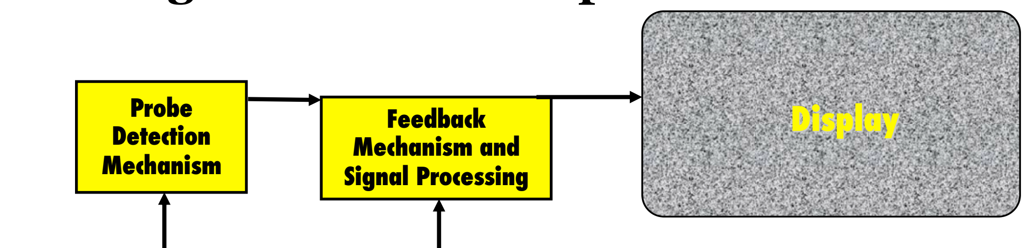
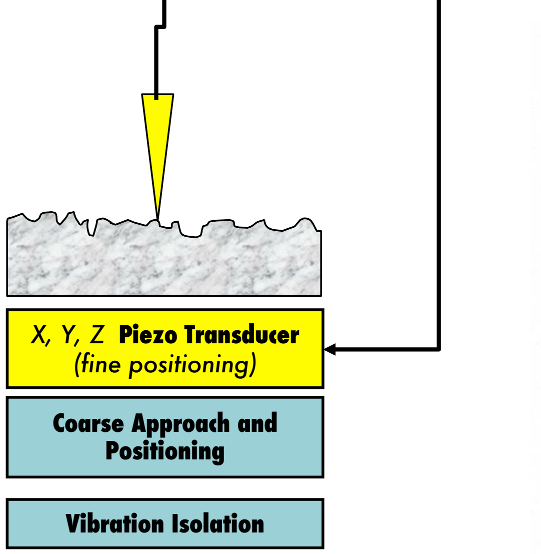


Fig. 4. (a) An image (240 Å by 35 Å, 1 nA, +200 mV) of a fluorinated nanotube treated with butyl lithium. The three bright spots along the tube appear to be due to butyl groups bonded to the nanotube sidewall. (b) A zoomed and filtered area of a higher resolution image taken in the vicinity of one of the butyl defects (large up-arrow). Both this one and the proceeding image were obtained with a C_{60}-functionalized STM tip. Near the defect a strong electronic modulation can be observed (small up-arrows). This $\sqrt{3}$ modulation seems to decay away to the right of the image where atomic resolution is once again obtained (slanted up-arrows). Scan parameters: 0.67 nA and +500 mV sample bias voltage. (c) Theoretical image of the perturbation in the local density of states at E_f caused by a carbon adatom on a (10,10) nanotube. This theory is based on similar calculations performed by Mizes and Foster [3] for carbon adatoms on graphite.

Generalized Schematic of a Scanning Probe Microscope





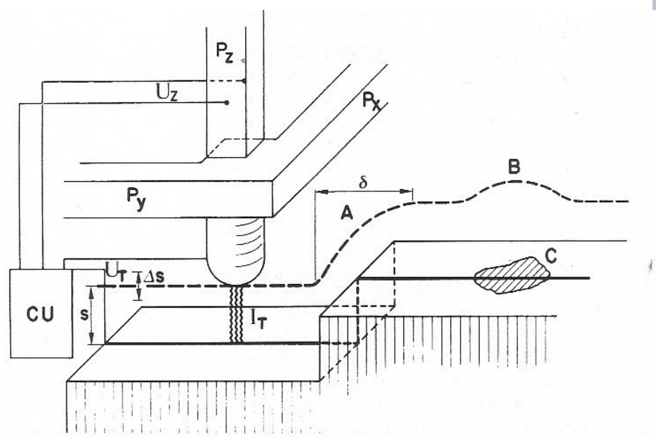
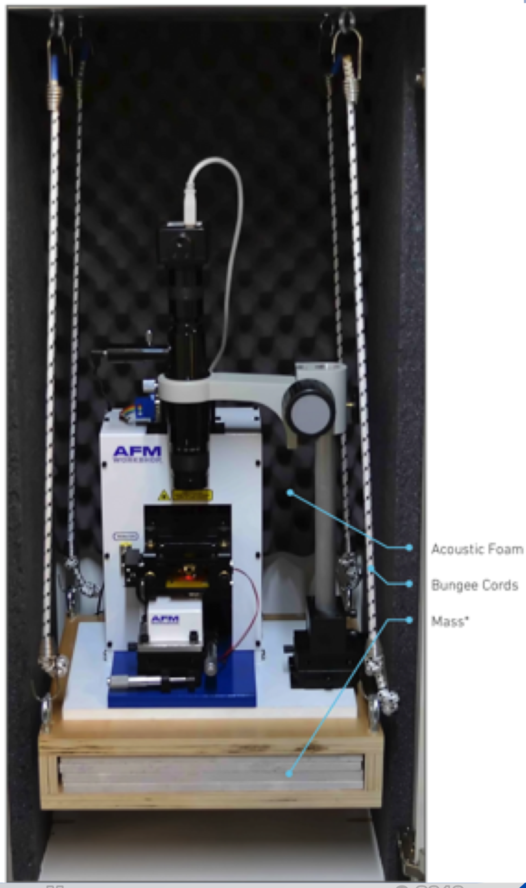


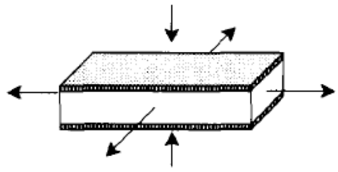
Fig. 0.1. Principle of operation of the STM. (Schematic: distances and sizes are not to scale.) Piezodrives P_x and P_y scan the metal tip over the surface. The control unit (CU) applies the appropriate voltage U_z to the piezodrive P_z for constant tunnel current I_T at constant tunnel voltage U_T. The broken line indicates the z displacement in a scan over a surface step (A) and a chemical inhomogeneity (B) (Binnig *et al.*, 1982b).

SPM Instrumentation: Vibration Isolation

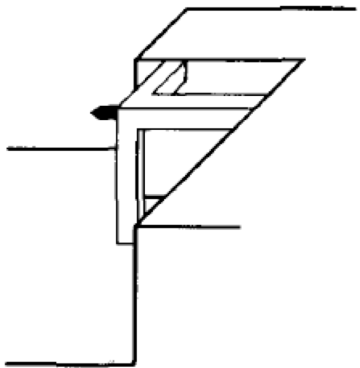
- Desired stability of sample-tip distance: 0.1 pm
  - This allows high vertical resolution of 1 pm (0.01 A, 0.001 nm) during imaging
- Vibrations from building or laboratory table, or acoustic noise can make instrument vibrate
  - Typical vibrations of floors: 0.1 – 1 µm
- Vibration Isolation is required
  - A stiff instrument design also helps reduce vibration
- Passive Vibrational Isolation Systems
  - Rubber, Viton (commercial fluoroelastomer) and a stiff, heavy platform
  - Metallic Springs combined with attenuation system
  - Metallic or granite plates separated by rubber spacers
  - Etc.
- Active vibration isolation
  - Vibration detection combined with feedback to a mechanism to counteract vibration

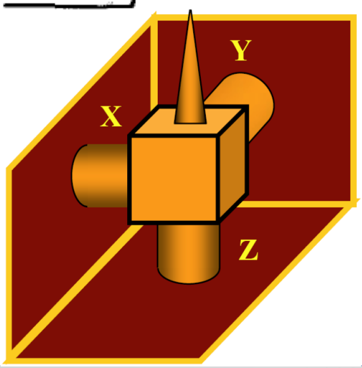


SPM Instrumentation: Positioning Devices



- Tridimensional movement of tip is required
  - Ideally, sample positioning in 3 dimensions is also required
- SPM tip moved by piezoelectric devices
  - Piezoelectric devices change their length when a voltage is applied
  - Bars, tripod bars
  - Tubes
    - Higher sensitivity
    - More common
  - Bimorphic
    - Higher sensitivity





Top two images from: Gerd Binnig and Heinrich Rohrer, "Scanning Tunneling Microscopy: From Birth to Adolescence" Nobel Lecture, December 8, 1986
Bottom image from: V. L. Mironov, Fundamentals of Scanning Probe Microscopy, Institute of Physics of Microstructures of RAS, Nishny Novgorod, ©NT-MDT 2004 (downloaded from http://ipmras.ru/en/structure/people/mironov)

Piezoelectric Devices

- Piezoelectric Tubes
  - Length change of a piezo element depends on width (smaller for tubes than for bars)
  - Inner element for movement on Z-axis
  - Lateral piezoelectric elements for X- and Y-axes (two for each)
    - Applying opposite voltages in opposite sides gives more control over deformation
  - Allows for compact designs

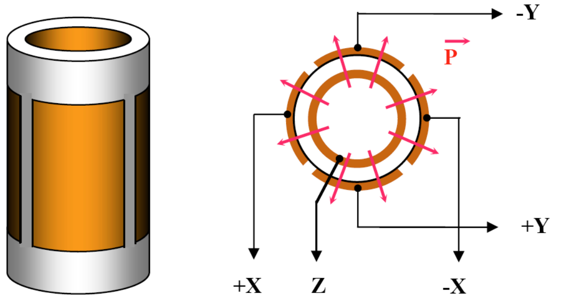


Fig. 5. Tubular piezo-scanner

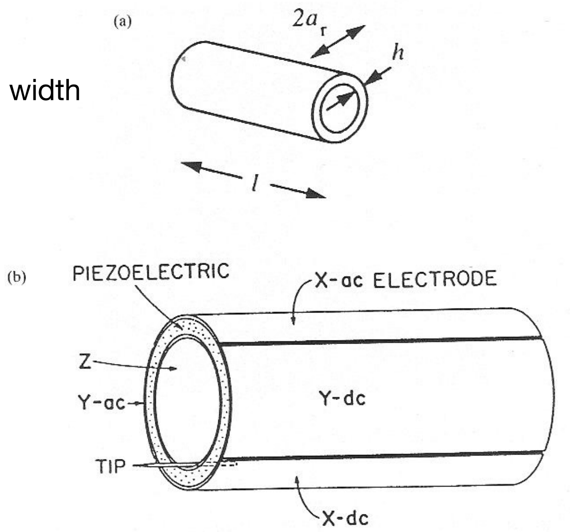


Fig. 1.51. (*a*) Piezoelectric tube. (*b*) Tube scanner with the outside electrode sectioned into four equal areas parallel to the axis of the tube. As a voltage is applied to a single outside electrode the tube bends away from that electrode. Voltage applied to the inside electrode causes a uniform elongation. A small a.c. signal and a large d.c. offset can be separated on electrodes 180° apart (Binnig and Smith, 1986).

Figure on left, from: V. L. Mironov, Fundamentals of Scanning Probe Microscopy, Institute of Physics of Microstructures of RAS, Nishny Novgorod, ©NT-MDT 2004.
Figure on right from: Roland Wiesendanger, "Scanning probe microscopy and spectroscopy : methods and applications" (1998)

Other Piezoelectric Devices

- Bimorph Elements
  - Deflection is due to voltage differences applied in opposite sides

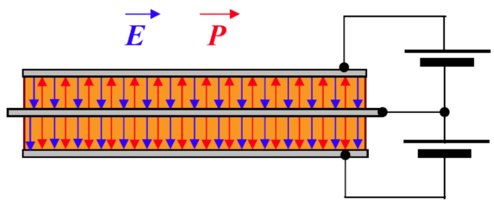


Fig. 6. Structure of a bimorph cell

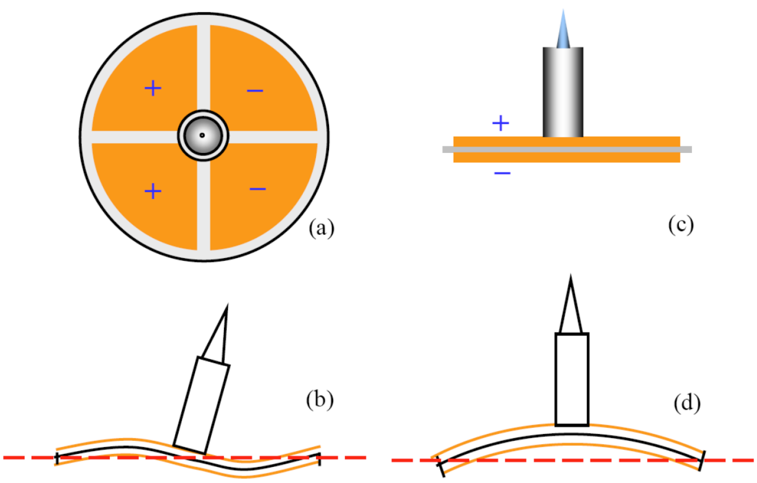


Fig. 8. Schematic representation of a bimorph piezo-scanner working mechanism

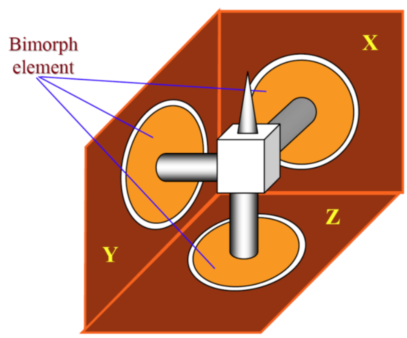


Fig. 7. Three-coordinate scanner made of three bimorph elements

Images from: V. L. Mironov, Fundamentals of Scanning Probe Microscopy, Institute of Physics of Microstructures of RAS, Nishny Novgorod, ©NT-MDT 2004 (downloadable from http://ipmras.ru/en/structure/people/mironov)

SPM Instrumentation: Electronics

- Design should avoid electric noise, feedback cycles and other sources of noise and interference
- Provide a voltage bias between sample and tip
  - Typically 1 mV to 4 V, from a battery or a digital-analog converter
- Measure tunneling current and pass it through a high gain amplifier
  - Amplification of $10^6 - 10^9\ \mathrm{V \cdot A^{-1}}$,
  - Measured currents are in the range of $10^{-12} - 10^{-9}\ \mathrm{A}$ (10 pA–10 nA)
  - Pass information to feedback system
- Z-position Control
  - Proportional amplifier and analog integrator
  - Transfer signal to Z-piezo element through a voltage amplifier
- X-Y Position Control
  - Scanning made by computer controlled digital to analog converters

SPM Instrumentation: STM Tips

- Requirements:
  - For atomic resolution, in relatively flat surfaces, the tip should end in a single atom
  - Macroscopic shape is not as important due to exponential dependence of tunneling current
  - If there was more than one atom at almost the same distance from tip artifacts of double or triple images may appear
- For rough surfaces or large structures shape of tip may be very important
  - Conical angle of tip may reduce resolution of abrupt vertical steps
  - If more than a “minitip” exists image artifacts can happen when tunneling changes from one tip to the other
- Chemical Composition of Tip
  - Oxide layers or adsorbed contaminants prevent tunneling through vacuum
  - Problems of mechanical contact with tip and tunneling through contaminants
  - Type of atom and atomic orbital in the edge of tip can have significant influence on atomic resolution measurements and spectroscopy

STM Tips: Material Selection

- Hard material required since contact between tip and sample is likely
  - Tungsten tips are most common, especially for ultra-high vacuum applications
  - Molybdenum, Iridium, monocrystalline TiC, ion-implanted diamond
- Inert tip preferred for studies under air, or with defficient vacuum
  - Pt-Ir alloys
    - Pt and Au are relatively soft, easily damaged if there is contact, not used
- For magnetic studies tips made of CoCr, Ni, Fe and Cr

STM Tips: Preparation

- Electrolytic Etching
  - W with KOH or NaOH solutions
  - Tips with curvature radius ≤ 10 nm
  - May result in formation of an oxide layer a few nm thick
    - Can be removed by post-processing

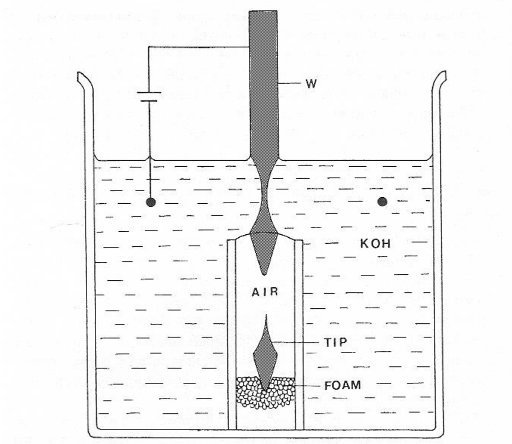


Fig. 1.55. A pretapered tungsten wire (W) is held by a micromanipulator with end protected in air column while the shank is etched in 3–5% aqueous KOH. After dropping off, the lower end is caught by the foam to avoid damage of the tip (Bryant *et al.*, 1987).

STM tips: Preparation Methods

- Combination of electrolytic etching and mechanical cutting
  - Etch to a ~50 μm constriction. Pull to break
  - Pointy edges due to elongation under tension
  - Better macroscopic tip shape than simple mechanical cutting
  - No oxide on stretched portion
  - Contamination can be avoided doing the stretching under vacuum
- Microfabrication
  - To have twin tips, or multiple tip arrays
  - Metrology applications
  - Parallel read-write applications
- CVD in electron microscopes
  - For extremely narrow and small tips
  - Electron beam induced CVD of organometallic tungsten chemical compounds (in a TEM or SEM)

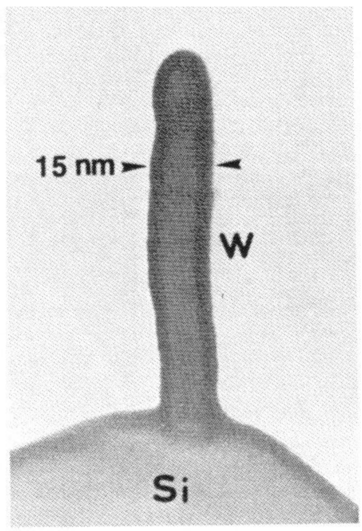


Fig. 1.57. SEM image of a W rod of 15 nm diameter. The rod was fabricated on a Si particle, using a focused electron beam, 3 nm in diameter (Ichihashi and Matsui, 1988).

STM Tips:Preparation

- Focused Ion Beam Milling
  - Sputtering with Ion beam (e.g. Ga+)
  - Tip radius down to ~4 nm, and conical angles to ~10°
  - Removes oxide layer

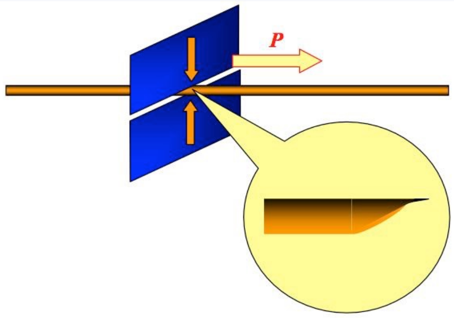


Fig. 45. Schematic picture of the STM tip preparation by cutting a Pt-Ir alloy wire

- Mechanical cutting of Pt-Ir wires
  - Nanoscale roughness at tip edge can allow atomic resolution
  - Macroscopic curvature radius may be large
  - Irregular shape does not allow use in rough surfaces

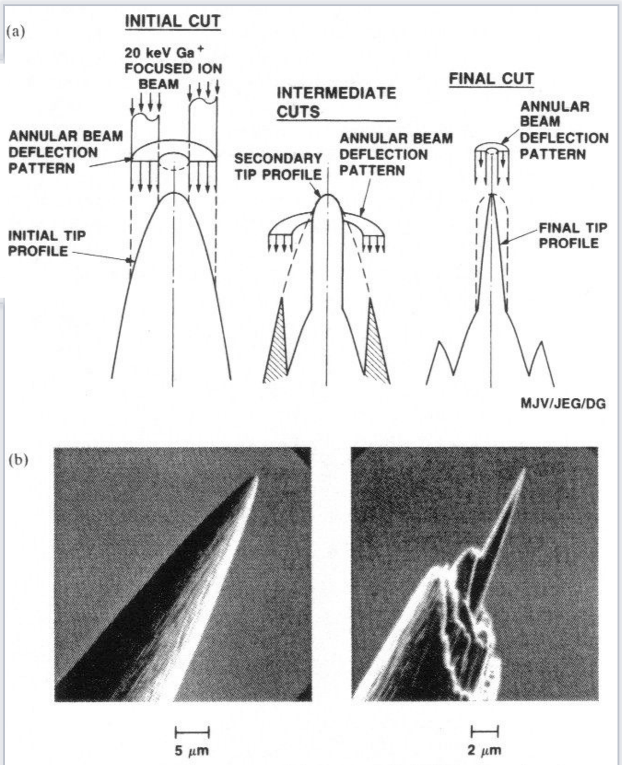


Fig. 1.56. (*a*) Focused ion beam milling steps: (1) Initial cut made using an annular beam deflection pattern (0.9 μm internal diameter, 4.0 μm outer diameter). (2) Intermediate shoulder cleaning step (approximately 2.0 μm i.e., 6.0 μm outer diameter). (3) Final cut (0.46 μm internal diameter, 1.5 μm outer diameter). (*b*) SEM images of a tungsten tip after electrochemical etching (left) and after focused ion beam machining (right) (Vasile *et al.*, 1991).

STM tips: Preparation Methods

- Controlled preparation of monoatomic tips
- Field Ion Microscope Techniques
  - Combines sputtering, annealing and field evaporation in a W(111) tip
    - NOTE: the field ion microscope was the first technique that generated images of atoms, before STM, in 1951
  - Heating W(111) in a strong electric field
  - Surface diffusion under electric field gradient
  - Atoms accumulate on the tip leading to equilibrium configuration: a single atom

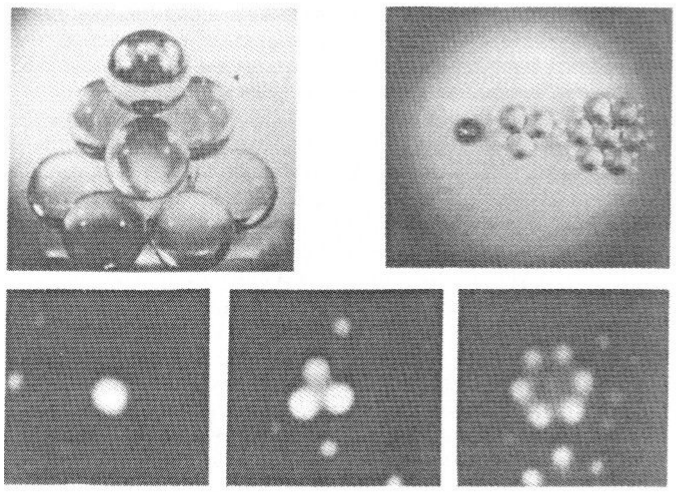
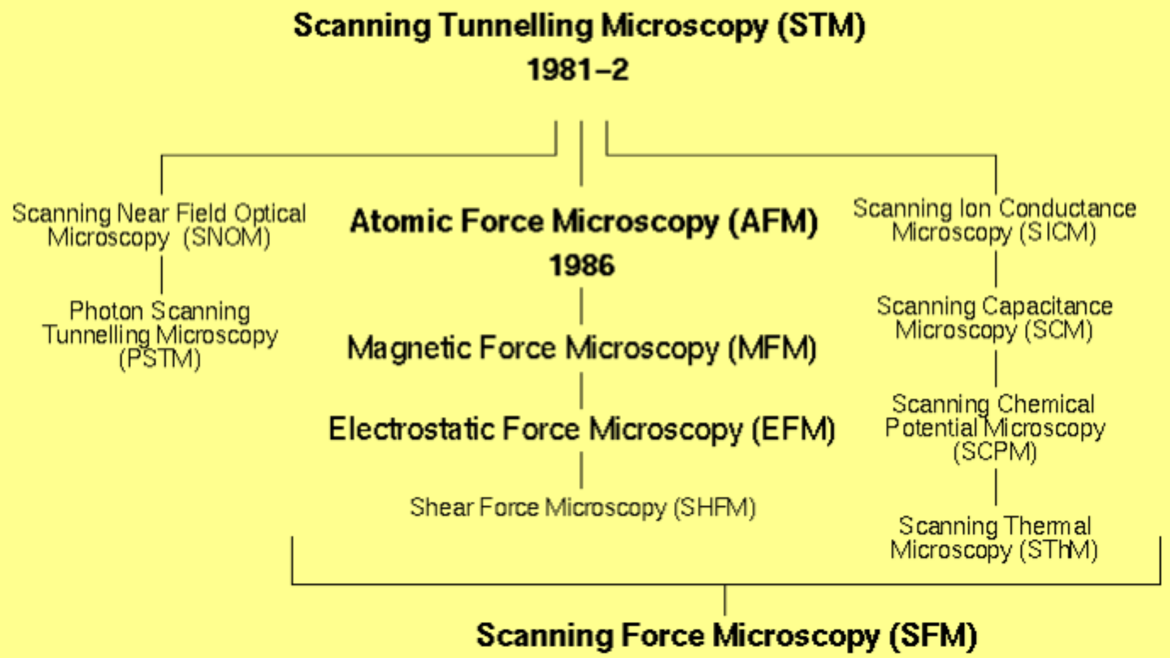


Fig. 1.58. First three layers of a monoatomic tip are made up of one, three, and seven atoms. Top: ball model of monoatomic tip. Bottom: successive removal by the field shows field-ion pattern of first three layers of the tip (Fink, 1986).

- Tip-sample interactions can change the configuration of the end of the tip
  - Even with a monoatomic tip there may not be absolute certainty about which is the effective tip for the STM

Scanning Probe Microscopy "Family Tree" (SPM)



Some SPM Variations

- Scanning Tunneling Microscopy, 1981
- Scanning Near Field Optical Microscopy, 1982
  - Resolution <50 nm in optical images
    - Uses the near field (evanescent field) of light
    - Short range interactions allow using light for imaging beyond the diffraction limit, down to ~15 nm
- Scanning Capacitive Microscope, 1984
  - Differences in capacitance, lateral resolution ~ 500 nm
- Scanning Thermal Microscope, SThM, 1985
  - Thermal imaging, resolution of ~ 50 nm

- Atomic Force Microscope, AFM, 1986
  - Atomic resolution for isolating (and conducting) samples
- Magnetic Force Microscope, MFM, 1987
  - Resolution ≤100 nm for magnetic features
- Friction Force Microscopy, FFM, LFM (lateral force microscopy), 1987
  - Lateral forces (friction) imaged at atomic scales
- Electric Force Microscope, EFM, 1987
  - Detection of individual charges in the sample surface is possible

▪ Prof. Fernando J. Rodríguez Macías ▪ ▪ Tecnologico de Monterrey ▪ ▪ © 2019

Some (More) SPM Variations

- Scanning Tunneling Microscopy with Laser Excitation, 1987
  - Laser can interact with sample or tip
    - Added energy of laser can be used by electrons for tunneling
  - "Laser Driven STM" interactions of tip and laser result in an electric signal used to control distance between tip and sample
- Inelastic Tunneling STM Spectroscopy, 1987
  - Detection of phonon spectra of molecules

- Ballistic Electron Emission Microscope (BEEM), 1988
  - Analyze Schotky barriers with nanometer resolution
- Inverse Photoemission Microscope, 1988
  - Detection of luminescence spectra at nanometer scale
- Near-Field Acoustic Microscope, 1989
  - Low frequency acoustic waves measured with resolution of ~10 nm
- Scanning Noise Microscope, 1989
  - Tunneling current detected without applying a voltage bias

(And Even More) SPM Variations

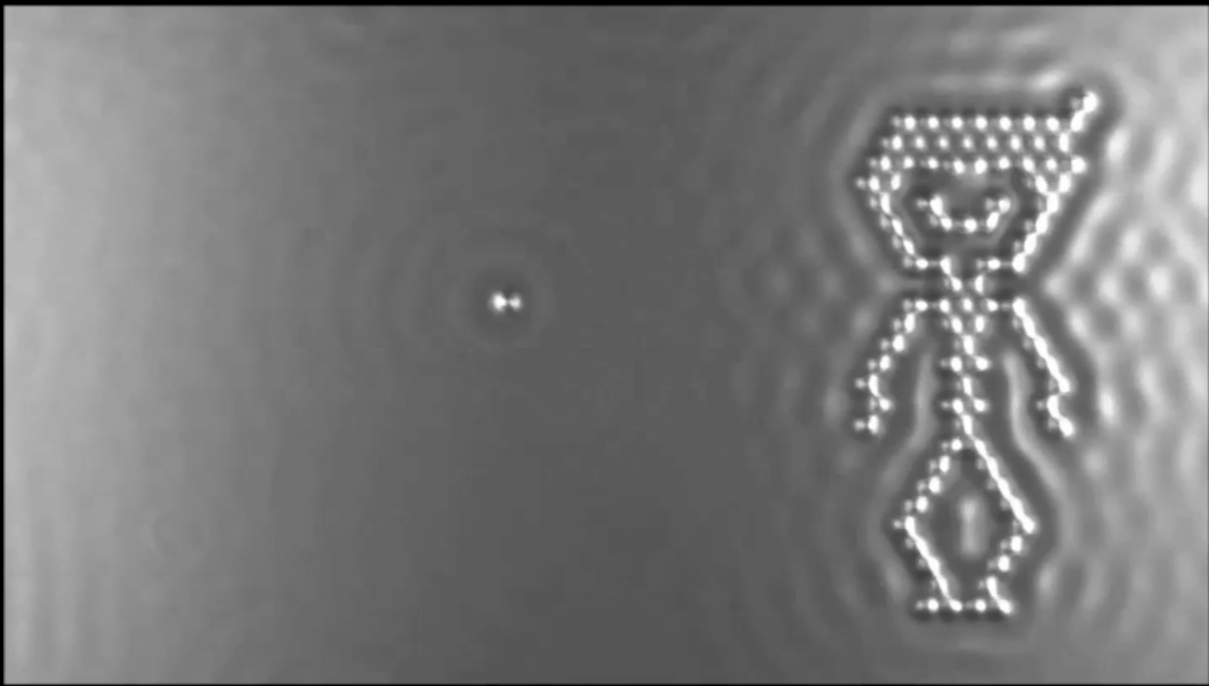
- Spin-Polarized Scanning Tunneling Microscopy, SPSTM, 1989
  - Visualization of spin in paramagnetic materials with resolution of ~ 1nm
- Scanning Ion-Conductance Microscope, 1989
  - Imaging in electrolytes with resolution of ~500 nm
- Scanning Electrochemical Microscope
- Scanning Chemical Potential Microscope, 1990
  - Imaging of variations in chemical potential at the atomic scale

- Apertureless SNOM
  - Near Field Optical Microscopy with 1 nm resolution

- List above taken from Roland Wiesendanger (Ed.) Scanning Probe Microscopy and Spectroscopy : Methods and Applications, Cambridge University Press, Cambridge, (1994). Resolutions listed may have improved

- Other variations are still being developed
  - Radio Frequency STM, much higher time resolution
    - Nature 450, 85-88 (2007)
  - High Speed AFM
    - Allows video rate image acquisition
    - See for example review article Nanotechnology 23 062001 (2012)

A Boy and His Atom (STM movie)



More information: http://www.research.ibm.com/articles/madewithatoms.shtml

Video available on https://www.youtube.com/watch?v=oSCX78-8-q0