The Scanning Tunneling Microscopy

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Abstract

Ever since its discovery in 1981, the Scanning Tunneling Microscope (STM) has been used to visualize atoms and electronic density of states. Most of all, it has given a freedom of manipulating matter with the atomic scale precision.

Microscopy started in the 15th century when magnifying glasses were used to observe insects.First Optical Microscope was built in the late 17th century by Antony van Leauwenhoek.But the fact that diffraction obscures details smaller than about one half the wavelength of the radiation prevented optical microscopes from atomic resolution.But another fact that an electron of sufficient energy exhibits a wavelength comparable to the diameter of an atom led to the invention of the electron microscope in 1930s.But its deep penetration into the matter reveals very little information of surface.In 1981, a very different microscope was built which, unlike any other microscopes,uses no free particles and thus need no lenses and special light or electron sources.The microscope was called Scanning Tunneling Microscope (STM),which allows one to image the conducting surface with atomic-scale details and manipulate the atoms.For this impressive achievement,Gerd Binnig and Henrich Rohrer were awarded Nobel Prize for Physics in 1986.

INSTRUMENTATION

The basic principle of STM lies on the very heart of quantum mechanical tunneling.Even though classical physics does not allow electron from crossing the sharp boundaries of surface,quantum mechanics does so as electrons behave like waves.This accounts for the existence of electron cloud beyond the surface of matter.The probability of finding an electron beyond the surface of a conductor falls exponentially with distance from the surface.

The schematic of STM is shown in Fig.1 [1].A sharp probe tip is attached to a piezodrive, which consists of three mutally perpendicular piezoelectric transducers: x piezo, y piezo, and z piezo.The probe tip is usually made of W or Pt-Ir alloy and has the tip gound consisting of a single atom and measuring just 0.2 nanometer in width.Applying voltage will expand or contract a piezoelectric transducer.By applying a sawtooth voltage on the x piezo and a voltage ramp on the y piezo, the tip scans on the xy plane.Using the coarse positioner and the z piezo,the tip is brought to within a nanometer or two of the surface of a conducting specimen-so close that the electron clouds of the atom at the probe tip and of the nearest atom of the specimen overlap.When a small voltage is applied to the tip, electrons "tunnel" across the gap, generating a minuscule tunneling current.The strength of the current is exquisitely sensitive to the width of the gap; typically it decreases by a factor of 10 each time the gap is widened by 0.1 nanometer.

The tunneling current is amplified by the current amplifier to become a voltage, which is compared with a reference value.The difference is then amplified again to drive the z piezo.The phase of the amplifier is chosen to provide negative feedback: if the tunneling current is larger than the reference value,then the voltage applied to the z piezo tends to withdraw the tip from the sample surface,and vice versa.Therefore,an equlibrium z position is established through the feedback loop.As the tip scan over x-y plane,a two-dimensional array of equilibrium z positions,representing a contour plot of the equal tunneling-current surface,is obtained and stored.By sweeping the tip through a pattern of parallel lines,which are separated by perhaps a fraction of a nanometer,a three-dimensional image of the surface is obtained.The contour plot is displayed on a computer screen,either as a line-scan image or as a gray-scale image .The line-scan image is a sequence of curves,each of which represents a contour along the x direction with constant y.The curves with different ys are displayed vertically.The gray-scale image is similar to a black-and-white television picture.

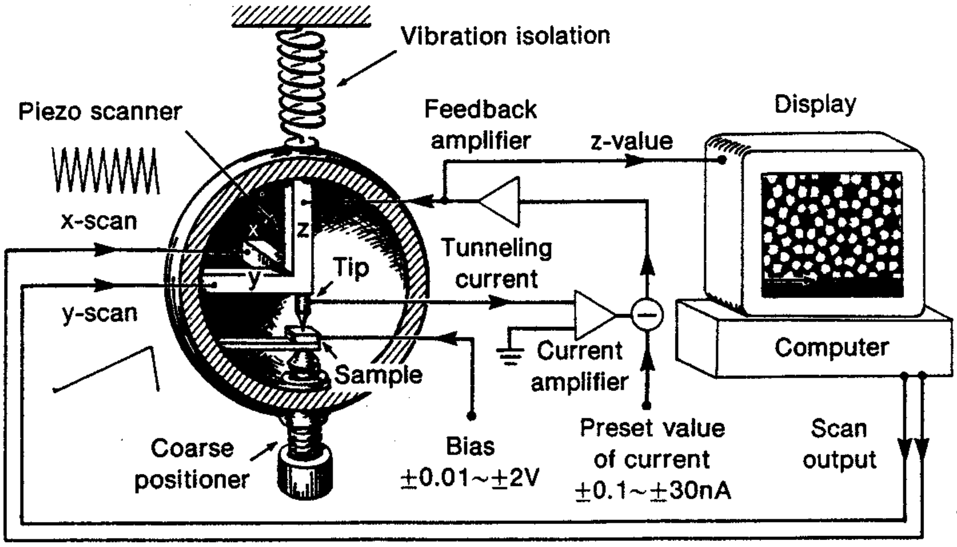

Figure 1: *Schematic for the scanning tunneling microscope [1].*

For atomic resolution,vibration such as those caused by sound in the air and by people walking around in a building must be isolated.One way of doing this is to make the STM unit as rigid as possible.Besides,the transmission of environmental vibration to the STM unit must be reduced.A commonly used vibration isolation system consists of a set of suspension springs and a damping mechanism.The STM experiments can be performed in a variety of ambiences:in air, in inert gas,in ultrahigh vacuum, or in liquids.The operating temperature ranges from absolute zero to a few hundred degrees centigrade.

SEEING ATOMS

To produce images,the STM can be operated in two modes:constant-current and constant-height mode.In constant-current imaging,a feedback mechanism is enabled that keeps the tunneling current constant by adjusting the height of the scanner at each measurement point.For example,when the system detects an increase in tunneling current,it adjusts the voltage applied to the piezoelectric scanner to increase the distance between the tip and the sample.In this mode,the motion of the scanner constitutes the data set.If the system keeps the tunneling current constant to within a few percent,the tip-to-sample distance will be constant to within a few hundredths of an angstrom.In similar manner,in constant-height mode, the tip travels in a horizontal plane above the sample and the tunneling current varies depending on topography and the local surface electronic properties of the sample.The tunneling current measures at each location on the sample surface constitute the data set,the topographic image.Each mode has advantage and disadvantages.Constant-height mode is faster but it provides useful information only for relatively smooth surfaces.Constant-current mode can measure irregular surfaces with high precision and produce contrast directly related to electron charge density profiles,but the measurement takes more time.Atomic resolution images are possible only under optimized sample and tip condtions.

Fig.2 [3] shows a low-temperature (250 mK),high vacuum STM image of a single zinc atom in a high-temperature superconductor and the disturbances it has produced nearby.The image shows the density of electronic states around a single zinc atom sitting at the site normally occupied by a copper atom in a bismuth-strontium-calcium-copper-oxide (BSCCO) superconductor.This confirms the d-wave nature ($l = 2$, clover-leaf symmerty) of electron-pair wavefunction in the surrounding superconductor.

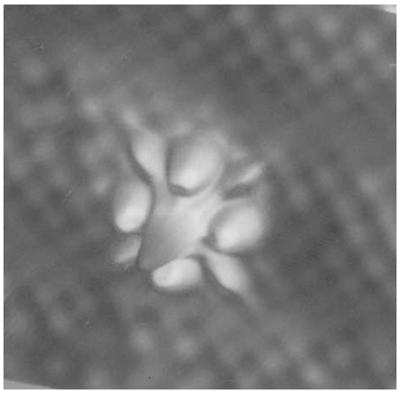

Figure 2: *Single Zinc impurity [3].*

SEEING ELECTRON WAVE FUNCTION

Scanning tunneling spectroscopy (STS) studies the local electronic structure of a sample's surface by probing the sample density of states as a function of energy.The electronic structure of an atom depends upon its atomic species and also upon its local chemical environment.The wave functions of several adjacent energy levels can be displayed simultaneously by plotting the differential conductance dI/dV as a function of the voltage V and the position x,because the experimental quantity dI/dV is a measure of the squared amplitude of the quantized electron wave function $|\psi(E,x)|^2$.

There are two methods of performing STS.The first,referred to as point spectroscopy,involves moving the tip to a feature of interest,disengaging the feedback mechanism,modulating the tip bias,and recording the resulting variation in current (constant-height).As the bias is ramped,either positively or negatively,the current varies in response to the changing electron density in the energy window.Ramping in both direction probes both the occupied and unoccupied energy states,with the magnitude of the current at a specific voltage directly related to the density of states of the sample at that energy.Thus current vs. voltage (I-V) curves characteristic of the electronic structure at a specific x,y location on the sample suface is obtained.STM can be set up to collect I-V curves at every point in a data set,providing a three-dimensional map of electronic structure.With a lock-in amplifier, dI/dV (conductivity) or dI/dz (work function) vs. V curves can be collected directly.The second method of obtaining spectroscopic information involves simultaneously collecting "topographic" (constat-current) images at various biases.This can be accomplished by modulating the bias at a high frequency and recording the current at several discreet values of applied bias or using the same sample and hold method of point spectroscopy at every image point.

Fig.3 [4] shows a "quantum corral" of 48 iron atoms adsorbed on a copper(111) surface enclosing ripples in the surface-electron local density of states.A STM contained in ultrahigh vacuum and cooled to 4 K was used first to position the iron atoms and then to image the electron densities.The corral is about 143 Å in diameter,and the ripples closely match what is expected for a particle in a circular box.All STM images were acquired in the constant current mode .

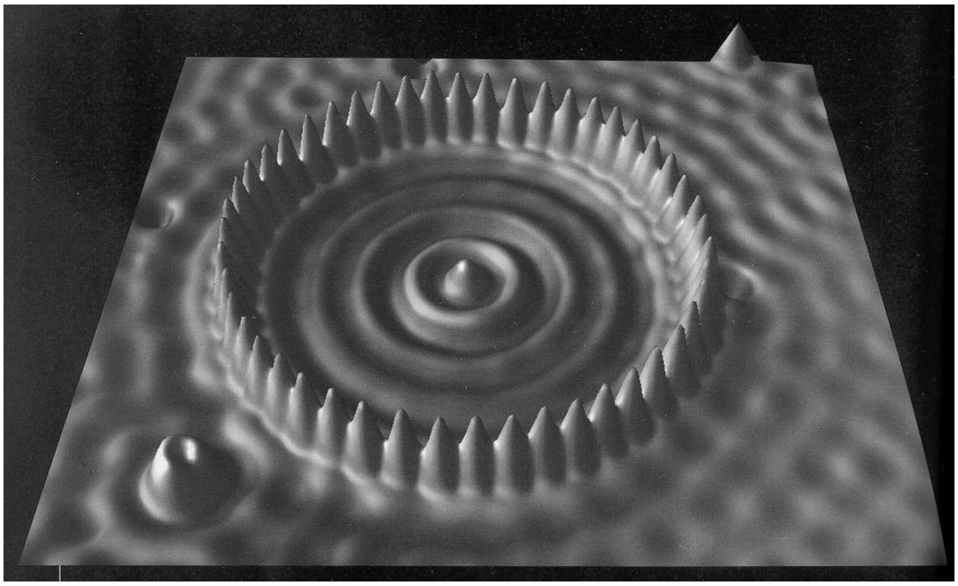

Figure 3: *Quantum corral [4].*

The spectroscopy measurements at selected locations inside the circular corral is shown in Fig.4[4].At the circle's center,six or seven peaks are observed in the spectrum.These correspond closely to the energies of zero-angular-momentum ($l = 0$) eignstates for a particle in a circular box and having mass $0.38m_e$,the effective mass of a surface electron.At a position 9 Åaway from the center there are four additional peaks-corresponding to the $l = 1$ eigenenergies.

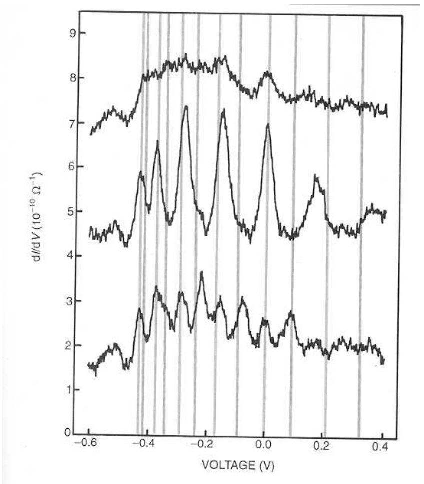

Figure 4: *Scanning tunneling spectroscopy (STS) [4].*

MOVING ATOMS

The STM has given the freedom of manipulating matter on the atomic scale.A variety of different atomic manipulation processes have been demonstrated that may be divided into two classes:parallel processes and perpendicular processes [5].In parallel processes an adsorbed atom or molecule is induced to move along the surface,while the atom or molecule is transferred from the surface to the tip of the STM or vice versa in perpendicular processes.

The first class of atomic manipulation processes is parallel processes where the bond between the manipulated atom and the underlying surface is never broken.The process is further divided into field-assisted diffusion and sliding process.Field-assisted directional diffusion is not only a manipulation technique but also offers the ability to measure the dipole moment and polarizabilities of adatoms.An atom in an electric field becomes polarized with a dipole moment given to first order in E.An intense electric field is present between the STM tip and the surface, in the range from 0.2 to 2 V$\AA^{-1}$.This field is inhomogeneous and concentrated in the vicinity of the probe tip.Field-assisted manipulation of atoms is possible at lower field,where the interaction of the spatially inhomogeneous electric field with dipole moment of an adsorbed atom can lead to a potential energy gradient, or force along the surface,which results in a field-assisted directional diffusion of the adatom.Similarly,the sliding process is possible due to the fact that an STM tip always exerts a force on an adsorbate bound to the surface.One component of this force is due to the interatomic potential between the adsorbate and the outermost tip atom or atoms.By adjusting the position of the tip we may tune the magnitude and the direction of the force exerted on the adsorbate by the tip.First,the adsorbate to be moved is located with the STM in its imaging mode and then the tip is placed near the adsorbate.The tip-adsorbate interaction is then increased by lowering the tip toward the adsorbate .The tip is then moved laterally across the surface under constant current conditions to the desired destination,pulling the adsorbate along with it.The process is terminated by reverting to the imaging mode,which leaves the adsorbate bound to the surface at the desired destination.

The STM allows a second class of atomic manipulation called perpendicular processes,in which an atom,molecule,or gourp of atoms is transferred from the surface to the tip,or from the tip to the surface.The relevant energy for the former case,for example, is the height of the energy barrier that the adsorbate must traverse in order to go from the surface to the tip.The height of this barrier depends on the separation of the tip from the surface.By adjusting the height of the tip we may tune the magnitude of this barrier to suit our purposes.In some of the processes the tip is moved toward the adsorbate until the adsorption wells on the tip and surface sides of the junction coalesce .While in some other process field evaporation is done by applying the voltage for an atom to transfer between the tip and surface.

A "quantum mirage" formed by moving several dozen cobalt atoms on a copper surface into an ellipse-shaped ring is shown in Fig.5 [6].Experiments were performed with a STM operating at 4 K in ultrahigh vacuum in constant current mode.When an atom of magnetic cobalt was placed at one focus,a mirage appeared at the other focus:the same electronic states in the surface electrons surrounding the cobalt atom were detected even though no magnetic atom was actually there.The intensity of the mirage is about one-third of the intensity around the cobalt atom.

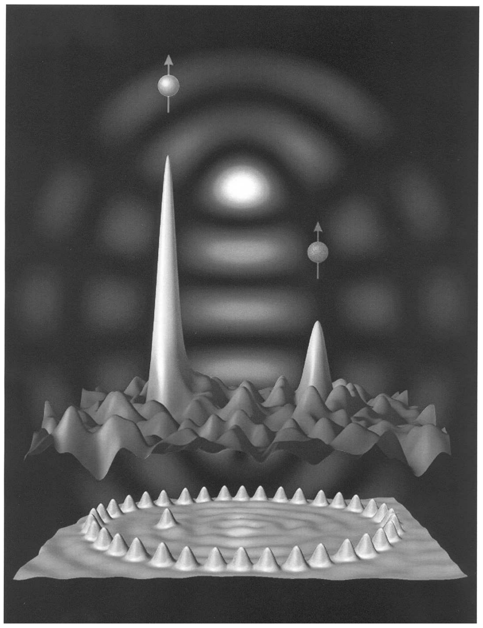

Figure 5: *Quantum Mirage [6].*

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