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Scanning Tunnelling microscopy (S.T.M)

A Scanning Tunnelling Microscope is an instrument for imaging surfaces at the atomic level. It's developement in 1981 earned its inventors, Gerd Binnig and Heinrich Rohrer (at IBM Zürich), the Nobel Prize in Physics in 1986. For an STM, good resolution is considered to be 0.1nm lateral resolution and 0.01 nm (10 pm) depth resolution. With this resolution, individual atoms within materials are routinely imaged and manipulated. The STM can be used not only in ultra-high vacuum but also in air, water and various other liquid or gas ambients, and at temperatures ranging from 0K to over 1000°C.

Working Principle

Scanning Tunnelling microscope's principle of operation is based on the quantum mechanical phenomenon known as tunneling, in which the wavelike propertie of electrons permit them to "tunnel" beyond the surface of a solid into regions of space that are forbidden to them under the rules of classical physics. The probability of finding such tunnelling electrons decreases exponentially as the distance from the surface increases. The STM makes use of this extremely sensitivity to distance. The sharp tip of a tungsten needle is positioned a few angstroms from the sample surface. A small voltage is applied between the probe tip and the surface, causing the electrons to tunnel across the gap. As the probe is scanned over the surface, it registers variations in the tunnelling current, ~~as the~~ and this information can be processed to provide a topographical image of the surface.

Tunnelling is a [~~functional~~] functioning concept that arises from quantum mechanics. Classically, an object hitting an impenetrable barrier will not pass through. In contrast, objects with a very small mass, such as the electron, have wavelike characteristics which permit such an event, referred to as tunnelling.

Electrons behave as beams of energy, and in the presence of a potential $U(z)$, assuming 1-dimensional case, the energy levels $\psi_n(z)$ of the electrons are given by solutions to Schrödinger's equation.

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

where $\hbar$ is the reduced Planck's constant, z is the position, and m is the mass of an electron. If an electron of energy E is incident upon an energy barrier of height $U(z)$, the electron wave function is a travelling wave solution,

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

where $k = \frac{\sqrt{2m(E-U(z))}}{\hbar}$

If $E > U(z)$, which is true for a wave function inside the tip or inside the sample. Inside a barrier, $E < U(z)$ so the wave functions which satisfy this are decaying waves, $\psi_n(z) = \psi_n(0)\, e^{\pm kz}$

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

quantifies the decay of the wave inside the barrier, with the barrier in the $+z$ direction of $-k$.

CONSTRUCTION OF STANDARD TUNNELLING MICROSCOPE

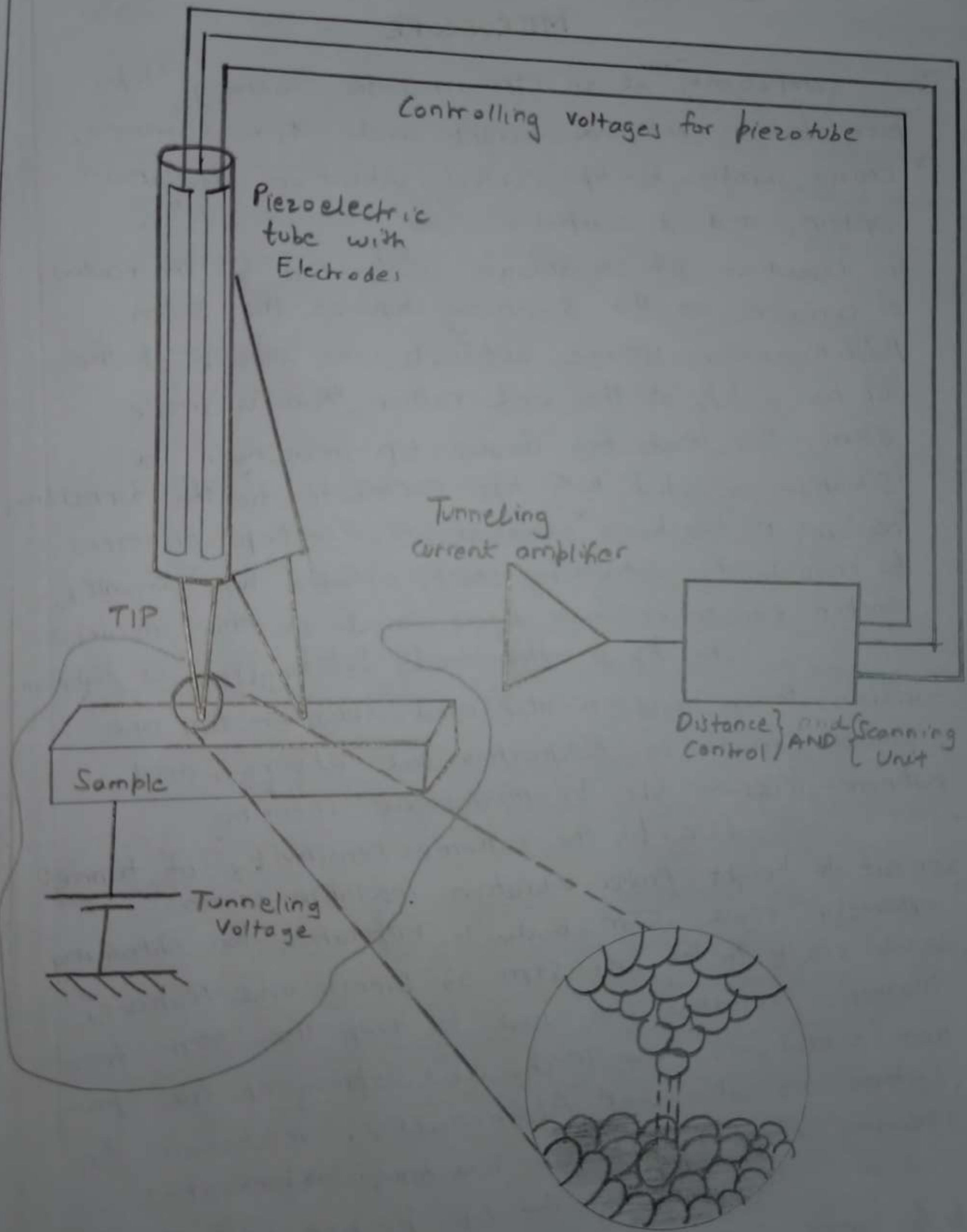
The components of an STM include scanning tip, piezoelectric controlled height and x, y scanner, coarse sample-to-tip control, vibration isolation system, and a computer.

The resolution of an image is limited by the radius of curvature of the scanning tip of the STM. Additionally, image artifacts can occur if the tip has 2 tips at the end rather than a single atom; this leads to "double tip-imaging," a situation in which both tips contribute to the tunnelling. Therefore, it has been essential to develop processes for consistently obtaining sharp, useable tips. Recently, carbon nanotubes have been used in this instance.

The tip is often made by tungsten or platinum-iridium, though gold is also used. Tungsten tips are usually made by electrochemical etching, and platinum-iridium tips by mechanical shearing.

Due to the extreme sensitivity of tunnel current to height, proper vibration insulation or an extremely rigid STM body is imperative for obtaining usable results. In the first STM by Binnig and Rohrer, magnetic levitation was used to keep the STM free from vibrations; now mechanical spring or gas spring systems are often used. Additionally, mechanisms for reducing eddy currents are sometimes implemented.

Maintaining the tip position with respect to the sample, scanning the sample and acquiring the data is computer controlled. The computer may also be used for enhancing the image with the help of image processing as well as performing quantitative measurements.


Controlling voltages for piezotube
Piezoelectric tube with Electrodes
Tunneling current amplifier
TIP
Sample
Tunneling Voltage
Distance Control
AND
Scanning Unit

Operation of Scanning Tunnelling microscopy

First, a voltage bais is applied and the tip is brought close to the sample by coarse sample-to-tip control, which is turned off when the tip and sample are sufficiently close. At close range, fine control of the tip in all 3 dimensions when near the sample is typically piezoelectric, maintaining tip-sample seperation W typically in the 4-7 Å (0.4-0.7nm) range, which is the equilibrium position between attractive ($3 < W < 10$ Å) and repulsive ($W < 3$ Å) interactions. In this situation, the voltage bias will cause electrons to tunnel between the tip and sample, creating a current that can be measured. Once tunneling is established, the tip's bias and position with respect to the sample can be varied (with the details of this variation depending on the experiment) and data are obtained from the resulting changes in current.

If the tip is moved, across the sample in the x-y plane, the changes in surface ~~might~~ height and density of states causes change in current. These changes are mapped in images. This change in current with respect to position can be measured itself, or the height z, of the tip corresponding to a constant current can be measured. These 2 modes are called height mode and constant current mode, respectively. In constant current mode, feedback electronics adjust the height by a voltage to the piezoelectric height control mechanism. This leads to a height variation and thus the image comes from the tip topography across the sample and gives a constant charge density surface; this means contrast on the image is due to variations in charge density. The benefit to using a constant height mode is that it is faster as the piezoelectric movements require more time to register the height change in constant current mode than the current change in constant height mode. In constant height mode, the voltage and height are held both constant, while the current changes to keep the voltage from changing; this leads to an image mode of current changes over the surface, which can be related to charge density. All images produced by STM are grayscale, with colour optionally added in post-processing in order to visually emphasize important features.

In addition to scanning across the sample, information on the electronic structure at a given location in the sample can be obtained by sweeping voltage and measuring current at a specific location. This type of measurement is called scanning tunneling spectroscopy (STS) and typically results in a plot of the local density of states as a function of energy within the sample. The advantage of STM over other measurements of the density of states lie in it's ability to make extremely local measurement. for example, the density of states at an impurity site can be compared to the density of states far from impurities.

Framerates of at least 25 Hz enable so called video-rate STM. Framerates upto 80 Hz are possible with fully working feedback that adjusts the height of the tip. Due to the line-by-line scanning motion, a proper comparison on the speed requires not only the framerate, but also the number of pixels in an image, with a framerate of 10 Hz and 100×100 pixels the tip moves with a line frequency of 1 kHz, whereas it moves only with 500 Hz, when measuring with a faster framerate of 50 Hz but only 10×10 pixels. Video-rate STM can be used to scan surface diffusion.

APPLICATIONS OF SCANNING TUNNELING MICROSCOPY

Several surfaces have been studied with the STM. The arrangement of individual atoms on the metal surfaces on gold, platinum, nickel and copper have all been accurately documented. The absorption of and diffusion of different species such as oxygen and the epitaxial growth of gold on gold, silver on gold, and nickel on gold also have been examined in detail.

The surfaces of silicon have been studied more extensively than those of any other material. The surfaces are prepared by heated in vacuum to temperatures so high that the atoms there rearrange their positions in a process called surface reconstruction. The reconstruction of the silicon surface designated (111) has been studied in minute detail. Such a surface constructs into an intricate and complex pattern known as the Takayangi 7x7 structure. The position, the chemical reactivity, and the electronic configuration of each atomic site on the 7x7 surface has been measured with the STM. The reconstruction of the silicon surface designated (100) is more simple. The surface atoms form pairs, or dimers, that fit into rows that extend across the entire silicon structure.

"Vacuum tunneling" of electrons from tip to sample can take place even though the environment in the region surrounding the tip is not a vacuum but is filled with molecules of gas or liquids. With a tip-sample spacing as small as ~~£~~ 5 Å, there is little room for molecules even though they may exist in the surrounding atmosphere as well as in high vacuum. Indeed, it has been operated in air, in water, in insulating fluids, and in the ionic solutions used in electrochemistry. It is much more convenient than ultra-high vacuum instruments. When a high-vacuum environment is employed, its purpose is not to improve the performance of the STM but rather to ensure the cleanliness of the sample surface.

The STM can be cooled to temperatures less than 4K (−269°C or −452°F) – the temperature of liquid Helium. It can be heated above 973K (700°C or 1300°F). The low temperature is used to investigate the properties of superconducting materials, while the high temperature is employed to study the rapid diffusion of atoms across the surface of metals and their corrosion.

The STM is used primarily for imaging, but there are many other modalities that have been explored. The strong electric field between tip and sample has been utilized to move atoms along the sample surface. It has been used to enhance the etching rates in various gases. In one instance, a voltage of 4V was applied; the field at the tip was strong enough to remove atoms from the tip and deposit them on a substrate. This procedure has been employed with a gold tip to fabricate small gold ~~structure~~ islands or clusters on the substrate with several hundred atoms of gold in each cluster. These nanostructures are used to pattern the surface on a scale that is unprecedented.