Scanning Tunneling Microscopy

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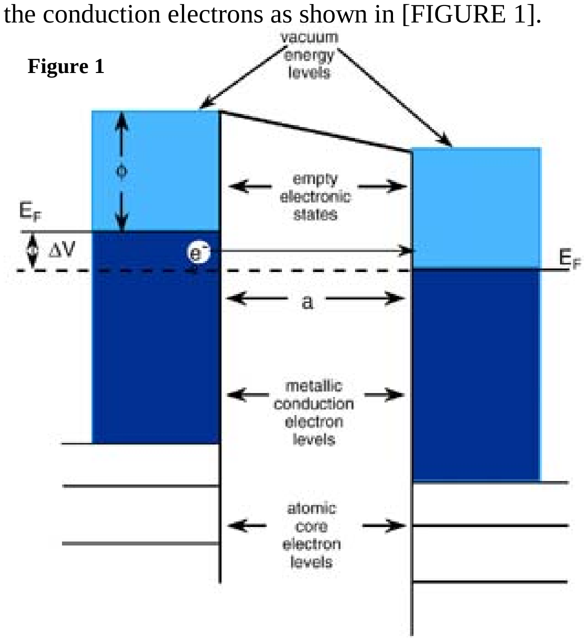
All scientists believe that matter consists of atoms. However, the evidence for the existence of atoms is mostly indirect. There are only three known methods for actually imaging individual atoms and thus studying their behavior directly. These are transmission electron microscopy, field ion microscopy, and scanning tunneling microscopy. Of these three, the last is the most recently developed and the most versatile. Gert Binnig and Heinrich Rohrer were awarded the Nobel Prize in Physics in 1986 for the development of this technique, jointly with Ernst Ruska who was honored for his work on the development of electron microscopy.

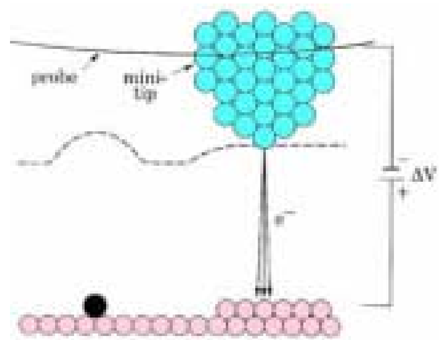
To understand scanning tunneling microscopy (STM), we first need to understand a little bit about the behavior of electrons in metals (or any other electrically conducting material). A metal consists of a large number of atoms, which are held together by the electrostatic forces acting between the electrons and the nuclei of the atoms. Most of the electrons are bound tightly to the individual nuclei, just as in the case of isolated atoms. However, the electrons that are farthest from the nuclei feel a relatively weak electrostatic attraction, and thus are free to wander about in the space between the nuclei. These are called the conduction electrons because they are the ones that carry (or conduct) electric current. It is a pretty good approximation to treat these electrons as if they are moving in a nearly constant attractive potential, so that they behave very much like particles in a one-dimensional box. We draw an energy-level diagram for the conduction electrons as shown in [FIGURE 1].

Figure 1



Because there are large numbers of levels (~10^{23}), they overlap to provide a continuous distribution of states available to the conduction electrons. Only the lower energy levels are occupied by electrons. The energy of the most weakly bound electrons is called the Fermi energy (E_F). The electrons at the Fermi energy are held in the metal by an energy barrier of about 5 eV, the work function (+). Classically, these electrons can never leave the metal unless they are given the energy necessary to go over this potential barrier. Quantum mechanically, however, electrons near the Fermi energy can tunnel through the potential barrier. By placing two pieces of metal close to one another, as shown in Figure 1, a finite square-well barrier can be created. The probability for the electrons at the Fermi energy to tunnel through the barrier is proportional to $e^{-\alpha a}$, where a is the distance separating the two pieces of metal and a depends on the barrier height (in this case the work function). As explained below, this exponential dependence of the transmission probability on separation is what makes STM possible.

Figure 2



The mechanism of STM is illustrated in Figure 2. If a pointed metal probe is placed sufficiently close to a sample and a small voltage (say DV about 10 mV) is applied between the probe and sample, then electron tunneling can occur. The net flow of electrons can be measured as a tunneling current, which is proportional to the transmission probability. If we then scan the probe back and forth above the sample, any bumps on the sample surface will change the separation. Because of the exponential relationship between the separation and the transmission probability, changes in the separation as small as 0.01 nm result in measurable changes in the tunneling current. Measurement of the tunneling current while scanning thus generates a topographic map of the surface. Thus, in principle, it is possible to measure the topography of the surface using STM. In practice, formidable experimental problems arise in trying to image individual atoms on the surface.

The challenges lie in three general areas: vibrations, tip sharpness, and position control.

Vibrations are important because the separation between the sample and probe must be very small. For a work function of around 5 eV, a separation of only a few nanometers (comparable to the size of atoms) is needed. For such a small separation, a minor perturbation such as vibrations set up by a sneeze can jam the probe right into the sample, ruining the experiment. The most common source of vibrations is motion of the floor, which typically has as an amplitude of about 1 ^{a}m-a thousand times larger than the tip-sample separation that must be maintained. Thus, very careful engineering is required to make the instrument rigid and to isolate it from these external disturbances

The second problem-probe sharpness-determines how small a structure can be imaged on a surface. Electrochemical etching can be used to sharpen the end of a metal wire to a radius of about 1^{a}m (1000 nm). A probe with such a large surface area would allow tunneling to occur over a large region of the sample surface. In order to resolve small features such as atoms, it is necessary to have a probe comparable in size to the features. In trying to fabricate such a probe, we are rewarded for not being able to do a perfect job in making micron-radius tips on the probe. The metal wires that we polish electrochemically are rough on an atomic scale: Their surfaces bear many mini-tips like the one illustrated in Figure 2. The end of such a mini-tip will present a single atom (perhaps a few) close to the surface. The exponential dependence of transmission probability on separation then guarantees that tunneling will occur preferentially from the end of the mini-tip.

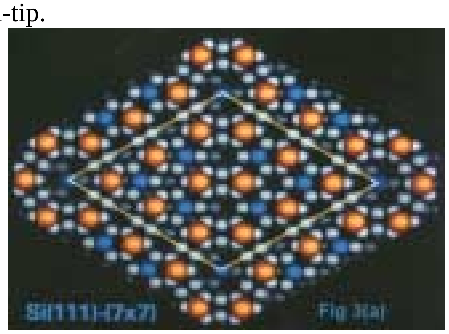


Figure 3a: This model, which was developed on the basis of combined STM, Ion Scattering and Electron Diffraction measurements, shows the positions of the top layers of Si atoms on the 7x7 reconstructed Si(111) surface. The figure was created by R. Tromp of IBM T.J. Watson Research Laboratories.

The third problem in STM is that of position control. How is it possible to move the probe around with controllable displacements of less than 0.1 nm? The answer lies in a special type of material known as piezoelectric ceramic**.** This material expands and contracts when an external voltage is applied to electrodes on opposite faces. Typically, expansions are on the order of a few tenths of a nanometer per applied volt. As a result, a probe attached to a piece of piezoelectric ceramic can be moved with great precision by application of external voltages.

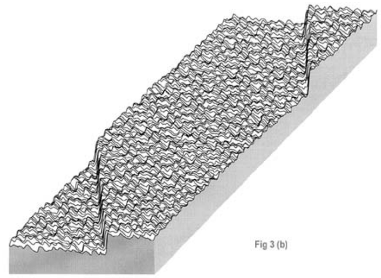


Figure 3b: STM data measured on a 7x7-Si(111) surface shown in the original line scan format (no data smoothing or filtering has been applied). The two lines where the surface height steps to a new level are 0.3 nm high-the interplanar spacing of Si(111). The area imaged is approximately 15 nm by 30 nm. This image was measured by Dr. Xue-Sen Wang of the University of Maryland Surface Group.

When Binnig and Rohrer first demonstrated that these challenges could be surmounted, it generated tremendous excitement because it opened the possibility of answering fundamental questions about the properties of surfaces, as well as a wealth of potential practical applications. The power of STM is illustrated in Figure 3, where a model of the atomic structure of atoms on the surface of silicon is compared with STM images of the real surface. The data from an STM scan of the surface consist of values of the surface height versus position. This can be immediately presented in the form of a line scan, as shown by the dashed line in Figure 2. The line scan image of Figure 3b is easier to visualize if the data are represented by a gray scale as in Figure 3c. Here, the height at each point is represented by the intensity of color-ranging from white for the highest points to black for the lowest-showing a striking correspondence to the atomic model in Figure 3a. The deep holes correspond to the positions of missing atoms in the model, and the bright spots are due to the atoms that protrude above the average surface plane. There are also two lines where the surface abruptly changes in height in this image. These surface steps are important in practical processes such as crystal growth and microfabrication.

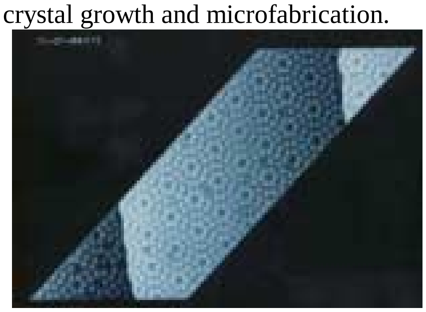


Figure 3c: The same data as in Fig. 3b is shown in a gray-scale format in which the height is represented by intensity of color (white is highest, black is lowest). This allows the periodic structure of the 7x7 unit cells (approximately 20 unit cells are visible in the center region between the steps) and the correspondence of the positions of the top layers atoms to the model in Fig. 3a to be seen immediately.

In addition to fundamental studies of the physics of atoms at surfaces, STM has a range of potentially practical applications, in part because STM is quite insensitive to its microscopic environment. For the description of tunneling presented above, the material in the gap between the sample and probe is not too important. Tunneling microscopes operate in vacuum, air, liquid helium, oil, water, and even in electrolyte solutions. This makes it possible to apply the STM to such important problems as imaging DNA in a biological environment and observing the surfaces of battery electrodes while they are operating. Variations of STM have also been developed that are capable of imaging samples that are not conductors (atomic force microscopy) and of imaging the magnetic properties at surfaces. Perhaps the most stunning possibility is that of using STM to write with atomic resolution. Features a few nanometers wide have been written by using the probe to scratch or dent the surface directly or by using the tunneling current to heat the surface. However, the ultimate limit of resolution has been demonstrated by using the probe to nudge individual atoms of xenon around on a surface to spell out a message, as illustrated in Figure 4.

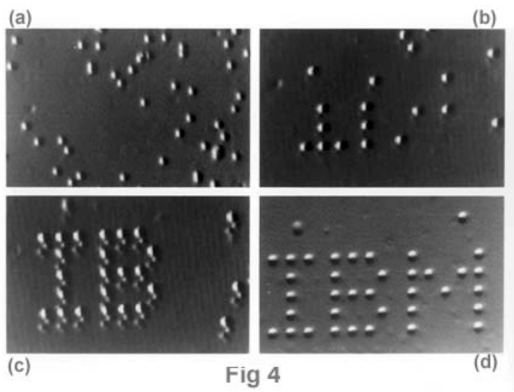


Figure 4: Work by D.M. Eigler and E.K. Schweizer, presented in Nature, vol 344, p. 524 (1990). A sequence of STM images taken during the construction of a patterned array of xenon atoms on a nickel surface at temperature 4 K. Xenon atoms were allowed to stick randomly on the surface from the gas phase (panel a), and then were moved one by one (panels b-f) to spell out the name of the company sponsoring the research. This image was provided by D. Eigler of IBM Almaden Research Laboratories.

Scanning tunneling microscopy is a practical demonstration of quantum mechanics and an illustration that understanding of basic concepts of physics can yield tremendous gains in advanced technology. It is also an object lesson in the long-term and often unforeseeable benefits that accrue from developing fundamental ideas. The scientists who first explored the physical possibility of tunneling during the early part of this century would be amazed and delighted to see its application in STM.

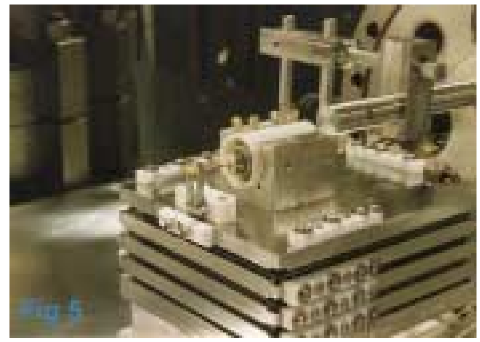


Figure 5: This photo of one of the working UHV-STMs in the University of Maryland Surface Science Group illustrates the deceptive simplicity of the instrument. Vibration isolation is provided by a stack of viton plates and by the rigidity of the tip and sample mounting system. Sample approach is done with a Burleigh piezo-electric inchworm mechanism, and tip scanning is accomplished with a piezo-electric tube scanner.

To learn more about STM and SPM, the reader can consult the following review articles:

1. *Scanning Tunneling Microscopy from Birth to Adolescence*, G. Binning and H. Rohrer (Nobel Address), Reviews of Modern Physics 59, p. 615, (1987)
2. *Wandering Surface Atoms and the Field Ion Microscope*, G. Ehrlich, Physics Today, June 1981
3. *The Development of the Electron Microscope and of Electron Microscopy*, E. Ruska (Nobel Address), Reviews of Modern Physics 59, p. 627 (1987)
4. *Scanning Tunneling Microscopy: a surface science tool and beyond*, H. Rohrer, Surface Science 2991300, p. 956 (1994)
5. *Scanning Tunneling Spectroscopy*, R. Feenstra, Surface Science 2991300, p. 965 (1994)
6. *The AFM as a tool for Surface Imaging*, CF Quote, Surface Science 299/300, p.980 (1994)