Surface Physics and the Scanning Tunneling Microscope

The advent of quantum mechanics in the 1920's contributed immensely to our understanding of atoms, nuclei, molecules, and solids. New ideas in statistical mechanics accelerated the quest for greater understanding of the behavior of liquids and solids (condensed matter). In the last half of the 20th century, the study of condensed matter (semiconductors, superconductors, magnetic systems, superfluids, polymers, and synthetic nanostructures) became the largest single subfield of physics. The study of surfaces plays an important role in condensed matter physics, with particular applications in semiconductor physics and microelectronics.

In the early 1980's Gerd Binnig and Heinrich Rohrer at IBM's research laboratory in Zurich developed the scanning tunneling microscope (STM) in order to explore the physics of surfaces. In 1986, their accomplishment was recognized with the Nobel Prize in Physics. The device uses the phenomenon of quantum tunneling to make extremely sensitive maps of surfaces that can resolve individual atoms in a surface. In this exercise you will use an STM to create an image of a solid surface with atomic resolution.

Objectives:

1) Use an STM to produce an image of graphite and interpret your results.

2) Explore the relationship between the quantum tunneling current I_t and gap distance d.

Introduction:

With a scanning tunneling microscope, images of surfaces with atomic resolution can be readily obtained. The images produced by this instrument are not like those from any type of optical microscope since the STM does not use reflected light to create a magnified image. Rather, an STM uses quantum tunneling of electrons to map the density of electrons on the surface of a sample. Since electron density is generally greater near the nucleus of an atom located at the surface of the sample, the STM image can be used to determine the position of those surface atoms on the surface.

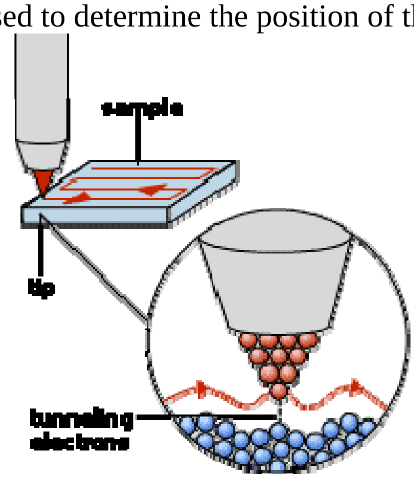

Fig. 1. Mapping the surface of a sample with an STM.

The STM works by bringing a metal wire with a sharp tip very close to a conducting surface. The distance is generally on the order of 1×10^{-9} m, a distance corresponding to a few atomic diameters. Electrons in the tip and the sample are classically forbidden from traversing the region between the tip and the sample, and no electrical current should flow from the sample to the tip. However, if the gap between the tip and sample is sufficiently small and a small voltage potential V_t is applied, quantum mechanics allows the electrons to tunnel between the two and a small tunneling current I_t flows. In the simplest model of quantum tunneling, this current is exponentially dependent on the distance *d* between the tip and structures on the surface of the sample. The tip is scanned over the surface of the sample while keeping either the height *z* or the tunneling current I_t constant. A computer maps the surface by scanning in parallel lines across the surface and recording either I_t or *d* as shown in Fig. 1. By plotting tunneling current or height as a function of position, a three dimensional representation of the surface is obtained. A sample image of a graphite surface in Fig. 4 shows a plot of tip height vs. position along one line of the image together with a plot of a 1.1nm x 1.8nm portion of the surface.

Quantum Electron Tunneling

In classical mechanics, an electron moving in a potential *V(x)* with total energy *E* is described by the equation:

$$\frac{p_x^2}{2m} + eV(x) = E_{Total}$$

where $p_x = mv_x$ is the z component of the electron's momentum, *e* is the charge of the electron, and *m* is its mass. The electron has a nonzero momentum and is allowed to move in regions where $E_{Total} > V(x)$. Fig. 2 depicts the potential energy $eV(x)$ of an electron as a function of position. The potential energy is low inside the material of either the sample or tip because the electron is attracted to the positively charged nuclei in the solids. The potential energy rises abruptly at the edge of the material. The horizontal line at energy *E* indicates the total energy of a given electron.

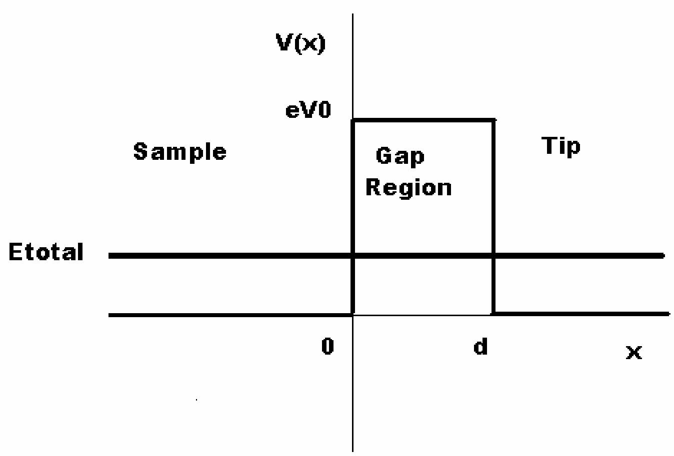

Fig. 2. Potential energy as a function of position showing the sample, tip, and gap regions. The horizontal line represents the total energy of an electron in this system.

Classically, an electron of energy E_{Total} can be found in the region $x < 0$ or in the region $x > d$, but **never** in the gap region $0 < x < d$.

In quantum mechanics this strict locational prohibition is relaxed. The state of the electron is described by an electron wave *Ψ(x)* that is related to the probability that one will find the electron at some position *x*. This wave must satisfy the Schrödinger wave equation of quantum mechanics. Fig. 3 shows plots of the wave function $\psi(x)$ both inside and outside the classically forbidden gap region.

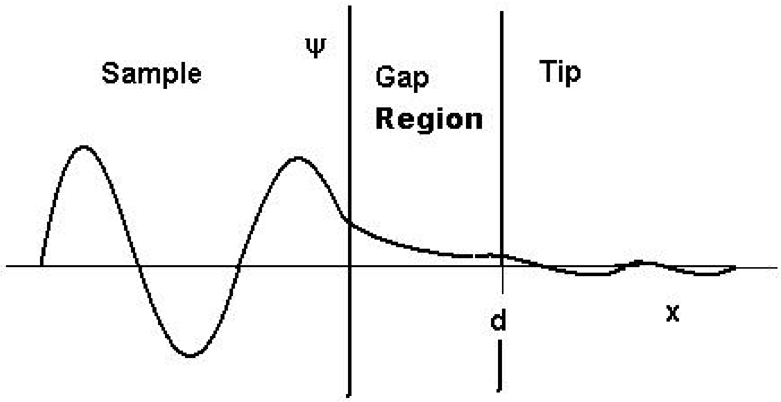

Fig. 3. Quantum wave function for an electron of total energy *E* in the potential energy environment described in Fig. 2.

Inside the sample, the electron wave has large amplitude corresponding to a high probability that the electron will be found inside the sample with the momentum expected classically. In the classically forbidden gap $0 < x < d$, the wave function decays approximately exponentially

$$\psi(x) = \psi(0)e^{-\kappa x}$$

where $\kappa = \sqrt{2m\left(E_{Total} - V_0\right)}$ is called the decay constant. This wave depicts the state of decaying probability for finding the electron in the gap between sample and tip. The probability for finding an electron near a point *x* is proportional to $|\psi(x)|^2 = |\psi(0)|^2 e^{-2\kappa x}$, which is nonzero inside the barrier. To the right of the gap (inside the tip) the wave oscillates again but with small amplitude, indicating that there is only a slight probability that the electron passes across the forbidden gap and appears in the tip. Notice that the probability density of an electron tunneling through the gap decays exponentially with respect to the width of the gap *d.*

Tunneling Current:

Electrons can tunnel from the sample to the tip or from the tip to the sample. The model wave above represents the case where electrons approach the gap from the left side and no electrons come from the right. If there are initially electrons on both sides of the barrier with the same energy, then the number tunneling from right to left equals the number tunneling from left to right and there is no net current. By applying an external tunneling voltage V_t, we can raise the energy of electrons on one side relative to the other and create the situation depicted in Fig. 3. We predict a tunneling current

$$I_t(x) = A(E)V_t e^{-2\kappa d}.$$

This equation predicts that the tunneling current I_t decreases exponentially with distance d and increases linearly with voltage potential V_t. The function $A(E)$ represents the density of electrons with energy E in the sample.

Measurements:

1.) Use the STM to produce an image of the surface of crystalline graphite. Follow the instructions of your lab guide to
   a. Move the tip close to the surface and establish the tunneling current;
   b. Adjust the scan so that it is parallel to the crystal surface;
   c. Gradually look at smaller sections of the surface until atomic features emerge. Notice the honeycomb structure that appears. An actual image of a graphite surface obtained with one of the instruments in the surface physics laboratory is shown in Fig. 4 below..

2.) Use the spectroscopic mode of the STM at one point to make a plot of tunneling current as a function of distance to the surface.

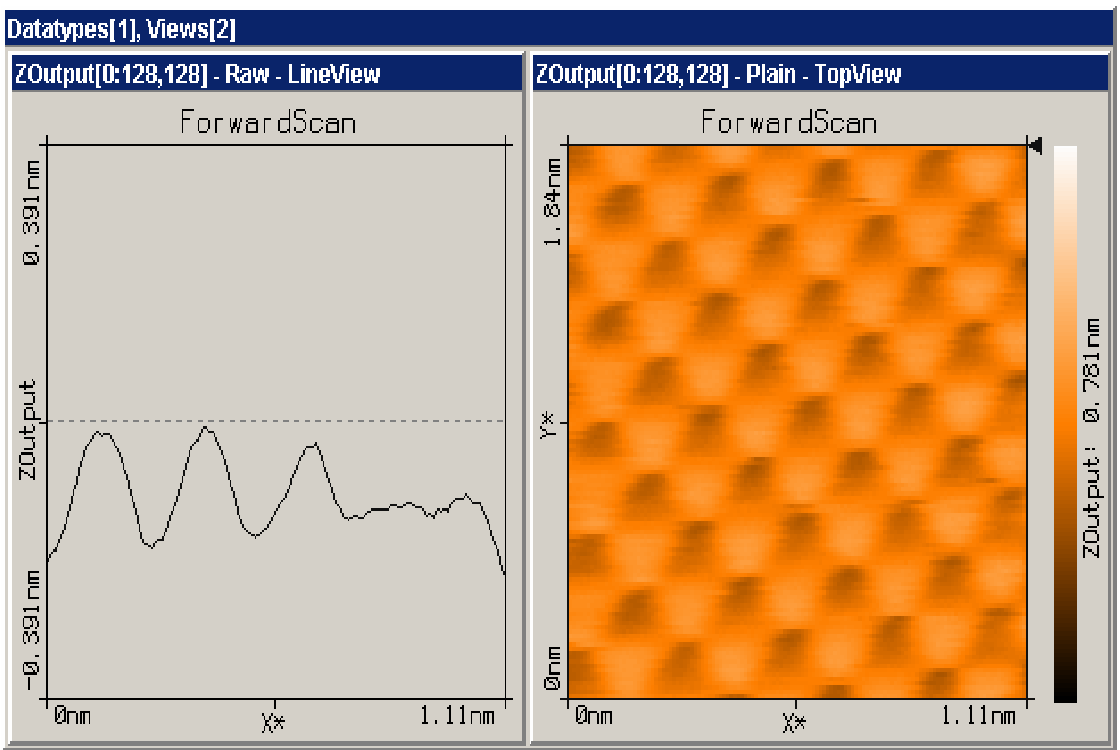

Fig. 4. The graph on the left shows the vertical position of the tip relative to the sample as the tip scans across the line in the image corresponding to the arrow in the right panel. The instrument adjusts the height to keep the tunneling current at precisely 1 nanoampere (1×10^{-9} ampere). The right panel shows a representation of the set of lines that cover the full 1.11 by 1.84 nanometer region under examination.