ACTIVITY 5

Creating an Image in a Scanning Tunneling Microscope

In the previous activity you learned about the potential energy diagram for an electron in a scanning tunneling microscope and used it to understand the phenomenon by which electrons can tunnel from the sample's surface to the probe tip. You also learned how changing the probe tip voltage and electron energy affects the potential energy diagram, the wave function of the tunneling electron, and the probability with which electrons will tunnel.

In this activity you will learn about the tunneling current, which is used to create the image of the sample's surface. You will see how changes in the ease with which an electron tunnels influences the tunneling current and the effect of these changes on the creation of the image.

Objectives
After completing this activity, you should:

- Understand another factor that affects tunneling in a scanning tunneling microscope.
- Understand how the tunneling probability and tunneling current change with all these factors discussed before.

In the previous activity, we learned that applying voltage to the probe tip increases the probability of moving electrons from a sample to the probe tip. Different samples, however, could be made up of different materials — different kinds of atoms in different arrangements. Extracting electrons from some materials is easier than it is from others. Next we will study how the ease of removing electrons affects the potential energy diagram.

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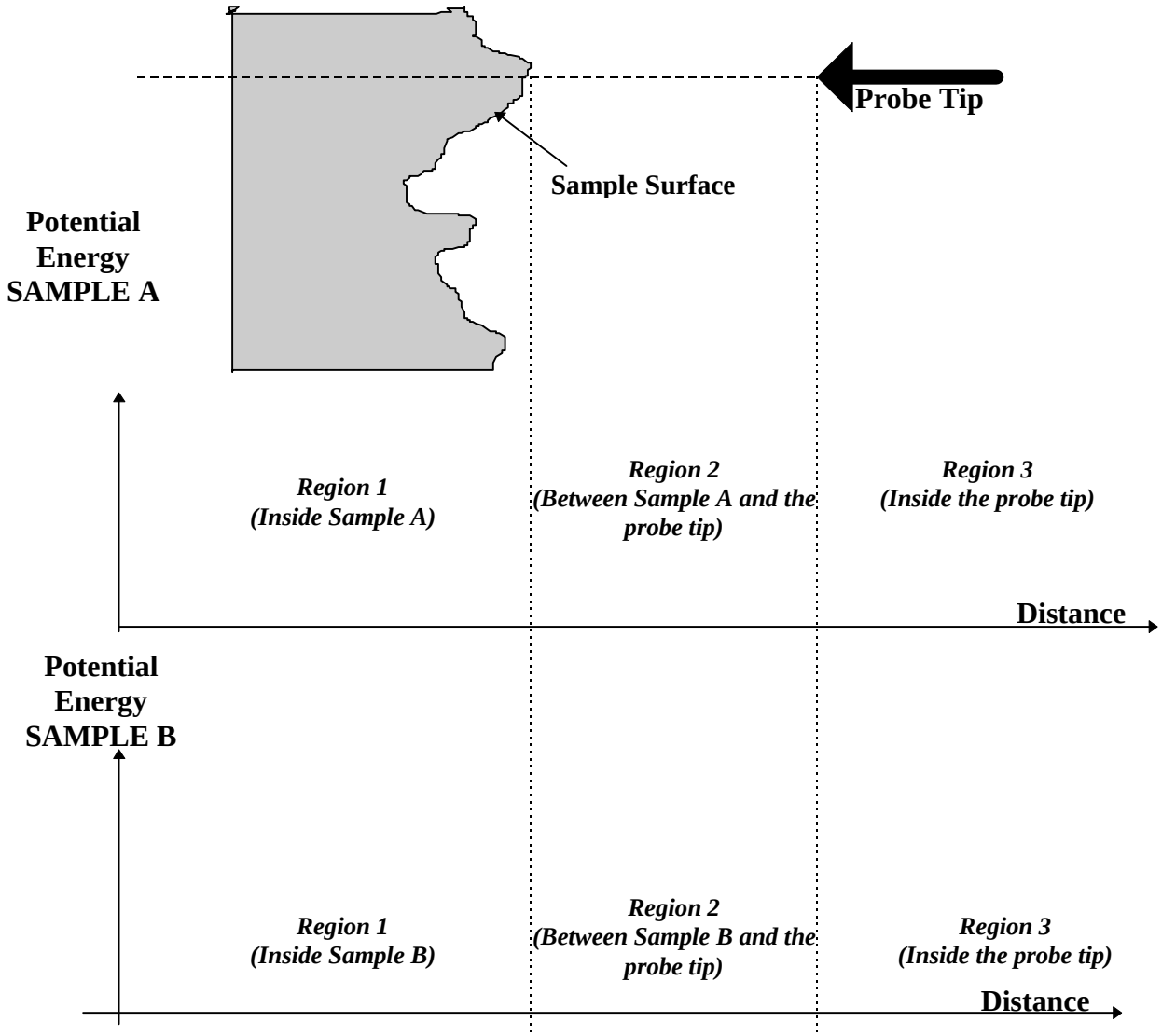
- Consider two identical samples each composed of different materials. Suppose that it is easier to extract electrons from sample A than from sample B. Sketch the potential energy diagrams for the electrons in each case.



Test your prediction using the *Scanning Tunneling Microscope Simulator* program. Use File/Open from the pull-down menu and, again, open the file *Image1.stm*. The file that you had saved with all its settings based on instructions in Activity 4 opens. Choose Settings/Options from the pull-down menu. In the dialog box that opens, change the parameter "Barrier Height" from 5eV to 8eV. The *barrier height* is a measure of the amount of external energy that is needed by each electron in the material to move from the material into the vacuum. The name "barrier" is used by physicists to describe this potential energy diagram because the diagram has a shape very similar to that of a visible object encountered by a physical barrier. The name can be misleading though because the electron approaches no physical barrier. However, "barrier height" is a common and convenient description of the energy difference between the sample region and the vacuum region.

- What changes do you observe in the potential energy diagram when the "barrier height" increases from 5eV to 8eV?

- What are the related changes in the wave function?

So far you have been exploring the effects of changing various parameters on the potential energy diagram and wave functions of the electron that tunnels from the sample to the probe tip.

Wave functions are rather abstract quantities that are not measurable by any means. Fortunately, we are not interested in the wave function itself, but in the number of electrons that actually travel from the sample to the probe tip.

The probability that an electron of a particular energy can tunnel from the sample surface to the probe tip is called *tunneling probability*. Now you will learn about various factors influencing tunneling probability and how it is physically measured.

- Based on your experience with wave functions of the tunneling electron, how will the tunneling probability change if the energy of the tunneling electron is increased?

Verify your results by opening the *Tunneling Probability* window of the program and using View/Tunneling Probability from the pull-down menu. Notice two graphs in this window. Look at the graph on the left, which shows the variation of tunneling probability with energy of the electron when the probe tip is at a constant voltage. We will focus on this graph.

- Does the graph agree with your prediction above? Explain.

Based on your experience with these wave functions of the electron, how will the tunneling probability change if we:

- increase the distance between the probe tip and the sample surface?

- increase the probe tip voltage?

- Explain your answers to the above questions by describing the effect of each change on the potential energy diagram.

To verify your prediction, observe the graph on the right side of the *Tunneling Probability* window (labeled Tunneling Probability vs. Tip Voltage). This graph illustrates the dependence of the tunneling probability on probe tip voltage.

- How does this graph change when you move the probe tip closer to the sample surface in the *Cross Section* window?

- How does the graph change when the energy of the electron is increased? (To change the electron energy, use the mouse pointer to move the horizontal dashed blue line in the *Potential Energy* window.)

So far we have been investigating the influence of various parameters on the tunneling probability of electrons. An increase or decrease in the tunneling probability will be observed as an increase or decrease in the number of electrons that reach the probe tip from the sample's surface.

One of the parameters that we examined was the electron energy. In a real scanning tunneling microscope, however, electrons with a range of energies will tunnel from the sample to the probe tip. A flow of these electrons constitutes a *tunneling current*, which can be measured. In fact, it is physically impossible to control a single electron and its energy. We will discuss a more realistic physical quantity – the tunneling current.

- Based on the relationship between tunneling probability and tunneling current as described above, how does the tunneling current change when the probe tip is moved closer to the surface of the sample? Explain.

- Suppose the probe tip were moved over the surface of the sample, along the horizontal line shown below. Consider your answer to the previous question and sketch a graph showing how the tunneling current would depend on the horizontal position of the probe tip.

To verify your prediction, open the *Current Profile* window, by using View/Current Profile from the pull-down menu. Click on the second button in the lower tool bar. In the *Cross Section* window, drag the probe tip to the far left side, placing it at a height just slightly above the highest point on the sample surface. While keeping the *shift* key pressed, drag the probe tip across to the right side. If you clicked the proper button in the lower tool bar, the probe tip will draw a straight, blue horizontal line across the graph. This action simulates moving the probe tip over the sample surface at a constant height. Now look at the graph in the *Current Profile* window which shows the dependence of the current on the position of the probe tip.

- How does the current profile compare with the cross-sectional view of the sample?

- Explain the observed relationship between the current profile and the cross section of the sample.

- Based on the correlation between the current profile and the cross-sectional view of the sample, explain how the scanning tunneling microscope generates an image of the sample.

In this activity, you have learned how the scanning tunneling microscope measures the contour of a sample's surface along a line. In the next activity, you will continue to use potential energy diagrams to investigate other applications of the scanning tunneling microscope.