ACTIVITY 7

Optional Activity

Another Application of Tunneling — The Tunnel Diode

Several electrical appliances — such as the television and telephone — use a built-in amplifier to magnify low-power electrical signals (sent from distant locations). While we will not be discussing the design of amplifiers in detail, some of these amplifiers use a device which acts like a negative resistor, that is, a device through which the current *decreases* when the voltage is increased. None of the devices that you have previously studied exhibit such behavior.

In this activity, you will learn about this device, called a tunnel diode, which is widely used in appliances where amplification is needed.

Objectives

After completing this activity, you should be able to:

- Measure the Current-Voltage (I-V) characteristics of a tunnel diode.
- Understand the relationship between the I-V characteristics and the energy band diagram of the tunnel diode.
- Understand how the I-V characteristics are explained by tunneling.

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The tunnel diode is housed in a small cylindrical metallic case with three leads. Only two of these leads, however, will ever be used simultaneously. Figure 7-1 shows how to connect the tunnel diode in a circuit. The tunnel diode that is supplied to you has the positive and negative terminals labeled.

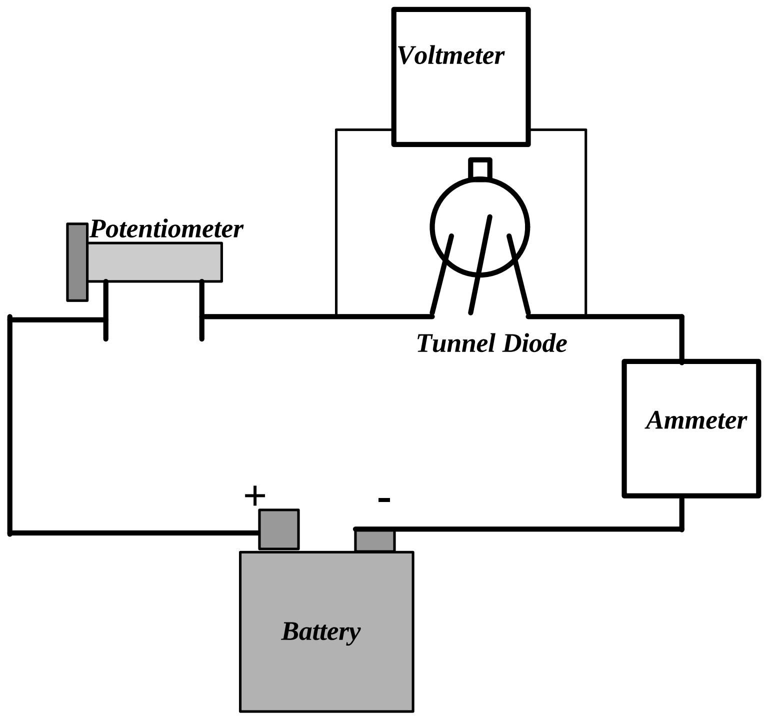


Figure 7-1: Circuit diagram for measurement of the tunnel diode

♦ Set the ammeter on the 20 mA scale and the Voltmeter on the 20 V DC scale. Watch the response of the ammeter and voltmeter as you *increase* the *current* (NOT the voltage) in steps of 0.1 mA, from 0 mA to 1.0 mA, by turning the potentiometer *counter-clockwise*. Record your observations in the table below.

Current (mA)	Voltage (V)
0	
0.1	
0.2	
0.3	
0.4	
0.5	
0.6	
0.7	
0.8	
0.9	
1.0	

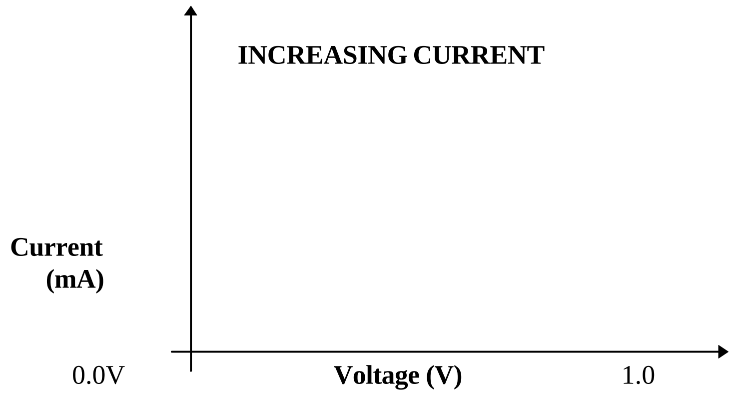
- Now *decrease* the *current* by turning the potentiometer *clockwise*, in steps of 0.1mA, from 1.0 mA to 0 ma. Use the same settings of the ammeter and voltmeter as before. Record your observations in the table below.

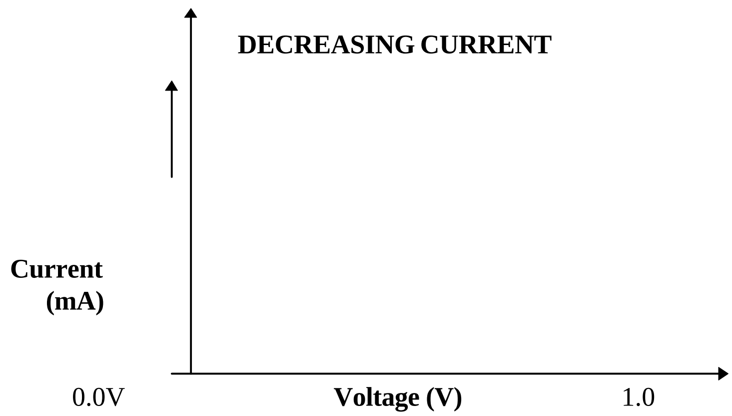
Current (mA)	Voltage (V)
1.0	
0.9	
0.8	
0.7	
0.6	
0.5	
0.3	
0.2	
0.1	
0.0	

- How did the voltage across the tunnel diode change when you increased the current? When you decreased the current?

- Choose a value of current (not 0.0mA or 1.0mA) and compare the measured voltage at that current from each of your tables above. Does the voltage measured at a particular current depend upon whether the current was increasing or decreasing?

♦ Plot your data on a current vs. voltage graph (I-V graph) for both the increasing and decreasing cases. Be sure to include a numerical scale on the *Current* axis.

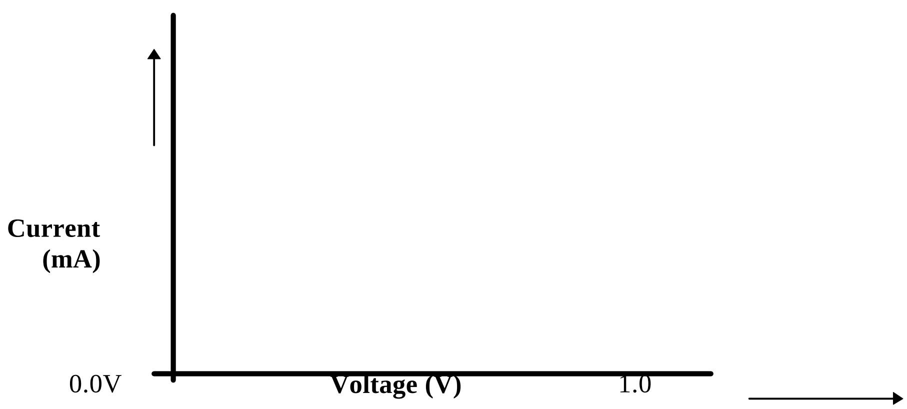




♦ How does the I-V graph for a tunnel diode differ from that of an LED studied in the *Solids and Light* unit? In what ways is it similar?

To understand the current-voltage curve that you obtained above, open the *Semiconductor Device Simulator* program by clicking on the icon. Click File/Open in the pull-down menu, and open the file *Tunnel_1.sds*. The screen will show a circuit that includes a tunnel diode. With the mouse pointer, click the black dot on the potentiometer (circle in the middle) and drag it in a circle, as if to rotate the knob. As you rotate the knob, you will see changes in the energy band diagram at the bottom of the screen. Next, click the Draw Graph button at the bottom right of the screen. The I-V graph for the circuit will appear in the top frame.

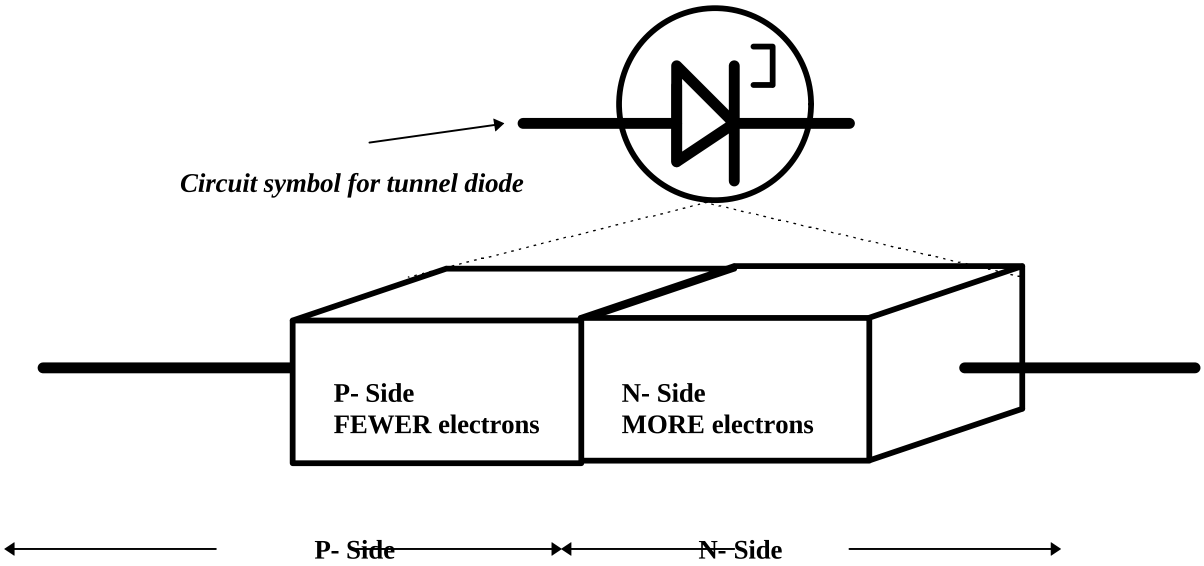
♦ On the axes below, sketch the current-voltage graph that you observed on the computer. If needed, "zoom" in on part of the graph by clicking the mouse at one corner of the area you want to expand, then drag the box to cover that area.



♦ How does the current-voltage graph from the computer program compare with the current-voltage graph that you sketched from your measurements recorded in the tables above?

To understand how the tunnel diode works, we must examine its internal construction.

A tunnel diode consists of two different solid materials that are joined together. These materials are chosen so that one of them possesses far more electrons than the other. Because electrons are negatively charged, the side with more electrons will have a more negative charge, and is therefore called the *N-side* (N for negative). The other side, which has a deficiency of electrons, will have a lack of negative charge, and hence is called the *P-side* (P for positive). An energy band diagram showing the allowed energies for both sides is shown in Figure 7-2.



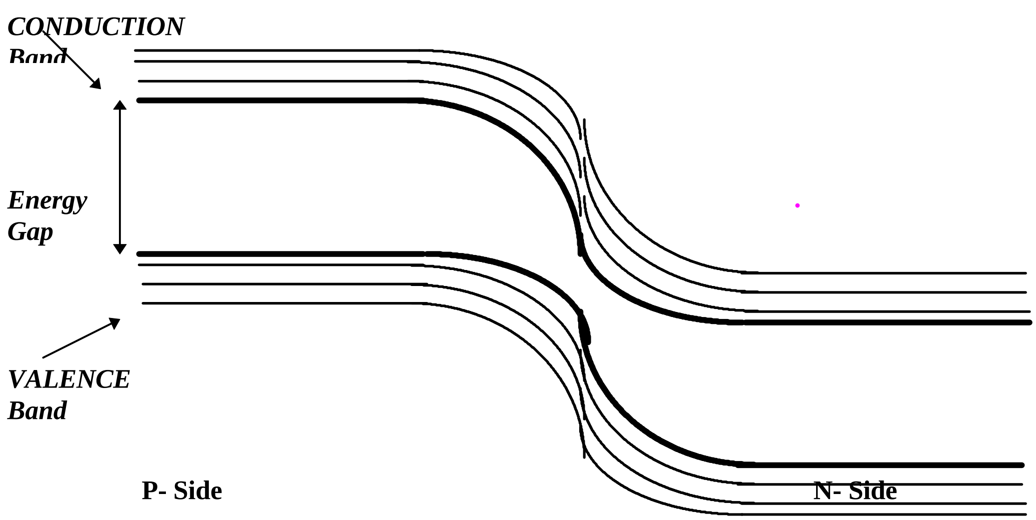


Figure 7-2: Energy band diagram of a tunnel diode

The excess electrons on the N-Side are not attached to the individual atoms, but rather are very energetic and free to wander throughout the N-Side. For the tunnel diode to conduct current, the electrons on the N-side (which has *more* electrons) should flow to the P-side (which has *fewer* electrons). The reverse cannot happen, because the P-side does not have as many free electrons as the N-side. Since the potential energy on the P-Side is *higher* than on the N-Side, the free electrons on the N-side must be supplied with additional energy if current is to flow across the junction.

- ♦ Use the energy band diagram (Figure 7-2) to determine how much additional energy is required. Label Figure 7-2 to indicate the amount of energy needed.

To verify your estimate of the amount of energy required, you will use the *Semiconductor Device Simulator* computer program again. Click File/Open in the pull-down menu and open the file *Tunnel_2.sds*. Notice the voltage applied across the tunnel diode by moving the scroll bar in the circuit diagram on the screen. The scroll bar is initially at 0.00 V indicating that no voltage is applied by the battery. Slowly move the scroll bar to the *left* (so that the applied voltage is *positive* up to +1.00 V) and observe the energy difference between the P and N sides in the energy band diagram at the bottom of the screen. To see the entire I-V graph click the Draw Graph button at the bottom right corner of the screen.

- How does the energy difference between the N-side and the P-side change when you increase the applied voltage from 0.00 V to +1.00 V?

- From the observed changes in the energy band diagram, at what voltage would the energy difference between the P-side and the N-side be equal to zero?

- What happens to the current when the voltage is increased to a value which is greater than the voltage needed to make the energy difference zero?

- What are the ranges of voltage (between 0 and +1V) where the current *increases* as the voltage increases?

- Try to explain the increase in the current in each of these ranges in terms of the energy level diagram.

- ♦ Were there any increases in current that you could not explain in terms of the energy level diagram (the changes in the difference in energies on the P and N sides)? If so, in which range(s) of voltage did they occur?

We have used potential energy diagrams to explain the operation of the scanning tunneling microscope. Let us use the same approach here

- ♦ From the energy band diagram that you see on the computer screen (similar to the one in Figure 7-2) try to predict how the potential energy diagram would look for an electron moving from the right side of the diagram to the left. Draw the diagram below.

- ♦ How does the potential energy diagram change when the voltage across the tunnel diode is increased?

Compare the potential energy diagram for a tunnel diode to that for the scanning tunneling microscope.

- ♦ How are they similar?

- ♦ How are they different?

- ♦ Use the potential energy diagram of a tunnel diode and its comparison with the scanning tunneling microscope to explain the reason for the increase in current in the tunnel diode which you could not explain in terms of the energy bands.

In this instructional unit, you have learned about a new physical phenomenon called quantum tunneling. Tunneling is a phenomenon in which an object which is originally present in one region, almost mysteriously appears in another region, in spite of the fact that the two regions are separated by a region where the potential energy of the object is greater than its total energy.

Tunneling can be explained by describing a particle as a wave. Only microscopic objects which are traveling extremely fast exhibit tunneling, because their de Broglie wavelength is comparable to the width of the region where their total energy is less than the potential energy.

In this unit, you also learned how tunneling is used in devices such as tunnel diodes that are commonly used in several appliances, as well as more sophisticated equipment such as the scanning tunneling microscope. You also learned how tunneling can be applied to create nanostructures which can revolutionize the world we live in.