

## Light Emitting Diodes

**Goal**

- To make measurements to describe the variation in light intensity with voltage for light emitting diodes.
- Use computer simulations to model the energy levels of light emitting diodes.
- To build a model to describe the processes by which semiconductors can be used to produce light.

### Introduction

A modern light source that requires low voltages is the light emitting diode (LED). LEDs are typically used as on/off indicator lights in electrical appliances such as televisions, VCR's, video cameras, computers, and stereos. They are also used to display numbers in some alarm clocks, radios, and microwave ovens. Another use is very large video displays at sporting events and concerts. For example, the music group *U2* during its 1997 *POPMART* tour was using a 56 feet x 170 feet video screen consisting of LEDs. In the 1997 movie, *Batman & Robin*, the Mr. Freeze costume worn by Arnold Schwarzenegger consisted of 3,800 blue LEDs to illuminate his appearance. The low voltage requirements needed to operate LEDs as well as their small size and mass make them an attractive light source to use for these applications.

### A. LEDs

A diagram of the inside of an LED is shown in Figure 1. The chip at the heart of the LED consists of a p-n junction --- two different solid materials that have been joined together. It is surrounded by a transparent, hard plastic that protects the LED from vibration and shock. The LED is constructed in such a way that the light emitted by the chip is reflected off the base it sits on and is focused through the top of the LED. Thus, the light is brightest at the top of LEDs.



Figure 1: Schematic Diagram of an LED

In this part of the activity, we will connect LEDs to an electrical energy source and investigate the effects of changing the amount of electrical energy supplied to them. The apparatus uses a small battery as an energy source. The amount of energy supplied to the LED is controlled by a potentiometer — a small rectangular device with a screw on one end. The apparatus is shown below in Figure 2.

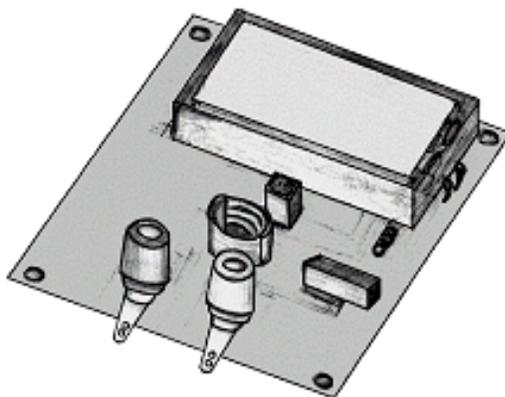


Figure 2: The circuit board for the LED.

We will measure light intensity as a function of voltage. Both variables will be recorded by the computer. Start *Science Workshop* and set it up so that it will measure voltage and light intensity, record the data in a table, and plot intensity vs. voltage.

Check the setup by inserting the incandescent lamp in the socket. Connect the voltage measuring wires to the clips on the board and hold the light sensor near the lamp. (Note: you may need to adjust the gain switch on the sensor.) To vary the energy supplied to the incandescent lamp turn the screw of the potentiometer by using the tiny screwdriver. Either end of this screwdriver can be used. However, the end where the blade of the screwdriver is recessed in a cavity is easier to use. The diagram in Figure 3 shows how to increase and decrease the energy.

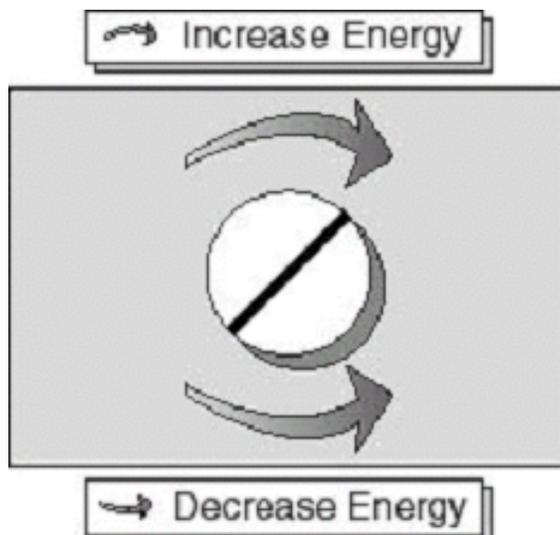


Figure 3: side view of the potentiometer.

A-1. Remove the incandescent lamp from its socket and place LEDs assigned by your instructor in the LED holder. Record sufficient data to describe the variation in light intensity with voltage.

A-2. Record your data on a floppy disk so that it can be shared with others.

## B. p-n junctions

A solid can be a pure material in which all atoms are the same element. As a result, each nucleus of the atom contained in this solid has the same electrical charge. Thus, each atom in this solid has identical properties. The interactions among these atoms create the energy bands and gaps that we have studied. Modern technology can create materials that are very close to being all identical atoms. These pure materials have light emitting properties much like we have studied here.

For today's technology pure materials are not the most valuable. Instead, a wide range of devices — from LEDs to computer chips — use almost pure materials into which an *impurity* has been introduced. Then materials with different impurities are joined.

Suppose we start with a pure material and add atoms of a different element. These different elements will have a different number of electrons than the atoms of the original material. We place the impurities into two groups:

- *Donors*, or n-type, have more electrons than the material's pure elements. They donate electrons to the solid.
- *Acceptors*, or p-type, have fewer electrons than the material's pure element. They accept electrons from the solid.

Both the donors and acceptors have zero electrical charge. They have more or less charge in the nucleus to balance the more or fewer electrons.

The LED chip consists of two solids — a material that has been supplied with donor atoms and the same material that has been supplied with acceptor atoms. The combination is called a p-n junction.

## C. Simulating Energy Levels in LEDs

We will now use the *LED Constructor* computer program to understand how these two materials are combined to construct an LED. Open the *LED Constructor* computer program. Notice that on the left of the screen is an illustration of 6 different LEDs and a version of the circuit apparatus that we used in part A when we explored the properties of LEDs. On the right of the screen are the two blocks of material that simulate the LED chip with an energy scale below the blocks and an output spectrum illustrated above the blocks.

In this program, we can:

- Select an LED and drag it to the power supply (LED socket).
- Create an energy band diagram for each of the two parts of the p-n junction.
- Add donors or acceptors to each part of the p-n junction with a click of the mouse on the the Add Impurities button and merge them together to create the LED chip.
- Control the voltage applied across the LED by moving the slider.

When the voltage is appropriate, transitions (represented by a vertical arrow) will occur and light will be emitted, and a corresponding spectrum will appear.

Drag the LED assigned to you by the instructor to the LED socket. The energy bands that appear on both sides of the energy scale represent the bands and gaps for materials associated with these LEDs.

Notice that the valence bands of both semiconductor materials are shaded darker than the conduction band. This shading indicates that the majority of electrons have energies associated with the valence bands. Electrons are naturally found in these bands because they seek the lowest possible energies. Also notice that energy of the energy gaps of both blocks are the same to represent that the LED is constructed of two blocks of the same semiconductor.

C-1. Record the color of the LED you were assigned and the energy (in eV) of the energy gap.

Now, click on the **Add Impurities** button. This places acceptors in the left block and donors in the right block.

C-2. How does adding acceptors — atoms with fewer electrons — affect the energy bands of the left block?

C-3. What is the effect on the energy bands of adding donor atoms to the right block?

C-4. Do the sizes of the energy gaps for either semiconductor block change as donor or acceptor atoms are added?

- C-5. A material that has donor atoms has more electrons than one with acceptors. When these two materials are joined together, the electrons can move from one material to the other. Which way would you expect the electrons to move? Why?

To see the effect of this process on the energy bands, click the **Merge** button to bring the two semiconductor blocks together and, thus, create a “chip” that makes up the LED. Figure 4 illustrates the screen that should appear.

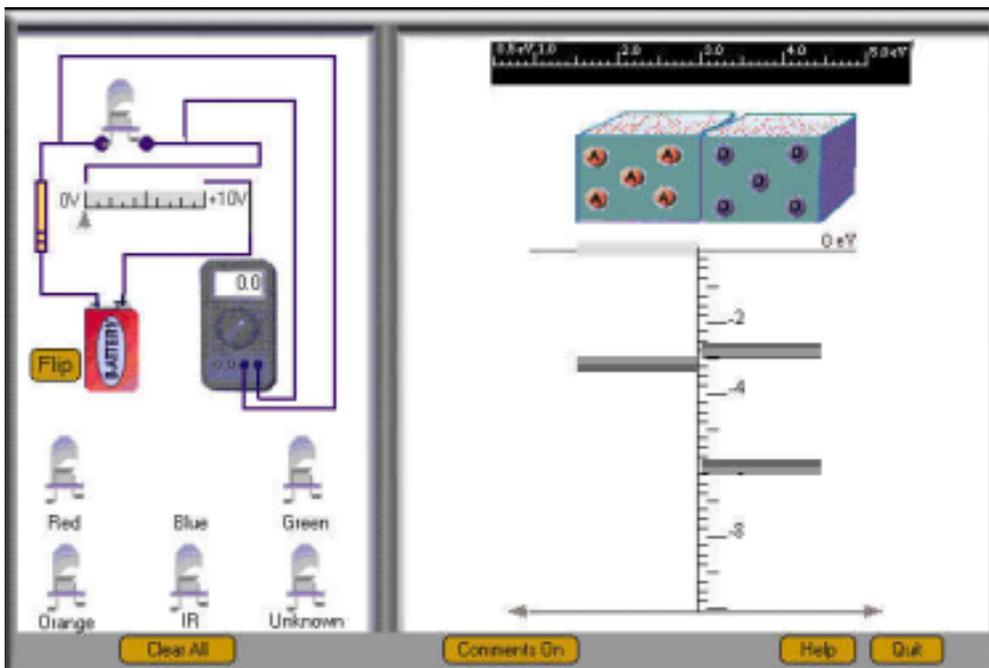


Figure 4: The screen of the LED Constructor after merging two semiconductor blocks.

As you see, the bands and gaps shift from their usual energies. This shift is a result of the movement of electrons from one material to the other.

- C-6. Compare the energy diagram for your LED with the diagrams of other students who used different LEDs.

- How are they similar?
- How are they different?

The situation that is now represented on the screen is equivalent to an LED that is not connected to an energy source. The energy diagram for the merged material is similar to Figure 5.

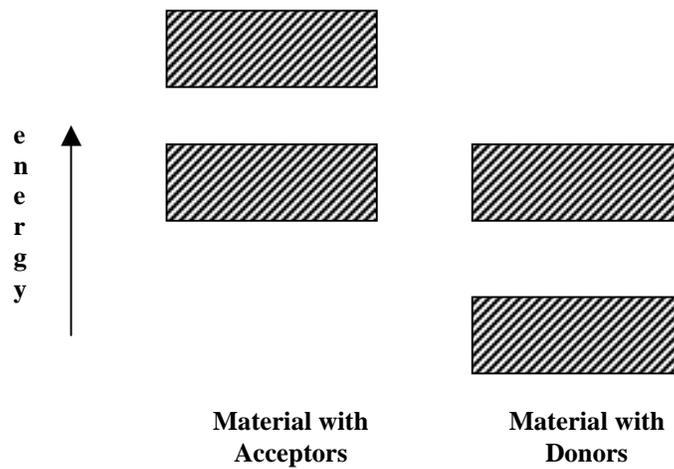


Figure 5: Energy level diagram for a chip made of a material with acceptors and a material with donors.

In this situation extra electrons are still available on the right (donor) side. However, they cannot change energies from the conduction band to valence band in the donor side. All of the valence energies are already filled with electrons. We must move the electrons to the other material where the change in energy is easy.

Now, we wish to apply a voltage to the LED and see what happens to

- the energy levels in both materials, and
- the light emitted.

C-7. Use the slider control (upper left) to vary the voltage (input energy) applied the LED. The energy diagrams show how the energy level responds to the voltage. What is the effect on the energy bands as the applied voltage changes from 0.0 Volts to +1.0 Volts?

C-8. To apply a negative voltage we need to flip the LED and place it in the circuit with the wires reversed (long lead on the right). Use the flip button to reverse the LED. What is the effect on the energy bands as the applied voltage changes from +1.0 Volts to -1.0 Volts by flipping the LED?

C-9. For which of the two applied voltages (-1.0 Volts or +1.0 Volts) would it be more likely for the electrons to move from the conduction band of the right block to the conduction band of the left block? Explain.

Reverse the LED again by flipping it so that the long lead is on the left, and move the slider to the minimum voltage necessary for the LED to begin emitting light.

C-10. What happens to the energy bands of the two semiconductor blocks when the threshold voltage is applied to the LED?

C-11. Record the threshold voltage displayed on the voltmeter. Indicate the LED that you were assigned.

C-12. Record the range of color(s) and energies (in eV) of the output spectrum of your LED.

C-13. Compare your results with others in the class.

- How are all results similar?

- How are they different?

Since the energy bands on the material with acceptor atoms are higher than the bands of the material with donor atoms, the excess, free electrons found in the conduction band of the right block must be supplied additional energy to move to the conduction band of the left block which has a deficiency of electrons. Electrons cannot flow from the left block to the right block because there are not many free electrons on the left block.

## D. Light, Electrons and Semiconductors

When a battery is properly connected across an LED and when the electrical energy (voltage) supplied by the battery is increased, the difference in energy between the right and left energy bands decreases. As the difference in energy decreases, the likelihood of the free electrons moving from the right block to the left block increases. When the appropriate voltage (threshold voltage) is applied, the right and left energy bands reach the same energy level, and the free, energetic electrons of the conduction band of the donor material move to the conduction band of the acceptor material which has fewer electrons. Once there, the energetic free electrons collide with atoms and dislodge their electrons. The dislodged electrons have energies in the conduction band. Within a very short time, however, they are recaptured by their atoms and lose their energy in the form of light emitted by the LED while making the transition to the valence band as shown in Figure 6.

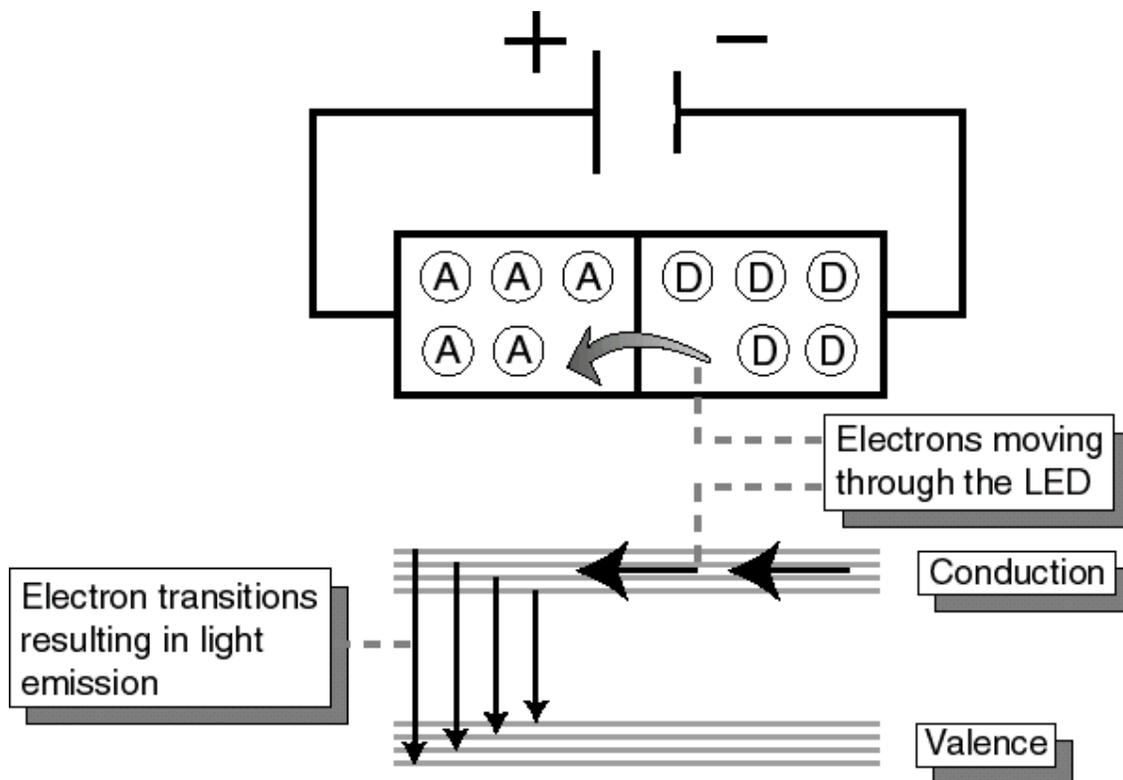


Figure 6: Energy Band Diagram of an LED Emitting Light at the Threshold Voltage

The free and excess electrons (which are negatively charged) of the material with donor atoms must be pushed toward the material with acceptor atoms. When a battery is properly connected to an LED, it supplies these excess electrons with sufficient electrical energy to go to the acceptor side of the chip. Because the negative terminal of the battery repels electrons, the donor side must be connected to the negative terminal of the battery so that the excess electrons are pushed to the acceptor side.

The short lead of the LEDs is connected to the side of the LED chip that contains the semiconductor with the donor atoms. The long lead connects to the side of the LED chip that contains the semiconductor with acceptor atoms.

When the positive terminal of the battery is connected to the donor side atoms, the free electrons are attracted to the positive terminal of the battery instead of being pushed into the acceptor side. This situation is shown in Figure 7. They have insufficient energy to reach the acceptor side. They can only emit light on the acceptor side, so no light is emitted.

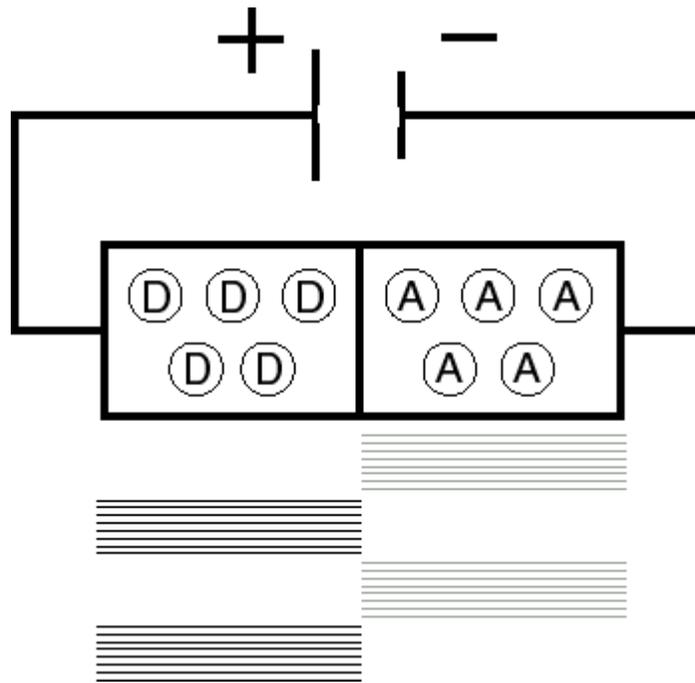


Figure 7: Placing the LED in backwards results in the available electrons on the donor side having insufficient energy to move to the acceptor side. No light is emitted.

In our energy level model we have assumed that electrons in a solid acquire and lose energy. Our energy level model of how an LED works, like all models, has limitations. It is not perfect and should not be considered a description of all processes that occur in an LED. The model, however, does enable us to explain the general nature of the phenomena that we observed and gives us a general idea of how an LED works at the atomic scale.