Name Partners Date

The Great White LED

Goal
In this tutorial we will investigate the properties of an unusual light emitting diode – one that emits white light. Then, we will construct and test some models to explain how this device works at the atomic level.

Introduction

LED, short for Light Emitting Diode, has become a common household name. Traffic lights, alarm clocks, and now even big screen megatrons are constructed of LEDs. Since LEDs are fairly bright and are extremely energy efficient, white LEDs could provide bright light at a low cost. This is a reason why white LEDs are an interesting specimen: they could be used for lighting. How do we construct a white LED? On one hand, LEDs only emit certain parts of the spectrum depending on the color of the LED, but on the other hand, white light consists of emission from the entire spectrum. Contradiction? Let us examine the premises.

A. Observations of LED Properties

Light sources (for example LEDs, incandescent lamps and Christmas tree lights) have a number of observable properties we can use to build models of how they work. We will examine two properties of several different types of LEDs:

1. The threshold voltage and
2. The spectrum of light produced

By analyzing and comparing our observations we will be able to determine how a white LED works.

Threshold Voltage

The threshold voltage is the voltage required for the light source to turn on. Using a simple circuit, a multi-meter, a battery and a selection of LEDs make some measurements of threshold voltages.

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A-1. Complete the table below.

LED color	Threshold Voltage

The energy of light is related to its color, we usually represent this relationship using the equation below:

$$E = hf$$

Where E is the energy of the light, h is Planck's constant ($h = 4.14 \times 10^{-15}$ eV.s) and f is the frequency of the light.

A-2. Examine your table of the LED threshold voltages. Do your measured threshold voltages correlate with the energy equation? Please explain why/why not.

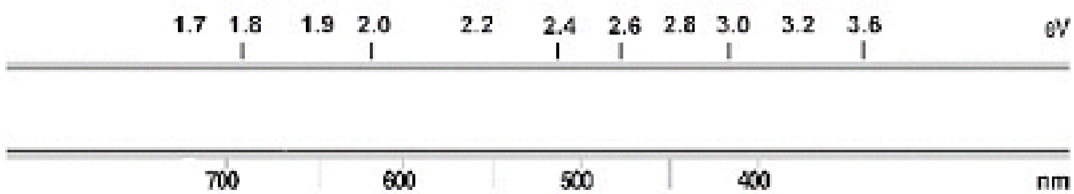
A-3. How does the white LED compare to the others in terms of threshold voltage?

A-4. What predictions can you make about the white LED based on its threshold voltage?

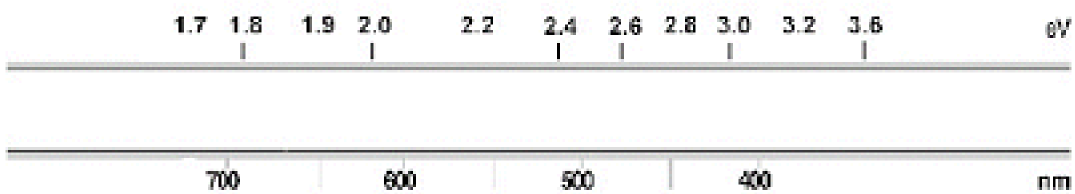
Spectra

The spectrum emitted from a light source provides information that can help us build an energy model of the light producing process. Examine the spectrum from three of the LEDs provided - include the white LED as one of the three. Accurately sketch the spectra you observe on the scales provided below:

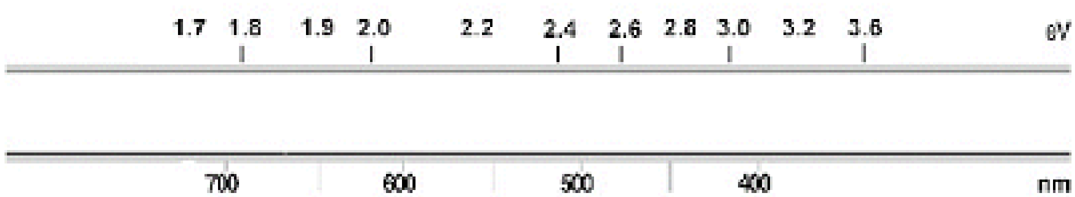
A-5. ________ color LED



A-6. ________ color LED



A-7. ________ color LED



NOTE: If you have not already developed an energy model for LEDs or would like to review this material, please complete Appendix 1 before continuing with part B.

B. Building an Energy Model for the White LED

For the moment let us assume that a white LED works just like any other LED except for the color of light it emits. The model we have developed for red, blue, green and orange LEDs consists of two energy bands – the conduction band and the valence band- and electrons moving from the conduction to the valence band emit light with a range of energies.

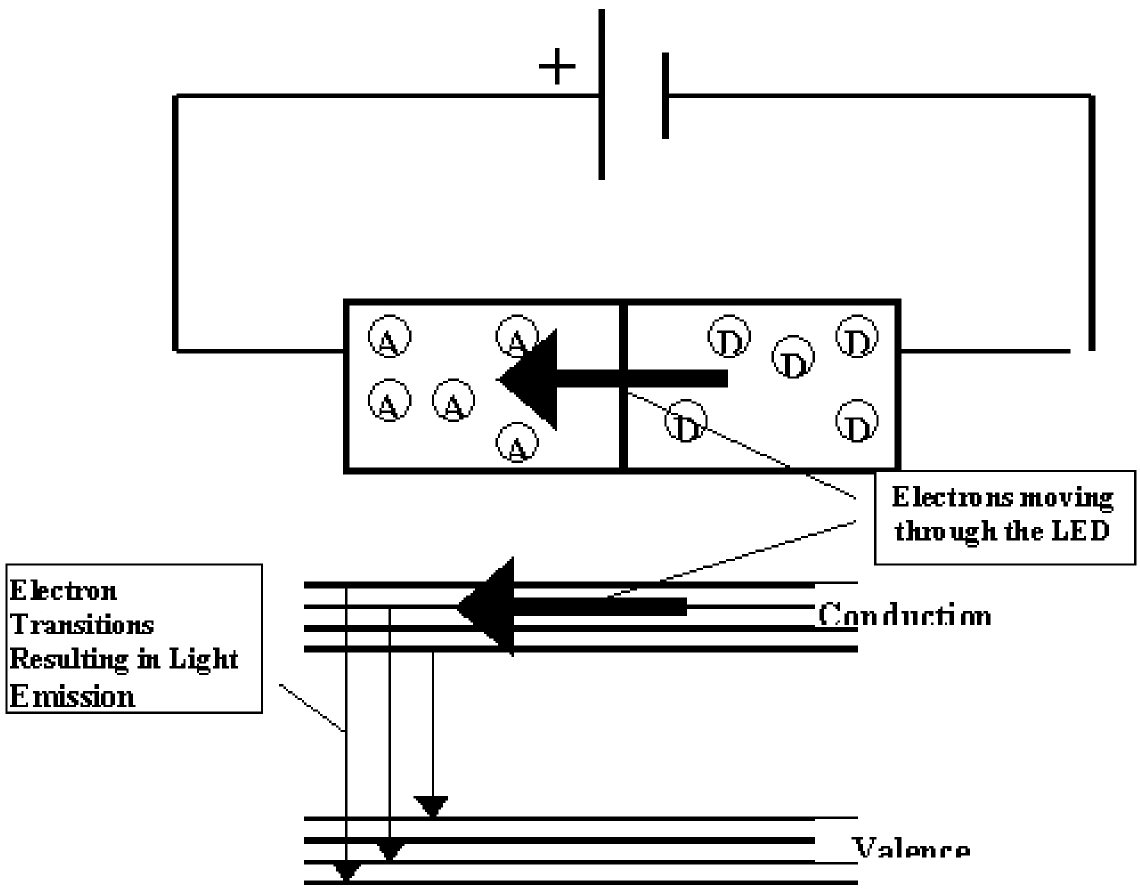


Figure 1. Energy band diagram of an LED emitting light at the threshold voltage

Open the program *Spectroscopy Lab Suite* and select *LEDs* from the menu. Choose an LED from the bottom left-hand corner. Click on the *Add Conduction Band* button and then the *Add Valence Band* button. Manipulate the conduction and valence band widths and the size of the band gap until the real and simulated spectra match.

B-1. What effect does changing the size of the band gap have on the spectrum?

B-2. How does changing the width of the bands affect the spectrum?

Now manipulate the energy bands so the simulated spectrum is the same as the spectrum you observed for the white LED.

B-3. Sketch the band structure for your simulated LED below. Show energy values on the vertical axis where appropriate.

B-4. From your diagram calculate the following:

Energy Level	**eV**
1. Bottom of the conduction band	
2. Top of the valence band	
3. Difference between 1 & 2 (smallest difference in energy)	
4. Top of the conduction band	
5. Bottom of the valence band	
6. Difference between 4 & 5 (largest difference in energy)	

B-5. Does this energy model fit with your white LED threshold voltage measurement? Please explain your answer.

Using what you know about the way LEDs produce light and your observations of the white LED so far discuss with your classmates potential models for a white LED.

B-6. After consulting with your classmates, select the white LED model you like the best. Describe and or sketch the model as completely as you can below.

B-7. Give an outline for possible experiments you could do to test the validity of your model.

C. Testing possible models for the white LED

Model 1

One possible model may be that the white LED is made up of three different LEDs: red, green and blue. The LED would have to be specially constructed so that when a voltage is applied, the three LEDs light up and the mixture of light produced is white.

C-1. What would you expect the threshold voltage to be for a white LED made up of a combination of red, green and blue LEDs?

C-2. You have been provided with a “bi-color” LED. Using your circuit and multi-meter measure the threshold voltages of each type of LED. How could you get both LEDs to light up at the same time? What color would you see?

C-3. Do you think the white LED you have tested is made from a combination of red, green and blue LEDs? Please justify your answer.

NOTE: If you have not already developed an energy model for fluorescence or would like to review this material, please complete Appendix 2 before continuing with Model 2.

Model 2

Another possible model is that the white LED produces its wide spectrum by a fluorescence process. This means that the white LED has an initial energy source that excites the electrons in a special fluorescent coating leading to the emission of photons with a broad range of energies.

C-4. Based on your threshold voltage measurements what do you suspect the initial energy source to be?

C-5. Examine the white LED very closely at the threshold voltage. Describe what you see. Do your observations correlate with your answer to C-4?

Using the program *Spectroscopy Lab Suite* select *Fluorescence* from the menu. Try and set up an energy diagram that shows how the white LED works.

C-6. After consulting with your classmates draw an energy band diagram for the white LED below:

D. Conclusions

D-1. Write two paragraphs describing how you think a white LED works. Summarize the direct observations and measurements you made and what conclusions you drew from these observations.

Appendix 1 – Primer on LED energy models

Use a spectroscope to carefully examine the light emitted by several LEDs. Open the program *Spectroscopy Lab Suite* and select *Emission* from the menu. Place the gas lamp labeled "unknown" in the gas lamp socket.

When the unknown lamp is in the socket you can create any spectrum you wish by clicking on the *Edit* button and typing in up to 5 specific spectral lines. Use this function to generate a spectrum that resembles the spectrum emitted by one of the LEDs. Make a note of the spectral lines values you selected below.

Q-1. ________ color LED

Line	Energy (eV)
1	
2	
3	
4	
5	

Add energy levels and transitions on the right-hand side of the screen. Make an energy level model for your LED spectrum.

Q-2. Sketch the energy level model below; include energy values on the vertical scale where appropriate.

The energy level model for LEDs is different to gases primarily because LEDs are solid. The close interaction of atoms in solids results in very closely spaced energy levels or *energy bands*. There are two types of energy bands in solids:

- Conduction Band – This band has the highest energy and contains electrons that cannot leave the solid but are not firmly attached to any atom.
- Valence Band – This band contains electrons that are bound to their respective atoms more strongly and are unable to break free.

We will now select *LEDs* from the *Spectroscopy lab Suite* program menu. Choose a LED from the bottom left hand corner of the screen and drag it into the socket. Click on *Add Conduction Band* button and then *Add Valence Band* button. Two bands should appear on the energy diagram on the right hand side of the window.

The real spectrum of the select LED and the simulated spectrum (from the energy diagram) should be visible. You can change the energy diagram in two ways:

1. Move either of the two bands up and down and/or
2. Change the width of either band.

Experiment with these two parameters and try to match the real and simulated spectra.

Q-3. Try moving either the conduction band or the valence band up and down. What changes to you see to the simulated spectrum?

Q-4. How does changing the width of the bands affect the output spectrum?

Q-5. Sketch the energy band diagram for the selected LED below. Include energy values on the vertical axis where appropriate.

The energy bands in LEDs are like energy lines in gases but much more concentrated. Electrons can jump from any point of the conduction band to any point in the valence band. Based on this fact, the output spectrum should consist of the energies ranging from the smallest to the largest difference in energy between the two bands. The threshold voltage should be equal to the "energy gap" between the two bands.

Appendix 2 - Primer on Fluorescence

Fluorescent materials emit light when light is shined upon them. Open the *Fluorescence* program in *Spectroscopy Lab Suite*. Click on the *Create Excited State Band* button. This is the excited energy state valence atoms transition into when a certain amount of energy has been received. Now, click on the *Create Impurity State Band* button. This band serves as a midway transition point for atoms returning from the excited state back to ground state. No light is emitted during transition from conduction band to impurity band; heat is generated during this stage. Light is only emitted during the transition from the impurity band to the valence band. Adjust the input spectrum on the bottom left hand side of the window. As you drag the slider, a golden pointer will appear on the right side of your energy scale next to the transition diagram. Observe how much energy is needed to turn on the lamp by clicking on the *Turn on Lamp* button.

Q-1. How much energy is required to turn on the mercury lamp?

Q-2. How does this amount relate to the valence band energy and the conduction band energy?

The input energy needs to be greater than the energy gap difference between the conduction band and the valence band for the mercury lamp to turn on.

Q-3. Turn on the lamp. The mercury gas should change its color depending on the input spectrum, but does the phosphor coating depend on the input spectrum as well? Try changing the input spectrum. What differences, if any, are there in the output spectrum or the color of emitted light?

Q-4. We now see that the color of the light does not depend on the input spectrum, at least not directly. Now, try modifying the placement of the conduction band. What changes occur in the output spectrum?

Changing the placement of the conduction band may require a higher input energy, but the change does not affect the output spectrum. Now modify the placement of the impurities band.

Q-5. What changes occur now?

Q-6. How does the output spectrum correlate to the different energy levels?

Q-7. Now that we know the output spectrum has something to do with the impurities band, let's make some simple calculations to see which transition produces light. Note: the following may be ranges of numbers.

- Energy level of conduction band
- Energy level of impurities band
- Energy level of valence band
- Output spectrum energy
- Energy level of conduction band – energy level of impurities band
- Energy level of impurities band – energy level of valence band

The transition from impurities band to valence band is the transition that produces the output spectrum. The energy from the transition from conduction band to impurities band produces heat instead of light.