MRSEC Education and Outreach

# *Light Emitting Diodes (LEDs) Activity Guide*

## **Quick Reference Activity Guide**

### *Activity Materials*

LED miniature flashlight
LED color strip
Blue LED circuit
Lamp with incandescent light bulb

### *Starting Points*

What is light? Light is a form of energy. Light that is seen by the human eye is called visible light. Light is a wave and has amplitude and wavelength. The amplitude is the height of the peak of the wave, and the wavelength is the distance from one peak to another. White light is the result of near equal amounts of the entire visible spectrum or near equal amounts of red, green, and blue light.

How does an incandescent light bulb work? A wire filament is heated by passing an electric current through it. It works on the principle that any material heated to a high enough temperature will glow. The color of light given off depends on the temperature of the object being heated.

What is a diode? A diode is a semiconductor device that allows electricity to flow in only one direction. They are used in various ways including as rectifiers to convert alternating current into direct current, as sensors to measure light intensity as photodiodes, and as sources of light as light emitting diodes, LEDs, the subject of this activity guide.

Have you ever seen a LED? Where? How was it being used? LEDs have been used for many years as indicator lights and in digital displays. Today very bright LEDs are used in flashlights and traffic lights. Soon super bright white LEDs will appear as headlights in motor vehicles.

### *Demonstration Procedures*

Touch the battery to the color strip. Make sure the LEDs are pointed at the audience and then disconnect the battery. Which LED goes out first? Next? Last? The order in which the LEDs go out is the order of the energy required to cause the LED to emit light with the LED requiring the most energy going out first.

Re-connect the battery to the color strip. Place a hand near the LEDs. Repeat with the battery-energized incandescent bulb. Do you feel any difference in the amount of heat radiated? Incandescent bulbs generate light by heating a wire filament. Thus, they get hot when operating. LEDs generate very little heat when emitting light.

With a volt-ohm meter, measure the voltage required for each LED. Connect the black lead of the meter to the common test point, TP1. Then connect the red lead to TP6 for the blue LED, TP5 for the green LED, TP4 for the yellow LED, TP3 for the orange LED, TP2 for the red LED, and TP7for the infrared LED. The order of increasing voltages is the order of increasing energy required for emitting light from the LED. The amount of energy is called the band gap energy.

Examine the blue LED circuit. The resistor connected between the red lead of the battery snap and the LED limits the current reaching the LED, preventing its destruction.

## Fact Sheet

LEDs are small, a few tenths of a millimeter for the semiconductor itself.
They have low energy consumption, ~10% of the energy of an incandescent bulb.
LEDs can last up to 100,000 hours (>10 years).
They produce little heat with the emitted light, allowing use in very small spaces.
LEDs are composed of atoms of elements from Groups 13 and 15, so-called III-V semiconductors.
More specifically they are made of n-type and p-type semiconductors that form a p-n junction where they are in contact.

- Light is emitted from the side of the chip, at the p-n junction.
- n-type semiconductors are created by doping that region of the device with a small quantity of an element that is electron-rich compared to the bulk of the semiconductor, e.g., replace a Group 15 element with a group 16 element dopant.
- p-type semiconductors are created by doping with a small amount of an electron-deficient element compared to the bulk of the semiconductor, e.g., replace a Group 13 element with Group 12 element.

Most LEDs are made by Organometallic Vapor-Phase Epitaxy (OMVPE, also known as Metal-Organic Chemical Vapor Deposition, MOCVD), which allows controlled growth of thin semiconductor layers.
The color of the light depends on the chemical composition of the semiconductor chip. Smaller atoms lead to higher energy light of shorter wavelength.
LEDs often have zinc blende or wurtzite crystal structure, derived from the diamond structure.
Some common LED compositions are $GaAs_xP_{1-x}$ , $Ga_xIn_{1-x}P$ , $Al_xIn_{1-x}P$ , $Al_xGa_yIn_zP$ , and $Ga_xIn_{1-x}N$.
Atoms with subscripts can substitute for one another in the original structure allowing the color of the emitted light to be tuned.

### Applications

*Traditional*

- Indicator lamps.
- Infrared remote controls for TVs, VCRs, etc.

*Current*

- Vehicle brake lights and turn signals– light 200 milliseconds faster than incandescent bulbs, alerting trailing drivers sooner; 19 ft more stopping distance at 65 mph.
- Message boards – vary from small, single color boards, to bicolor LEDs, to tricolor LEDs, to a combination of 19 million LEDs in the NASDAQ Tower in Times Square New York (varying numbers of red, green, and blue LEDs).
- Sports replay screens – a combination of 2.5 million LEDs in the Donald Reynolds Razorback Stadium replay screen in Fayetteville, AR (varying numbers of red, green, and blue LEDs).
- Traffic signals (including turn signals and walk lights) – save energy (12-25W vs. 135W) and maintenance costs (incandescent bulbs must be changed annually at ~$250/intersection); payback period through energy and maintenance savings with LEDs is less than 2 years.
- Flashlights.
- Holiday lights.

*Future*

- Vehicle headlights.
- Replace most, if not all, incandescent and fluorescent lighting, both residential and commercial.

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## Background and Supporting Information

Materials are divided into three categories: conductors, insulators, and semiconductors. In extended solids the electrons in the chemical bonds occupy filled energy levels ("valence band"). Electrons can gain energy and be excited from bonds into higher, unoccupied energy levels (" conduction band"). The energy difference between the valence band and the conduction band is called the band gap. In metals, the band gap is very small or non-existent and electrons can easily move between bands, thus metals are conductors. Insulators have a large band gap and the electrons cannot readily gain the energy required to move to the conduction band. Semiconductors have small band gaps that allow them to conduct an electric current when a small amount of energy is added to the material. Light-emitting diodes (LEDs) are made from semiconductors.

Semiconductors can be pure elements, like Si and Ge; compounds of AZ stoichiometry that have the same number of valence electrons as Group 14 elements, like GaAs, ZnSe, CuBr, etc; and alloys of three or four elements that have the same number of valence electrons as Group 14 elements, like $GaP_xAs_{1-x}$ ($0 \leq x \leq 1$), $Al_xGa_{1-x}As$ ($0 \leq x \leq 1$), $In_{0.06}Ga_{0.94}N$, $Al_xGa_yIn_zP$ ($(x + y + z) = 1$), etc.

An ordinary incandescent light bulb generates light by passing an electric current through a metal filament, usually tungsten. The electric current heats the wire, and, when it gets hot enough, above 2000-3000ºC it begins to radiate visible light. LEDs emit light when a current is passed through a semiconductor chip. The passage of the electric current through the semiconductor causes light to be emitted with little generation of heat. Thus, LEDs are far more efficient as sources of light than incandescent bulbs.

LEDs are produced by techniques such as Organometallic Vapor-Phase Epitaxy (OMVPE, also known as Metal-Organic Chemical Vapor Deposition, MOCVD) that allows controlled growth of semiconductor layers. They are composed of an n-type and a p-type semiconductor. The n-type material is created by adding a small quantity of an element that has one more electron than that comprising the bulk of the semiconductor. Introducing a small amount of an element that is electron deficient compared to the bulk of the semiconductor creates the p-type material. These processes are called doping. The two types of semiconductors are layered, and the interface between the layers is called a p-n junction. When an electric current passes through an LED, electrons move from the n-type material, holes move from the p-type material, and electrons and holes re-combine at the p-n junction. Energy in the form of light is emitted when the electron and hole re-combine because the electron is moving from a higher energy state in the conduction band to a lower energy state in the valence band. The wavelength of emitted light depends on the size of the band gap in the semiconductor. A larger band gap leads to more energetic light with a shorter wavelength.

LEDs emit light of many colors, from red to violet, depending on the composition of the semiconductor material used. Some even emit light outside of the visible spectrum, i.e., infrared and ultraviolet. The protective plastic cover over the semiconductor chip may be tinted, but this will not affect the color observed from the LED if the lens color is the same as the emitted color.

In the early 1990s, Dr. Shuji Nakamura was successful in producing a blue LED, which opened up the possibility of full color displays by color mixing: red + green = yellow; green + blue = cyan; red + blue = magenta; and red + green + blue = white. A white LED, as used in flashlights, can also be created by using a blue LED to emit light that is then partially absorbed by a phosphor that emits in the yellow range of the spectrum. The combination of blue and yellow appears white: blue + yellow = blue + (green + red) = white.

**Table 1.** Chemical Composition of Commercial LEDs.

| Color | Wavelength (nm) | Composition |
|---|---|---|
| Blue | 470 | $In_{0.06}Ga_{0.94}N$ |
| Green | 556 | $GaP_{1.00}As_{0.00}$ |
| Yellow | 578 | $GaP_{0.85}As_{0.15}$ |
| Orange | 635 | $GaP_{0.65}As_{0.35}$ |
| Red | 660 | $GaP_{0.40}As_{0.60}$ or $Al_{0.25}Ga_{0.75}As$ |
| Infrared | 700-1000 | GaAs |

**By the end of the 12th grade, students should know that***

- Electromagnetic forces acting within and between atoms are vastly stronger than the gravitational forces acting between the atoms. At the atomic level, electric forces between oppositely charged electrons and protons hold atoms and molecules together and thus are involved in all chemical reactions. On a larger scale, these forces hold solid and liquid materials together and act between objects when they are in contact—as in sticking or sliding friction.
- There are two kinds of charges—positive and negative. Like charges repel one another, opposite charges attract. In materials, there are almost exactly equal proportions of positive and negative charges, making the materials as a whole electrically neutral. Negative charges, being associated with electrons, are far more mobile in materials than positive charges are. A very small excess or deficit of negative charges in a material produces noticeable electric forces.
- Different kinds of materials respond differently to electric forces. In conducting materials such as metals, electric charges flow easily, whereas in insulating materials such as glass, they can move hardly at all. At very low temperatures, some materials become superconductors and offer no resistance to the flow of current. In between these extremes, semiconducting materials differ greatly in how well they conduct, depending on their exact composition.
- Accelerating electric charges produce electromagnetic waves around them. A great variety of radiations are electromagnetic waves: radio waves, microwaves, radiant heat, visible light, ultraviolet radiation, x rays, and gamma rays. These wavelengths vary from radio waves, the longest, to gamma rays, the shortest. In empty space, all electromagnetic waves move at the same speed—the "speed of light."
- Whenever one thing exerts a force on another, an equal amount of force is exerted back on it.
- The observed wavelength of a wave depends upon the relative motion of the source and the observer. If either is moving toward the other, the observed wavelength is shorter; if either is moving away, the wavelength is longer. Because the light seen from almost all distant galaxies has longer wavelengths than comparable light here on earth, astronomers believe that the whole universe is expanding.
- Waves can superpose on one another, bend around corners, reflect off surfaces, be absorbed by materials they enter, and change direction when entering a new material. All these effects vary with wavelength. The energy of waves (like any form of energy) can be changed into other forms of energy.

**References**


http://www.mrsec.wisc.edu/edetc/LED/index.html

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* (Taken from "Benchmarks for Science Literacy," Project 2061, American Association for the Advancement of Science, 1993.)


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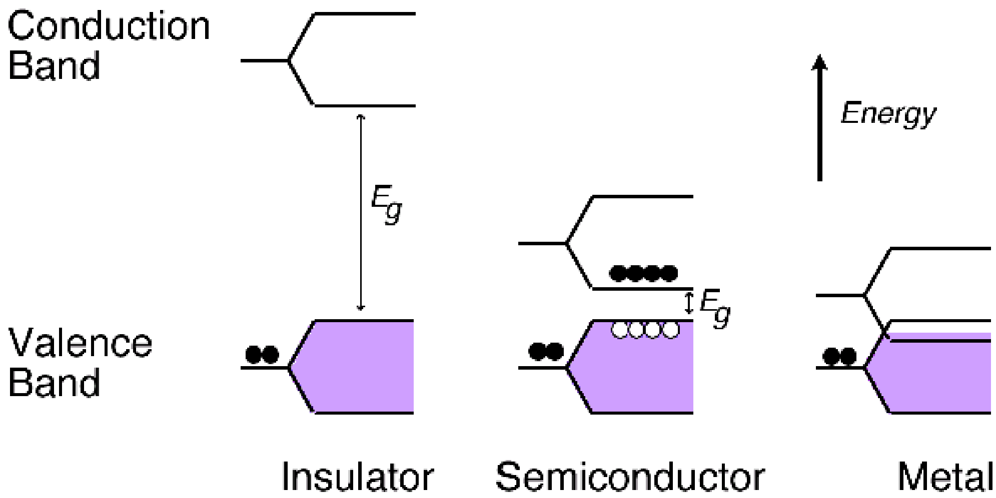
# Energy Levels in Solids




# Band Gap and Periodic Properties

| Element | Unit Cell, Å | $D_o$, kJ/mol | $E_g$,eV ($\lambda$, nm) |
|---|---|---|---|
| C | 3.57 | 346 | 5.5 (230) |
| Si | 5.43 | 222 | 1.1 (1100) |
| Ge | 5.66 | 188 | 0.66 (1900) |
| Sn | 6.49 | 146 | < 0.1 (12,000) |

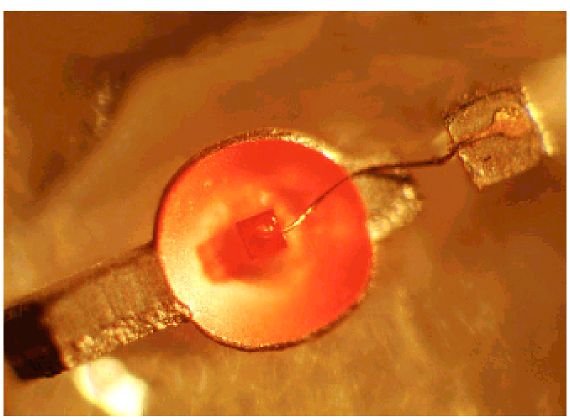
# Which formula is NOT valid?

A. $Ga_xAl_{1\text{-}x}As$
B. $GaP_xAs_{1\text{-}x}$
C. $InAl_xP_{1\text{-}x}$
D. $(Al_xGa_{1\text{-}x})_{0.5}In_{0.5}P$

| 11 | 12 | 13 | 14 | 15 | 16 | 17 |
|---|---|---|---|---|---|---|
| | | B | C | N | O | F |
| | | Al | Si | P | S | Cl |
| Cu | Zn | Ga | Ge | As | Se | Br |
| Ag | Cd | In | Sn | Sb | Te | I |
| Au | Hg | Tl | Pb | Bi | Po | At |

# 1,000,000 nanometers

millimeter



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