Light Emitting Diodes

Instructor Information

Center for Nanotechnology Education

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Introduction

In this module students will have the opportunity to investigate the phenomenon of band gaps in light emitting diodes using readily accessible experimental materials, LEDs, and inexpensive digital meters. In this activity LED's are used both as the light source and as the light detector. It surprises some that LEDs are to some extent reversible – apply a voltage and they produce light, apply light and they produce a voltage, i.e, they act as small solar cells. The basic idea is to show that in order to excite a voltage in an LED, the illuminating light photons have to have an energy equal to or greater than the band gap energy of the detecting LED. A laser pointer is used as an illuminating source to replace the LED to show that this is not a light intensity effect – it depends on the light energy/color. This lab is designed to allow students to attempt to discover this through instructor directed group discussion.

This experiment is similar to the classical photoelectric effect. In the photoelectric effect, light of colors corresponding to photon energies of greater than some threshold are required to liberate electrons from a surface; the photoelectric effect depends only on photon energy and is independent of intensity. This is the discovery that led to Albert Einstein's only Nobel Prize in 1921. Here, light of colors corresponding to photon energies greater than some threshold are required to promote electrons to the conduction band in an LED detector independent of the light intensity. The photoelectric effect was one of the experimental underpinnings of quantum physics. This activity offers a similar demonstration of these principles that is less quantitative but more accessible to the classroom environment.

The primary purpose of this lab is to demonstrate the presence of band gaps in semiconductor devices and the quantized nature of light; however LEDs are having an increasing social, economic, and environmental impact on the world which is described in the supplementary material and references.

Learning Objectives

Upon completion of this module students should be capable of:

- **Describing the band gap structure of LEDs** - Here the students should be able to explain the basic idea that what were discrete energy levels for isolated atoms spread into energy bands as the atoms aggregate into crystal structures.
- **Describing the quantized nature of light** – This experiment is similar to the classical photoelectric effect. In the photoelectric effect, light of colors corresponding to photon energies of greater than some threshold are required to liberate electrons from a surface independent of intensity. Here, light of colors corresponding to photon energies of greater than some threshold are required to promote electrons to the conduction band in an LED detector, independent of the light intensity.
- **Performing calculations to determine the energy of a photon as a function of wavelength (color)**
- **Building a simple LED circuit and performing measurements using it** – This can be as simple as twisting/clipping leads together

Associated "big ideas of nanoscience" (see www.mcrel.org/Nanoteach/pdfs/big_ideas.pdf):

1. **Quantum Effect** – The photoelectric effect was one of the experimental underpinnings of quantum physics. This activity offers a similar demonstration of these principles that is less quantitative but more accessible to the classroom environment.

2. **Science Technology and Society** – LED lighting is emerging as an important component of energy savings. Once only used for low intensity indicator lamps, LEDs are quickly making their way into automotive lighting (even headlights), commercial/residential area lighting and LCD display backlighting. Economically, LED production is approaching in size some of the substantial digital semiconductor device markets.

3. **Tools and Instrumentation** – Normally the mention of tools and instrumentation in nanotechnology brings to mind electron microscopes, atomic force microscope, etc. However the knowledge of working efficiently with simple instrumentation such a digital meter is an important skill.

Pre lab activities/review: A good "hook" to get students interested is to show what happens if you don't use a resistor to limit the current through the LED, it flashes brightly once and never lights again. This usually gets students interested and also provides a warning to be mindful of polarity as they progress through this lab. Another hook is demonstrating that the infrared LEDs in an entertainment center remote are visible to silicon-based sensors but not the human eye. This can be demonstrated by looking at a remote being activated (buttons pushed) on the view screen of a digital camera. Cell phone cameras work well.

The activity begins with an explanation (or review) of the band gap structure of semiconductors. Several good tools to allow students to observe this before the lab activity are:

- A free, no registration required tool to investigate a simplified band gap structure in 1 dimension can be found at http://www.falstad.com/qm1drystal/ Use of this tool was used to produce the band gap behavior illustrations in the graphical material provided with this module.

- An advanced tool "Band Structure Lab" that allows calculation of band structures for a variety of materials including semiconductors, thin films and nanowires is available at www.nanohub.org (registration is free). http://nanohub.org/resources/1308 This would require instructor to walk students through the material.

An explanation or review of the quantized nature of light and the relationship between color, wavelength and energy should also be provided. Students will need to understand and be able to use the formula for the energy of a photon as a function of wavelength: $E=hc/\lambda$ and the relationship between color and wavelength. At this point the concept that light is made up of photons, individual energy packets energy $E=hc/\lambda$, is an abstract notion to many students. The purpose of this lab is to bring some experimental reality to this abstraction

Before starting the lab activities students should be capable of:

- Qualitatively drawing the band structure of a semiconductor
- Calculating the energy of a photon of a known wavelength
- Describing the relationship between wavelength and color

The construction and operation of LEDs can also be introduced at this point. A reference providing information on the uses, fabrication and operating principles of LEDs can be found at http://nanohub.org/resources/11829, this also contains additional information on the societal impact of LEDs.

General LED Discussion (optional): *(This information is not central to this activity but provides some background to tie LEDs into the general topic of nanoscale fabrication.)*

The history of LEDs shows trends towards:

- Higher brightness
- Increased color selection (red came first, blue most recently)

This trend was achieved by parallel advances in two areas:

Thin film deposition techniques: As described in the preceding reference, LED fabrication involves a number of nanoscale thin film deposition steps producing

- the basic pn junction structure of the diode
- an efficient means to extract light from the diode (some people have pointed out that making light at a PN junction is relatively easy, getting it out of the junction is what is difficult.)
- structures to allow for higher current/brighter LEDs

Advanced semiconductor materials: The first red LEDs used fairly simple doped silicon variations and were in the infrared range. Over the years more advanced materials with larger band gaps were introduced culminating with the production of bluer LEDs in the 1990's.

These areas are not covered in detail but provide a hook into further lesson or classes on nanoscale fabrication techniques.

Once blue LEDs were available white LED lighting became a possibility. Intuitively many students may assume that white LEDs are really red, green and blue LEDs in a common case. This would be based on the common demonstration that combining a range of colors additively produces white light. While white LEDs have been produced this way, current white LEDs are achieved by putting a yellowish phosphors over a blue LED.

http://en.wikipedia.org/wiki/Light-emitting_diode shows a good example of the resulting spectrum of such a white LED. As an optional activity, students can observe a white LED spectrum using a diffraction grating if available or even a CD/DVD which acts as a diffraction grating. Incandescent lights or sunlight will show a continuous spectrum, while the white LED will show concentrations of brightness in the blue and yellow regions.

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Equipment required and sources

Light Emitting Diodes **-** Assorted LED's of different colors are needed, one set per student or student team. LED's should have clear covers for best results. Here is a typical product available (as of 2012) from Amazon.com. The same seller also offers an 8 color set if you want to extend the options.

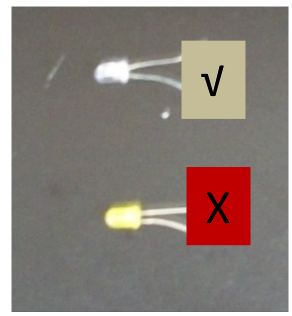
5mm Assorted Clear LED with 1/4 W Resistors (6 Colors, Pack of 60) by microtivity

Buy new: **$9.56**

8 new from $7.25

Get it by **Wednesday, Apr 18** if you order in the next **7 hours** and choose one-day shipping.

Only 13 left in stock - order soon.



In selecting LEDs: Use clear-cased LEDs as the filtering effect of LEDs with colored lens covering can be a confounding effect in this activity. Because clear LEDs are used it is helpful to label them with their colors to avoid later confusion.

If using infrared LEDs make sure to have a digital camera (cell phone cameras work) on hand to test them. While not visible to the human eye, the band gap structure of image sensors allows for infrared detection, it will show up as a bright spot in the image. (This is a good discussion point in general and surprises many students. Point out that this is a good test for the infrared LEDs of their entertainment system remote controls.)

Most LEDs have molded lens structures focusing light in a forward direction. This is ideal as in this experiment we want as much light as possible from the illuminating LED to be directed forward into the detecting LED. Avoid LEDs labeled as "diffuse" or those which have milky/clouded appearance to their plastic cases. Unfortunately in buying inexpensive "bulk LEDs", detailed specification sheets are often not available or incomplete. Most of the general purpose LEDs we have encountered are forward focused unless otherwise noted.

Leads with alligator clips or similar to make connections. Make certain to have polarity color coded leads. Students coming from different backgrounds (AC wiring vs. digital electronics) may have used various conventions. Have students decide on and adopt a color convention for this lab, we use + red, -black.

A 9V battery or equivalent low voltage low amperage power supply – it is suggested that the + and – markings on the battery be clearly visible. On some batteries, emphasizing this using a marker pen is useful to students. 9v batteries are becoming increasingly expensive so 6 or 9V DC power supplies (the ubiquitous power adapters used for consumer electronics) may be more economical. The instructor will want to verify that these provide short circuit protection before use.

Current limiting resistors, ~470 Ohm (included with the above example LED assortment) pack and necessary to protect the LED from over current.

Small diameter tubing to slide over and couple the two LEDs a soda straw, heat shrink tubing or similar fairly opaque material can be used. This acts to both mechanically hold the LEDs in place and as a light shield to block ambient light effects.

Voltmeter - Fortunately, cheaper voltmeters seem to give better results than the more sophisticated expensive units. Here is an example of one that works well (as of 2012) but most portable digital meters found around labs have been found to work. More expensive bench top meters are more accurate and can measure smaller voltages but often use a mechanism which results in slower acquisition of a stable reading.

Digital Amp Ohm Volt Meter Ac Dc Voltmeter Multimeter by CenTech
Buy new: ~~$19.95~~ $6.99
21 new from $2.25   1 used from $12.99
In Stock
(23)

Red laser pointer - Other color laser pointers are becoming available and can easily be incorporated into this activity.

Optional – soldering equipment, circuit boards, or breadboard circuits rather than twist/clip to connect components.

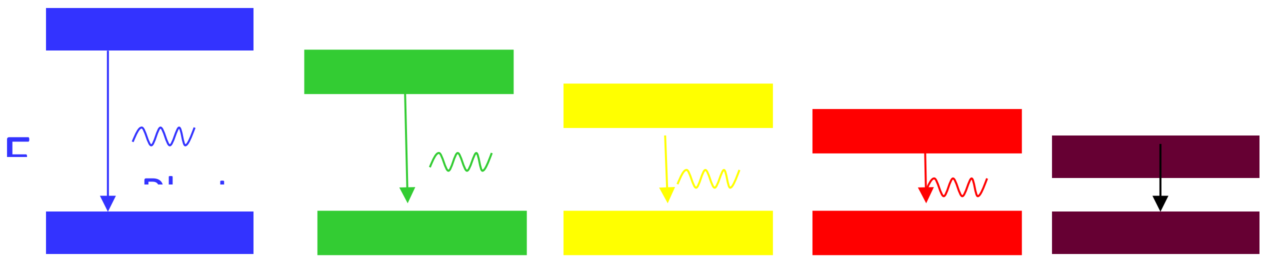
Optional - Purchase LED kits ready for the experiment (a more costly option). Available from http://ice.chem.wisc.edu/ . This is suitable for the illuminating LEDs but as constructed cannot be easily used for the detecting LEDs.

Lab Activity: (this is a brief overview of the activity covered more thoroughly in the Activity and the background material documents)

Students will build a simple LED circuit with a current limiting resistor and a 9 volt battery or similar power supply. This can be by done twisting some leads together and/or using alligator clips. However, If possible, soldering the connections allows for a more robust setup. This is a good opportunity to practice basic soldering skills if appropriate for the course. Students next make some qualitative observation about the color of LEDs and try to match them to online or printed spectral charts.

This activity uses a chart found at http://quarknet.fnal.gov/fnal-uc/quarknet-summer-research/QNET2010/Astronomy/   although any suitable spectrum chart can be used. It's interesting to point out to students that this matching is not very accurate as the printing processes and even more so computer displays do not accurately render color.   The relationship between photon energy and color (wavelength) is introduced or reviewed and students calculate the energy of several colored LEDs. In the main activity of the lab, students direct the light from one illuminating LED into another detecting LED connected to a voltmeter. Students note which colors of LED will excite other colors of LEDs. A red laser pointer will also be used as an illumination source to demonstrate that this is not an intensity effect, but is dependent on the relative colors of the source and detector.

<u>Post lab activity:</u> Through directed class or lab group discussions, students should note the general trend that higher energy (bluer) LEDs will excite a voltage in lower energy (redder) LEDs.



Bluer LEDs will excite a voltge in blue LEDs and other color LEDS towards the lower photon energy (redder) areas of the spectrum. (The dark red gap at the right of this picture is used to represent the nonvisible infrared LED which can be used.)

By shining the intense red light (laser pointer) into the blue LED and noting that no voltage is produced, students will verify that this is not an intensity related phenomena but is truly related to the photon energy (color) of the exciting light source. The students will note a possibly anomalous observation in that the yellow (lower energy) LED color excites a small voltage in the green (higher energy) LED color. This is a good opportunity to contrast the light from a single excited atom as compared to that from the band gap structure of a semiconductor LED. Excited atoms emit sharp spectral lines. LEDs emit broader spectra of light because of the spread of the band structure. Yellow and green LEDs are close enough in their spectral output that there is some overlap – the higher end of the yellow emitting LED can excite the lower end of the detecting LED.