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Demonstration

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Demonstrations of Frequency/Energy Relationships Using LEDs

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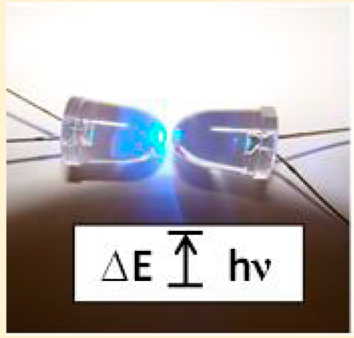
ABSTRACT: The use of LEDs (light-emitting diodes) to demonstrate the relationship between frequency (or wavelength) and semiconductor energy level differences is described. LEDs can function as light detectors, and this ability is exploited to show the minimum light frequency needed to produce a voltage response in the LED. Light having higher energy (lower wavelength) than the detector LED bandgap energy produces a significant voltage response, whereas lower-energy light results in minimal response. The light sources can be other LEDs or a flashlight with colored filters. Alternatively, the voltage measured across an LED as it emits light under power can also be related to the LED bandgap energy, providing a somewhat more accurate estimate of the bandgap energy than that obtained from the LED detector mode. Although these demonstrations using LEDs are not technically the same as the classic photoelectric effect as presented in most freshman chemistry courses, they nevertheless illustrate the same relationships between frequency, wavelength, and energy level differences.



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INTRODUCTION

Freshman chemistry textbooks typically cover the important relationship between photon energy and its interaction with matter rather early in the pedagogical sequence. This fundamental concept is usually covered in terms of the photoelectric effect.[1] The photoelectric effect involves the emission of electrons from a photosensitive metal in an evacuated tube in response to sufficiently energetic photons.[1] Photoelectric effect demonstrations are available commercially[2] at some expense, or as a locally built apparatus using LEDs as light sources[3] with considerable construction required. There are also existing demonstrations involving the discharge of an electroscope by a UV lamp[4] or excitation of a phosphorescent dye with a violet LED[5] (Educational Innovations "Write & See Square"), but the results are only qualitative. A laboratory experiment has also been devised for a quantitative study of the photoelectric effect,[6] but the apparatus is too complex for a classroom demonstration. Another experiment used the minimum turn-on voltage for various LEDs to determine Planck's constant.[7] Finally, there are excellent tutorials[8] and simulations[9] of the photoelectric effect, but they, of course, do not use actual experimental devices. The relationship between light frequency and electrical response can also be demonstrated quantitatively by solid-state devices such as LEDs.[10] Although technically not the same as the photoelectric effect, interactions of light with LEDs can nevertheless provide simple and quantitative presentations of general energy/radiation relationships. The present demonstration uses the fact that LEDs can be used as both light-emitting and light-sensing devices[11,12] to provide an extremely simple yet effective demonstration of the relationship between light frequency and LED response. If desired, calculations can be included to introduce or reinforce the relationships between energy, frequency, and wavelength. This demonstration uses a blue LED "detector" to coincide with the usual blue-sensitive phototubes mentioned in textbooks, but other LED colors can also be used. Finally, another approach to energy/frequency (or wavelength) relationships is illustrated by simply measuring the voltage across an LED as it emits light.

EQUIPMENT LIST

The LEDs listed here were used as detectors in this demonstration, providing a range of bandgap energies.

Detectors (with Clear, Colorless Lenses for Best Results)

Blue Jumbo 10 mm LED (Radio Shack 276-0006), nominal wavelength 466 nm, clear lens.

Red Jumbo 10 mm LED (Radio Shack 276-0086), nominal wavelength 660 nm, clear lens.

Green 5 mm LED (Radio Shack 276-0304), nominal wavelength 565 nm, clear lens.

LED detectors must have colorless lenses to avoid absorption of source light.

Various light sources can be used to excite the LED detectors in order to explore the frequency/energy relationships of the detectors.

Light Sources

UVB LED: Dri-Mark Counterfeit Detector Pen, 351UVB, wavelength 374 nm.

Various color LEDs (Photon "Micro-Light II" LEDs: violet, blue, green, red), available through Educational Innovations, Inc.

LED sources can also be constructed using LEDs requiring a 3 V voltage supply (Figure 1). The circuit consists of an LED

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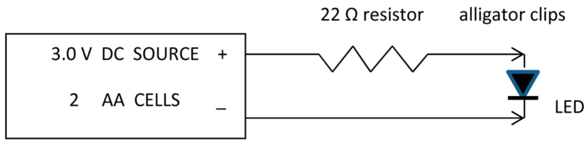

Figure 1. Circuit diagram for LED voltage source.

with 22 ohm series resistor, and battery (2 AA, 3.0 V). All LEDs have clear lenses (RadioShack part numbers): green (276-0304, 565 nm), yellow (276-0351, 587 nm), red (276-0086, 660 nm). LEDs can, of course, also be obtained from other electronics retailers.

The circuit in Figure 1 is designed for LEDs operating on approximately 3 V and 100 mA. The use of other LEDs would need an appropriate current-limiting resistor to give the proper operating current for the LED.

Another possible blue source is a forensic light (Sirchie Mini BLUEMAXX BMK200).

If light sources other than LEDs are desired, colored plastic film (ClearLay[13]) can be placed over a flashlight. It has been found that four sheets are necessary to filter out other than the desired wavelength. It should be noted that incandescent bulb flashlights generally emit very little blue radiation, so their use is restricted to LED detectors having lower excitation energies.

A simple multimeter was used for the classroom demonstration.

Multimeter TENMA 72-5095, or similar, capable of current and voltage measurements. The voltage measurements were verified with a Fluke 8050A digital multimeter.

A Vernier SpectroVis Plus spectrophotometer, with fiber optics probe SVIS-FIBER, was used to measure visible LED wavelengths when nominal values were not available. The Dri-Mark pen UVB wavelength was measured with an Agilent 8453 diode array and SVIS-FIBER.

PROCEDURE

LED Detector Method

The equipment layout is shown in Figure 2. As mentioned above, this is an extremely simple setup, which is one of its biggest advantages! The entire setup can be placed under a document camera for easy viewing by a large class. All experiments were carried out at room temperature (23 ± 1 °C).

Observation of the effect of radiation on the LED characteristics can be carried out by measuring the voltage across the LED contact leads, which are connected to the multimeter probes by means of alligator clips. The longer (positive) LED lead is connected to the red multimeter lead to give a positive current reading. Reversed connections still work but give a negative sign for readings. The voltage measurement gives reproducible results, but attempts to measure current in the circuit (milliampere mode) gave results that depended greatly on the exact incidence angle of the radiation, the current

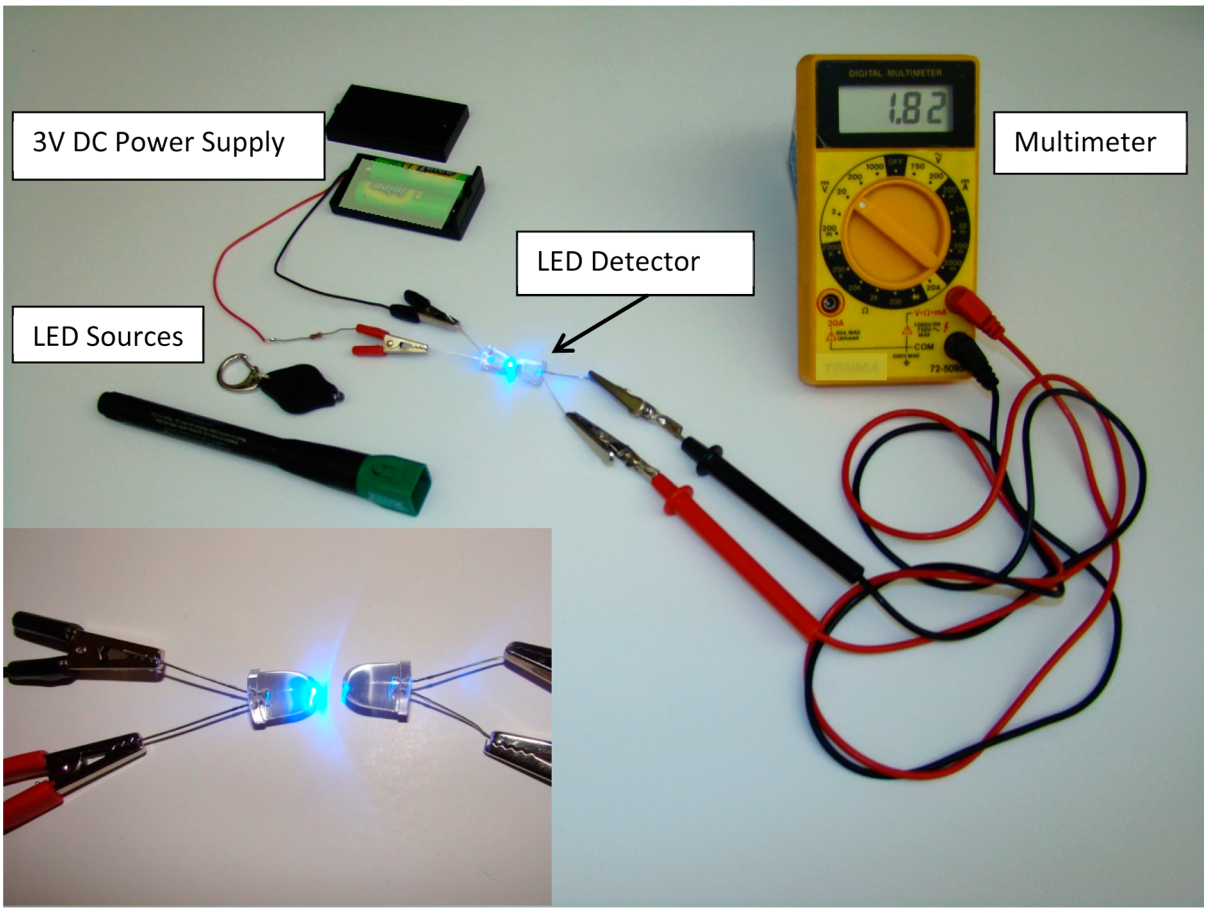

Figure 2. Experimental setup for LED detector demonstration (blue LED source). Other sources (Photon LED, UVB pen light) are also shown. Inset is closeup of blue LED source/detector arrangement.

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Table 1. Comparative Results for LED Detectors[a]

Source			Detector		
			Blue 466 nm, 2.66 eV	Green 565 nm, 2.19 eV	Red 660 nm, 1.88 eV
	λ	Energy Per Photon	Voltage	Voltage	Voltage
Dri-Mark UVB	374 nm	5.30×10^{-19} J	2.32 V	0.07 V	0.93 V
Photon Violet	404 nm	4.91×10^{-19} J	2.30 V	0.15 V	1.18 V
RadioShack Blue	466 nm	4.26×10^{-19} J	1.82 V	1.51 V	1.25 V
Photon Green	519 nm	3.82×10^{-19} J	0.01 V	1.48 V	1.45 V
Photon Yellow	594 nm	3.34×10^{-19} J	0.00 V	1.44 V	1.48 V
Photon Red	643 nm	3.08×10^{-19} J	0.00 V	0.00 V	1.55 V
Laser Pointer Red	655 nm	3.03×10^{-19} J	0.00 V	0.00 V	1.56 V

[a]Detectors from the equipment list, with bandgap energies (in electronvolts) calculated from the nominal LED wavelengths.

scale used, and even the quality of the multimeter. Nonzero, however erratic, current readings were observed for the blue and UVB light sources, whereas no current was observed for longer-wavelength sources. The current mode, then, provides at best qualitative results, so the voltage mode is greatly preferred and is essential for relating incident wavelength to the electrical characteristics of the LED.

Voltage Measurements

The multimeter is set to a voltage range capable of measuring up to 3 V. Direct the source beam onto the detector LED. Light of wavelength less than that of the blue detector LED produces a voltage of about 2.30 V, whereas longer wavelength sources, which have insufficient energy to excite electrons across the LED bandgap, give only 0.00 V. See Table 1 for typical results. It should be noted that another blue 466 nm LED as source also produces a significant output, although the LEDs must be carefully aligned. As mentioned in the Introduction, the responses of other color LED detectors can also be investigated, as shown in Table 1. The use of other color LED detectors shows that the relationship of detector response to source wavelength is valid for any color detector. The green LED detector is activated by the blue and green sources, partially by yellow but not by the red LED source. Surprisingly, the UVB (Dri-Mark) LED gave only 0.07 V, possibly because the green LED lens, although colorless, absorbs UVB radiation. The green LED, which was not available in the jumbo size, does not have the same design as the blue and red LEDs. The red LED detector (lowest bandgap energy) is activated by all sources. It was found that the red LED detector did produce a small response (<0.1 V) to room lights even with no other source, apparently due to the small bandgap of the red LED detector. If the use of another LED as a light source is found objectionable, other light sources, such as a flashlight with colored filter sheets over it, can be used with similar results. Finally, textbooks typically mention that red light does not activate the photocathode even with red light of high intensity. The use of high-intensity red light (laser pointer, or large flashlight with red filter) was found to give no response for the blue and green LEDs used in this work.

One can combine this demo with the "Write & See Square" using the Photon lights (Educational Innovations SS-910), which is a more qualitative kind of photoelectric effect demo.

LED Voltage Method

Another type of demonstration, which avoids the use of LEDs as light sources, can be presented by measuring the voltage across the LED contacts in the circuit in Figure 1. A similar circuit has been used in published laboratory experiments and demonstrations dealing with LEDs,[10] and this approach can be used to augment the previous demonstration mode. The source voltage (3.0 V) in Figure 1 is sufficient to activate all LEDs studied in this work so that the voltage across the LED contacts can be used as an approximate measure of the bandgap energy of the LED.[10] Table 2 shows that the agreement between the measured voltage values and the nominal bandgap energies for LEDs of the same design is generally good, and it is somewhat better than the agreement found in Table 1. The previously published laboratory experiment[10] used a 1 MΩ resistor in the circuit. In the present demo, minimal or no visual light was observed from the LEDs due to the low (microamperes) level of current through the LEDs. For this reason, a 100 kΩ variable resistor (potentiometer) was placed in the circuit in Figure 1, and the voltage was measured for each LED by adjusting the potentiometer until the point just before the light suddenly increased to its maximum intensity (turn-on level entry). The resulting voltages are somewhat lower than those using the 22 Ω resistor. Use of the 1 MΩ resistor gave even lower voltage values across the LEDs. Under the present conditions, it appears that the use of very low currents does not give accurate

Table 2. Comparative Results for LED Responses in the Figure 1 Circuit[a]

LED		Voltage Full power (22 Ω)	Voltage Turn-on Level	Voltage 1 MΩ
Blue	468 nm	2.75 V	2.54 V	0.90 V
5 mm	2.65 eV			
RS	276–0316			
Green	565 nm	2.17 V	2.04 V	1.56 V
5 mm	2.19 eV			
RS	276–0304			
Yellow	587 nm	1.99 V	1.86 V	1.55 V
5 mm	2.11 eV			
RS	276–0351			
Red	660 nm	1.92 V	1.66 V	0.88 V
5 mm	1.88 eV			
RS	276–0307			
Blue	466 nm	2.78 V	2.58 V	2.17 V
Jumbo	2.66 eV			
RS	276–0006			
Red	660 nm	2.08 V	1.68 V	1.38 V
Jumbo	1.88 eV			
RS	276–0086			

[a]Bandgap energies (in electronvolts) are calculated from the nominal LED wavelengths. All LEDs have clear, colorless lenses. RS denotes Radio Shack.

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bandgap estimates. This problem is apparently due to the use of dopants in LEDs, which produces additional states within the bandgap[10] and, consequently, lowered measured voltages. Such complications are evidently not a problem at the currents used in Figure 2 circuit with a 22 Ω resistor, or at the turn-on level. In any event, the voltage values measured in the 22 Ω circuit agree most closely with the calculated bandgap values, particularly with the 5 mm lens LEDs, although the red and blue bandgap energies fall between the full power and turn-on values.

■ HAZARDS

Do not look directly into the light beam from the LEDs, especially the blue, violet, and UVB LEDs! The beams can be very bright! This applies especially to the long-wavelength ultraviolet (UVB) source used in this demo. If the red laser pointer is used, care should be taken to avoid reflection of the beam into the audience.

■ DISCUSSION

The results from this demo are consistent with those observed for an actual vacuum phototube in that no current (or voltage) is observed for source wavelengths longer than that corresponding to the response of the detector.[1,6] In the case of the phototube, the incident energy must be greater than the work function of the photocathode to produce current. For the LED detector, no current or voltage is to be expected unless the source radiation can provide sufficient energy to allow electrons to surmount the band gap of the semiconductor material in the LED. This demonstration provides, then, a solid-state analog to the traditional phototube circuit, which is, of course, much more complex to assemble and operate.

Some simple calculations, which can be done by the class, allow easy interpretation of the results. For the blue LED detector, the nominal wavelength is 466 nm, so the equivalent photon energy is 4.26×10^{-19} J, and the corresponding bandgap voltage is 2.66 eV. These wavelength-to-energy calculations can be performed using $E = h\nu$ and $c = \lambda\nu$ (Table 1). The difference in behavior for the various light sources then becomes even clearer. In addition, this exercise provides valuable experience for the class in exploring energy/wavelength relationships. These considerations also apply to the LED voltage method.

■ CONCLUSION

The present demonstration provides a conveniently implemented presentation of the relationship between energy levels and frequency (or wavelength). In one approach, a conventional phototube is replaced by a blue LED, which serves as a solid-state detector. This approach can also be extended to other LED colors for a more complete illustration of the concept. For the demonstration, the only equipment necessary is an LED detector, a multimeter, and some light sources, which can be either LEDs or conventional sources of various wavelengths. These sources are commercially available, or they can be made with simple components from electronics retailers. The multimeter is used to monitor either the voltage or the current response for the LED detector connected to it, the voltage mode providing much more reproducible results. A response is observed for sources having wavelengths equal to or less than that corresponding to the LED detector bandgap, whereas minimal (or zero) voltage is observed for longer wavelength sources. Another demonstration method involves simply measuring the voltage across the leads of an operating LED, which gives a good approximation of the bandgap value. In either implementation, calculations involving the conversion of wavelengths to energies can be used as a useful introduction or review of these very important concepts. In the opinion of the author, the demo using an LED detector and a light source has the advantage of being perhaps more visually appealing to students, and it also provides a solid-state analog to a photoelectric effect demonstration. The use of non-LED light sources, provided that they produce sufficient energy in the desired wavelength region, may alleviate any confusion pertaining to the use of LEDs as both detector and light source.

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Notes

The authors declare no competing financial interest.

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