The Photoelectric Effect Using LEDs as Light Sources

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The photoelectric effect is demonstrated in many introductory physics courses. We have developed an apparatus for this experiment using a phototube and inexpensive LEDs as light sources instead of the usual mercury lamp. Planck's constant can be measured to better than 10% by using several LEDs in the spectrum from 470 nm to 631 nm. Changing the intensity of the LED allows us to measure the electron energy and photocurrent as a function of light intensity. The photocurrent time response also can be measured using a function generator and oscilloscope.

It has been 85 years since Albert Einstein was awarded the Nobel Prize for his explanation of the photoelectric effect. This explanation is central in our understanding of light and it is demonstrated experimentally in many introductory physics courses.[1,2] The classic apparatus for these demonstrations includes a phototube, a variable voltage source, current and voltage meters, and a light source capable of generating several narrow bandwidths of light, for example a mercury lamp[3,4] or an incandescent bulb.

Fig. 1. The apparatus used for demonstration of the photoelectric effect. The light shield has been removed to show the phototube and LED. It is not required if the apparatus is used in a darkened room.

One drawback to using these experiments in a student laboratory is the light source. The incandescent source has an inherently low intensity, especially at the shorter wavelengths, while the mercury source is quite expensive (several hundred dollars) and can be dangerous due to its high temperature, ultraviolet output, and of course, the mercury vapor.

In this paper we describe a low-cost apparatus that may be used to demonstrate the photoelectric effect using LEDs as light sources. It should be noted that our use of LEDs is in contrast to other apparatuses[5-7] that use the LED "turn-on" voltage as a measure of the photon energy. The LEDs we use are blue (470 nm), green (525 nm), yellow (593 nm), and red (631 nm). All cost less than two dollars each.[8] In addition to their brightness, a desirable feature of the LEDs is that they can be turned on in less than 1 μs, which makes them useful for time response experiments. Such experiments are not easily performed using other light sources.

Apparatus

A photograph of the apparatus is shown in Fig. 1.

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Aside from the LED light source, a 1P39 vacuum phototube is the heart of the apparatus and is the most expensive component. It can be obtained from any of several suppliers at a cost of less than \$50.[9-11] It is mounted on the cover of a plastic electronic enclosure (175 mm x 135 mm x 60 mm) and faces the LED at a distance of about 60 mm. At this distance, the light from the LED just fills the photocathode of the tube. The LED is mounted in a hole drilled through an aluminum bracket. Connections to the LED are made using a push-on connector. This arrangement makes it easy to change the LED when performing the experiment. A light shield made from a thin piece of aluminum covers both the phototube and LED and prevents ambient light from reaching the photocathode. This shield is removable to allow students to view the light striking the photocathode. A 3-mm strip of black electrical tape is placed on the glass envelope of the phototube to shield the anode from the direct light of the LED, thus preventing the anode from emitting spurious electrons. All other components including the batteries are placed inside the enclosure.

Figure 2 shows the electrical circuit for this apparatus. Readily available digital meters are used to measure the photocurrent and stopping voltage. A photocurrent resolution of 1nA is obtained by using a digital meter on the 200-mV range and by reading across the 100-kΩ resistor. The LED intensity is varied by simply changing a resistor in series with it. One of four resistors can be selected with a switch. The resistance of each has been chosen to make the LED intensity proportional to the switch position (1:2:3:4).

Experiments

The classic photoelectric effect experiment is to illuminate the photocathode with monochromatic light of wavelength λ and record the voltage required to stop the most energetic electrons emitted from it. Applying conservation of energy and assuming light is quantized gives the famous Einstein equation

$$eV_s = h\nu - W_o, \qquad (1)$$

where e is the electronic charge, V_s is the stopping voltage, h is Planck's constant, ν is the frequency of the light ($\nu = c/\lambda$), and W_o is the minimum energy necessary to liberate the electron from the photocathode, i.e., the work function (W_o).

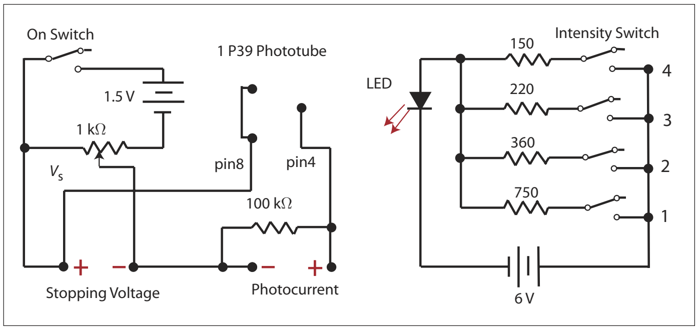

Fig. 2. Circuit used for the photoelectric effect apparatus. All resistors are 5% at 0.25 W. The 1.5-V battery is a "C" cell and the 6-V battery is made from four "C" cells in series.

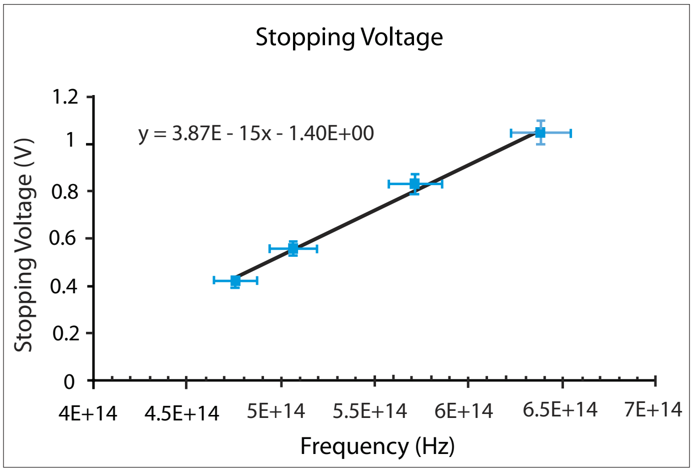

Fig. 3. Stopping voltage as a function of the LED frequency. The slope of the plot is *h/e* and the magnitude of the ordinate-intercept is the work function. From these data the value of *h* is measured to be 6.19 x 10^{-34} J·s. The error bars represent the 5% uncertainty in the LED frequency and stopping voltage.

The experiment is performed using each LED as the monochromatic light source. The stopping voltage (V_s) is then adjusted until the photocurrent just becomes zero and this value of stopping voltage is recorded for each of the wavelengths (LEDs). The LEDs are not really monochromatic light sources, but given the accuracy of this experiment, they are quite adequate. This approximation is justified because their spectral width is typically less than 20 nm in wavelength. The spread in wavelength (or frequency) compared with the peak is therefore less than 5%.

Figure 3 shows typical data recorded using the LEDs at maximum intensity. The data points were fit to a straight line; the slope of which is equal to h/e. Our measurements lead to a value for Planck's con-

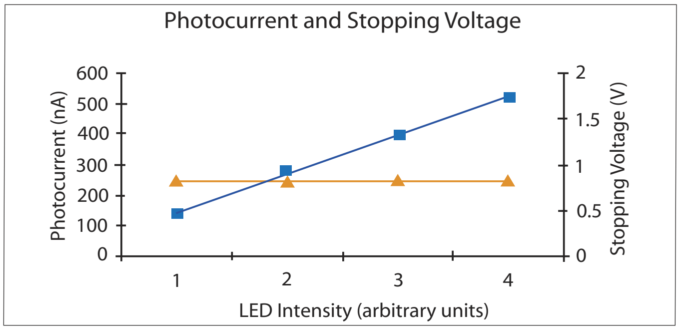

Fig. 4. Measurements of photocurrent (squares) and stopping voltage (triangles) as a function of LED intensity for the green LED (525 nm).

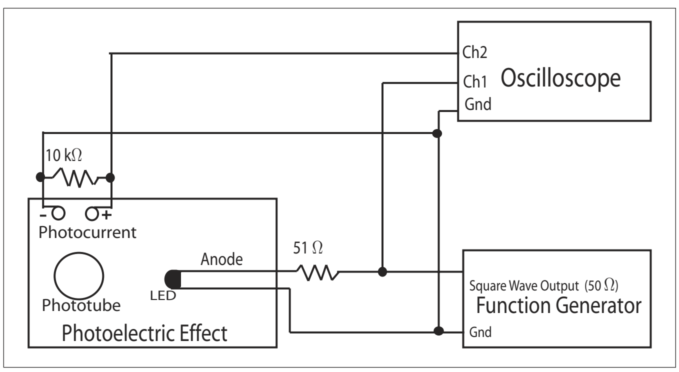

Fig. 5. Electrical circuit for measurement of the photocurrent time response. Twisted wires or shielded cables are used for the photocurrent connections. This reduces electrical pickup from the current pulses to the LED.

stant of $6.19 \pm 0.44 \times 10^{-34}$ J·s. The assigned uncertainty of 7% is the result of assumed uncertainties of 5% in the determination of V_s and the LED wavelengths. Our measurement of h is smaller than the accepted value of Planck's constant of 6.62×10^{-34} J·s. The likely cause is reflection of light from the photocathode with a concomitant emission of spurious electrons from the anode. The work function (ordinate-intercept) is 1.4 eV.

Another easy experiment that can be performed with this apparatus is to measure the photocurrent and stopping voltage (V_s) for a range of intensities. Figure 4 shows our results using the green LED. From these data it is clear that while the photocurrent increases with incident light intensity, the stopping voltage does not. This result clearly demonstrates that light energy is quantized because the energy of the emitted electrons does not depend on the intensity of the light. A further demonstration of this is a simple experiment in which the phototube is illuminated

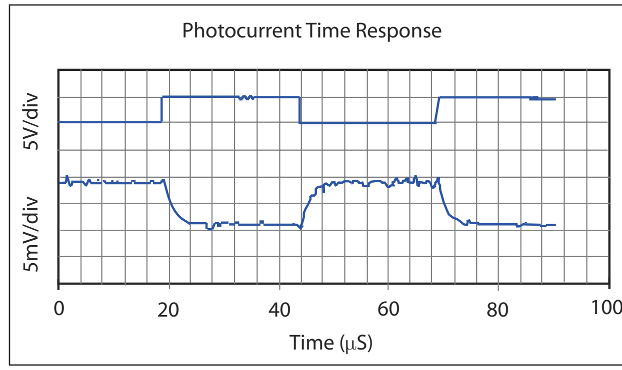

Fig. 6. Oscilloscope traces of the LED voltage (top) and photocurrent (bottom) when driven by a 0-5-V square wave from a function generator at 20 kHz. The LED turns on at about 20 µs and turns off at about 45 µs. The photocurrent is negative (electrons) and responds to the light from the LED in less than 2 µs. The stopping voltage is set to zero.

with the infrared output of a 945-nm LED. A photometer or digital camera will verify that the LED actually emits light. In fact, the intensity of this LED is greater than any of the four visible LEDs used for data acquisition. Nonetheless, no photoelectrons were observed! The explanation is that the energy per photon (1.31 eV) for the infrared LED is lower than the 1.4-eV work function of the photocathode.

If a function generator and oscilloscope are available, the time response of the photocurrent also can be measured. The function generator provides a square wave to pulse the LED on and off at a rate of 20 kHz. Comparing the time response of the resultant photocurrent to that of the incident light is yet another demonstration of the quantum nature of light. Figure 5 shows the electrical circuit for this experiment. Note that a 10-kΩ resistor is added in parallel with the 100-kΩ current measuring resistor to decrease the inherent time constant of the photocurrent measurement. Our measured waveforms of the LED and photocurrent are shown in Fig. 6. It is evident from these waveforms that electrons are emitted from the photocathode in a time of less than 2 µs from the onset of the light. An order of magnitude calculation shows that this result is inconsistent with the wave view of light. The LED uses 3 V at 20 mA and therefore consumes 60 mW of power (P_{LED}). If all of this electrical power is converted into light and deposited as a wave uniformly over the photocathode, then each electron receives a fraction of power given by

$$P_e = P_{LED} \frac{A_e}{A_{pc}}, \qquad (2)$$

where P_{LED} is the LED electrical power, A_e the area occupied by an electron, and A_{pc} the area of light on the photocathode. In a solid, atoms are typically 0.3 nm from each other, so each electron is confined to an area of 9×10^{-20} m^2. The photocathode area is 3 cm^2 so from Eq. (2), the power an electron can absorb is 1.8×10^{-17} J·s. Since one eV is equivalent to 1.60×10^{-19} J, an electron can absorb 113 eV of energy per second. The photocathode has a work function of 1.4 eV, so it should take at least 12 ms for an electron to absorb enough energy to escape the photocathode. Nevertheless, emitted electrons are observed in less than 2 μs and that is nearly four orders of magnitude earlier than calculated for a wave! The conclusion is that the electrons must absorb the light in packets of energy (photons) that are sufficient to free the electrons almost immediately.

Acknowledgments

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