Photoelectric Effect

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Abstract

Photoelectric effect, which was discovered by Hertz and explained further by Einstein, is the effect that produces electricity when a metallic surface is illuminated by light of sufficient frequency. The primary purpose of this experiment was to understand the quantum behavior of light through photoelectric effect and to measure the Planck's constant. There are three methods for measuring Planck's constant in this lab. The first is the traditional method as explained in elementary text books. Light of varying wavelengths is incident on a metal surface and the kinetic energy of the emitted electrons are measured. In the second method the process is reversed. Light Emitting Diodes (LED) are used to inject electrons into a PN junction where they recombine with holes and emit light. In the third method, black box testing is used to record the stopping voltage for different wavelengths. For all three methods, h/e value is determined from the slope of stopping potential vs. frequency, with the calculated Planck's contant to be (6.65$\pm$0.88)*$10^{-34} J * s$ for stopping voltage method, (9.52$\pm$0.88)*$10^{-34} J * s$ for LED method, (6.44$\pm$0.88)*$10^{-34} J * s$ for black box photoelectric effect method.

Introduction

In 1887, Hertz discovered that electricity may be produced when light strike a metallic surface. The effect was called Hertz Effect (and later on Photoelectric effect). Later on, Einstein explained this scenario using the quantum property of radiation suggested by Planck. He proposed that the energy of the ejected electrons is proportional to the energy of incident light with an offset that is unique to the specific metals, which is called the work function. It was for his explanation of the photoelectric effect that Einstein received the Nobel prize. The photoelectric effect is very important in that it shows wave-particle duality of light and lays a foundation for quantum mechanics.

In this lab, in order to measure the Planck's constant, there were three methods used. The first is the traditional method as explained in elementary text books. Light of varying wavelengths is incident on a metal surface and the kinetic energy of the emitted electrons are measured. In the second method the process is reversed. Light Emitting Diodes (LED) are used to inject electrons into a PN junction where they recombine with holes and emit light. In the third method, black box testing is used to record the retarding voltage for different wavelengths. For all three methods, stopping voltage is determined correspond to frequency and the slope of the relationship gives us the values for Planck's contant.

Theory

A. Problems from classical wave description

As mentioned earlier, Hertz discovered the photoelectric effect when light strike a metallic surface and produces electricity. However, there are some main features of photoelectric effect that cannot be explained by the classical wave description of light.

(1) First problem is that, according to Maxwell's equation,

$$|\vec{E}| \propto \sqrt{I}$$

Which states that as intensity increases, the electric field magnitude also increases. And since $\vec{F}=q\vec{E}$, the kinetic energy of the photoelectron should be expected to increase with the intensity of the incident light. However, the observational data showed that the maximum kinetic energy of the photoelectrons did not depend on intensity.

(2) Second problem is that in classical theory, when the light is shining on the metal surface, electron would take some time to be emitted since the transferring of energy would take some time and thus would cause a delay on the emitting of electrons since the start of metal's exposure to light. However, the experimental data showed that the emission of electrons occurred almost right after the exposure of the metal to light.

(3) Third problem is that in classical theory, the emission of electrons should happen at all wavelength as long as the intensity if light reach a certain threshold. In reality, however, experiment showed that the wavelength longer than certain wavelength threshold cannot emit electrons on the metal's surface when shined upon.

B. Einstein's correction

In order to make a correction for the mismatch of theory and data mentioned above, Einstein proposed in his 1905 paper, "A heuristic point of view concerning the production and transformation of light," that treated light particles as packages or photons, each with an energy proportional to its frequency, $E=h\nu$.

To explain the problem of (3) above, Einstein suggested that there is a certain threshold for work required for an electron to escape the metal surface. In determining the amount of work needed, complicated factors such as metal internal lattice configuration and electron structures are

involved. Energy exchanges include energy for exciting valence band electron to conduction band and energy for diffusion of electron in solid. As a result, the energy threshold is very specific for the metal itself and thus each metal has its own work threshold.
Thus, when a photon hits an electron on the metal, it transfers its energy to the electron. And if this energy is less than the metal's work function, the photon is re-emitted and no electrons are liberated. If this energy is greater than an electron's binding energy, the electron escapes from the metal with a kinetic energy equal to the difference between the photon's original energy and the electron's binding energy. Therefore, the maximum kinetic energy of any liberated electron is equal to the energy of the photon minus the minimum binding energy (the work function) as follows:

$$K_{max} = h\nu - W_0$$

C. Determination of Planck's constant

In the following experiments, three methods were used to measure the Planck's constant. The first is the traditional method as explained in elementary text books. Light of varying wavelengths is incident on a metal surface and the kinetic energy of the emitted electrons are measured. In the second method the process is reversed. Light Emitting Diodes (LED) are used to inject electrons into a PN junction where they recombine with holes and emit light. In the third method, black box testing is used to record the retarding voltage for different wavelengths.
If we divide the above equation by e and rewrite it in units of electron-volt (which can be converted to J*s later on):

$$K_{max}[\text{in eV}] = V_s = (h/e)*\nu - W_0 \text{ [in eV]}$$

Cut-off voltage is determined correspond to frequency and the slope of the relationship gives us the values for Planck's contant from the equation above.

Experiment

A. Part I: Stopping Voltage method

The textbook example of the photoelectric effect uses a stopping voltage method. In this part of the lab a Mercury light source provides a broad spectrum of photons. Specific wavelengths from the source are selected using a series of interference filters and/or a prism. The light is focused onto a conducting screen inside a vacuum tube as below in Fig. 1.

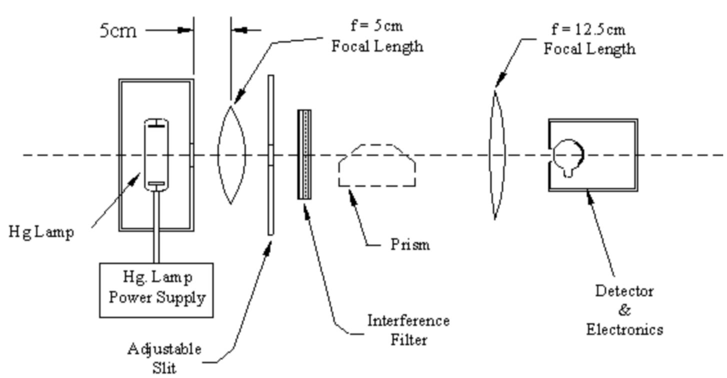


Figure 1: Schematic of the stopping potential method apparatus arranged on optical bench. The details of the photocell are shown in Fig. 2.

Inside the vacuum tube a thin wire is biased by a retarding voltage, V_r (see Fig. 2). The field from the detector wire allows photoelectrons with energies greater than approximately V_r to leave the screen. Those with energy less than $\sim V_r$ are turned around by the detector field and are eventually re-adsorb in the screen.

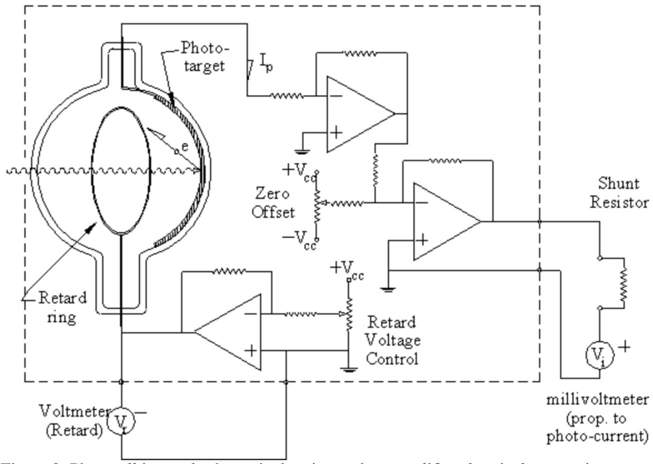


Figure 2: Photocell internal schematic drawing and preamplifier electrical connections.

To understand the photoelectron current refer to the energy diagram in Fig. 3. For a potential, V_R, applied between the screen and detector Fermi energies, electrons emitted from the Fermi level have the largest Kinetic energies (see Fig. 3a). All electrons with KE < 0 have sufficient energy to be collected at the detector wire. As the retarding potential is increased fewer electrons are collected until the threshold voltage, $V_{R,min}$, is reached (Fig. 3b). At this voltage the current to the detector goes to zero.

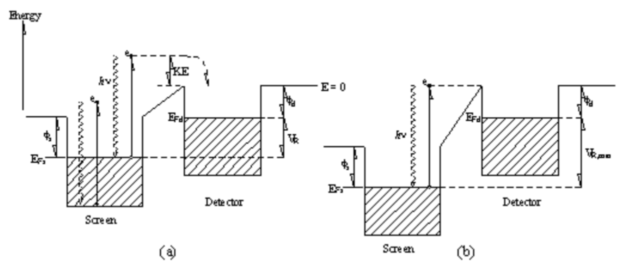


Figure 3: Energy diagram of the photoelectric effect. (a) Two transitions above and below the threshold retarding voltage, VR,min. (b) Threshold transition.

At threshold the following relationship holds:

$$hv = eV_{R,min} + e\emptyset_d$$

By measuring the threshold potential for light with different incident frequencies, a plot of *V* versus ν should be a straight line with slope *h/e* and intercept φ_d.

Unfortunately the threshold voltage is not so easily identified. The reason for this is that the number of energy state, N(E), in the metal near E_F may be very small. In general the number of electron states increase below E_F. So even though the retarding voltage is below the threshold for emission, very few electrons are in fact emitted. This means that the current rises very slowly with retarding voltage even below threshold.

The use of filters was applied to get specific wavelength as follows:

UV	465 nm
Violet	405 nm
Blue	436 nm
Green	546 nm
Yellow	578 nm

Figure 4. wavelength of filters used in part I

The principle of interference filter is accounted for the wave-characteristic of electromagnetic radiation, i.e. our light. Interference filters use the phenomenon of interference in order to transmit or reflect particular spectral ranges of the electromagnetic radiation. In order to achieve this effect, a number of thin coatings with different refractive indices is applied to neutral glass. When the electromagnetic radiation hits these coatings, it is split into a passing, a reflected and an absorbed portion on each boundary between two materials of different refractive indices. The same split-up occurs on any further boundary so that a great number of partial rays is generated which overlap and interfere constructively or destructively as demonstrated below:

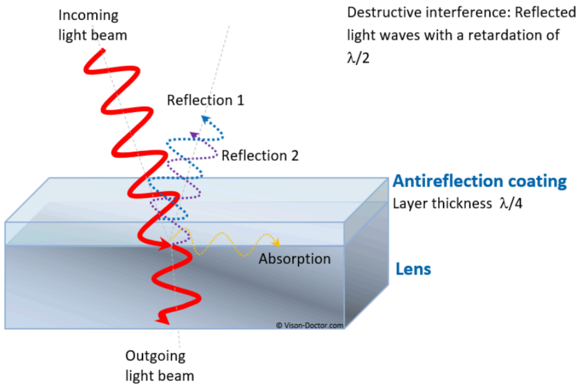


Figure 5. diagram of interference filter for incoming light

B. Part II: Light emitting diodes method

LEDs are based on the injection luminescence principle. They consist of simple p-n junction diode. Without an externally applied voltage, a diffusion potential V_D is generated in the depletion layer between the n- and p-type material as in figure below. The diffusion potential prevents electrons and holes from leaving the n- and p-regions respectively and entering the opposite regions. In chemical equilibrium (no external bias) the Fermi energy, E_F, is a constant across the junction. On the n-side E_F lies between the donor level, ε_d, and the conduction edge, ε_c. On the p-side E_F lies between the acceptor level, ε_a, and the valance band edge, ε_v.

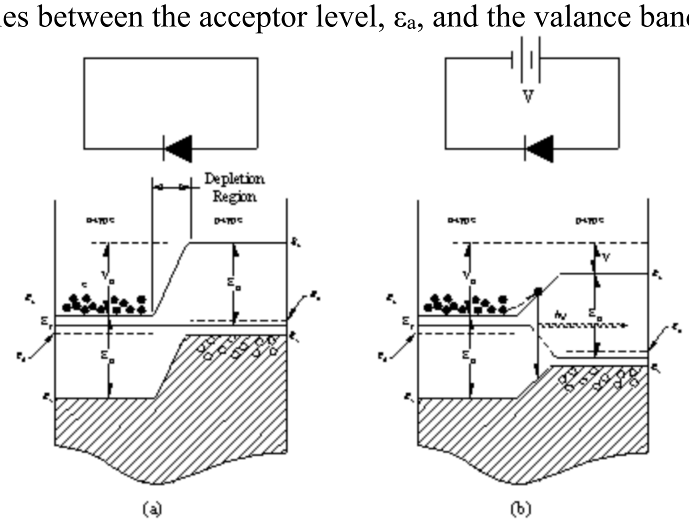


Figure 6. The electron energy level diagram of a p-n junction light-emitting diode. (a) unbiased diode. The solid circles are electrons and the open circles are positive holes. (b) forward biased diode. The bias voltage is V.

In most doped semiconductors the energy differences ε_c-ε_d or ε_a-ε_v are small compared to the band gap E_g. Usually ε_c-ε_d or ε_a-ε_v are a few meV while E_g can be ~ 1eV. This means that to a very good approximation:

$$eV_D \approx E_g$$

If we assume that, of those electrons injected into the depletion region, all of their energy supplied by the electric field is converted into light, then the frequency of that light is approximately:

$$hv \approx E_g$$

Combining two equations above,

$$hv \approx eV_D$$

Thus, knowing the wavelengths of light emitted by LED in table below, we can use the photodiode apparatus set up in Figure 7 to measure the diffusion potential and obtain h/e value from the graph of V_D $vs.$ v:

Table 1
Physical Properties of the LEDs

	Diode 1	Diode 2	Diode 3	Diode 4	Diode 5	Diode 6
Wavelength (nm)	950±20	665±15	635±15	590±15	560±15	480±40
Color	IR	Red	Super-Red	Yellow	Green	Blue
Composition	GaAs:Si	$GaAs_{.6}P_{.4}$: N	$GaAs_{.35}P_{.65}$: N	$GaAs_{.15}P_{.85}$: N	GaP:N	SiC

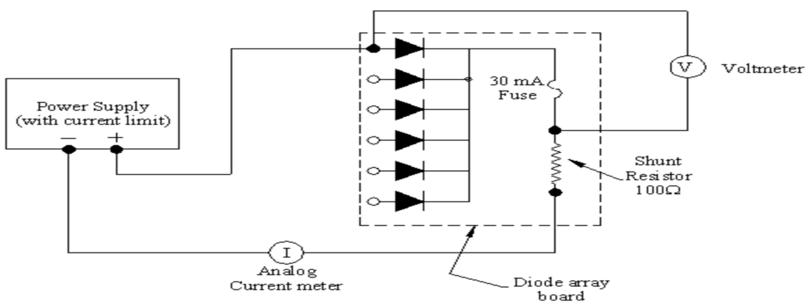


Figure 8. setup of photodiode experiment

The current through the diode rises exponentially for V>0 according to the equation:

$$I = I_s(e^{\frac{eV}{kT}} - 1)$$

We find the diffusion potential by finding the "knee" in the curve where the current begins to increase rapidly. The applied voltage at the "knee" is proportional to the minimum emission voltage for light. From the discussion above, the voltage at the "knee" must be approximately V_D.

C. Part III: black-box photoelectric method

In the last part of the experiment, we shine light of known wavelengths on metal surface within a black-box and record the voltage generated across the metal surface within. The approximate setup of the experiment is below, where incident light cause electrons to emit on the surface within the black-box and thus we can approximate the stopping voltage across the circuit for each wavelength.

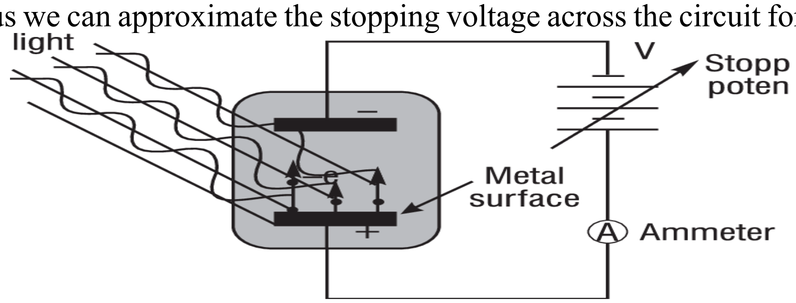


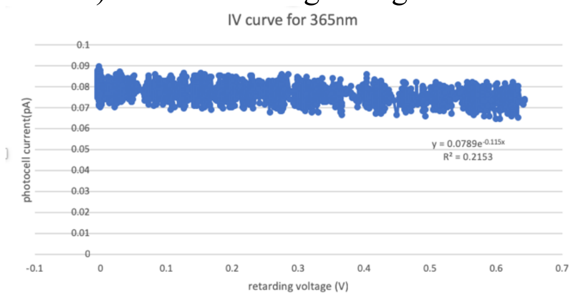
Figure 9. black-box photoelectric effect setup

Later on, in analysis section, we can obtain h/e value from the graph of stopping potential vs. frequency of light in the same mechanics as the methods before.

Results and Analysis

A. Part I: Stopping Voltage method

The graphs of five wavelengths for plots of photocell current (i.e., a voltage proportional to the current) versus retarding voltage are as follows:



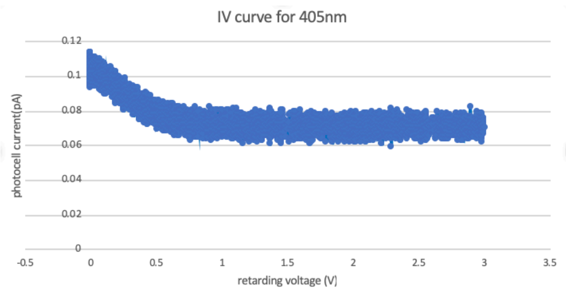
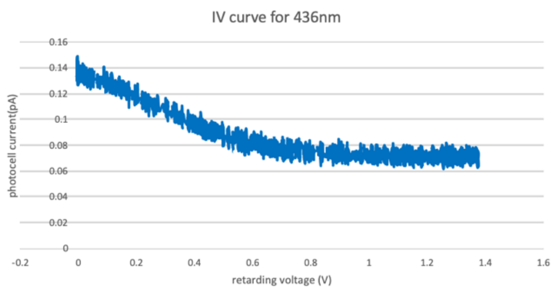


Figure 10a. IV curve 365nm (stopping voltage method) Figure 10b. IV curve 405nm (stopping voltage method)



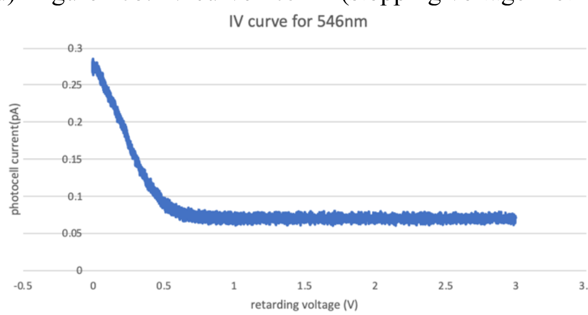


Figure 10c. IV curve 436nm (stopping voltage method) Figure 10d. IV curve 546nm (stopping voltage method)

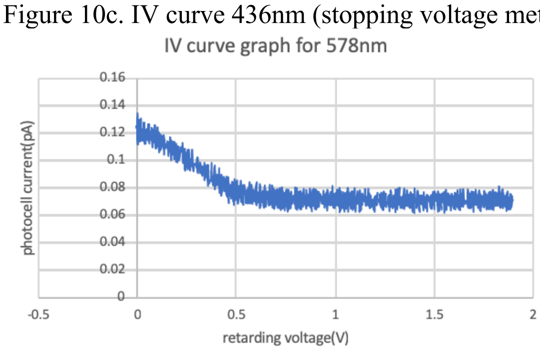


Figure 10e. IV curve 578nm (stopping voltage method)

Take the derivative of the graph and find when the derivative of the current vs. V_R begins to increase and that point would be the cut-off potential $V_{R,min}$. We can do so since $I(V_R)$ is an integral of the number of electrons emitted with an energy between V_R and $V_{R,min}$:

$$I(V_R) \propto \int_{e\emptyset_d+eV_R}^{e\emptyset_d+eV_{R,min}} N(E)dE$$

N(E) goes to zero faster than its integral making the onset of emitted current more apparent. From the estimated stopping voltage, plot stopping voltage versus frequency as shown below in Figure 11. The calculated values for stopping voltage method:

$$h = (6.65 \pm 0.88)*10^{-34} J*s,$$

$$\emptyset_{eff} = (1.08 \pm 0.32) eV$$

Comparing to the accepted value of h which is $6.63*10^{-34} J*s$, the first method corresponds to the expected value of h greatly with a percentage error of 0.30%.

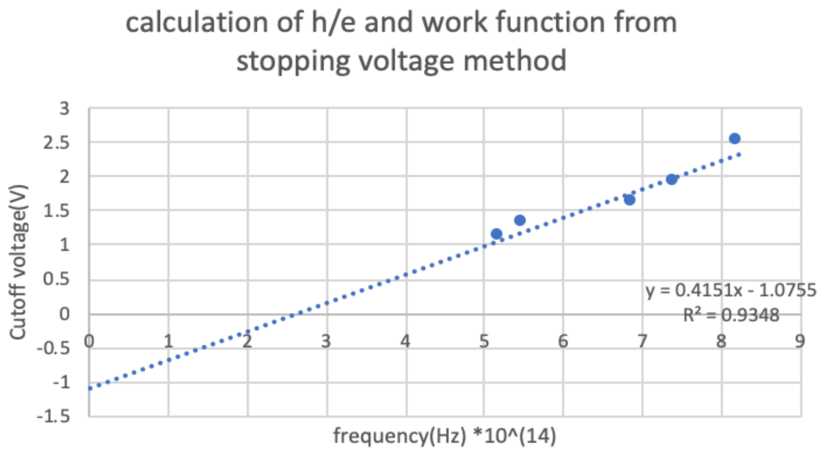


Figure 11. The linear fits to the cut off voltage points for each frequency for stopping voltage method

Another topic of investigation is whether stopping potential depends on the incident intensity. The following graph shows three scenarios for case of 546nm when (1) aperture is closed (orange line), (2) reduced intensity of light (grey line), and (3) normal lighting (blue line).

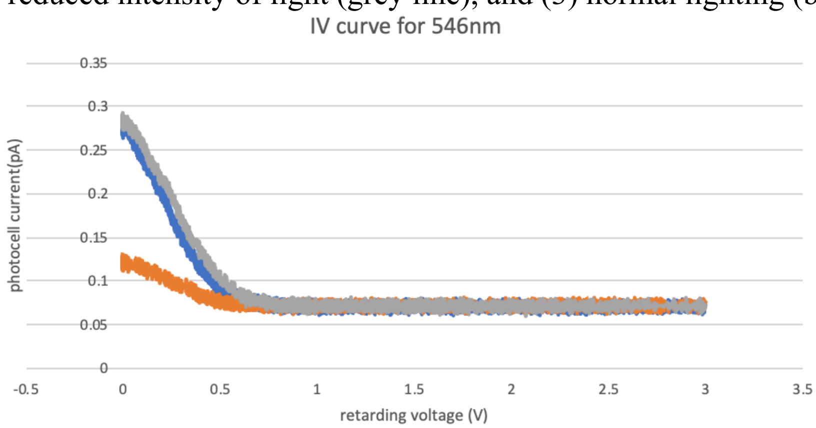


Figure 12. The IV curves of 546nm for when (1) aperture is closed (orange line), (2) reduced intensity of light (grey line), and (3) normal lighting (blue line).

From the graph above we can see that the stopping voltage does not depend on the incident intensity of light, which meets our expectation.

Source of error includes that there remain lots of noise in the data and it could have been improved by doing more trails of experiment and average the result to reduce the noise. Another source of error comes when determining the stopping potential, the derivatives of the graphs do not show a clear increase sometimes and the estimated stopping potential can be off around 0.2V.

B. Part II: Light emitting diodes method

The following graphs show the "IV" curve for p-n junction diode under the different wavelengths. And we can see that the curves demonstrate the exponential tendency corresponding to the equation:

$$I = I_s(e^{\frac{eV}{kT}} - 1)$$

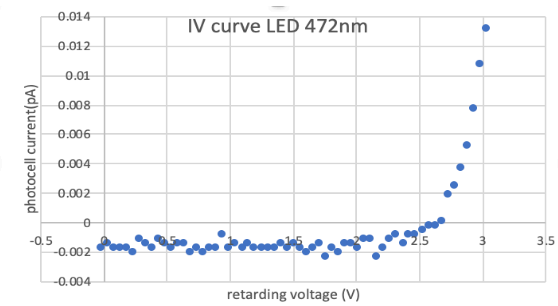


Figure 13(a) IV curve for diode for 472nm

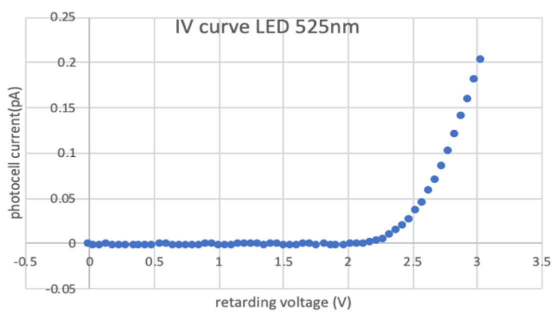


Figure 13(b) IV curve for diode for 525nm

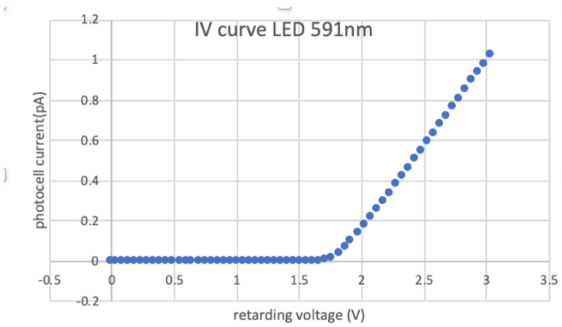


Figure 13(c) IV curve for diode for 591nm

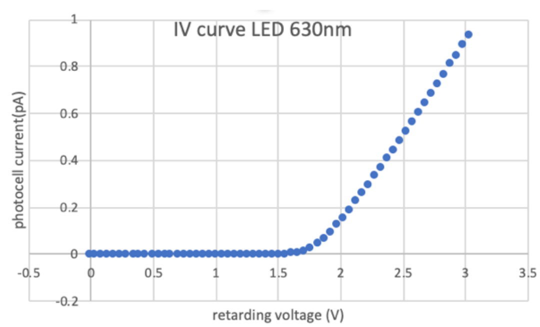


Figure 13(d) IV curve for diode for 630nm

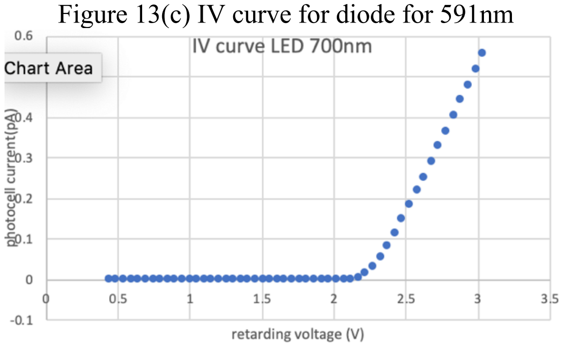


Figure 13(e) IV curve for diode for 591nm

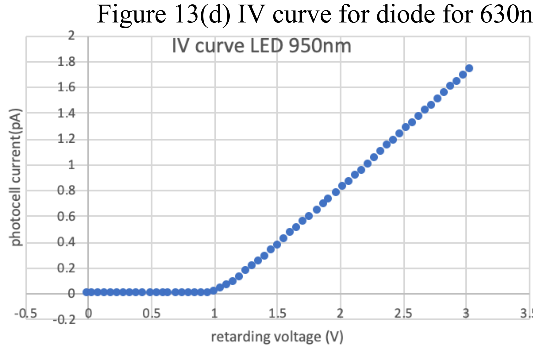


Figure 13(f) IV curve for diode for 950nm

Take the derivative of the graph and find the part of the IV curve where the exponential approximation is good since the highest voltages in the derivative IV curve do not follow a simple exponential. The estimated value for diffusion voltage versus corresponding frequency is graphed below in Figure 14.

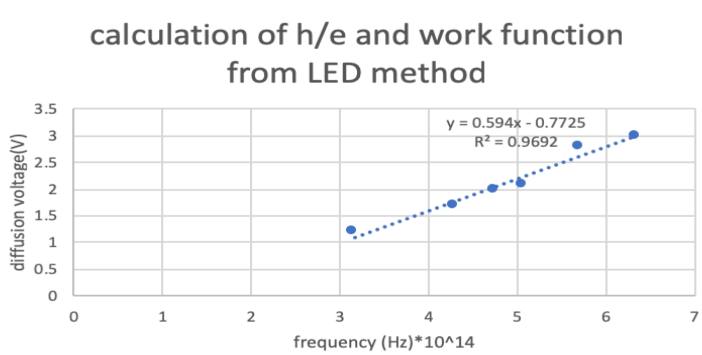


Figure 14. graph of diffusion voltage (stopping voltage) vs. frequency in LED method

The calculated values for light emitting diode method:

h= $(9.52 \pm 0.88)*10^{-34} J*s$,

$\emptyset_{eff}$=$(0.97 \pm 0.32) eV$

The result of h is a little far from the accepted value $6.63*10^{-34} J*s$ with a percentage error of 43.59%. One source of error comes from the estimation before that all of the energy supplied by the electric field is converted into light, that the frequency of that light is approximately $h\nu \approx E_g$. Since the energy cannot be perfectly converted to light, other source of energy such as heat is also generated, this approximation causes error in h value.

On the other hand, when looking at the wavelength distribution from each diode using the grating spectrometer, the wavelengths also have spectral distributions and the ranges are provided in table 1 above in experiment discussion section. This would also produce error bar of about $0.2*10^{14}$Hz. Also, estimation of the diffusion voltage can also be about 0.2V error bar. Another source of error comes from the fact that the diffusion potential is a function of temperature. Investigation of the temperature dependence of V_D and comparison with reference data shows that V_D rises with falling temperature:

$$\frac{\Delta V_D}{V_{D,o}} \Delta T = -5.7 * 10^{-4} K$$

Where ΔT and ΔV_D are the changes in temperature and diffusion potential, respectively, relative to their T = 0 K values. Also $V_{D,0}$ is the diffusion potential at T = 0 K. This increase can explain the systematic error found in measurements at room temperature. Using equation above to estimate $V_{D,0}$ and replotting $V_{D,0}$ vs. ν and we found out that the difference is too little to take into account. The h/e value obtained after correcting the temperature influence is too close to the value above to record separately.

C. Part III: black-box photoelectric method

The estimated value for stopping voltage versus corresponding frequency is graphed below in Figure 14. The calculated values for black-box photoelectric effect method:

h= $(6.44 \pm 0.88)*10^{-34} J*s$,

$\emptyset_{eff}$=$(1.87 \pm 0.32) eV$

The result of h corresponds nicely to the expected value of h which is $6.63*10^{-34} J*s$ with a percentage error of 2.87%.

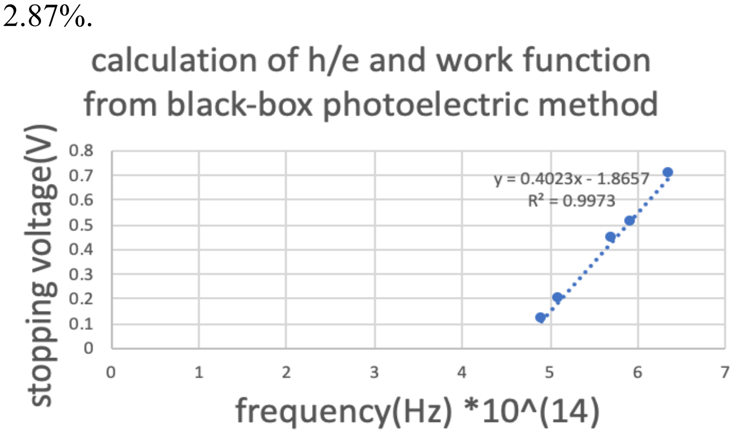


Figure 14. graph of stopping voltage vs. frequency in black-box photoelectric effect method

Source of error include inaccurate reading of stopping voltage, and that the wavelengths of the lights may be slightly off.

Conclusion

The main purpose of Photoelectric Effect experiment is to observe the effect that produces electricity on the metal when incident lights of different wavelength shined upon. The linear relationship between stopping voltage versus frequency of light corresponds to Einstein's quantum explanation of the light. In the experiment we used three methods: stopping voltage method, LED method, and black box photoelectric method to obtain the value of Planck's contant. The values of Planck's contant we obtained from the slope of the graphs were (6.65± 0.88)*$10^{-34} J * s$ for stopping voltage method, (9.52± 0.88)*$10^{-34} J * s$ for LED method, (6.44± 0.88)*$10^{-34} J * s$ for black box photoelectric effect method, with percentage errors of 0.30%, 43.59%, and 2.87% correspondingly. This experiment can be improved by collecting more series of data to reduce the noise.

References

1. Lab manual of advanced lab in Georgia tech
http://advancedlab.physics.gatech.edu/labs/photoelectric/photoelectric-3.html
2. Interreference filter from Vision Doctor
https://www.vision-doctor.com/en/interference-filters.html