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Five decades of determining Planck's constant using light emitting diodes in Undergraduate Laboratories - A Review

Harish Venkatreddy*, Shivaprasad Nambhihalli Gopalakrishna†, Ashok Godekere Visweswaraiah‡ & Nagendra Naik Keemya Naik§

Abstract

Determination of Planck's constant using LEDs has been a favourite experiment even from student perspective because of its simplicity and taught in undergraduate laboratories for the past five decades. Several modifications and improvements adopted in both experiment procedure as well as data analysis part of this experiment during this period have been revisited in this paper. From the simplest experiment to determine turn-on voltages using human judgement with naked eye to advanced equipment to detect even pico ampere current flowing through LED's have been proposed by various researchers. Many of these proposals were successful in arriving at Planck's constant with excellent agreement with standard value. Reasons for yielding unrealistic values of Planck's constant have also been reported by several researchers.

* Department of Physics, Government First Grade College, Bapujinagara, Shivamogga, Karnataka, India; harishvenkatreddy@gmail.com
† Department of Physics, Government First Grade College, Srirangapatna, Karnataka, India; ngsprasad1981@gmail.com
‡ Department of Physics, Government College, Mandya, Karnataka, India; ashok.godekere@gmail.com
§ Department of Environmental Science, Government First Grade College, Bapujinagara, Shivamogga, Karnataka, India; nagendranaik78@gmail.com

Keywords: Planck's constant, Light emitting diode, Cut-off voltage, Turn-on voltage, Barrier potential, Activation voltage

1. Introduction

Planck's constant is one of the most important fundamental physical quantities which play a very significant role in quantum mechanics, electronics, statistical mechanics, astronomy and astrophysics, and in many other related areas of science. It was proposed by Max Planck while explaining the black body radiation using quantum principles. Even after learning about Planck's constant for more than a century, determining its value is still a field of research interest. During this period, several new experiments involving Planck's constant were designed and conducted to evaluate the proper value of Planck's constant. With an advancement in measurement precision of physical quantities, value of Planck's constant is also advancing towards precision. Value of Planck's constant plays very important role in re-defining many other fundamental physical quantities such as volt, ampere, ohm, kilogram etc. At present, the accepted value for Planck's constant is about $6.62607015 \times 10^{-34}$ JS in SI units. It was measured and proposed by International Bureau of Weights and Measures and also National Institute of Standards and Technology (NIST), USA.

Several methods have been employed in accurate determination of Planck's constant. Important methods identified by Richard Steiner are, (Richard Steiner, 2012) Josephson junction, a superconducting quantum interference device used to define a volt standard, Absolute volt balance method, Absolute ampere balance method, Quantum Hall Effect to define resistance standard, Avogadro constant method, Quantum Hall Effect based electronics, Superconducting magnetic levitation, Joule balance method, Watt balance method etc. Among these, watt balance method was quite popular among researchers. Above mentioned methods are meant for high precision measurements involving high end equipment.

To introduce undergraduate students on determination of Planck's constant, few simple methods involving low-cost apparatus were proposed. Among them, less accurate tungsten bulb method was proposed by Crandall & Delord in 1983 (Crandall and Delord, 1983) and with considerable accuracy Photoelectric effect based photocell method was proposed by RD Mac Queenin 1966 (R D Mac Queen, 1966) and other researchers as well (HH Hall & RP Tuttle, 1971, R Powell, 1978). Light emitting diode (LED) method was proposed by P J O'Conner and L R O'Conner in 1974 (P J O'Conner & L R O'Conner, 1974) and many other researchers (Dennis Sievers & Alan Wilson, 1989, L Nieves and et al., 1997, Feng Zhou & Todd Cloninger, 2008, Ryan Eagan, 2011, V. Indelicato et al., 2013, Richard Ward, 2013, Andrea Checchetti & Alessandro Fantini, 2015, Cliff Orori Mosioriet al., 2017, C Calvo Mole et al., 2019, Mila Bileska 2020). LED method of determining Planck's constant has become quite popular in introductory undergraduate physics laboratories due to its simple principle and affordable equipment. LED method also gives the value of Planck's constant with fair accuracy and required apparatus can be easily built using 'do it yourself' ideas even by students. In this paper, five decades of progress of determining Planck's constant using light emitting diodes has been presented. From the literature available, papers which propose new approaches either in experiment or in data analysis were only considered for discussion.

2. Materials & Methods

Determination of Planck's constant using LED's involves simple apparatus such as, a variable voltage source (B), different colored LED's of known wavelength (L), a current limiting resistor (R), voltmeter (V) and an ammeter (A) connected as shown in the figure 1.

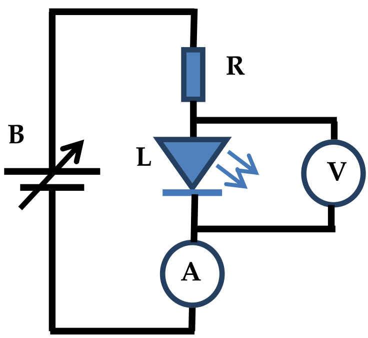

Figure 1.

This setup uses a principle based on phenomenon of 'Inverse Photoelectric Effect'. Flow of electron in an LED emits a light photon. This flow of electron is possible only after certain minimum applied voltage called cut-off voltage or turn-on voltage across the barrier of LED. Energy carried by the electron is emitted as light photon and hence cut-off voltage varies with the wavelength of light photon emitted. Hence, electron energy and photon energy are related as,

$$Electron\ energy = eV,\ Photon\ energy = hf,\ hence\ eV = hf = h\frac{c}{\lambda} \ldots\ldots(1)$$

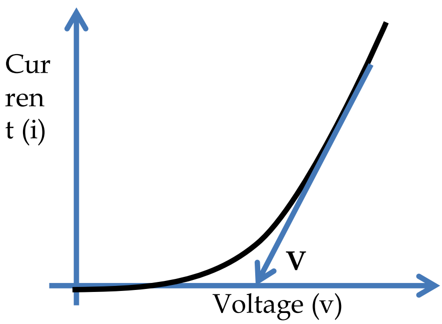

Figure 2.

Where, e be the electron charge, f be the frequency of emitted photon, λ be the wavelength of emitted photon and c be the velocity of light. To determine the value of Planck's constant, the above equation can re-written as,

$$h = \left(\frac{e}{c}\right)(V\lambda) \ldots\ldots(2)$$

An experiment may be conducted to find the critical voltage for a given LED of known wavelength and assuming standard values for $e=1.602176634\times10^{-19}$ Coulomb and c=299792458 meter per second, Planck's constant can be evaluated using equation 2. Since the accuracy of the determined Planck's constant mainly depends on the proper values of the critical voltage (turn-on voltage) and corresponding wavelengths, different approaches have been proposed for determining cut-off voltage. Further, commercial LED's also do not emit monochromatically. Emitted light has a maximum for the given wavelength with a considerable widening on both sides of the maximum. This further affects the value of Planck's constant. Hence in order to overcome these issues, several researchers have adopted different approaches to determine cut-off voltage and to consider proper wavelength emitted.

P J O'Conner & L R O'Conner (1974) has explained the principle well and proposed a method as explained above using a similar circuit as shown in figure 1. Procedure proposed was to measure current (i) and voltage (v) across the given LED in forward bias mode and to plot a graph of I-V characteristics. To find the barrier voltage or cut-off voltage, a tangent was projected back from linear portion of the plot to cut voltage axis (as shown in method 2 of figure 5). Dennis Sievers & Alan Wilson (1989) has also explained the principle well and proposed a method similar to explained circuit shown in figure 1. Procedure proposed was to determine the turn-on voltage directly based on the principle that any emission of light from the LED must cause flow of current in the circuit. Hence, flow of current was taken as an indicator of light emission. Applied voltage at which ammeter starts showing deflection was proposed as turn-on voltage.

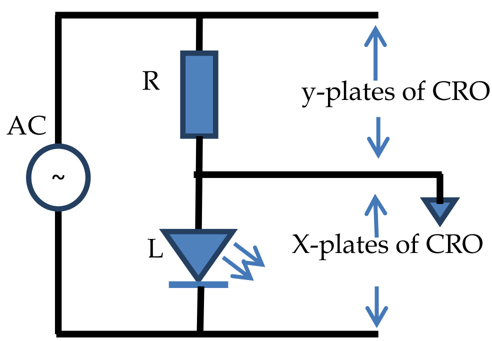

Figure 3.

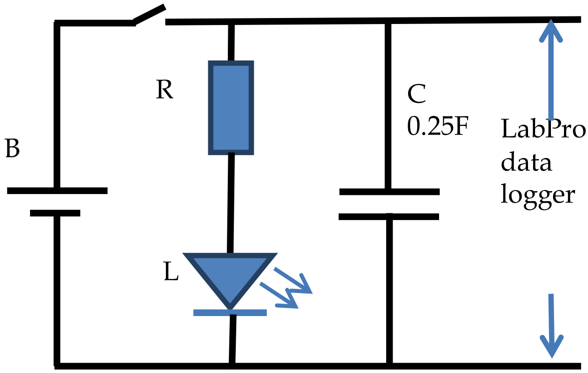

Figure 4.

L Nieves and et al., (1997) proposed a slightly different approach to solve problem in determining both wavelength of light emitted by LED and corresponding forward voltage. They propose to measure the voltage using an oscilloscope and wavelength using monochromator (spectrophotometer) with a schematic as shown figure 3. Applied forward voltage is varied till intensity of the light emitted becomes maximum at a particular wavelength of light emitted by LED. Voltage and wavelength related to the maximum intensity were taken for calculations. Interestingly, they proposed to use an AC source to light the LED's, but in principle LED's flicker when connected to AC sources.

Feng Zhou & Todd Cloninger (2008) have proposed to connect a capacitor in parallel with LED as shown in figure 4 and charge it with a DC source till LED glows fully. Then DC source was disconnected and charge stored on the capacitor was allowed to discharge through LED. Capacitor was expected to discharge till a voltage equal to barrier voltage of the LED. Voltage across capacitor was recorded using VernierLabPro data logger interfaced to a computer. Terminal voltage remaining on capacitor after discharge was used for calculation of Planck's constant. Ryan Eagan (2011) has followed a similar method proposed by L Nieves and et al., (1997) but with a highly sensitive PASCO spectrophotometer and a PASCO voltage probe. The experiment was repeated for three LED's of different color.

Valeria Indelicato and et al., (2013) have determined Planck's constant using photoelectric method which uses different LED's and a photocell to find retarding potential and also inverse photoelectric method using different LED's in a circuit similar to figure to find I-V characteristics using high precision Keithley meters. They propose two different methods to analyse I-V characteristics data to find turn-on voltage as shown in figure 5. First approach was to identify the voltage at which current begins to flow through LED and the second was to draw a tangent to linear part of the graph and extrapolate it to voltage axis to find turn-on voltage. They have also proposed different methods of analysis of data obtained for different LED's. Richard Ward (2013) proposes the simplest method using a circuit similar to figure 1 to find the turn-on voltage of a given LED by human judgement with a dark paper wrapped around LED and using a lens to carefully detect the glow inside LED as shown in figure 6. Also propose to add ultraviolet and infrared LED's to rectify the errors caused by visible light LED's in determining Planck's constant. Milli ammeter was used to find turn-on voltages for ultraviolet and infrared LED's as they do not emit visible light.

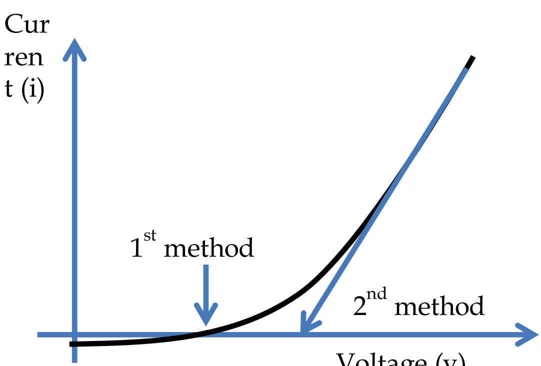

Figure 5.

Andrea Checchetti & Alessandro Fantini (2015) have proposed to determine Planck's constant using a circuit as shown in figure 1. From the I-V characteristics plot for each LED, this method proposes to find turn-on voltages by theoretically extrapolating the linear part of the graph to voltage axis. Cliff Orori Mosioriand et al., (2017) propose to use a Vernier make spectrometer to determine the peak and maximum wavelength emitted by LED's and a data logger with computer interface to determine turn-on voltages. Further propose to analyse the results for zener tunnelling of electrons using a semi-classical model. C Calvo Mole and et al., (2019) have added an ARDUINO board for automatic measurements of I-V data and propose two methods of data analysis. First was to plot I-V characteristics plot and find knee voltage and in second, more rigorous Shockley diode model was applied. Light emitted from LED's was analysed for spectral distribution and wavelength corresponding to peak wavelength was considered. Mila Bileska (2020) has modified the experiment setup as shown in figure 7, to with a grating to select and measure desired wavelength emitted from LED's and also a photodiode (P) as sensor to detect light emission from LED's. ARDUINO UNO board was employed to record the photodiode outputs with respect to applied voltage on LED's. 10 trials of experiment were conducted for each LED to reduce the measurement error. In data evaluation part, two methods were followed with a good theoretical support. First method was to calculate Planck's constant from wavelength and respective photodiode activation voltage for each LED and then to consider average value. Second method was to plot a graph of activation voltage versus inverse wavelength according to equation

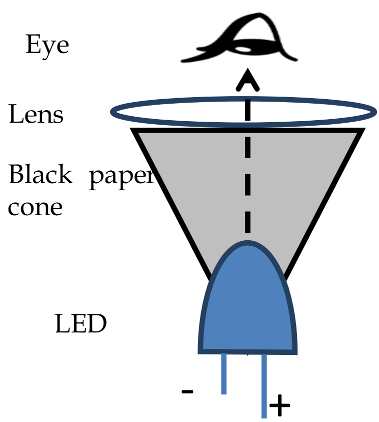

Figure 6.

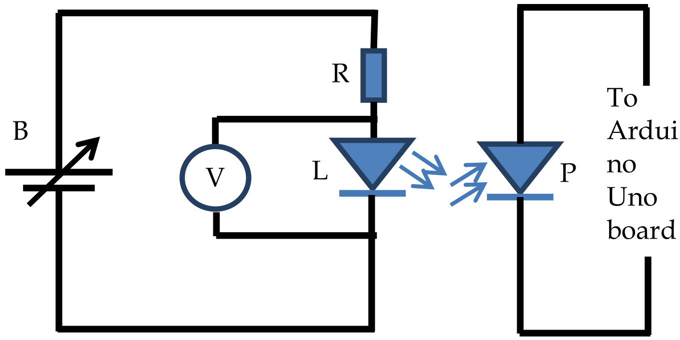

Figure 7.

$\frac{1}{\lambda} = \frac{e}{hc}V$ ... .(3) and calculate Planck's constant from slope of straight line fit of the data.

3. Results & Discussion

In this section, wavelengths of LED's used, values of Planck's constant obtained, average value of Planck's constant obtained and deviation from the standard value from different methods have been discussed and reported values are presented in table 1. Predicted reasons for unrealistic deviation in Planck's constant reported by various researchers also been presented.

From the literature review, P J O'Conner & L R O'Conner (1974) method seems to be the first method reported, using standard wavelength values of the LED's, Planck's constant values were found for Infrared, Red, Amber and Green colours. Obtained values were shown in table 1 and are in good agreement with the standard value of Planck's constant. In Dennis Sievers & Alan Wilson (1989) method, an analog milli-ammeter of limited sensitivity was used as a sensor to detect flow of current and hence emission of light from LED's. Applied voltage at this point was recorded as turn-on voltage and the experiment was repeated for LED's of wavelengths 475, 525, 550, 580 and 650 nm. Obtained value of Planck's constant was reported to be within an error of 10%. They have also presented a BASIC program to do calculations easily and repeatedly. L Nieves and et al., (1997) method considers the wavelength and forward voltage corresponding to maximum emission intensity of light emitted by the LED's. They have used LED's of wavelengths 574, 597, 598, 644, 656, 678 and 900 nm. Obtained average value of Planck's constant was about 6.6(±0.6)x10^{-34} JS with an error of 10%. Reason for using an AC source was not revealed in the article.

Feng Zhou & Todd Cloninger (2008) has measured the discharge voltage of the capacitor and noted the terminal voltage remaining in the capacitor equal to that of barrier voltage of the LED was noted for calculations. Experiment was conducted for LED's of different wavelengths and a graph of band gap energy (=eV) versus frequency of light emitted was plotted. From the slope of straight line graph, average Planck's constant was evaluated to get 6.625x10-34Js very close to standard value. They have reported that this method is very accurate and reliable. In addition, also mentioned that Planck's constant value will be affected by band structure of LED material, temperature effects and emission spectrum width of LED. Ryan Eagan (2011) method has improvisation only in precise measurement with better equipment over L Nieves and et al., (1997) method and considered three LED's for measurement to obtain Planck's constant value within 6.7% of error. He has also proposed to reduce the random error by further refinement of experimental procedure and considering more LED's within each colour group to reduce randomness due to inherent inconsistencies in manufacturing of LED's.

Valeria Indelicato and et al., (2013) have showed that turn-on voltages found by both the methods when plotted with wavelengths of respective LED's yield almost same slope and hence lead to almost same Planck's constant. Among the wavelengths/colours used (472, 505, 525, 588 and 611nm), blue colour was found to deviate from the linear fit of all other colours in the plot. Further they have shown this deviation of blue LED from the other LED's through a careful analysis of data by taking current axis in logarithmic scale. Hence, they proposed that considering blue LED's for determination of Planck's constant would yield un-realistic values. Hence after omitting blue LED data, Planck's constant value obtained by using first method for turn-on voltage was 6.41(±0.28)x10^{-34}JS, while using second method was 4.04(±0.45)x10-34Js. Further they have carried out a detailed analysis I-V characteristics by considering different orders current flowing in the LED from pico-ampere to milli-ampere and detected discrepancies in turn-on voltages of different LED's and showed how turn-on voltage affects the Planck's constant.

Richard Ward (2013) method to find turn-on voltage seems to be the simplest but subjected to human judgement. He could show the deviation caused by visible only LED's to give Planck's constant value as 7.7(±0.4) x10^{-34} JS and as a correction, suggested to use ultraviolet and infrared LED's in addition to visible ones to get better value of Planck's constant as 6.2(±0.3) x10-34 Js. He further claims that obtained results are in good agreement with the assumption defined by equations 1 and 2. Andrea Checchetti & Alessandro Fantini (2015) have determined Planck's constant from both LED method as well as photocell method and compared them well. They have neatly presented the laboratory procedure to be followed by the students while doing these measurements. From I-V plots of four LED's (red, yellow, green and blue), turn-on voltage was determined theoretically by determining the straight line equation of the linear part of the graph. For this purpose, MS-EXCEL was used to plot the graphs and to find the straight line equation. Planck's constant values individually obtained were found to be in good agreement. Among the four LED's used, blue LED value was observed to deviate towards higher side compared to other three LED's. Surprisingly good agreement was observed in the average value of Planck's constant to less than 1% deviation from standard value. Planck's constant obtained from photocell method was also reported for comparison.

Cliff OroriMosiori et al., (2017) have determined the peak and maximum wavelengths of light emitted by LED's and their respective turn-on voltages with good accuracy. This method allows two set of data from each LED's in terms of peak wavelength and maximum wavelength. Planck's constant values obtained were in good agreement with standard values and average value deviates 6.5% only. Results obtained were further used for theoretical predictions of excitation energy of electrons for zener tunnelling using a semi-classical model. More detailed and rigorous nature theoretical analyses may find answers to uncertainty in turn-on voltages caused due to fabrication deviations. C Calvo Mole et al., (2019) have compared the two methods data analysis. In spite of limited theoretical acceptance, surprisingly, the first method being the simplest from student point of view and yields Planck's constant value close to standard value with only 3.36% deviation. On the other hand, the second method having a theoretical acceptance fails to give a good value for Planck's constant. They have attributed this deviation to improper non-ideality factor (η) and further highlight that yellow LED behaves differently compared to other LED's. Mila Bileska (2020) approach was observed to be new and different to determine the activation voltages rather than turn-on voltages. Further, the methods of analysis were also found to be quite acceptable and yield Planck's constant with reasonable accuracy.

Table 1. Planck's constant values reported from different methods

Method	LED Wavelengths	*h* (Js)	Average & deviation %
PJ O'Conner and LR O'Conner	910nm 670nm 610nm 560 nm	$6.57 x 10^{-34}$ $6.07 x 10^{-34}$ $6.5 x 10^{-34}$ $6.87 x 10^{-34}$	$6.5025 x 10^{-34}$ 1.86%
Dennis Sievers and Alan Wilson	475, 525, 550, 580 & 650 nm	values not reported in the article	< 10%
L Nieves and et al.,	574, 597, 598, 644, 656, 678 and 900 nm	values not reported in the article	$6.6(\pm 0.6) x 10^{-34}$ 10%
Feng Zhou and Todd Cloninger	430, 565, 585, 660 and 940 nm	$5.77 x 10^{-34}$ to $7.67 x 10^{-34}$	$6.625 x 10^{-34}$ < 1%
Ryan Eagan	562.7, 586.2 and 629.9 nm	$6.138 x 10^{-34}$ $6.211 x 10^{-34}$ $6.192 x 10^{-34}$	$6.180 x 10^{-34}$ 6.7%
Valeria Indelicato and et al.,	472 (omitted), 505, 525, 588 and 611nm	$4.04(\pm 0.45) x 10^{-34}$ to $6.41(\pm 0.28) x 10^{-34}$	<10%

Richard Ward	395 (UV), 470, 505, 525, 590, 605, 625 and 940 (IR) nm	6.2(±0.3) x10^{-34}	6.2(±0.3) x10^{-34} <6%
Andrea Checchetti and Alessandro Fantini	460nm 565nm 600nm 665nm	7.29x10^{-34} 6.18x10^{-34} 6.54x10^{-34} 6.28x10^{-34}	6.572x10^{-34} <1%
Cliff OroriMosiori and et al.,	564 nm 591 nm 594 nm 610 nm 618 nm 625 nm 627 nm 635 nm 646 nm 685 nm	6.02 x 10^{-34} 6.07 x 10^{-34} 6.20 x 10^{-34} 6.08 x 10^{-34} 6.19 x 10^{-34} 6.12 x 10^{-34} 6.12 x 10^{-34} 6.20 x 10^{-34} 5.73 x 10^{-34} 7.21 x 10^{-34}	6.194 x 10^{-34} 6.5%
C Calvo Mole and et al.,	474.29 nm 520.27 nm 567.8 nm 646.4 nm	Individual values not evaluated but average value found from graphs.	6.41(±0.16) x10^{-34} 3.26% 8.2(±0.93) x10^{-34} 23.75%
Mila Bileska	490 nm 534 nm 576 nm 627 nm	6.484 (±0.526) x10^{-34} 6.421 (±0.586) x10^{-34} 6.095 (±0.837) x10^{-34} 6.132 (±0.628) x10^{-34} Average value found method 2.	6.279(±0.644) x10^{-34} 5.24% 6.378(±0.312) x10^{-34} 3.74%

4. More discussion

Nearly for two decades from 1974 to 1996, based on simple assumption that turn-on voltage or critical voltage required to drive charges across the junction to emit light photon of definite wavelength can be used to estimate band gap energy and hence to calculate Planck's constant proven to be right and yielded fairly good value for Planck's constant compared to standard value. However, F Herrmann & D Schatzle (1996) doubted this procedure of determining Planck's constant using LED's in his 'Question #53'. As an 'Answer to Question no 53', Roger Morehouse (1998) gave a proper explanation of the flaws in the experiment followed and proposed corrections in experiment as well as data analysis part. Also suggested to determine the emitted wavelength properly to get value for Planck's constant. As a follow up action, many of the experiments reported after this for nearly two more decades, kept the suggestions in consideration and arrived at better values. During the last decade, Chetan Kotabage (2019) has revisited the suggestions of Roger Morehouse on proper determination of band gap energy to arrive at better values of Planck's constant within 10% of error. Further Dean Zollman & Ian G Bearden (2020) have listed the possibilities where the experiment as well as data analysis may go wrong to yield erroneous values for Planck's constant.

5. Conclusion

An attempt was made in this paper to identify and report five decades of progress in determination of Planck's constant in undergraduate laboratories both in experiment procedure as well as data analysis methods. Even though the direct turn-on voltage measurement or cut-off voltages determined from I-V plots have no theoretical relation to band gap energy of junction of LED's, these data surprisingly yield Planck's constant value in excellent agreement with standard value. This observation may be attributed to the fact that both turn-on voltages and diffusion voltage value related to band gap of LED's turns out be almost close and do not differ much. Unrealistic values of Planck's constants obtained for some colours reported by different authors may be attributed to improper band gaps caused due to tunnelling effects and largely to fabrication errors. Good theoretical treatments given in determining both critical voltage as well as wavelength of light emitted have shown to give Planck's constant value within acceptable limits. It may be noted that, in spite of good theory, fabrication errors as well as structural modifications made in LED's with commercial intentions lead to unrealistic values of Planck's constant. This experiment still has scope for further theoretical refinement both in terms of experiment and data analysis approaches. Hence, a careful selection LED's and a good experiment would yield Planck's constant with fair accuracy. Students will naturally appreciate to conduct experiments to understand and implement the concepts to determine the Planck's constant using LED's in undergraduate laboratories.

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