Measuring Planck's Constant

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Abstract

Planck's constant is determined to within 10% by measuring the voltage required to stimulate light emission from six different light emitting diodes (LEDs), and plotting the voltage required versus the frequency of light emitted. The slope of this line gives Planck's constant, which relates the energy of the light quanta to their frequency.

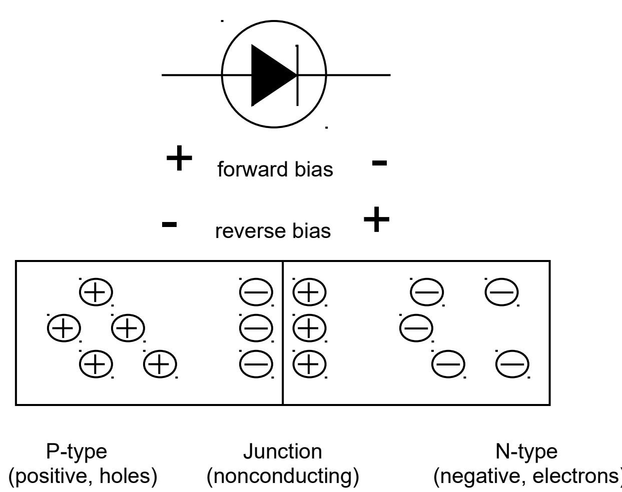
Background and Motivation

LEDs will emit light of a characteristic frequency when a voltage of the correct polarity is applied. The required voltage and frequency of the light are determined by the particular characteristics of the semiconductors used. LEDs are made of N and P-doped semiconductor material (often silicon or germanium) - the N-type material is doped with atoms that have extra electrons and the P-type material with atoms that have extra "holes" (absence of electrons). At the junction of these materials, a barrier exists that normally prevents current from flowing. If the correct polarity voltage is applied though, this junction will be eliminated and charge will be able to flow (the diode is then said to be "forward-biased"). In an LED, when electrons fall into "holes" they emit radiation in the form of light. The frequency of light is determined by the voltage drop across the junction, according to Planck's law:

$$E = hv = eV$$

where E is the energy of the light quanta, h is Planck's constant, v is the frequency of the light, e is the charge of the electron, and V is the voltage drop across the LED. Hence by measuring the voltage at which a diode begins to conduct, we can determine Planck's constant if we know the wavelength of the light being emitted.

The diagram below shows the standard schematic symbol for a diode, and the corresponding semiconductor materials it is made of.



The current through the LED as a function of resistance assumes a characteristic shape, which is modelled by the (ideal) diode equation,

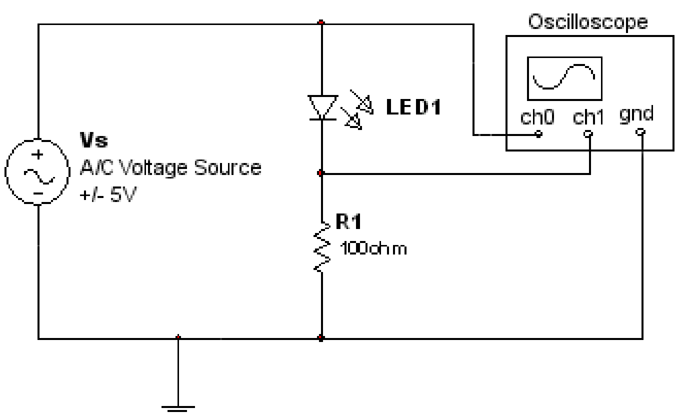
$$I = I_s \left(\exp(V/\eta V_t)-1\right)$$

where

I_s = Saturation current (Amps)
V_t = Thermal voltage = kT/q = 26 mV
k = Boltzmann's Constant = 1.38e-23 J/K
T = Temperature (Kelvins) = 300K
q = Electron Charge = 1.602e-19 C
η = Diode Ideality Factor or Emission Coefficient, usually 1 to 2

Experiment and Methodology

A 6 VAC power supply is used to generate a sawtooth waveform, which ramps through the voltage range of interest (0-3V). A National Instruments DAQ (Data Acquisitions) card is used as a digital oscilloscope to measure and record the voltages across the LED and the 100Ω resistor (see circuit diagram below). Channel one reads the voltage across the LED and channel two reads the voltage across the resistor. This shows the voltage at which the LED becomes forward biased and starts to conduct and emit light at a specified wavelength. This procedure is repeated for each of the 6 LED's, each with a different wavelength of emitted light.



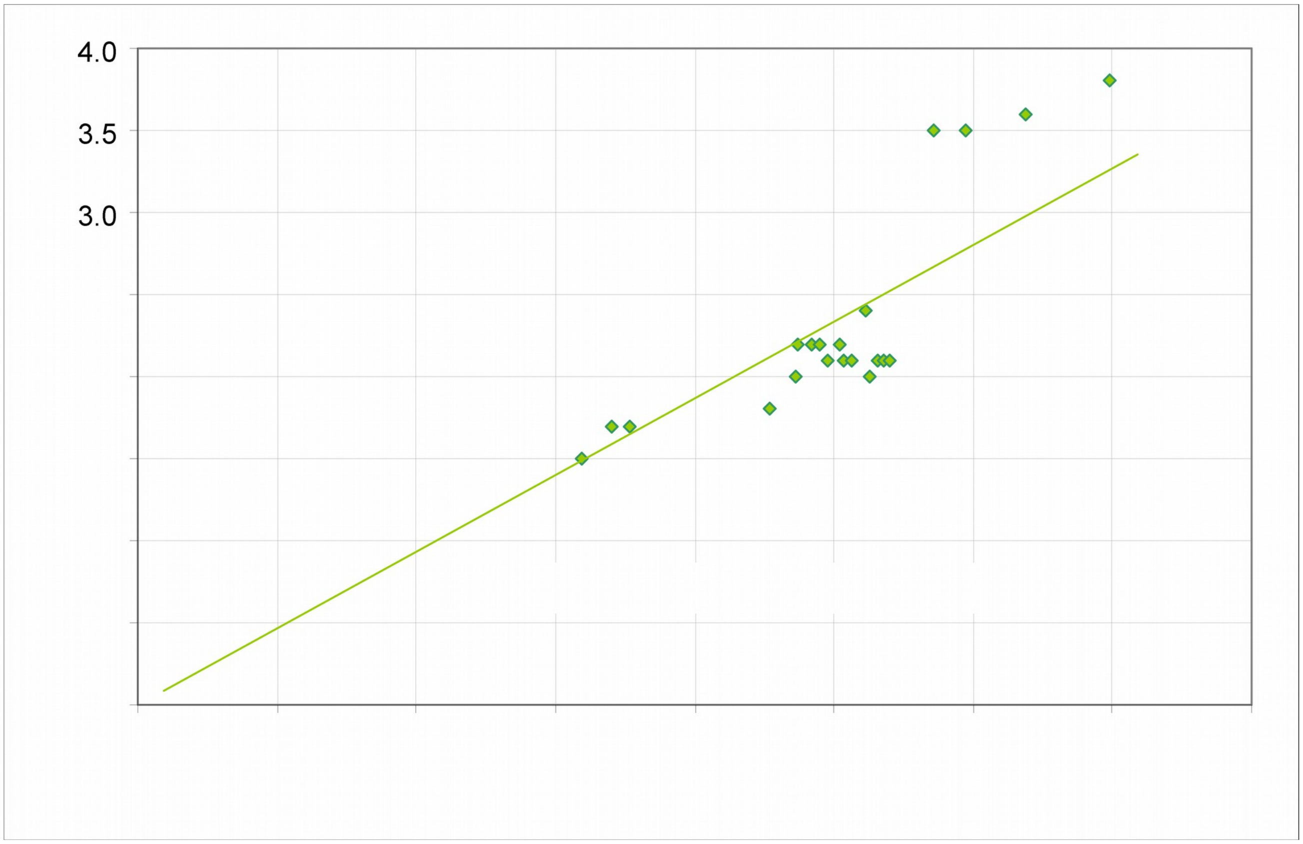
The data is then plotted, with voltage across the LED against the light frequency, with Planck's constant determined from the slope of the least-squares line that fits the data. In the plot below, Energy is the forward voltage times electron charge (qVf), and Frequency is the speed of light divided by the wavelength of the LED. Data was fitted with assumption that the line passes through origin, i.e. that energy is proportional to frequency. The slope of the curve gives Planck's constant / electron charge.

Our value for Planck’s constant is **5.67e-34 Js**, which compares with the accepted value of **6.63e-34 Js**. Our value is thus 14% low.

Data From Web

Data was also found on the web for several different colors of LED [4], and this data was plotted to determine Planck's constant.

Wavelength (nm)	Color Name	Forward Voltage (Vf @ 20ma)	LED Dye Material
940	Infrared	1.5	GaAlAs / GaAs
880	Infrared	1.7	GaAlAs / GaAs
850	Infrared	1.7	GaAlAs / GaAs
660	Ultra Red	1.8	GaAlAs / GaAs
635	High Eff. Red	2.0	GaAsP / GaP
633	Super Red	2.2	InGaAlP
620	Super Orange	2.2	InGaAlP
612	Super Orange	2.2	InGaAlP
605	Orange	2.1	GaAsP / GaP
595	Super Yellow	2.2	InGaAlP
592	Super Pure Yellow	2.1	InGaAlP
585	Yellow	2.1	GaAsP / GaP
574	Super Lime Yellow	2.4	InGaAlP
570	Super Lime Green	2.0	InGaAlP
565	High Efficiency Green	2.1	GaP
560	Super Pure Green	2.1	InGaAlP
555	Pure Green	2.1	GaP
525	Aqua Green	3.5	SiC / GaN
505	Blue Green	3.5	SiC / GaN
470	Super Blue	3.6	SiC / GaN
430	Ultra Blue	3.8	SiC / GaN



The data doesn’t look too consistent. It gives a value for Planck’s constant of h = **7.49e-34 Js**, which is 13% too high.

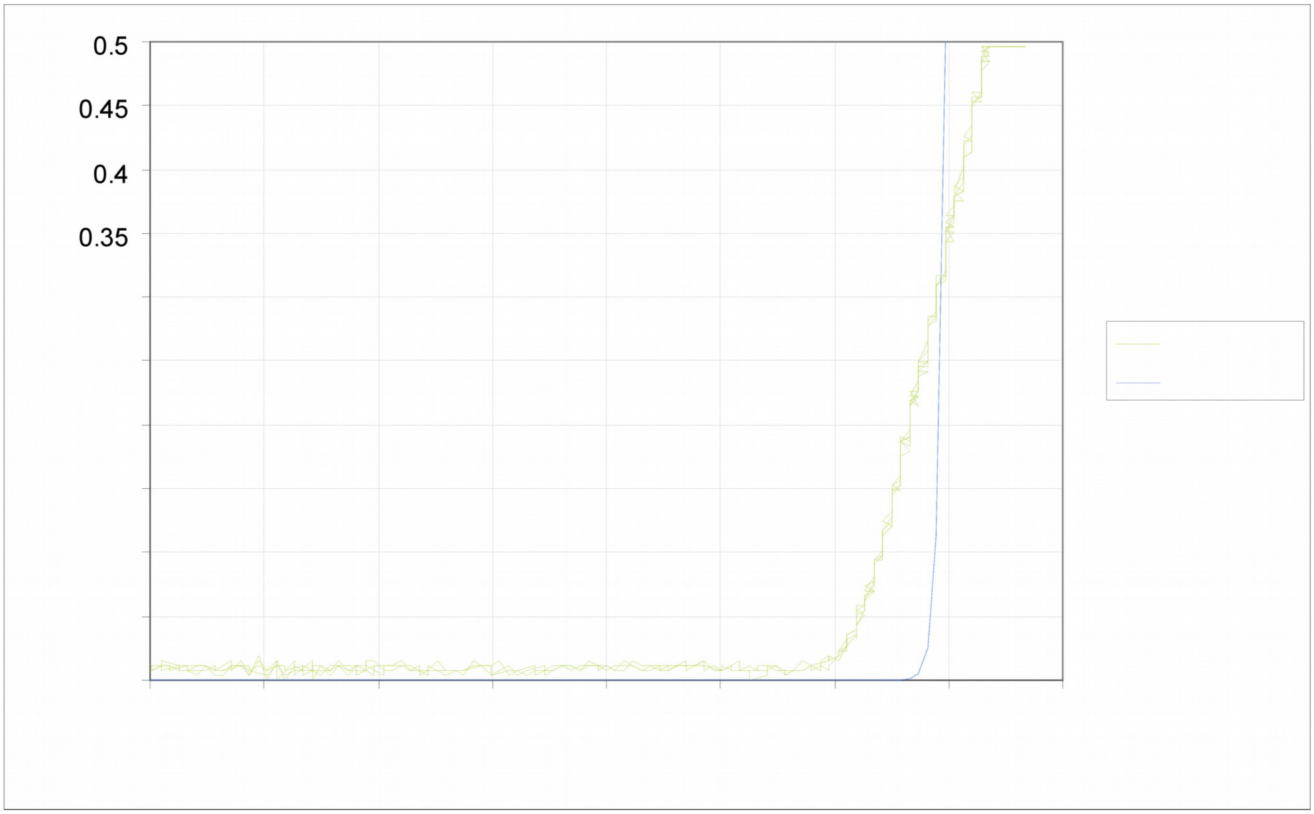
Fitting to the Diode Equation

We next try to fit the observed IV curve to the ideal diode equation given in the Introduction.

$I = I_s (\exp(V/\eta V_t)-1)$

Using least-squares analysis with Mathematica we find a value for I_s and plot the resulting curve against the observed data:

I_s = 5.818e-29 Amps



The fit is not very good – various modifications to the ideal diode equation were tried, including adding a V^2 term, but the results were the same.

XY.vi

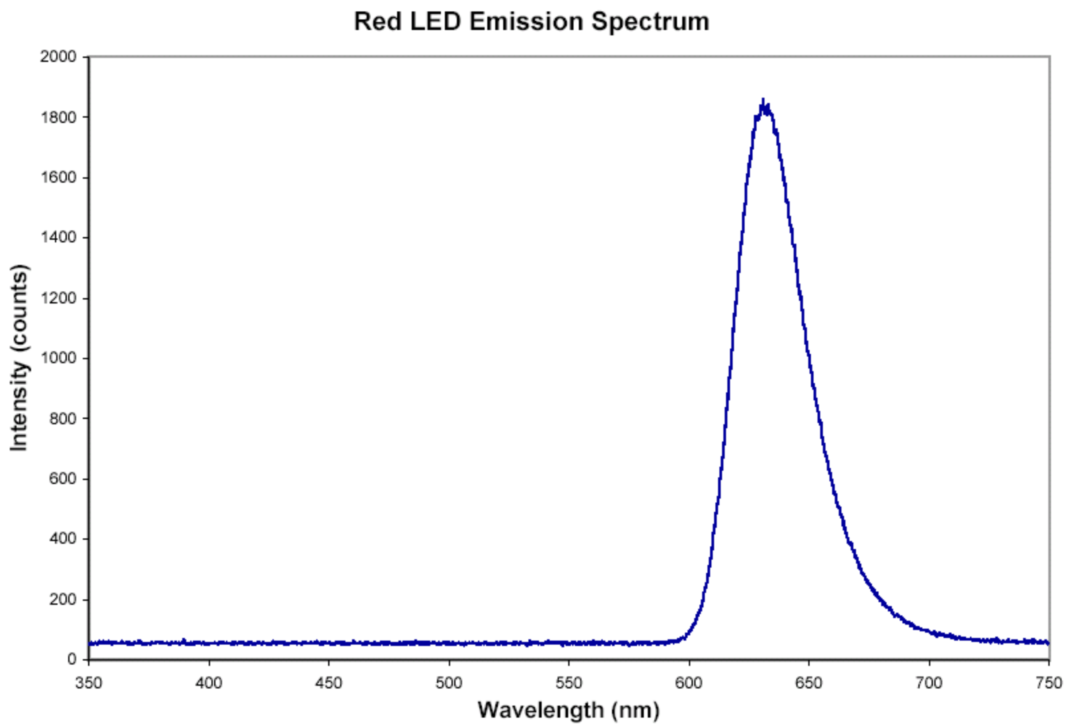
The NI-Scope program that came with the DAQ card did not include an XY plot mode, which necessitated writing one in LabView. This program (called XY.vi) was adapted from some of the examples that came with the DAQ card. It splits the array of data obtained from the card apart and repackages it for the XY graph control. When the user stops the program, it gives the option of saving the data to a text file.

The program "listing" is given at the end of this document.

Discussion

The method used was sufficient to obtain a value of Planck's constant to within 15%, which is good considering the crudeness of the experiment. The wavelengths of the LED's were assumed to be correct as given by the manufacturer - to be certain one would need to saw off the top of the LED's (which were of colored plastic) and use a spectrometer to measure the wavelengths of light emitted.

LED's emit light across a range of frequencies due to thermal variances in the semiconductor materials, as the following plot [5] shows. It's possible that using the heel of the peak rather than the peak frequency itself would give more accurate determination of Planck's constant, since the IV curve likely starts when the LED begins to emit light at the lower voltage associated with the heel of the curve.



Also, the IV data did not fit the ideal diode equation very well, though we're not sure why this was the case.

Conclusion

LED's are quantum devices that convert electrical energy to light of a specific frequency (or a sharp range of frequencies). The frequency of light is dependent on the amount of energy converted, which is based on the voltage drop across the LED. Since this voltage drop and the frequency of the light can be measured, Planck's constant, which relates the two, can be determined experimentally.

The IV curve of a diode or LED can be determined through theoretical considerations, though the quantum physics of those derivations was beyond the scope of this paper.

References

[1] Bevington, *Data Reduction and Error Analysis for the Physical Sciences 3e*, 2003, McGraw Hill.

[2] Cirovic, *Semiconductors: Physics, Devices and Circuits*, 1971, Prentice-Hall.

[3] Tipler, *Modern Physics 3e*, 1999, W. H. Freeman.

[4] [website] TheLedLight.com

[5] [website] www.assumption.edu/users/bniece