THE CURRENT-VOLTAGE CHARACTERISTICS OF AN LED AND A MEASUREMENT OF PLANCK'S CONSTANT

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I. INTRODUCTION

Max Planck (1858-1947) was an early pioneer in the field of quantum physics. Around 1900 Planck developed the concept of energy quantization to explain the spectral distribution of blackbody radiation[1]. This idea is fundamental to the quantum theory of modern physics. Planck received a Nobel Prize for his work in the early development of quantum mechanics in 1918. Interestingly, Planck himself remained skeptical of practical applications for quantum theory for many years. Planck proposed that atoms absorb and emit radiation in discrete quantities given by

$$E = nhf, \tag{1}$$

where n is an integer known as a quantum number, f is the frequency of vibration of the molecule, and h is Planck's constant. The smallest discrete amount of energy radiated or absorbed by a system results from a change in state whereby the quantum number n of the system changes by one.

In 1905 Albert Einstein (1879-1955) published a paper[2] in which he used Planck's quantization of energy principle to explain the photoelectric effect. The photoelectric effect involves the emission of electrons from certain materials when exposed to light and could not be explained by classical models. Einstein assumed that the electrons absorbed one quantum of electromagnetic energy at a time and that the energy of this quantum (photon) is

$$E = hf = \frac{hc}{\lambda}, \tag{2}$$

where f is the frequency of the light and λ is its wavelength. An electron would only be ejected if the photon energy was greater than the energy binding the electron to the metal. Einstein received the Nobel Prize in Physics for this work in 1921.

Niels Bohr (1885-1962) used Planck's ideas on the quantization of energy as a starting point in developing the modern theory for the hydrogen atom. Robert Millikan made the first measurement of Planck's constant in 1912. The best current value for Planck's constant is[4] $h = 6.6260693 \times 10^{-34}\,\mathrm{J\,s} = 4.13566743 \times 10^{-15}\,\mathrm{eV\,s}$.

In this experiment, you will use the current-voltage relationship of a set of light emitting diodes (LEDs) to measure Planck's constant. An LED is a semiconductor device that emits electromagnetic radiation at optical and infrared frequencies. The device is a p-n junction diode made from p-type and n-type semiconductors, usually GaAs, GaP or SiC. They emit light only when an external applied voltage is used to forward bias the diode above a minimum threshold value. The gain in electrical potential energy delivered by this voltage is sufficient to force electrons to flow out of the n-type material, across the junction barrier, and into the p-type region. This threshold voltage for the onset of current flow across the junction and the production of light is V_0. The emission of light occurs after

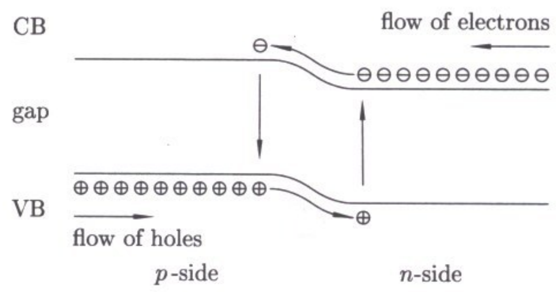

FIG. 1: The electrons flow over the barrier at the p-n junction when they are given sufficient potential energy by the external bias voltage.

electrons enter into the p-region (and holes into the n-region). These electrons are a small minority surrounded by holes (essentially the *anti-particles* of the electrons) and they will quickly find a hole to recombine with. Energetically, the electron relaxes from the excited state (conduction band) to the ground state (valence band). The diodes are called *light-emitting* because the energy given up by the electron as it relaxes is emitted as a photon. Above the threshold value, the current and light output increases exponentially with the bias voltage across the diode. The quanta of energy or photon has an energy $E = hf$. The relation between the photon energy and the turn-on voltage V_0, is

$$eV_0 = E_g = hf = \frac{hc}{\lambda}, \tag{3}$$

where E_g is the size of the energy gap, V_0 is the threshold voltage, f and λ are the frequency and wavelength of the emitted photons, c is the velocity of light, e is the electronic charge, and h is Planck's constant.

II. EXPERIMENTAL PROCEDURES

The main component of the apparatus is a circuit board containing 6 LEDs, each with a different emission wavelength. A particular LED can be connected to the circuit shown in Fig. 2, and the current and voltage are measured as the external voltage from the power supply is varied. Connect the power supply and ammeter to the + (RED) and – (BLACK)

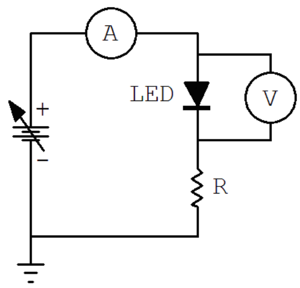

FIG. 2: The current through the LED is measured by the ammeter and the voltage across the LED is measured with the voltmeter. Be sure the power supply is off and the voltage knob is set to zero before you modify the circuit.

terminals on the LED board so that the 100 Ω current-limiting resistor is included in the circuit. Check that the voltmeter measures the voltage directly across the LED only, i.e. not including the 100 Ω resistor. Turn the power supply on and very slowly increases the voltage until the LED just starts to glow. Continually monitor the current so that you do not exceed the maximum current. Measure the current as a function of the voltage across the LED, being particularly careful to obtain sufficient readings around the *knee* of the curve. Do not exceed the 20 mA maximum current rating for this LED. Typical data is displayed in Fig. 3. Repeat these measurements of the I–V curves for each of the other diodes, noting that 5 of them have a maximum current rating of 20 mA and the IR LED has a 100 mA rating.

III. DATA ANALYSIS

Plot graphs of current (ordinate) vs voltage (abscissa) for each LED. The experimental problem here is how to determine V_0, the turn-on voltage. The human eye has a wavelength-

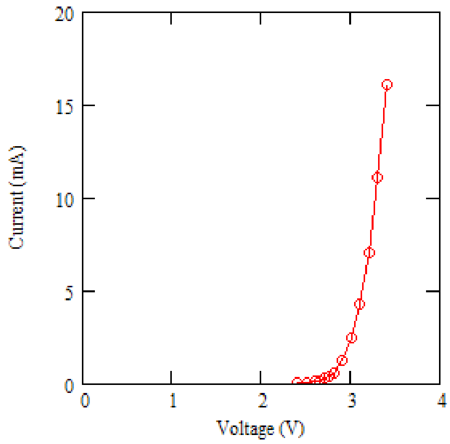

FIG. 3: A typical current–voltage curve for an LED. Note that once the LED turns on, the current increases very quickly with increasing voltage. Be especially careful in this region not to exceed the maximum current.

dependent sensitivity so that a visual determination will not work. And it is a difficult and error-prone task to measure a small current in the presence of electrical noise.

One method to consider begins with plotting the I–V data on a semi-log graph. Your data should approximate a straight line, indicative of the exponential nature of the current voltage relationship. An operational definition of the threshold voltage could be that value of the bias voltage when the current reaches 0.01 mA. Extrapolate your I–V curves to where they cross 0.01 mA current and use that as the working value of V_0.

Construct a table with columns for V_0, λ, and f. For each LED, use the measured value of V_0 and the value of f to determine a value for Planck's constant and enter it as a column in the table. Find the mean value of Planck's constant and its uncertainty from your experimental values. Compare to the value given earlier.

A difficulty here is our simplifying assumptions about the barrier height and the threshold voltage. Our simple model may be off by an additive constant ΔE, i.e. Eq. (3) should be replace by

$$eV_0 + \Delta E = E_g = hf = \frac{hc}{\lambda}. \tag{4}$$

But if we plot V_0 versus f for the set of six LEDs, then the slope of a straight-line fit is h/e, independent of the additive constant ΔE. Construct such a plot and do a least-squares fit to determine the slope h/e and the value of ΔE. Compare your value of Planck's constant to those above. (It is a bit easier here to work in units of eV s for Planck's constant.)

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[1] M. Planck, *Über das Gesetz der Energieverteilung im Normalspektrum*, Ann. d. Physik, **4**, 553, (1901).

[2] A. Einstein, *Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt*, Ann. d. Physik, **17**, 132 (1905).

[3] R. A. Millikan, *A Direct Photoelectric Determination of Planck's "h"*, Phys. Rev. 7, 355 (1916).

[4] http://physics.nist.gov/cuu/Constants/introduction.html

[5] The equation usually discussed is $I = B\exp(-E_g/kT + eV/kT)$ [see S.M. Sze, The Physics of Semiconductor Devices, p. 102, (Wiley, New York, 1969)].

[6] As pointed out by Morehouse [R. Morehouse, Am. J. Phys. **66**, 12 (1998)], the voltmeter measures the potential change across the junction *and* any IR loss at the junction. Thus at higher currents, some roll-off should be expected due to the IR term.