User's Manual

PLANCK'S CONSTANT APPARATUS
Model: PCA-01
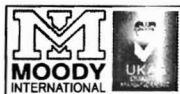
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DETERMINATION OF PLANCK'S CONSTANT FROM THE LED

INTRODUCTION

The Planck's constant is one of the universal constants which a student comes across quite early. It is one of the basic ingredients of quantum physics. Its measurement naturally has to be part of any college/university physics laboratory program.

Traditional method of measurement has been a determination of current cut-off voltage of a vacuum photocell irradiated by a monochromatic source of light. Vacuum photocells are not easily available now and a reasonably strong source of monochromatic light is also difficult to maintain in an undergraduate laboratory. An alternative method is, however, available. It employs light emitting diodes (LEDs) which are widely used in various consumer products and are easily available.

Most LEDs are based on GaAs and GaP crystals with general composition $GaAs_{1-x}P_x$ where the fraction x varies between 0 and 1. These materials are direct semiconductors. The crystals are doped with small amounts of different impurities in adjacent regions to form a PN junction or diode. These doped crystals emit light when a voltage is applied across the junction. The colour of the emitted light depends on the exact value of x.

THEORY

The basic idea in this measurement is that the photon energy, which from Einstein's relation is $E_\gamma = h\nu$, is equal to the energy gap E_g between the valence and the conduction bands of the diode. The gap energy E_g is in turn equal to the height of the energy barrier eV_0 that the electrons have to overcome to go from the n-doped side of the diode junction to the p-doped side when no external voltage V is applied to the diode. In the p-doped side they recombine with the holes releasing the energy E_g as photons with $E_\gamma = E_g = eV_0$. Thus a measurement of V_0 indirectly yields E_γ and the Planck's constant if ν is known or measured. However there are practical and conceptual problems in the actual measurement.

Let us consider the LED diode I-V equation:

$$I \propto \exp(-V_0/V_t) \, [\exp(V/V_t) - 1], \qquad V = V_m - RI \qquad \ldots(1)$$

where $V_t = \eta kT/e$, k, T and e are Boltzmann constant, absolute temperature and electronic charge respectively. V_m is the voltmeter reading in the external diode circuit and R is the contact resistance. The constant η is the material constant which depends on the type of diode, location of the recombination region etc. The energy barrier eV_0 is equal to the gap energy E_g when no external voltage V is applied, as pointed out earlier. The quantities which are constant in an LED are the impurity atom density, the charge diffusion properties and the effective diode area. The 'one' in the rectifier equation is negligible if $I \geq 2$ nA, and the equation becomes

$$I \propto \exp[(V-V_0/V_t)]$$
$$\propto \exp[e(V-V_0/\eta kT)] \qquad \ldots(2)$$

A direct method could be to apply a small voltage on the LED and increasing it till the LED is turned-on. This turning-on could be detected by visually observing the light emission. Plotting threshold voltage vs frequency of peak light output (obtained from LED datasheets or from separate spectroscopic measurement) provides the value of h/e. The visual observation of the emission on-set is quite vague. Use of a photo multiplier is sometimes suggested for this purpose but working with it raises maintenance problems and is quite costly. Alternately a measurement of threshold current ($< 10^{-11}$ A) through the LED may be attempted but it is difficult and not entirely accurate due to inefficiencies of actual LED's.

Another procedure some times used is to draw a tangent to the I-V characteristics of the diode and obtain its intercept. This procedure may give 'reasonable good' results if the tangents to the I-V characteristics of all the diodes are drawn at the same current. The method then really becomes equivalent to measuring voltage across the LED's at a single current (all the LED's of the set are connected in series). The intercepts of the tangents are, except for an additive constant, identical to diode voltages. The additive constant may be eliminated by considering data from different LED's. However, the bulk of data collected from the original I-V graph becomes irrelevant. A basic drawback of these methods is the assumption that the barrier height V_o is constant, equal to the gap energy E_g divided by the electronic charge E_g/e, which is true only when the external potential V is small or atleast less E_g/e. They further assume that the material constant η is unity which is not correct. It may have any value from about one to about two varying from LED to LED.

The present method is free from these infirmities. The height of the potential barrier is obtained by directly measuring the dependence of the diode current on the temperature keeping the applied voltage and thus the height of the barrier fixed. The external voltage is kept fixed at a value lower than the barrier. The idea is that the disturbance to the potential barrier is as little as possible.

In our experimental set-up the variation of the current I with temperature is measured over about a range of about 30°C at a fixed applied voltage V (≈ 1.8 volts) kept slightly below V_o. The slope of lnI vs 1/T curve gives e $(V_o - V)/\eta k$ (Fig.1). The constant η may be determined separately from I-V characteristic of the diode [Fig.2] at room temperature from the relation

$$\eta = (e/kT)(\Delta V/\Delta\ ln\text{I}). \qquad\qquad ...(3)$$

The Planck's constant is then obtained by the relation

$$h = eV_o\ \lambda/c \qquad\qquad ...(4)$$

The contact resistance of the LED is usually around 1 ohm, while overall internal resistance of the LED at applied voltage (≈ 1.8 V) is few hundred ohms. The factor RI in expression $V = V_m - RI$ may therefore be neglected.

The value of Planck's constant obtained from this method is within 5% of accepted value (6.62×10^{-34} Joules.sec)

EXPERIMENTAL SET-UP
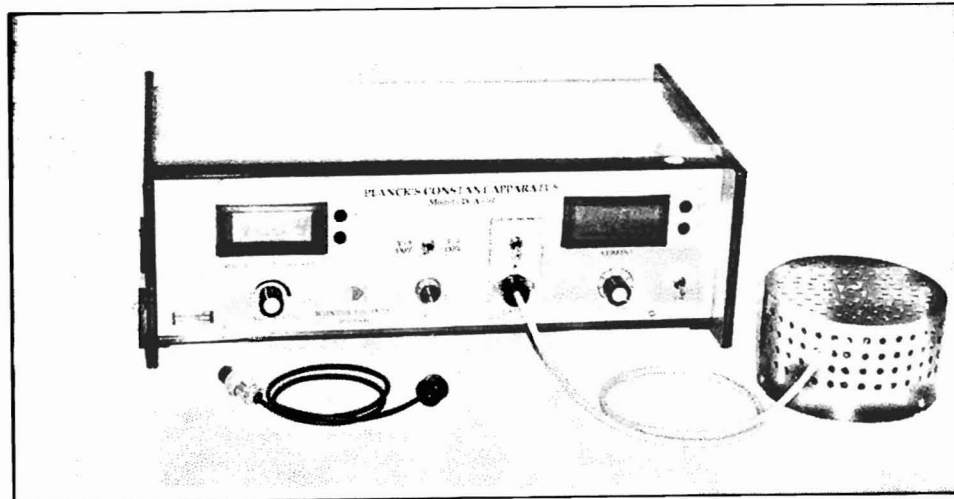
The set-up consists of the following units:

(1) To draw I-V characteristics of LED

   (i) Variable voltage source
- Range : 0-1.95 V Variable
- Resolution : 1mv
- Accuracy : ± 0.2%
- Display : 3½ digit LED DPM

   (ii) Current Meter
- Range : 0-2000 µA
- Resolution : 1µA
- Accuracy : ± 0.2%
- Display : 3½ digit LED DPM

(2) Dependence of current (I) on temp. (T) at constant applied voltage.

   (i) Current Meter
- Range : 0-20 mA
- Resolution : 10 µA
- Display : 3½ digit LED DPM

   (ii) Temperature Controlled Oven
- Range : Ambient to 65 °C
- Resolution : 0.1 °C
- Stability : ± 0.2 °C
- Display : 3½ digit LED DPM

   (iii) Variable Voltage source of 1st section is used to apply a constant voltage.

DESCRIPTION OF APPARATUS

1) MAINS ON/OFF SWITCH : To switch On/ Off the instrument

2) VOLTAGE ADJ KNOB : To adjust voltage

3) VOLTAGE/TEMPERATURE DPM : Read voltage in V-I mode and temperature of oven in T-I mode.

4) LED SOCKET: To connect LED samples

5) CURRENT DPM : Display current in μA in V-I mode and in mA in T-I mode.

6) V-I / T-I SWITCH : A two way switch to switch the system between V-I mode and T-I mode.

7) TEMPERATURE CONTROLLER

   a) ON/OFF : Switch for oven.

   b) OVEN: Socket on the panel is to connect the external oven

   c) SET-TEMP : Knob to set the temperature.

   d) OVEN : It is a small oven with built–in RTD sensor.

PROCEDURE

(1) To draw I-V characteristic of LED

   (i)   Connect the LED in the socket and switch ON the power.

   (ii)   Switch the 2-way switch to V-I position. In this position the 1st DPM would read voltage across LED and 2nd DPM would read current passing through the LED.

   (iii)   Increase the voltage gradually and tabulate the V-I reading. Please note there would be no current till about 1.5 V. Draw the graph : lnI (I in μA) Vs. V

(2) Dependence of current (I) on temperature (T) at constant applied voltage

   (i)   Keep the mode switch to V-I side and adjust the voltage across LED slightly below the band-gap of LED say 1.8 V for Yellow/Red LED and 1.95 for Green LED.

   (ii)   Switch the 'MODE' switch to T-I side.

   (iii)   Insert the LED in the oven and connect the oven to the socket. Please make sure before connecting the oven that oven switch is in OFF position and SET TEMP knob is at minimum position. Now the DPM would read ambient temperature.

   (iv)   Set the different temperatures with the help of SET-TEMP. Allow about 5 minutes time on each setting for the temperature to stabilize and take the readings of temperature and current. Draw the graph: lnI vs. (1/T).

PRECAUTIONS

1) V-I characteristics of LED should be drawn at very low current upto $\cong 1000$ μA only, so that the disturbance to V_0 is minimum.

2) In T-I mode, make sure that the oven switch is 'OFF' and SET TEMP knob is at **minimum** position before connecting the oven.

3) On each setting of temperature, please allow sufficient time for the temperature to stabilize, normally 5-6 minute is required.

4) Though temperature of oven may go upto 70°C, it is recommended that reading may be taken upto 60 °C only to avoid excessive heating of LED.

5) In case the LED is replaced please note that height of the portion inside the oven should not be more than 26mm, otherwise it may strike the RTD.

REFERENCES

1) R. Morehouse, Am. J. Phys. <u>66</u> (1998) 12

2) F. Herrmann and D. Schätzle, Am. J. Phys. <u>64</u> (1996) 1448

3) I.L. Nieves, The Physics Teacher <u>35</u> (1996) 108
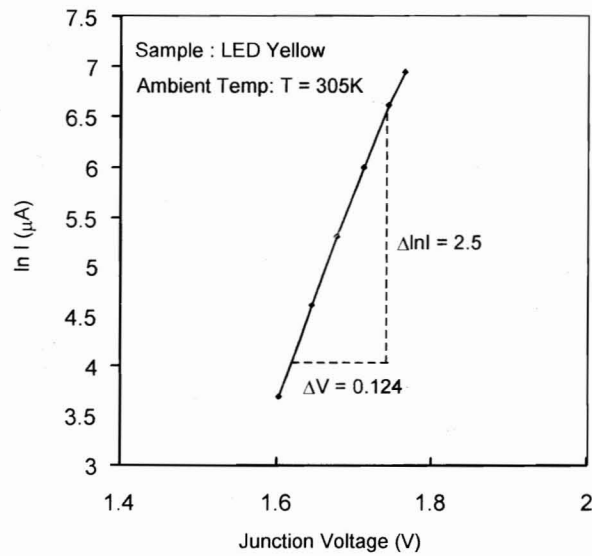
TYPICAL RESULTS

EXPERIMENT - I

Determination of Material Constant η

Sample : Yellow LED   Room Temperature : 305K

S. No.	Junction Voltage V in Volts	Forward Current I in μA	ln I
1.	1.604	40	3.69
2.	1.629	70	4.25
3.	1.644	100	4.61
4.	1.676	200	5.30
5.	1.711	405	6.00
6.	1.743	734	6.60
7.	1.765	1040	6.95

I-V Characteristics

Graph no. 1

From graph no. 1 (Junction Voltage V vs. lnI), we get

Slope of the curve $\dfrac{\Delta V}{\Delta \ln I} = \dfrac{0.124V}{2.5}$

Therefore, $\eta = \dfrac{e}{kT}\dfrac{\Delta V}{\Delta \ln I} = \dfrac{1.602 \times 10^{-19} \times 0.124}{1.381 \times 10^{-23} \times 305 \times 2.5}$
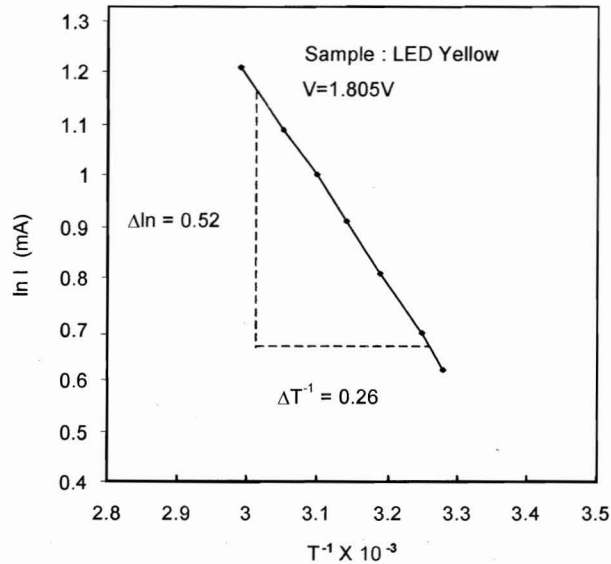
$\eta = 1.89$

LXPERIMENT - II

Determination of Temperature Coefficient of Current

Sample : Yellow LED

V = 1.805 V (Constant for whole set of readings)

S. No.	Temperature (°C)	Temperature (°K)	Current (mA)	1/T X 10^{-3} (K^{-1})	lnI (I in mA)
1.	32.0	305.0	1.85	3.28	0.62
2.	34.5	307.5	2.00	3.25	0.69
3.	40.0	313.0	2.25	3.19	0.81
4.	45.4	318.4	2.49	3.14	0.91
5.	50.3	323.3	2.71	3.09	1.00
6.	55.3	328.3	2.97	3.05	1.09
7.	61.6	334.6	3.34	2.99	1.21

T-I Characteristics

Graph No. 2

From Graph No. 2 (1/T vs lnI)

Slope of the curve $\dfrac{\Delta \ln I}{\Delta T^{-1} \times 10^{-3}} = -\dfrac{0.52V}{0.26 \times 10^{-3}}$

$$V_0 = V - \left[\frac{\Delta \ln I}{\Delta T^{-1} \times 10^{-3}} \cdot \frac{k}{e} \cdot \eta \right]$$

$$V_0 = 1.805 - \left[-\frac{0.52}{0.26 \times 10^{-3}} \times \frac{1.381 \times 10^{-23}}{1.602 \times 10^{-19}} \times 1.89 \right]$$

$V_0 = 1.805 + [\,2.0 \times 10^3 \times 0.862 \times 10^{-4} \times 1.89\,]$

$V_0 = 1.805 + 0.326$

$V_0 = 2.13 \text{ eV}$

$\lambda = 5800\,\overset{\circ}{A}$ (as measured by diffraction grating)

Now,

$$h = \frac{e \times V_0 \times \lambda}{c} = \frac{1.602 \times 10^{-19} \times 2.13 \times 5800 \times 10^{-8}}{3 \times 10^{10}}$$

$h = 6.60 \times 10^{-34}$ Joules. sec.

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