11.

Determination of Planck's constant

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OBJECTIVES: To Study the Planck's Constant

(i) Determination of the material constant 'η'

(ii) Determination of Planck's Constant, 'h'

THEORY:

The basic idea is that the photon energy (E_γ), which by Einstein's relation is $E_\gamma = h\nu$ is equal to the energy gap (E_g) between the valence and conduction bands of the diode. The energy gap, in turn, is equal to the height of the energy barrier, eV_o 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 holes releasing the energy E_g as photons with $E_g = E_\gamma = eV_o$. Thus, a measurement of V_o indirectly yields E_γ and 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 equation:

$$I \propto exp\left(\frac{-V_o}{V_t}\right)\left[exp\left(\frac{V}{V_t}\right) - 1\right] \tag{1}$$

where,

$V = V_m - RI$

$V_t = \frac{\eta k T}{e}$

k = Boltzmann Constant

T = Absolute temperature

e = electronic charge

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 recombination region etc. The energy barrier eV_o is equal to the gap energy E_g when no external voltage V is applied. The quantities which are constant in a LED are impurity atom density, the charge diffusion properties and the effective diode area. The 'one' in rectifier is negligible if $I \geqslant 2$ nA, and the equation becomes

$$\begin{aligned} I &\propto exp\left[\frac{(V - V_o)}{V_t}\right] \\ &\propto exp\left[\frac{e\,(V - V_o)}{\eta k T}\right] \end{aligned} \tag{2}$$

A direct method could be to apply a small voltage to the LED and increasing it till the LED turns 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) provides the value of $\frac{h}{e}$. The visual observation of the emission onset is quite vague though. Use of photo-multiplier is sometimes suggested for this purpose but working with it raises maintenance problems and it 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 LEDs.

Another procedure, sometimes used, is to draw a tangent to the $I - V$ characteristics of the diode and obtain its intercept. This procedure may give reasonably good results if the tangents to the $I - V$ characteristics of the diodes are drawn at the same current. The method then really becomes equivalent to measuring voltage across the LEDs at a single current. The intercepts of the tangent are, except for an additive constant, identical to diode voltages. The additive constant may be eliminated by considering data from different LEDs. 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 and is equal to the energy gap divided by the electronic charge (i.e., $\frac{E_g}{e}$), which is true only when electric potential V is small or less than $\frac{E_g}{e}$. Further, this method assumes that the material constant, η, is unity which is not correct.

The present method is free from these drawbacks. The height of potential barrier is obtained by directly measuring the dependence of diode current on the temperature keeping the applied voltage and thus, the height of the barrier is fixed. The external voltage is kept fixed at a value lower than the barrier. In our experimental set-up, the variation of current I with temperature is measured over a range of about 30° at a fixed voltage V (= 1.8 V) kept slightly below V_o. The slope of $ln(I)$ vs $1/T$ curve gives $\frac{e(V_o-V)}{\eta k}$. The constant η may be determined separately from $I-V$ characteristics of the diode at room temperature rom the relation

$$\eta = \left(\frac{e}{kT}\right)\left(\frac{\Delta V}{\Delta ln(I)}\right) \tag{3}$$

The Planck's constant is then obtained using the relation

$$h = \frac{eV_o\lambda}{c} \tag{4}$$

The contact resistance of LED is usually around 1 Ω, while overall internal resistance of 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 (6.626×10^{-34} Joules.sec).

EXPERIMENTAL SET-UP

The set-up consists of following units:

1. **Variable Voltage Source**
   - ▻ Specifications:
     - Range : 0-2 V DC
     - Resolution : 1 mV
     - Accuracy : ±0.5%
     - Display : $3\frac{1}{2}$ LED DPM
2. **Current Meter**
   - ▻ Specifications:
     - Range : 0-20 mA/2000μA
     - Resolution : 10 μA /1μA
     - Display : $3\frac{1}{2}$ LED DPM
3. **Temperature Controlled Oven**
   - ▻ Specifications:
     - Range : Ambient to 60°C
     - Resolution : 0.1°C
     - Sensor : PT-100
     - Display : $3\frac{1}{2}$ LED DPM

CONNECTION DIAGRAM OF EXPERIMENTAL SET-UP

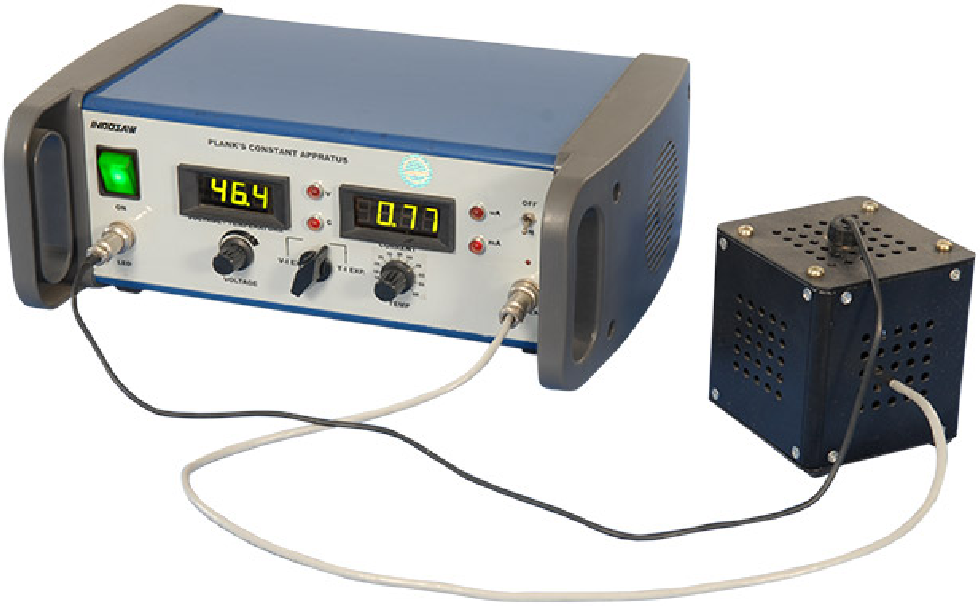

Figure 1: Set-up

EXPERIMENTAL SET-UP PROCEDURE

(a) To draw $I - V$ characteristics of LED

1. Connect the LED in socket on set-up and switch ON the power.
2. Switch the two-way switch to $V - I$ position. In this position, the first DPM would read voltage across LED and the second DPM would read current passing through LED.
3. Increase the voltage gradually and tabulate the $V - I$ readings. Please note that there would be no current till about 1.5 V.
4. Plot the graph between $ln(I)$ (I in μA) vs V.

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

1. 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 both yellow & red and 1.95 V for green LED.
2. Change the mode of two-way switch to $T - I$ side.
3. Insert LED in the oven and connect the other end of LED in the socket provided on the set-up. Before connecting the oven, check that the oven switch is in OFF position and Set Temperature knob is at minimum position. Now, first DPM would read ambient temperature.
4. Set the different temperatures with the help of Set Temperature knob. Allow about 5-7 minutes on each setting for the temperature to stabilize and take readings of temperature and current.
5. Find the inverse of temperature and draw the graph between $ln(I)$ & $\frac{1}{T}$.

OBSERVATIONS:

(a) **Determination of material constant η**
Sample: (RED/YELLOW) LED
Room Temperature: 300 K

Sr. No.	**Junction Voltage, V** (V)	**Forward Current, I** μA	$ln(I)$

- Plot the graph between $ln(I)$ and voltage (V).
- Determine the slope of the graph

$$Slope = \frac{\Delta ln(I)}{\Delta V}$$

- Using the slope of the graph, η can be determined from

$$n = \frac{e}{kT} \times \frac{1}{slope}$$

(b) Determination of Temperature Coefficient of Current

Sample: (RED/YELLOW) LED

Voltage = 1.803 V (constant for whole set of readings)

Sr. No.	**Temperature** (°C)	**Temperature** (K)	**Current** mA	$1/T \times 10^{-3}$ (K^{-1})	$ln(I)$ (I in mA)

From graph, $\dfrac{\Delta ln(I)}{\Delta T^{-1}} =$

Therefore,

$V_o = V - \left[\frac{\Delta ln(I)}{\Delta T^{-1}} \times \frac{K}{e} \times \eta\right]$

Now,

$h = \frac{e \times V_o \times \lambda}{c}$

$h =$ ____________ Joules.sec

CHECK POINTS:

1. $V-I$ characteristic of LED should be drawn at very low current (up to $\sim 1000\mu$A only), so that disturbance to V_o is minimum.
2. In $T-I$ mode, make sure that the oven switch is OFF and Set Temperature knob is at minimum position before connecting the oven.
3. On each setting of temperature, please allow sufficient time for the temperature to stabilize (between 6-7 minutes).

SUGGESTED READING:

1. Neamen, Donald A. *Semiconductor physics and devices.* McGraw-Hill Higher Education, 2003.
2. Sze, Simon M., and Kwok K. Ng. *Physics of semiconductor devices.* John wiley & sons, 2006.