NANYANG TECHNOLOGICAL UNIVERSITY
SCHOOL OF ELECTRICAL & ELECTRONIC ENGINEERING

H3 SEMICONDUCTOR PHYSICS AND DEVICES

Experiment L2003B
PN Junction Devices

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1. INTRODUCTION

A p-n junction diode is the most basic form of a semiconductor device. It is formed when an n-type semiconductor region is brought into close contact with a p-type semiconductor region. This gives rise to a rectifying property, shown by the asymmetrical current flow when connected under 'forward' and 'reverse' bias. This property has found the p-n junction useful in many applications such as the Light Emitting Diode (LED).

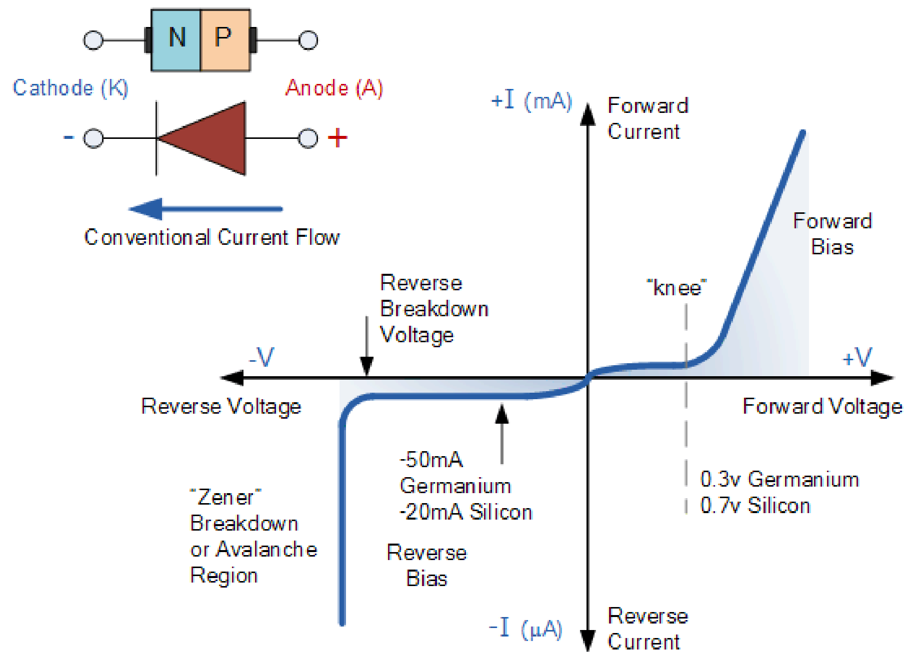

Figure 1: I-V Characteristics of P-N Junction Diode

It is useful to understand the basic concepts of the p-n junction and the light-emission properties of LEDs that are widely used in our daily lives.

2. OBJECTIVES

(a) To understand the basic concepts of the p-n junction: I-V (current-voltage) characteristics, diode parameter extraction and temperature dependence.

(b) To study the light emission properties of light-emitting diodes (LEDs)

3. THEORY

3.1 I-V Characteristics of P-N Junctions

The I-V characteristic of a real p-n junction diode is given by

$$I = I_0\left(e^{\frac{qV}{nkT}} - 1\right) \tag{1}$$

where I_0 is the reverse saturation current, q the electron charge, k the Boltzmann's constant, T the absolute temperature and n is the ideality factor. The ideality factor is a measure of how close to the ideal conditions were under which the diode was fabricated.

Under normal forward bias operation, the exponential term dominates and a good approximation for the current is

$$I = I_0 e^{\frac{qV}{nkT}} \tag{2}$$

In this experiment, we will determine the parameters n and I_0 through plotting a semilog graph.

Temperature Dependence

In equation (2), the I-V temperature dependence is due to I_0 and the temperature term in the exponent. Now

$$I_0 = qA\left(\frac{D_p}{L_p}p_{n0} + \frac{D_n}{L_n}n_{p0}\right) = qn_i^2\left(\frac{D_p}{L_pN_D} + \frac{D_n}{L_nN_A}\right) \tag{3}$$

and

$$n_i = \sqrt{N_cN_v}\exp\left(-\frac{E_g}{2kT}\right) = \text{constant} \times T^{\frac{3}{2}}\exp\left(-\frac{E_g}{2kT}\right) \tag{4}$$

Hence,

$$I_0 = AT^3\exp\left(-\frac{E_g}{kT}\right) \tag{5}$$

where A includes all terms approximately independent of T.

To determine the temperature dependence of the I-V characteristic, we have from equation (2),

$$V = \frac{nkT}{q}\ln\left(\frac{I}{I_0}\right) \tag{6}$$

$$\left.\frac{\partial V}{\partial T}\right|_{I=\text{constant}} = \frac{V}{T} - \frac{nkT}{q}\frac{1}{I_0}\frac{dI_0}{dT} \tag{7}$$

From equation (5)

$$lnI_0 = \ln A + 3\ln T - \frac{E_g}{kT} \tag{8}$$

$$\frac{d}{dT}(\ln I_0) = \frac{1}{I_0}\frac{dI_0}{dT} = \frac{3}{T} + \frac{E_g}{kT^2} \tag{9}$$

Substituting (7) and (9), we have

$$\left.\frac{\partial V}{\partial T}\right|_{I=\text{constant}} = \frac{-\frac{n}{q}\left(3kT + E_g\right) - V}{T} \; [V/K] \tag{10}$$

For a wide variety of diodes, it is found that, on the average,

$$\left.\frac{\partial V}{\partial T}\right|_{I=\text{constant}} = -2.4m\; V/K \tag{11}$$

When biased by a constant current source, an increase in temperature will cause the voltage across the p-n diode to decrease at a constant rate.

In this experiment, we will use this effect to derive the temperature change from the voltage shift at a constant current.

3.2 Light Emitting Diodes

LEDs utilize the recombination of minority carriers injected in a forward biased p-n junction with the majority carriers across the junction to obtain light emission. When an electron in the conduction band undergoes a transition to the valence band and recombines with a hole in a direct bandgap semiconductor, the energy given up by the electron may be released in the form of a photon.

In an LED, such recombination occurs randomly, and the emission is said to be spontaneous. Spontaneous emission can occur at a relatively small forward bias. The emitted photons have random phases and therefore the LED is an incoherent light source. The light emitted has a narrow band of wavelengths typically 30-50 nm at room temperature. The emitted photons have energy

$$hf = \frac{hc}{\lambda} \approx E_g \tag{12}$$

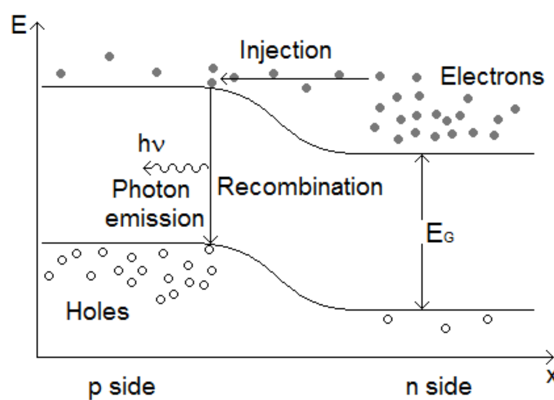

Figure 2: Photon Emission in an LED

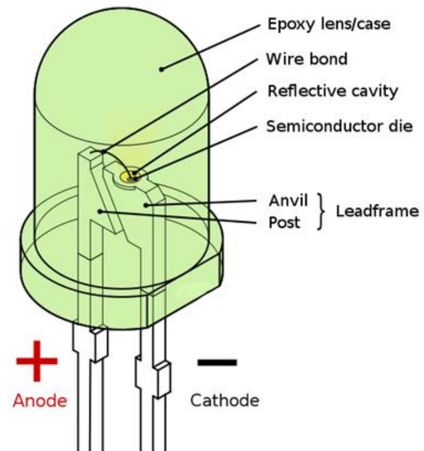

Figure 3: LED Components

4. P-N JUNCTION DIODE

4.1 I-V Characteristics

Procedure

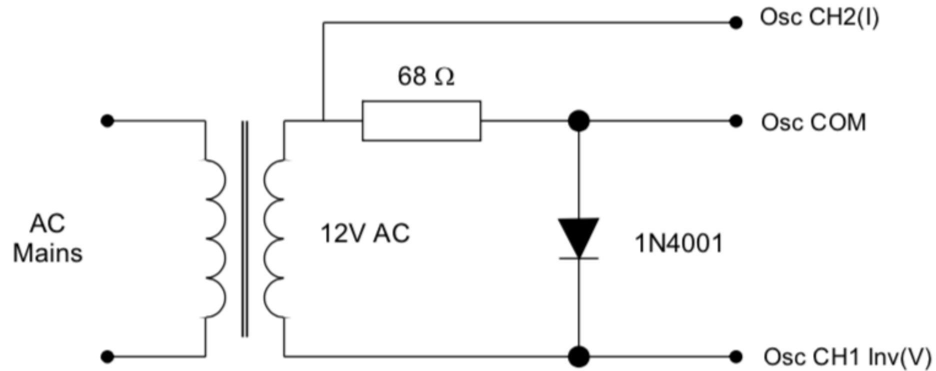

Figure 4: Sweep Circuit for I-V Display

1. The circuit is set up as shown in Figure 4.
2. When the AC mains is switched on, the waveforms measured by the oscilloscope is that of a half-wave rectifier circuit.
3. The oscilloscope is set to X-Y mode with CH1 plotted on the X axis[1] and CH2 plotted on the Y axis.
4. Using the cursors X1, X2 and Y1, Y2, data points are extracted.

From the X axis, we can obtain the voltage across the p-n junction diode. From the Y axis, we can obtain the voltage across the resistor and hence deduce the current flowing in the circuit.

Results

Let V_1 be the potential difference across the diode and V_2 be the potential difference across the resistor. A plot of V_1 against V_2 is shown in Figure 4.

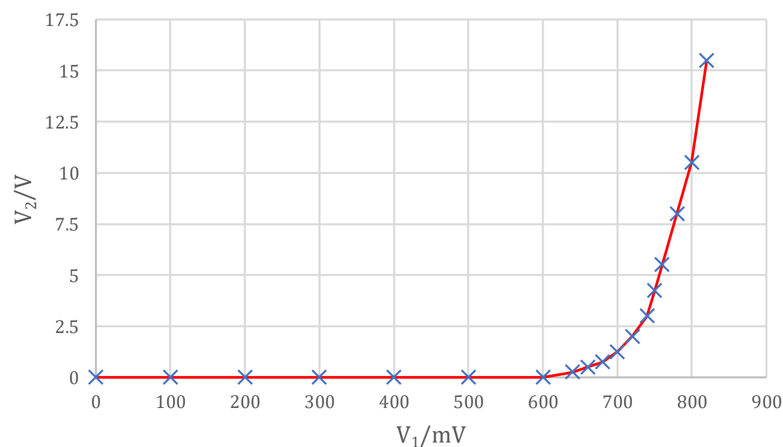

Figure 4: Graph of V_1 Against V_2

[1] The voltage data from CH1 is inverted so that both readings have the same polarity.

From $I = V/R$, by scaling the y-axis by a factor of 1/68, we obtain the I-V characteristics of the p-n junction diode in Figure 5.

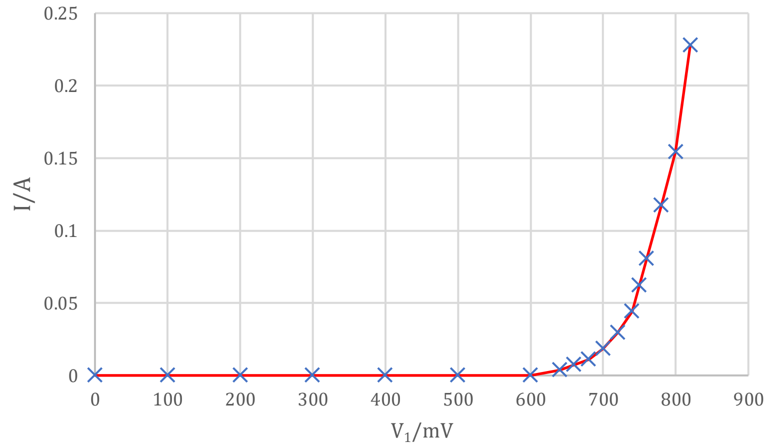

Figure 5: I-V Characteristic of Diode

The turn-on voltage is observed to be around 600mV, where the current flowing through the circuit starts increasing sharply.

The differential resistance of the diode is given by

$$r_{diff} = \frac{dV}{dI} \tag{13}$$

After turn-on, the differential resistance of the diode is observed to quickly tend towards a constant value.

$$r_{diff} \to \text{constant} = \frac{\Delta V}{\Delta I} \tag{14}$$

Hence, the differential resistance can be approximated by taking 2 points on the curve

$$r_{diff} = \frac{\Delta V}{\Delta I} = \frac{810mV - 785mV}{0.19A - 0.11A} = 0.3125mV/A \tag{15}$$

Discussion

1. What factors determine the turn-on voltage of a p-n junction diode? Explain its dependence on the factors that you mentioned.

   Combining equations (5) and (6) gives us

$$V = \frac{nkT}{q} \ln\left(\frac{I}{AT^3 \exp\left(-\frac{E_g}{kT}\right)} \right) \tag{16}$$

where I is the current at which we consider the diode to be 'turned on'. It can be observed that the turn-on voltage of the p-n junction diode has a dependence on temperature T.

The rate of change of voltage with respect to temperature is given by equation (10) by

$$\left.\frac{\partial V}{\partial T}\right|_{I=\text{constant}} = \frac{-\frac{n}{q}\left(3kT + E_g\right) - V}{T} \ [V/K]$$

which will yield a negative value.

Additionally, the turn-on voltage has a dependence on the ideality factor n. From equation (16), $V \propto n$ for constant I and T. As n increases, the turn-on voltage increases proportionately.

4.2 Temperature Dependence

Procedure

1. The voltage at 150mA is measured using the cursors on the oscilloscope.
2. The soldering iron is heated up to 200°C.
3. Heat is applied to the diode using the soldering iron for about 15 seconds.
4. The new voltage at 150mA is measured.

Results

Voltage Across Diode at 150mA Current	
Before Heating	After Heating
795mV	710mV

Using equation (11), we can deduce the diode temperature change.

$$\frac{dV}{dT} = \frac{\Delta V}{\Delta T} = -2.4m\frac{V}{K} \tag{17}$$

$$\Delta T = \frac{\Delta V}{-2.4mV} = \frac{710 - 795}{-2.4} = 35.4K \tag{18}$$

4.3 Ideality Factor and Reverse Saturation Current

Procedure

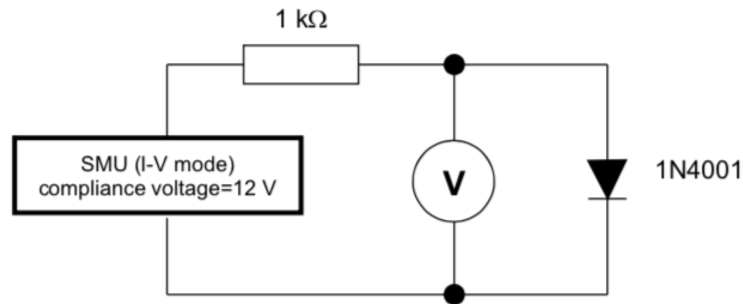

Figure 6: Circuit for Diode Parameter Extraction

1. The circuit it set up as shown in Figure 6.
2. The current is varied from 0.01mA to 10mA using the SMU, and the corresponding voltage is measured by the DMM.
3. The *lnI* versus *V* relationship is obtained.

Results

I/mA	I/A	$\ln(I/A)$	V/V
0.010	0.000010	- 11.51	0.81
1.250	0.001250	- 6.6846	0.85
2.500	0.002500	- 5.9915	0.88
3.750	0.003750	- 5.5860	0.89
5.000	0.005000	- 5.2983	0.91
6.250	0.006250	- 5.0752	0.93
7.500	0.007500	- 4.8929	0.94
8.750	0.008750	- 4.7387	0.95
10.000	0.010000	- 4.60517	0.96

To obtain the ideality factor and reverse saturation current, we can linearize equation (2) to get

$$\ln I = \ln I_0 + \frac{q}{nkT}V \tag{19}$$

The plot of *lnI* against *V* is shown in Figure 6.

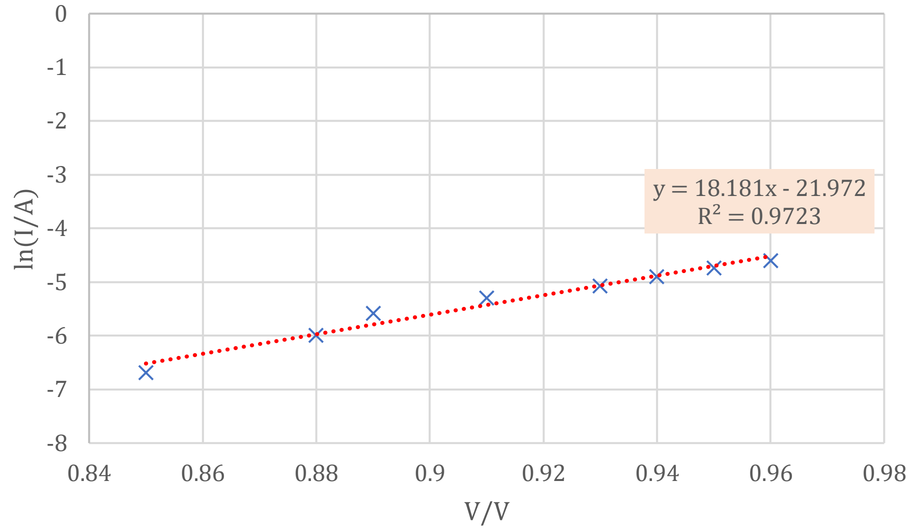

Figure 6: Graph of ln(I) Against V

The y-intercept of the trendline is given by lnI_0 and the slope is given by $\frac{q}{nkT}$.
From Figure 6, the trendline follows the equation $lnI = 18.181V - 21.972$. Comparing with equation (16), we have the y-intercept

$$\ln I_0 = -21.972 \tag{20}$$

$$I_0 = e^{-21.972} = 2.87 \times 10^{-10} A \tag{21}$$

and the gradient

$$\frac{q}{nKT} = 18.181 \tag{22}$$

Since the experiment was conducted at room temperature, we have $T \approx 300K$.

$$n = \frac{q}{18.181kT} = \frac{(1.6 \times 10^{-19})}{(18.181)(1.38 \times 10^{-23})(300)} = 2.13 \tag{23}$$

5. LIGHT EMITTING DIODE

5.1 Light Current Characteristic

Procedure

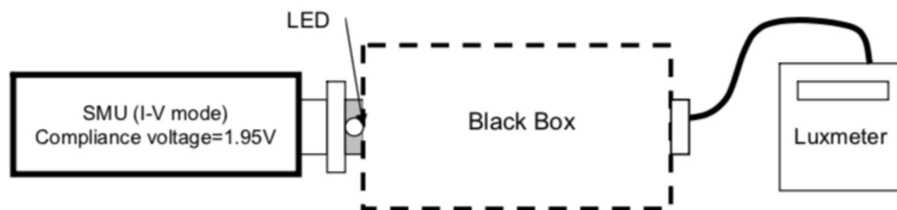

Figure 7: Schematic Layout for L-I Measurements

1. The experimental setup is shown in Figure 7.
2. The current from the SMU is adjusted from 0 to 35mA in step of 5mA and the corresponding luxmeter readings are recorded.
3. The luxmeter reading is proportional to the incident optical power. Hence, the L-I characteristic can be plotted.

The experiment is carried out in a black box so that the surrounding light does not interfere with the luxmeter readings. The luxmeter should only record optical intensity of the LED.

Results

At $I = 0\,$mA, the luxmeter recorded a reading of 002. This is because the setup does not completely block all surrounding light from reaching the luxmeter, resulting in some light measured even when the LED is turned off. This systematic error is subtracted from all readings.

I/mA	L/lx
0	000
5	021
10	044
15	068
20	091
25	113
30	130
35	130

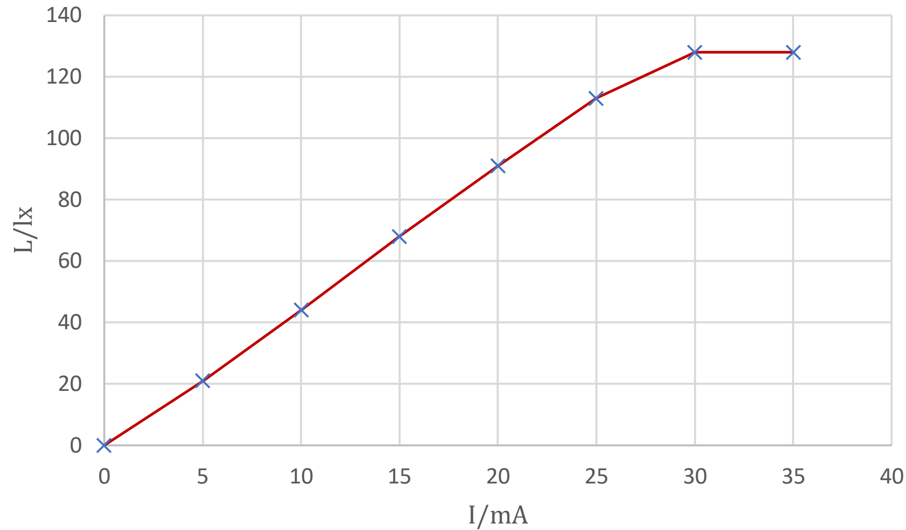

Figure 8: L-I Characteristic of LED

The gradient of the L-I curve is observed to initially increase then decrease sharply, with *L* reaching a peak of 130lx.

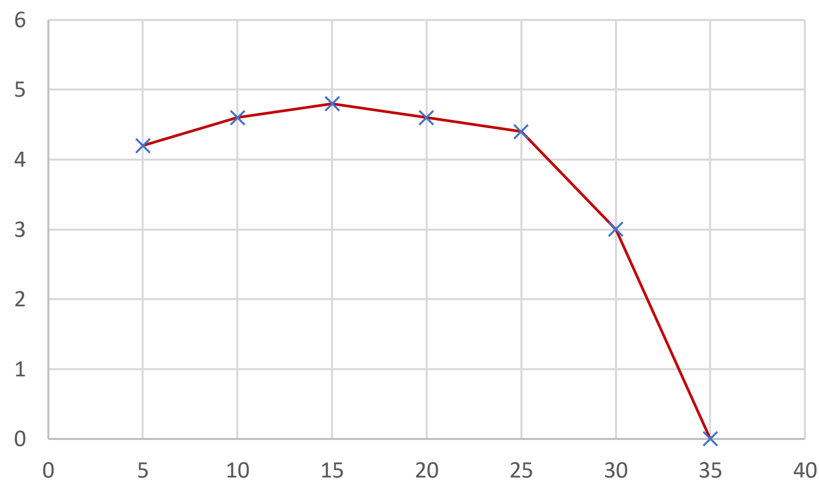

Figure 9: Gradient of L-I Curve Against I

Discussion

2. Explain why the gradient of the measured *L-I* curve in part 4.4 becomes smaller at large current.

   The gradient becomes smaller at large current due to the higher internal temperature associated with a large current. As the current increases, power loss $P = I^2R$ by the LED in the form of heat increases. There is therefore a higher internal temperature in the LED which in turn affects the output efficiency.

Specifically, there is a point at which the drop in internal quantum efficiency negates the effect of increased recombination rate from increased current density through the junction.

Bandgap Width

The energy bandgaps of semiconductors tend to decrease as temperature is increased due to the increased interatomic spacing from more vigorous vibrations. This reduces the potential seen by electrons in the material, in turn decreasing E_g.

The temperature dependence of the energy bandgap has been experimentally determined yielding the following expression for E_g as a function of the temperature T:

$$E_g(T) = E_g(0) + \frac{\alpha T^2}{T + \beta} \tag{24}$$

where $E_g(0)$, α and β are the fitting parameters [1].

As the bandgap decreases, photon energy $hf = \frac{hc}{\lambda} \approx E_g$ decreases. From Figure 10, the red shift as a result of increased wavelength causes the relative luminosity to decrease. Additionally, band-to-band absorptions of photons within the LED cause substantial optical losses [2], decreasing internal quantum efficiency.

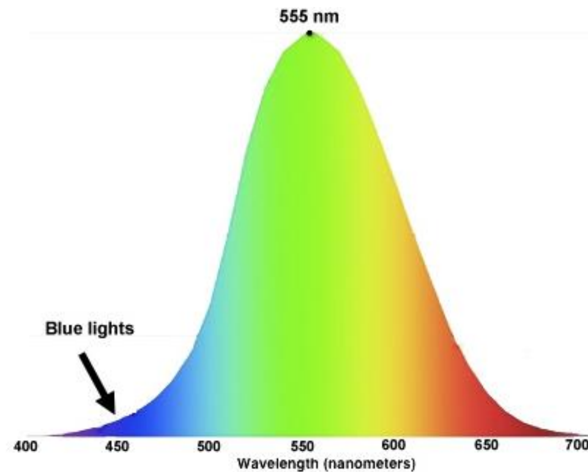

Figure 10: Relative Luminosity Function

Free Carrier Absorption

As temperature increases, the free carrier absorption in the LED contact layers increase [2]. This is because the free carrier concentrations have a temperature dependence causing them to increase with increasing temperature. As a result, higher temperatures lead to the enhancement of this process, decreasing internal quantum efficiency.

5.2 Emission Spectrum

Procedure

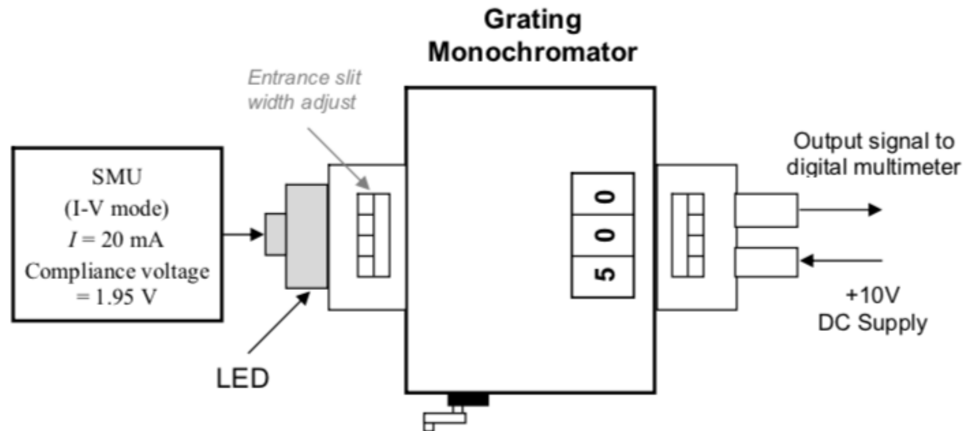

Figure 10: Measurement of Emission Spectrum Using Grating Spectrometer

1. The experimental setup is shown in Figure 10.
2. By rotating the grating in the spectrometer with the knob, the intensities of the source at different wavelengths can be recorded at the output slit.
3. The output port of the photodetector is connected to a voltmeter and the voltmeter reading is proportional to the intensity of light incident on the exit slit of the spectrometer.

Results

There is a zero error of 0.0935V registered by the voltmeter when the LED is turned off. This systematic error is subtracted from all readings.

The wavelengths of interest lies between 620 to 665nm.

λ/nm	V/V
620	0
625	0.01301
630	0.11767
640	0.8697
642	1.023
645	1.1441
648	1.131
650	1.0432
655	0.5957
660	0.16105
665	0

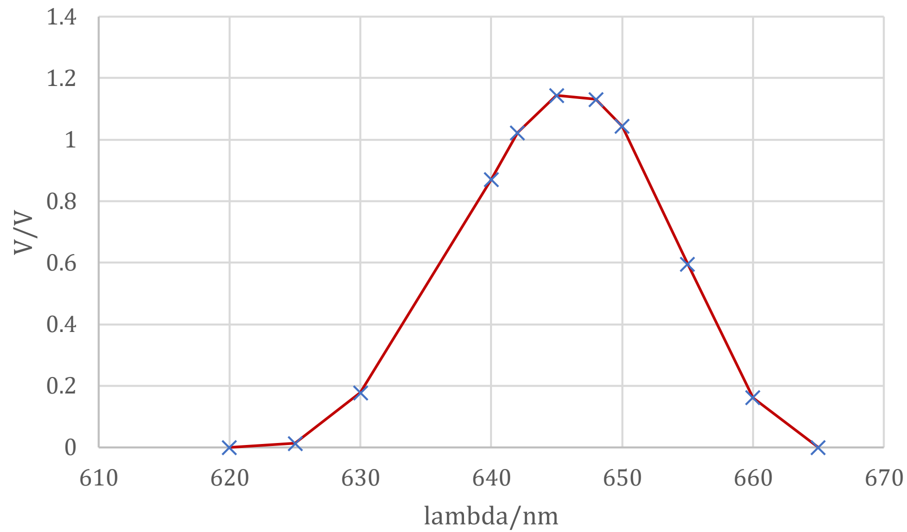

Figure 11: Emission Spectrum of LED

665nm is the maximum wavelength beyond which no more emissions are possible. Since the energies of the photons emitted $hf = \frac{hc}{\lambda} \geq E_g$, this represents the wavelength where $hf = E_g$. Hence, we can deduce the bandgap energy

$$E_g = \frac{hc}{\lambda} = \frac{(6.626 \times 10^{-34})(3.0 \times 10^8)}{(665 \times 10^{-9})} = 2.989 \times 10^{-19} J = 1.868 eV \quad (25)$$

The full width at half maximum of the spectrum (FWHM) occurs at $V = 0.57205$, which corresponds to $\lambda = 635.9nm$ and $\lambda = 655.2nm$ (Figure 12).

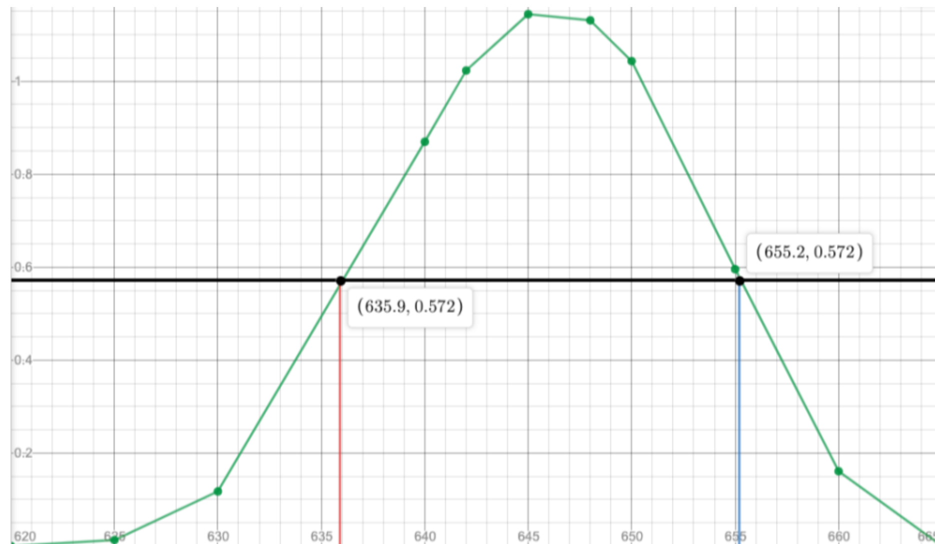

Figure 12: Full Width at Half Maximum (FWHM)

Hence,

$$\text{linewidth} = 655.2 - 635.9 = 19.3nm \quad (26)$$

Discussion

3. Explain the factors that influence the spectral line width of the emission spectrum that you measured.

   The electron concentration n_0 in the conduction band and hole concentration p_0 in the valence band depends on the density of states $g(E)$ and the Fermi-Dirac distribution $f(E)$ as shown in Figure 13.

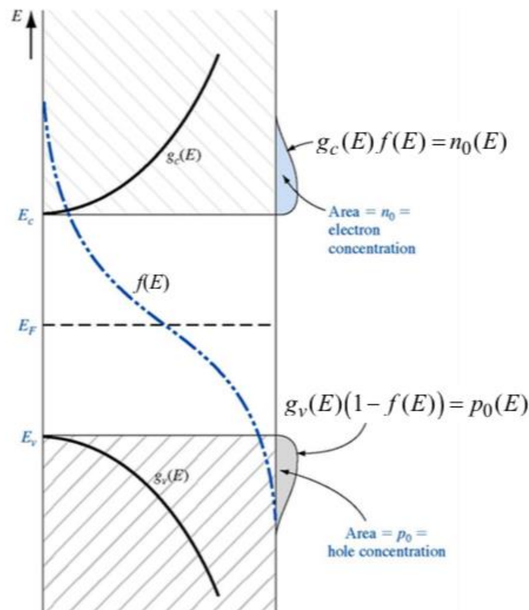

Figure 13: Electron and Hole Concentrations

A higher concentration near the band edges implies more likely recombination near the band edges, producing photon energy closer to E_g. In fact, the shape of the carrier concentration curves resembles that of the emission spectrum, and the peak of n_0 and p_0 corresponds to the peak of the emission spectrum.

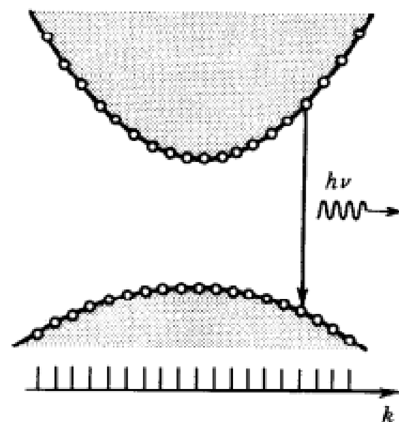

Figure 14: E-k Relation

From the semiconductor E-k relation (Figure 14), only electrons and holes of the same crystal momentum may recombine.

The rate of spontaneous emission at frequency v is therefore given by

$$r_{sp}(v) = \frac{1}{\tau_r} g(v) f_e(v) \tag{27}$$

where $g(v)$ is the optical joint density of states and $f_e(v)$ is the probability of the emission condition that a conduction band state of energy E_2 is filled and a valance band state of energy E_1 is empty, given by

$$f_e(v) = f_c(E_2)[1 - f_v(E_1)] \tag{28}$$

where f_c and f_v are the Fermi-Dirac distribution functions for the conduction band and valence band respectively [3].

As a result, the Fermi-Dirac distribution and the optical joint density of states affect the relative intensities at different frequencies. If $g(v)f_e(v)$ is higher at higher frequencies, i.e. there are more electron-hole pairs available for recombination, the relative intensities of higher frequency (lower wavelength) light would be higher. This will then increase the emission linewidth.

Finally, if the bandgap energy is higher, the maximum wavelength will be lower so that $\frac{hc}{\lambda} \geq E_g$. This will decrease the emission linewidth since the range of permissible wavelengths is lower.

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[3] Saleh, B. E., & Teich, M. C. (1991). *Fundamentals of photonics*. New York: Wiley.

6.2 Images

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(3) http://beaconlamps.com/blog/the-components-of-leds-and-how-they-work-3502

(4) H3 Semiconductor Physics and Devices Laboratory Manual 3

(5) H3 Semiconductor Physics and Devices Chapter 5a Lecture Notes