NANYANG TECHNOLOGICAL UNIVERSITY

SCHOOL OF ELECTRICAL & ELECTRONIC ENGINEERING

H3 LABORATORY 3

2023

LABORATORY MANUAL

Experiment No. L2003B

PN JUNCTION DEVICES

Electronics II

(S2-B4a-04)

Name : ______________________________

Group : ______________________________

Date : ______________________________

P-N Junction Devices

1. OBJECTIVES

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

ii. To study the light emission properties of light emitting diodes (LEDs).

2. THEORY

2.1 *I-V characteristics of p-n junctions*

A p-n junction is formed in a crystalline semiconductor when part of it is doped p-type and the other part n-type. It is fundamental to the performance of functions such as rectification, amplification, switching and other operations in electronic circuits. The I-V characteristic of an ideal p-n junction is given by:

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

where I_0 is the reverse saturation current, q the electron charge, k the Boltzmann's constant and T the absolute temperature [1]. At room temperature (~298 K), kT/q = 0.0252 V. In a real diode, a more accurate expression is:

$$I = I_0\left(e^{qV/nkT} - 1\right) \tag{2}$$

where n is called the ideality factor and is a measure of how close to the ideal conditions were under which the diode was fabricated. The value of n is usually between 1 and 2 depending on the material and physical structure of the diode.

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

$$I = I_0 e^{qV/nkT} \tag{3}$$

In order to determine the ideality factor and the reverse saturation current, we consider,

$$\ln I = \ln I_0 + \frac{q}{nkT}V \tag{4}$$

By plotting the I-V data on a semilog graph, a straight line can be obtained. We can then derive the ideality factor from the slope of the graph together with the reverse saturation current from its intercept.

In equation (3), the I-V temperature dependence is due to I_0 and the temperature term in the exponent. From semiconductor theory, I_0 depends on p_n and n_p, the minority carrier concentrations, which in turn depend on n_i^2, the square of the intrinsic carrier concentration.

Now

$$n_i = \text{constant} \times T^{3/2} \exp\left(-\frac{E_g}{2kT}\right) \tag{5}$$

Hence,

$$I_0 = AT^3 \exp\left(\frac{-E_g}{kT}\right) \tag{6}$$

where A includes all terms approximately independent of T.

To determine the temperature dependence of the I-V characteristic, we have from equation (3),

$$V = \frac{nkT}{q} \ln\left(\frac{I}{I_0}\right) \tag{7}$$

Then

$$\left.\frac{\partial V}{\partial T}\right|_{I=\text{constant}} = \frac{V}{T} - \frac{nkT}{q}\frac{1}{I_0}\frac{dI_0}{dT} \tag{8}$$

From equation (6)

$$\ln I_0 = \ln A + 3\ln T - \frac{E_g}{kT} \tag{9}$$

$$\frac{d}{dT}\left(\ln I_0\right) = \frac{1}{I_o}\frac{dI_0}{dT} = \frac{3}{T} + \frac{E_g}{kT^2} \tag{10}$$

Substituting (10) into (8), we have

$$\left.\frac{\partial V}{\partial T}\right|_{I=\text{constant}} = -\frac{\frac{n}{q}\left(3kT + E_g\right) - V}{T} \quad [V/K] \tag{11}$$

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

$$\left.\frac{\partial V}{\partial T}\right|_{I=\text{constant}} = -2.4m \ \ V/K \tag{12}$$

Thus, when biased by a constant current source, an increase in the temperature will cause the voltage across a p-n diode to decrease at a constant rate with respect to temperature. This effect can be exploited for temperature measurements, especially in the low-temperature range around 100 K.

2.2 Light emitting diodes

Many optoelectronic devices, such as light emitting diodes (LEDs), laser diodes (LDs) and solar cells are also based on the principle of the p-n junction. 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 as shown in Fig. 1 [2]. When an electron in the conduction band undergoes a transition to the valence band and recombines with a hole, the energy given up by the electron may be released in the form of a photon – thus light emission may occur. In an LED, such recombination occurs randomly and the emission is said to be spontaneous. Since photons carry very little momentum, their generation must involve electrons and holes, which have the same momentum. This implies that light emission is only possible from direct bandgap semiconductors. 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 spectral position of this band is directly related to the bandgap energy E_g of the semiconductor.

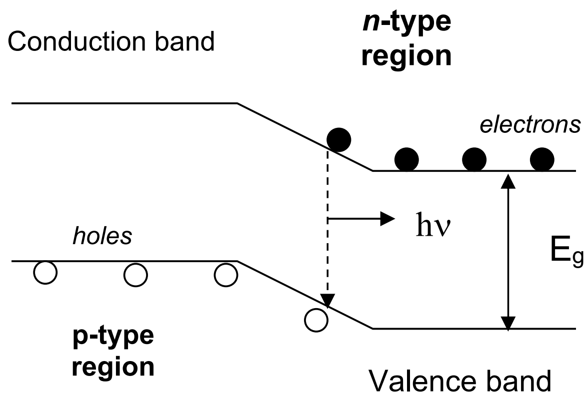


***Figure 1*: Injection of carriers for photon emission in an LED**

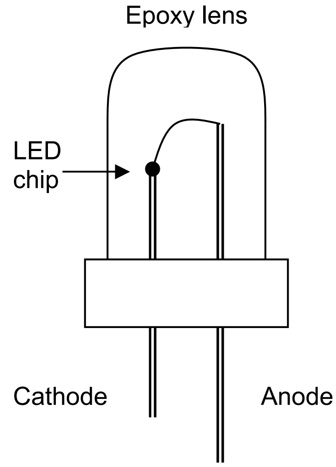


***Figure 2*: Lamp type LED**

The table below shows some examples of compound semiconductor materials used for LED fabrication. Compound semiconductors are used because they are direct bandgap semiconductors.

Semiconductor	Formula	E_g (eV)	Wavelength (nm)	Colour
Gallium arsenide phosphide	GaAsP	2.03	610	orange
Aluminium gallium arsenide	AlGaAs	1.91	650	red
Indium gallium arsenide phosphide	InGaAsP	2.00 2.10 2.24	620 590 555	orange yellow green
Gallium nitride	GaN	2.76	450	blue
Gallium arsenide	GaAs	1.44	860	infrared
Indium gallium arsenide	InGaAs	1.13–0.77	1100–1600	infrared

The brightness achievable in present day visible LEDs has reached a level where they are replacing incandescent lamps in various applications. Reliability is high – they take about a million hours to degrade to half power. A lamp-type LED is shown in Fig. 2.

References:

[1] B.G. Streetman, "Solid State Electronic Devices" 5th edition, Prentice Hall, (2000).

[2] P. Bhattacharya, "Semiconductor Optoelectronic Devices", 2nd edition, Prentice Hall, (1997)

3. EQUIPMENT AND COMPONENTS

Power supply	1	Resistor 68 Ω 5 W	1
Breadboard	1	Soldering iron	1
Digital multimeter (DMM)	2	Keithley source measure unit (SMU)	1
Dual channel oscilloscope	1	RS577-780 ultrabright red LED	1
Connecting wires and cables		Black box	1
Diode (1N4001 to 1N4004)	2	Luxmeter	1
Resistor (1 kΩ)	1	Oriel spectrometer	1
Step down transformer	1		

4. PROCEDURES

IMPORTANT: *Record all your measurement results, graphs, calculations and discussions in the* ***Results Sheet****. You are to submit the* ***Results Sheet*** *at the end of the laboratory session* ***unless*** *you are submitting a formal report for this laboratory work.*

4.1 I-V Characteristics

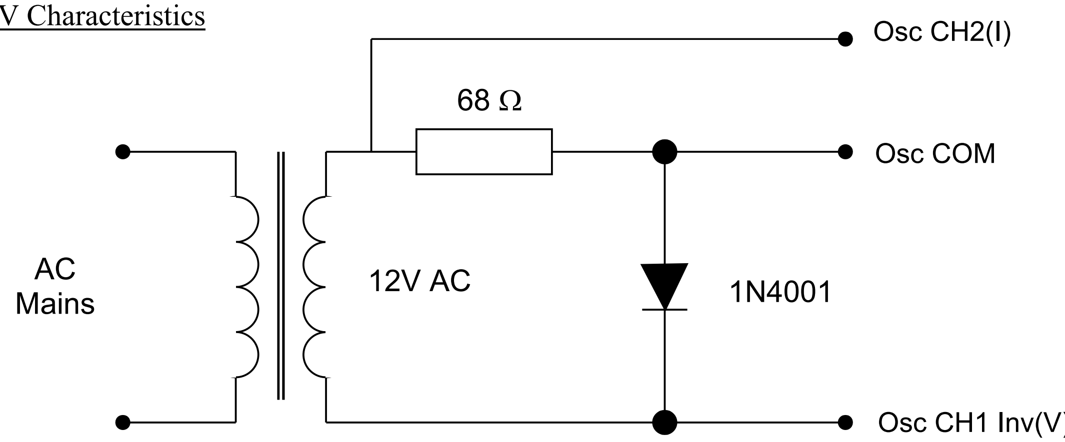


Figure 3**: Sweep circuit for I-V display**

Generate the *I-V* characteristic of the 1N4001 diode under forward bias by using the circuit shown in Figure 3. The oscilloscope should be set for the X-Y mode with the origin properly initialized.

Sketch the *I-V* characteristic of this diode in the **Results Sheet**, ensuring that the units of both axes are clearly labeled. Ensure that the displayed current range on the oscilloscope exceeds 150 mA.

- Determine the turn-on voltage and the differential resistance (dV/dI) after turn on for this diode.

4.2 Temperature Dependence

Apply heat to the diode for about 15 seconds by using the soldering iron. Care should be taken for preventing the 68 Ω resistor from being heated by the soldering iron. Observe and sketch the *I-V* characteristic on the same diagram in the **Results Sheet** as above. Note the amount of voltage shift (in mV) in the characteristic at a constant current of about 150 mA.

Provide an explanation for the observed shift in the characteristic. Determine the diode temperature change (in K) based on the measured decrease in diode terminal voltage at 150 mA. An answer in mV is not acceptable.

4.3 Ideality factor and reverse saturation current

Use the circuit of Figure 4 to determine the *I-V* characteristic over 3 decades of current from 0.01 mA to 10 mA. Record the current value using SMU and voltage value using the DMM and plot the *I* versus *V* data on the semilog graph paper provided in the **Results Sheet**.

Explain how you can determine the slope of the In *I* versus *V* relationship from the semilog plot. From this graph, determine the ideality factor *n* and reverse saturation current I_0.

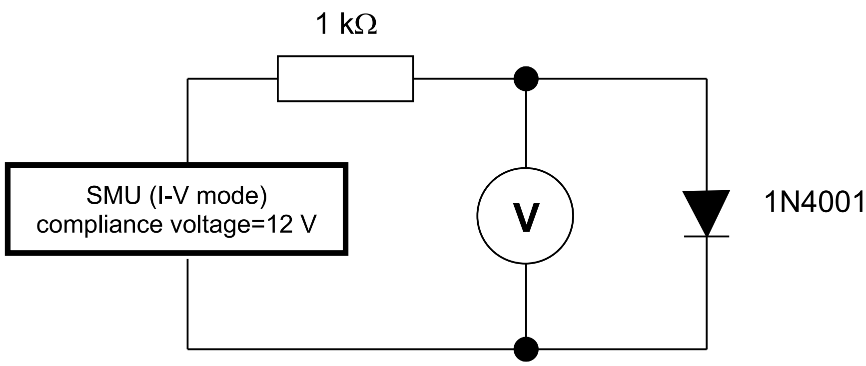


***Figure 4*: Circuit for diode parameter extraction**

4.4 Light current characteristic of an LED

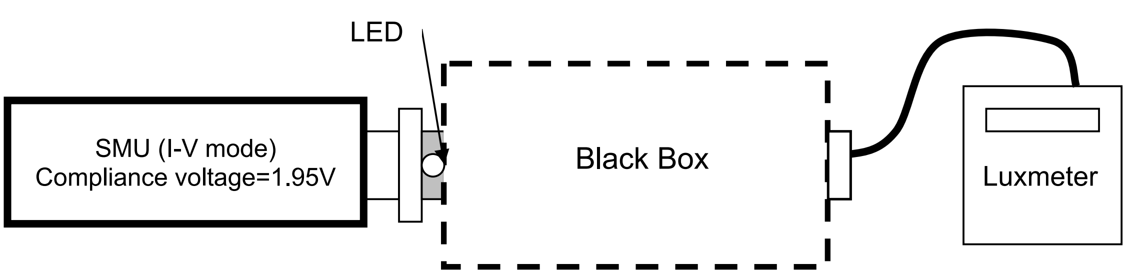


***Figure 5*: Schematic layout for L-I measurements**

Figure 5 shows the experimental setup for the measurement of the light current (*L-I*) characteristics of an LED. The source measure unit (SMU) should be set to a constant current source to drive a preset dc current through the ultra-bright red LED. The light emitted from the LED is detected by the luxmeter. The luxmeter reading is proportional to the incident optical power.

- Plot the L-I characteristic curve (I = 0 to 35 mA in step of 5 mA) on the graph paper provided in the **Results Sheet** and comment on your results.

- Why is the experiment carried out inside the black box?

- When the LED current is 0 mA, what is the luxmeter reading and why?

4.5 Emission spectrum of an LED

A spectrometer is essentially the optical equivalent of an electronic spectrum analyzer. The instrument uses a reflective grating to disperse the source radiation that is incident on the entrance slit into its various frequency components. By rotating the grating in the spectrometer using the knob provided, the intensities of the source at different wavelengths can be recorded at the output slit. For this experiment, the entrance slit and exit slit widths are both set to 1 mm. DO NOT ADJUST THE SLIT WIDTHS. The wavelength of interest lies within the range of 600 nm to 700 nm.

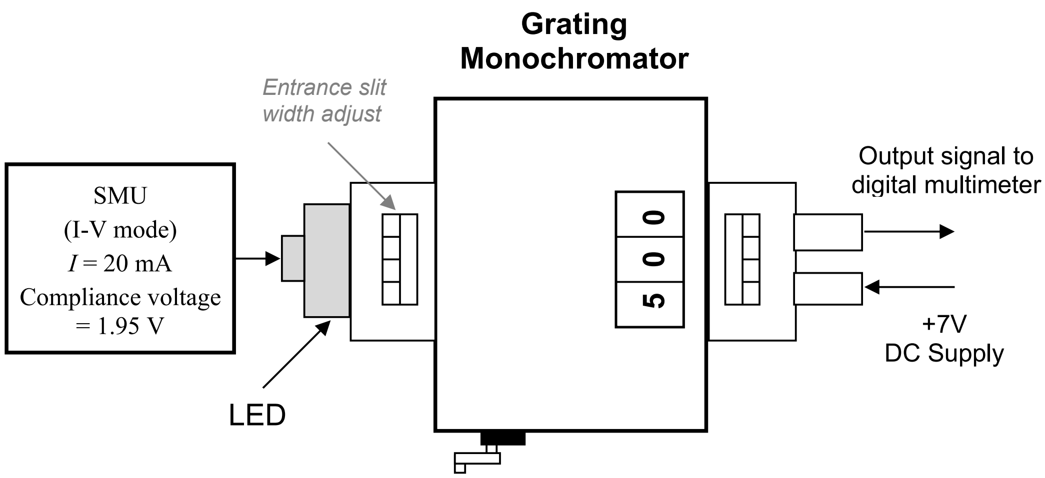


***Figure 6*: Measurement of emission spectrum using a grating spectrometer**

Figure 6 shows the schematic diagram of the spectral measurement set-up. A photodetector module is mounted next to the exit slit of the spectrometer. It should be operated using a voltage of 7 V dc from a regulated power supply. **Check the power supply voltage prior to connection.** Ensure that the photodetector output is switched to LED mode and connect the output port of the photodetector to a voltmeter. The voltmeter reading is proportional to the intensity of the light incident on the exit slit of the spectrometer.

i. Plot the emission spectrum of the LED in the **Results Sheet**, ensuring that your measurements are taken at a suitable wavelength interval to ensure that the peak and the spectral line width can be obtained accurately.

ii. The energy band gap (E_g) of a semiconductor can be obtained from $E_g = hc/\lambda$ where h is Planck's constant ($h = 6.625\times10^{-34}$ Js), c is the velocity of light and λ is the wavelength. Calculate the band gap energy in eV for the LED emission.

iii. The line width of the radiation of an LED is defined by the full width at half maximum (FWHM) of its emission spectrum. The FWHM is defined as the total width (in nm) of the spectrum at 50% from the peak of the spectrum. Determine the line width of the LED and comment on this result.

5. DISCUSSION

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

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

iii. Explain the factors that influence the spectral line width of the emission spectrum that you measured in part 4.5.

Formal Report

The report should read as a unit and not merely a reproduction of the manual. It should be concise, and be limited to between **10** and **14** A4 pages. Note that copying of information from the manual should be minimized. Instead, you should emphasize more on your own observations, comments on the results obtained and any special precautions taken. You should also answer all the questions stated in the various sections of the manual.

SAFETY TIPS

- **Safety First:** Execution of laboratory work in a safe manner is more important than performing accurate measurements.
- Follow laboratory safety rules and procedures at all times.
- Always be aware of the risk of electric shocks.
- Each group is responsible for your laboratory bench. At the end of the laboratory session, please power down all equipment and return all probes and cords to their proper position.

H3 LAB 03 RESULTS SHEET

(to be submitted at the end of the laboratory session)

Name : ____

Date : ____

Sketch of IV Curve of Diode

4.1 I-V Characteristics

Calculations:

Turn-on voltage of diode : ____________________________________

Differential resistance after turn-on : ____________________________________

4.2 Temperature Dependence

Explanation for observed shift:

Voltage shift at constant 150 mA current (mV) : ____________________

Deduced diode temperature change (K) : ____________________

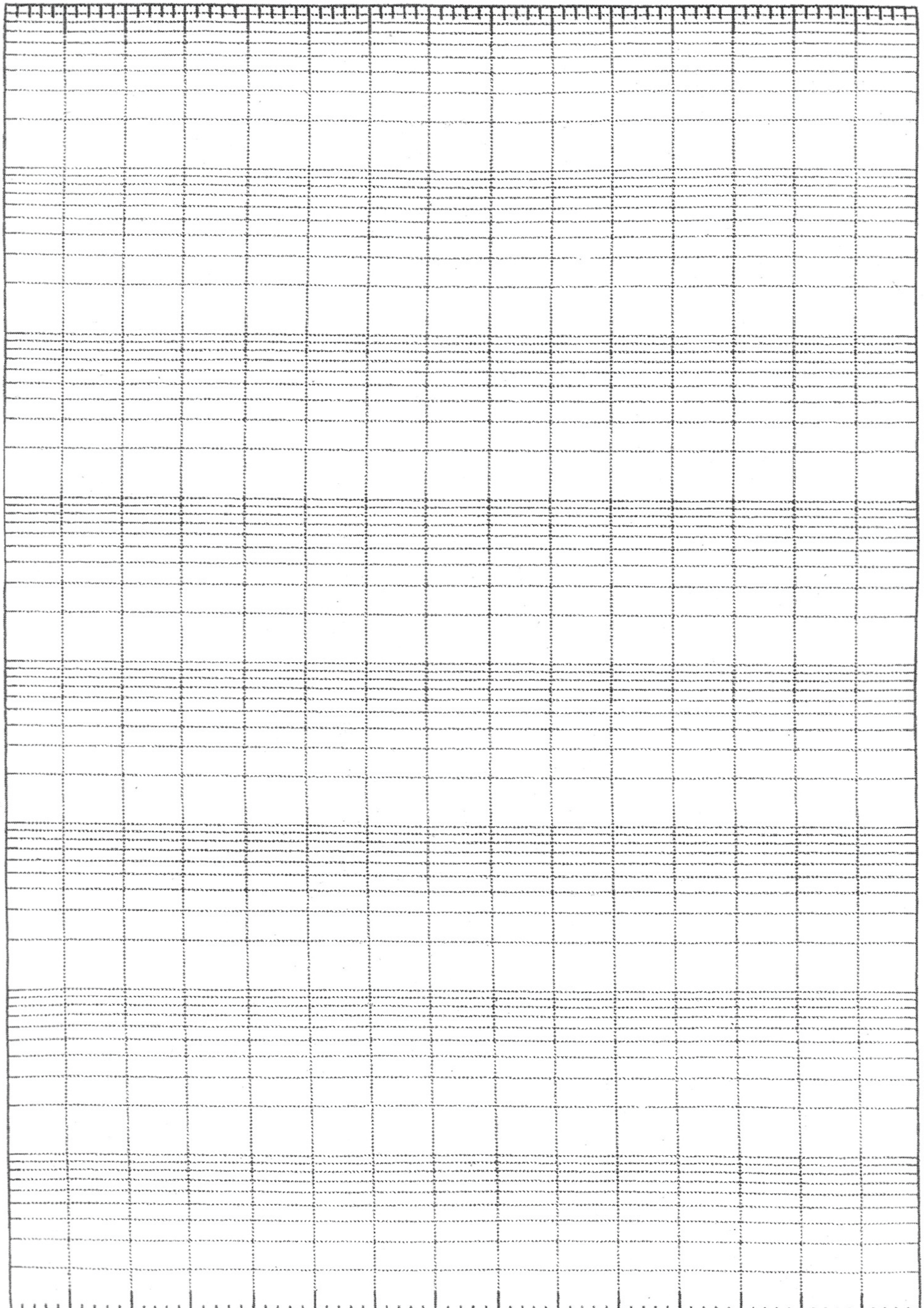
4.3 Ideality factor and reverse saturation current

Explanation on how to determine the slope of the InI-V plot:

Ideality factor, n : ____________________

Reverse saturation current, I_0 : ____________________

4.3 IV Curve of Diode (Semilog plot)



4.4 Light current characteristic of an LED

Comments on results:

Why is the experiment carried out inside the black box?

When the LED current is 0 mA, what is the luxmeter reading and why?

4.5 Emission spectrum of an LED

Bandgap energy of LED (eV) : ______________________________

Linewidth of LED (nm) : ______________________________

4.4 Light-Current Curve of LED

4.5 Emission Spectrum of LED

5. DISCUSSION

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

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

iii. Explain the factors that influence the spectral line width of the emission spectrum that you measured in part 4.5.