PG PHY S1-03 DSC

TWO YEAR MASTER'S DEGREE COURSE

(CBCS in Accordance with NEP 2020)

SEMESTER-I

PHYSICS LAB I

PHYSICS

Hiranya Chandra Bhuyan School of Science and Technology

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CONTENTS

		PAGE NO.
Experiment No. 1:	To measure the resistivity of a semiconductor and determine its band gap using the four-probe method.	**7-14**
Experiment No. 2:	To study V–I characteristics of PN junction diode and determine cut-in voltage and dynamic resistance.	**15-20**
Experiment No. 3:	To design a voltage regulator circuit and study the characteristics of a Zener diode.	**21-27**
Experiment No. 4:	To study input and output characteristics of BJT (CE mode) and determine current gain.	**28-34**
Experiment No. 5:	To design a Class-A amplifier using a transistor.	**35-39**
Experiment No. 6:	To study characteristics of FET / MOSFET and determine trans conductance.	**40-47**
Experiment No. 7:	To design and study a single-stage RC coupled amplifier and determine voltage gain and bandwidth.	**38-55**
Experiment No. 8:	To determine the wavelength of a given laser source using (a) Young's Double Slit experiment and (b) Single Slit diffraction method.	**56-61**
Experiment No. 9:	To study the input and output characteristics of a transistor in CE (Common Emitter), CB (Common Base) and CC (Common collector) configuration.	**62-72**
Experiment No. 10:	To determine Stefan's Boltzmann constant using a ballistic galvanometer/incandescent lamp.	**73-80**
Experiment No. 11:	To determine the modulus of rigidity of a wire using Maxwell's needle	**81-86**
Experiment No. 12:	To determine the wavelength of monochromatic light using Fresnel's biprism.	**87-93**
Experiment No. 13:	To calibrate a given temperature sensor (Thermistor)	**94-103**

COURSE INTRODUCTION

This laboratory-based course is the third Discipline Specific Course (DSC) of the first semester of Master of Science in Physics programme which is consists of thirteen experiments. The main objective of this course is to provide practical knowledge of semiconductor devices, electronic circuits, optics, and selected classical physics experiments through laboratory work. This course helps the learner understand important experimental techniques and develop skills in handling laboratory instruments and electronic components. The experiments included in this course introduce learners to the study of semiconductor devices such as PN junction diodes, Zener diodes, transistors, and FET/MOSFET. The course also involves the design and analysis of electronic circuits such as amplifiers and voltage regulators, which help learners understand their practical applications. In addition, the course includes optical experiments to study interference and diffraction phenomena, such as Young's double slit experiment and Fresnel biprism, which are used to determine the wavelength of light. Experiments on semiconductor resistivity using the four-probe method and determination of physical constants such as Stefan's constant and modulus of rigidity are also included. After completing this course, the learner gains the ability to analyse the characteristics of semiconductor devices, design simple electronic circuits, and determine important physical constants through experiments. The learner also develops practical skills in conducting laboratory experiments, taking accurate measurements, analyzing experimental data, and interpreting results related to electronics and optics.

The practical course consists of the following experiments:

Experiment No. 1: **Four-Probe Method (Band Gap of Semiconductor)**- In this experiment, the resistivity of a semiconductor is measured using the four-probe method. From the temperature dependence of resistivity, the band gap energy of the semiconductor is determined.

Experiment No. 2: **V–I Characteristics of PN Junction Diode**- This experiment studies the voltage–current characteristics of a PN junction diode. From the graph, the cut-in voltage and dynamic resistance of the diode are determined.

Experiment No. 3: **Zener Diode and Voltage Regulator**- This experiment examines the V–I characteristics of a Zener diode and demonstrates its use as a voltage regulator in electronic circuits.

Experiment No. 4: Characteristics of BJT (CE Mode)- In this experiment, the input and output characteristics of a bipolar junction transistor (BJT) in common emitter configuration are studied. The current gain of the transistor is also determined.

Experiment No. 5: Design of Class A Amplifier- This experiment involves designing a simple Class A transistor amplifier. It helps in understanding how transistors are used to amplify electrical signals.

Experiment No. 6: **Characteristics of FET / MOSFET**- In this experiment, the characteristics of a FET or MOSFET are studied. The transconductance of the device is determined from the obtained characteristics.

Experiment No. 7: **RC Coupled Amplifier**- This experiment involves designing and studying a single-stage RC coupled amplifier. The voltage gain and bandwidth of the amplifier are determined.

Experiment No. 8: **Wavelength of Laser (Young's Double Slit and Single Slit Diffraction)**- This experiment determines the wavelength of a laser source using interference and diffraction methods, namely Young's double slit experiment and single slit diffraction.

Experiment No. 9: **Transistor Characteristics in CE, CB and CC Modes**- In this experiment, the input and output characteristics of a transistor are studied in common emitter, common base, and common collector configurations.

ExperimentNo.10: Stefan's Constant Using Ballistic Galvanometer-This experiment determines the Stefan–Boltzmann constant by studying thermal radiation using a ballistic galvanometer.

Experiment No. 11: **Modulus of Rigidity Using Maxwell's Needle**- In this experiment, the modulus of rigidity of a given wire is determined using Maxwell's needle arrangement.

Experiment No. 12: **Wavelength of Light Using Fresnel Biprism**- This experiment uses Fresnel biprism to produce interference fringes and determine the wavelength of monochromatic light.

Experiment No. 13: **Calibration of a thermistor temperature sensor**- This experiment deals with the calibration of a thermistor temperature sensor by studying the variation of its resistance with temperature. It helps determine the temperature-resistance relationship of the thermistor and enables its use for accurate temperature measurement.

After performing these experiments, learners will develop practical skills in handling laboratory instruments and electronic devices and gain a clear understanding of important concepts in semiconductor devices, optics, and classical physics. They will also learn how to take accurate measurements, analyse experimental data, and relate theoretical concepts with real laboratory observations.

EXPERIMENT NO. 1

Measurement of Resistivity of a Semiconductor and Determination of its Band Gap Using the Four-Probe Method

LEARNING OBJECTIVES OF THE EXPERIMENT

After performing the experiment, you will be able to:

- explain the principle of the four-probe method.
- measure the resistivity of a semiconductor sample.
- study the variation of resistivity with temperature.
- determine the band gap energy of the semiconductor.

1.1 AIM

To measure the resistivity of a semiconductor and determine its band gap using the four-probe method.

1.2 INTRODUCTION

The four-probe technique is widely used for determining the electrical resistivity of conducting and semiconductor materials with improved accuracy. Unlike the two-probe arrangement, where the measured resistance includes contributions from the specimen, probe contacts, and connecting wires, the four-probe arrangement minimizes the effect of contact resistance and lead resistance. This is particularly important in semiconductor measurements, where contact resistance may significantly influence the observed value.

In this method, the outer pair of probes is used to pass a known current I through the specimen, while the inner pair measures the corresponding potential difference V. Since the voltmeter connected across the inner probes has very high resistance, the current through it is negligible and the measured voltage corresponds only to the potential drop across the sample. Thus, the resistivity obtained represents the intrinsic property of the material.

The resistivity of a semiconductor varies with temperature because of changes in charge-carrier concentration. By measuring resistivity at different temperatures and analysing the resulting variation, the energy band gap of the semiconductor can be determined.

1.3 APPARATUS REQUIRED

The experimental setup comprises two interconnected units:

Four-Probe Measuring Unit (Electronic Control Unit)
This is the main electronic instrument that provides a regulated constant current to the outer probes and measures the voltage developed across the inner probes. Its principal components are:

- Digital Current Display (left panel) — indicates the current (*I*) in milliamperes supplied to the outer (current) probes.
- Digital Voltage Display (right panel) — indicates the voltage (*V*) in millivolts developed across the inner (voltage) probes.
- Current Control Knob— allows fine adjustment of the current supplied to the sample.
- Range / Mode Selector Switch— selects the appropriate measurement range for current and voltage.
- Output Terminals (Red / Black for current; Yellow / Green for voltage) — provide connections to the probe head assembly.

Probe Head with Heating Arrangement
This cylindrical unit houses the probes, the sample, and the heating system. Its components are:

- Four Metallic Probes— arranged collinearly at equal spacing (*s*), and spring-loaded to ensure consistent contact pressure on the sample surface.
- Sample Holder— a recessed platform inside the cylindrical chamber on which the semiconductor wafer is placed.
- Heater Coil— an embedded resistance heater used to raise the sample temperature uniformly for band gap measurements.
- Temperature Sensor (thermocouple / thermometer) — mounted adjacent to the sample to measure its temperature accurately during the experiment.

1.4 CIRCUIT CONNECTIONS

1. Connect the outer probes (current probes) to the constant-current output terminals of the control unit.
2. Connect the inner probes (voltage probes) to the voltage measurement terminals of the control unit.
3. Place the semiconductor sample flat on the sample holder inside the heating chamber.
4. Position the temperature sensor in contact with or immediately adjacent to the sample surface.

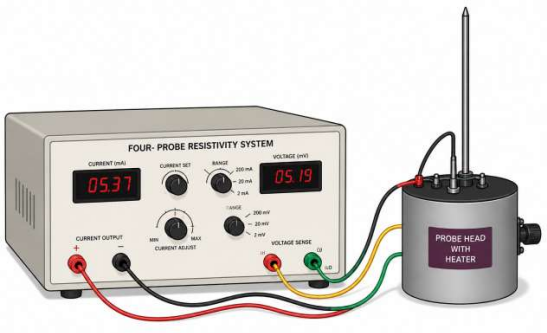


Figure 1.1*:* Schematic diagram of the four-probe experimental setup showing the probe head, heating arrangement, and electronic control unit.

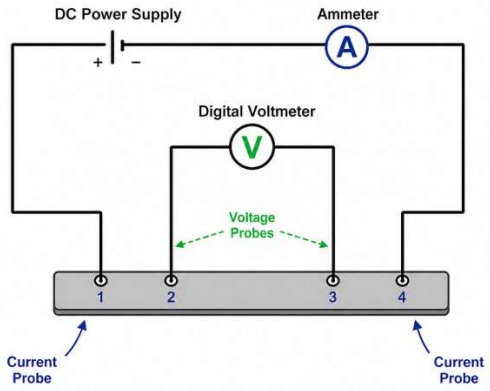


Figure 1.2*:* Circuit connection of four Probe method

1.5 THEORY

Principle of the Four-Probe Method

When a constant current *I* is passed through the outer two probes of a collinear four-probe array with uniform probe spacing *s*, a potential difference *V* is established in the sample. For a bulk semiconductor sample (where the sample thickness *t* is much greater than the probe spacing *s*), the resistivity is given by:

$$\rho = 2\pi\left(\frac{V}{I}\right) \qquad (1.1)$$

where:

ρ = electrical resistivity (Ω·cm)

s = distance between adjacent probes (cm)

V = voltage across the inner probes (V)

I = current through the outer probes (A)

When the sample is thin (thickness *t* comparable to probe spacing *s*), Equation (1.1) must be corrected using a geometric correction factor *f(t/s)*, so that the corrected formula becomes:

$$\rho = \left(\frac{2\pi s}{f\left(\frac{t}{s}\right)}\right) \times \left(\frac{V}{I}\right) \qquad (1.2)$$

The value of $f\left(\frac{t}{s}\right)$ is available in standard tabulated form and is provided with the laboratory instrument. For the purposes of this experiment, the sample is assumed to be sufficiently thick that $f\left(\frac{t}{s}\right) \approx 1$ and Equation (1.1) applies directly.

Temperature Dependence of Resistivity and Band Gap

In an intrinsic semiconductor, thermally excited carriers dominate electrical conduction. The number of such carriers depends exponentially on the temperature. As a result, the resistivity of a semiconductor varies with absolute temperature T according to:

$$\rho(T) = \rho_0 \exp\left(\frac{E_g}{2kT}\right) \qquad (1.3)$$

where:

ρ_0 = a pre-exponential constant (Ω·cm)

Eg = band gap energy of the semiconductor (eV)

k = Boltzmannconstant = 8.617×10^{-5} eV/K

T = absolute temperature (K)

Taking the common logarithm (base 10) of both sides of Equation (1.3):

$$\log_{10}\rho = \log_{10}\rho_0 + \left(\frac{E_g}{2.303 \times 2k}\right) \times \left(\frac{1}{T}\right) \qquad (1.4)$$

Equation (1.4) is of the linear form y = mx + c, where *y* = $\log_{10}\rho$, x = $\frac{1}{T}$ and the slope is:

$$m = \frac{E_g}{(2.303 \times 2k)} \qquad (1.5)$$

Rearranging, the band gap energy is:

$$E_g = 2.303 \times 2k \times m = 2.303 \times 2 \times 8.617 \times 10^{-5} \times m \qquad (1.6)$$

where m is the slope of the $\log_{10}\rho$ vs $\frac{1}{T}$ graph. This slope is obtained experimentally from the best-fit straight line drawn through the data.

1.6 PROCEDURE

1. Place the semiconductor sample carefully on the sample holder, ensuring all four probes make firm, uniform contact with the sample surface.
2. Switch on the electronic control unit. Ensure the heater switch is in the OFF position at this stage.
3. Set a constant current of 5 mA using the current control knob and confirm the value on the digital display.
4. Record the initial voltage (V) and room temperature (T) as the first data point.
5. Switch on the heater and allow the temperature to rise gradually. Record voltage and temperature readings at 10 °C intervals from room temperature up to 60 °C, and then at 5 °C intervals from 60 °C up to approximately 140 °C.
6. At each temperature step, wait until the temperature reading on the sensor stabilizes before recording the values of current (*I*), voltage (*V*), and temperature (T).

7. Do not exceed 140 °C. Switch OFF the heater when the maximum temperature is reached.
8. Allow the sample to cool to room temperature before switching off the control unit.
9. Calculate resistivity ρ for each data point using Equation (1.1) and populate both observation tables.
10. Plot the graph of $\log_{10}\rho$ vs 1/T and draw the best-fit straight line through the linear portion of the data.
11. Determine the slope (*m*) of the straight line and substitute into Equation (1.6) to calculate the band gap energy *Eg*.

1.7 OBSERVATIONS

Probe spacing**:** s = _____ cm (value provided with the instrument*)*

Table 1: Measurement of Resistivity at Various Temperatures

S.No.	Temp (°C)	Temp T (K)	Current I (mA)	Voltage V (mV)	$\frac{V}{I}(\Omega)$	Resistivity $\rho = 2\pi\left(\frac{V}{I}\right)$ (Ω·cm)
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						

Table 2: Data for Band Gap Calculation

Sl.No.	Temp T (K)	$\frac{1}{T}(K^{-1})$	Resistivity ρ (Ω·cm)	$\log_{10}\rho$	Remarks
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					

1.8 CALCULATIONS

Resistivity at each Temperature

1. Convert each temperature reading to Kelvin:

$$T\,(K) = t\,(°C) + 273.15$$

2. Calculate the resistance ratio:

$$\frac{V}{I}(\Omega) = \frac{V(V)}{I(A)}$$

3. Calculate the resistivity using the four-probe formula:

$$\rho = 2\pi s\left(\frac{V}{I}\right)$$

4. Record ρ for each temperature in Table 1.

Band Gap Calculation

1. Compute $\frac{1}{T}$ and $\log_{10}\rho$ for each data point and enter the values in Table 2.
2. Plot $\log_{10}\rho$ (y-axis) against $\frac{1}{T}$ (x-axis). The plot should show a straight-line region corresponding to intrinsic conduction.
3. Draw the best-fit straight line through the linear region and determine its slope:

$$m = \frac{\Delta(\log_{10}\rho)}{\Delta\left(\frac{1}{T}\right)}$$

4. Substitute the slope into Equation (1.6) to obtain the band gap:

$$Eg = 2.303 \times 2 \times 8.617 \times 10^{-5} \times m\,(eV)$$

1.9 RESULT

- The resistivity of the given semiconductor sample at room temperature = _____ Ω cm
- The band gap energy of the semiconductor: $Eg =$ _____ eV.

1.10 PRECAUTIONS

1. Ensure firm and uniform contact of all four probes with the sample surface before starting the experiment.
2. Maintain the current strictly constant throughout the entire experiment. Any drift in current will directly affect all resistivity values.
3. Raise the temperature slowly and uniformly. Rapid heating causes temperature gradients across the sample and leads to inaccurate readings.
4. Record voltage and temperature readings only after the temperature indicator has stabilized at each step, typically after waiting 30–60 seconds at the target temperature.
5. Do not heat the sample beyond 140 °C to prevent damage to the probes, the sample, or the temperature sensor.
6. Handle the probe head carefully. The spring-loaded probes are delicate. Do not press them forcefully onto the sample.

7. Allow the setup to cool completely before repositioning the sample or disconnecting any leads.

1.11 SOURCES OF ERROR

1. Improper or inconsistent probe contact leading to variable contact resistance.
2. Temperature fluctuations during a reading interval causing measurement scatter.
3. Non-uniform sample thickness, which invalidates the bulk-sample assumption of equation (1.1).
4. Instrumental drift in the current source or voltmeter over the duration of the experiment.
5. Thermocouple calibration error or a lag between the displayed temperature and the actual sample temperature.
6. Inaccuracy in the assumed probe spacing *s*, any mechanical wear or misalignment of the probe head affects all resistivity calculations.

1.12 REFERENCES

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1.13 ANSWER THE FOLLOWING QUESTIONS

1. Why is the four-probe method preferred over the two-probe method for measuring resistivity of semiconductors?
2. Explain the principle of the four-probe method and the role of current and voltage probes.
3. Under what condition is the formula $\rho = 2\pi s \frac{V}{I}$ valid?
4. What is the significance of maintaining constant current throughout the experiment?
5. Why is the temperature increased gradually, and readings taken only after stabilization?
6. Explain the relation between resistivity and temperature in an intrinsic semiconductor.
7. Why is a graph of $\log_{10}\rho$ versus $\frac{1}{T}$ plotted instead of ρ versus T?
8. How is the band gap energy of the semiconductor determined from the experimental data?
9. What are the major sources of error in the four-probe method experiment?
10. Why is it necessary to ensure uniform and firm contact between the probes and the sample surface?

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EXPERIMENT NO. 2

V-I Characteristics of a PN Junction Diode

LEARNING OBJECTIVES OF THE EXPERIMENT

After performing this experiment, you will be able to:

- study the V–I characteristics of a p–n junction diode.
- determine the cut-in voltage of the diode.
- calculate the dynamic resistance of the diode.
- understand the rectifying action of the diode.

2.1 AIM

To study the Voltage–Current (V–I) characteristics of a PN junction diode and determine cut-in voltage and dynamic resistance.

2.2 APPARATUS REQUIRED

- PN junction diode (e.g., 1N4007 for silicon or OA79 for germanium)
- Regulated DC power supply (0–30 V)
- Milliammeter (0–50 mA): For forward bias current measurement
- Microammeter (0–500 μA): For reverse bias current measurement
- Voltmeter (0–20 V)
- Rheostat (0–1 kΩ): For voltage variation
- Breadboard and connecting wires

2.3 THEORY

A PN junction diode is a two-terminal semiconductor device formed by joining a P-type and an N-type semiconductor. It conducts current readily in one direction (forward bias) and blocks current in the other direction (reverse bias). The V–I characteristic curve describes how the current through the diode varies with the applied voltage.

Forward Bias

When the P-side of the diode is connected to the positive terminal and the N-side to the negative terminal of the supply, the diode is said to be forward-biased. Under forward bias, the potential barrier at the junction is reduced. Current remains negligible until the applied voltage reaches a threshold value, after which the current rises sharply. This threshold is called the cut-in voltage (also known as the knee voltage or threshold voltage):

- Silicon diode: ≈ 0.6 – 0.7 V
- Germanium diode: ≈ 0.2 – 0.3 V

Reverse Bias

When the P-side is connected to the negative terminal and the N-side to the positive terminal, the diode is reverse-biased. The potential barrier at the junction increases, and only a very small reversesaturation current (leakage current) flows due to minority carriers. This current is of the order of microamperes for silicon. If the reverse voltage exceeds a critical value (breakdown voltage), the current increases sharply — this region is not studied in this experiment.

Dynamic (AC) Resistance

The dynamic resistance (r_d) of a diode is defined as the ratio of a small change in voltage to the corresponding change in current at a given operating point on the forward characteristic:

$$r_d = \frac{\Delta V}{\Delta I}$$

It is determined from the slope of the forward V–I characteristic in the linear (conducting) region. The dynamic resistance is not the same as the static (DC) resistance, which is simply V/I at a particular operating point.

2.4 CIRCUIT DIAGRAM

Forward Bias Circuit

Connect the anode (P-side) of the diode to the positive terminal of the power supply through the rheostat. Connect the milliammeter in series with the diode to measure current. Connect the voltmeter in parallel (across) the diode to measure the voltage drop across it. The rheostat is used to vary the applied voltage from zero upward in small steps.

Reverse Bias Circuit

Interchange the diode terminals so that the cathode (N-side) is connected to the positive terminal of the supply. Replace the milliammeter with a microammeter in series to measure the small reverse leakage current. The voltmeter remains connected across the diode to measure the reverse voltage.

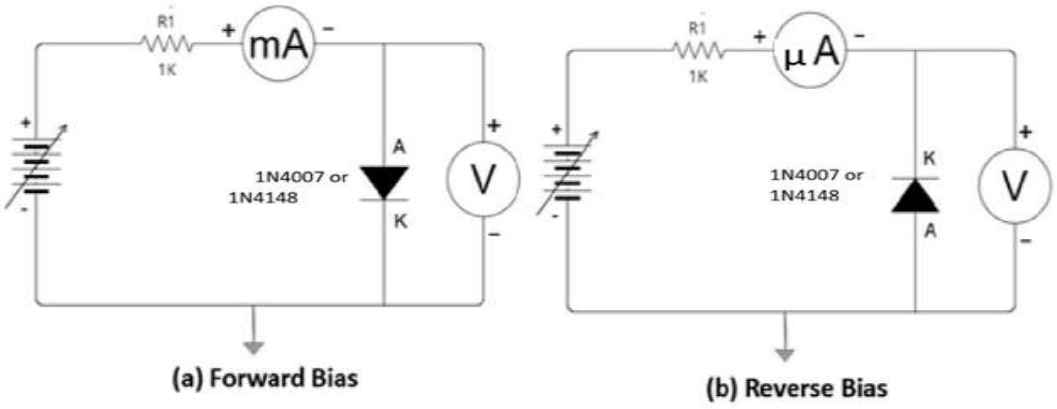


Figure 2.1: Circuit diagrams for (a) forward bias and (b) reverse bias configurations (Source: Sedra & Smith, Microelectronic Circuits).

2.5 PROCEDURE

A. Forward Bias

1. Connect the circuit as per the forward bias diagram (Fig. 1a). Ensure correct polarity of all meters and the diode.
2. Set the rheostat to its minimum position so that the initial voltage across the diode is zero.
3. Switch ON the power supply.
4. Increase the voltage across the diode in steps of 0.1 V. At each step, record the voltmeter reading (V) and the milliammeter reading (I). Continue until the current reaches the rated maximum value (or approximately 30–40 mA).
5. Record at least 10–12 readings to trace the complete forward characteristic curve.
6. Switch OFF the power supply after completing the readings.

B. Reverse Bias

1. Reconnect the circuit with the diode terminals reversed (reverse bias configuration, Fig. 1b). Replace the milliammeter with a microammeter.
2. Switch ON the power supply and increase the reverse voltage in steps of 1 V (or 2 V). At each step, record the reverse voltage (V) and the microammeter reading (I) in μA.
3. Take 8–10 readings up to the safe operating reverse voltage limit of the diode. Do not exceed the rated reverse breakdown voltage.
4. Switch OFF the power supply after completing the readings.

2.6 OBSERVATION TABLES

Table 1: Forward Bias Characteristics

Sl. No.	Voltage V (V)	Current I (mA)	Static Resistance R = $\frac{V}{I}$ (Ω)	Remarks
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				

Table 2: Reverse Bias Characteristics

Note: Voltage values in this table represent reverse voltages (0, 1, 2, 3 V … up to rated limit). Current values are in μA.

S. No.	Reverse Voltage V (V)	Reverse Current I (μA)	Static Resistance R = $\frac{V}{I}$(kΩ)	Remarks
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				

2.7 GRAPH

Plot the following graphs on the same set of axes (combined V–I characteristic) or on separate graphs:

1. Forward characteristic: Forward Voltage (V) along the positive X-axis vs Forward Current (mA) along the positive Y-axis.
2. Reverse characteristic: Reverse Voltage (V) along the negative X-axis vs Reverse Current (μA) along the negative Y-axis.

The two curves together form the complete V–I characteristic of the diode. Identify the knee point on the forward curve- the voltage at which the current begins to rise steeply is the cut-in voltage.

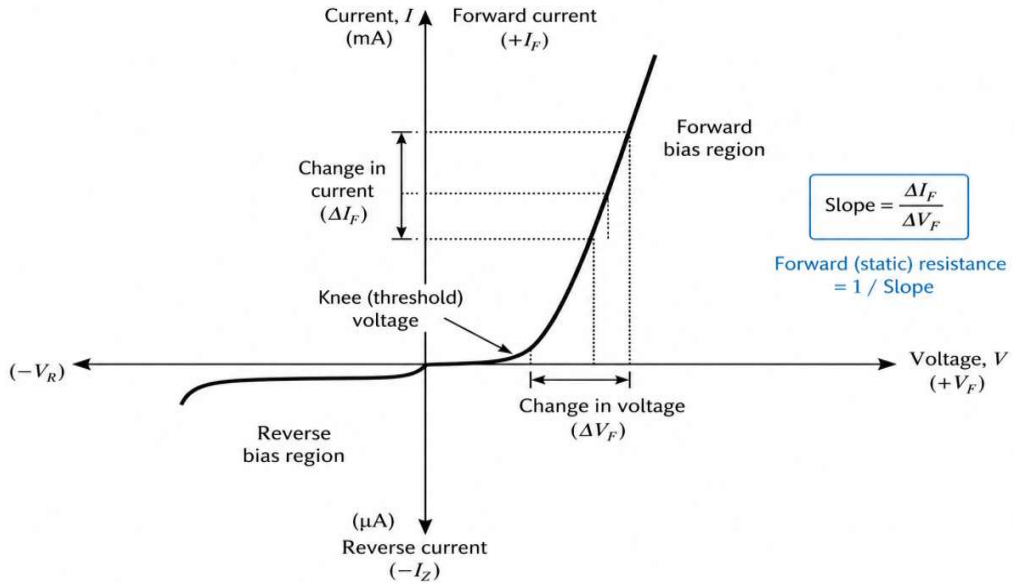


Figure 2.2: Expected V–I characteristic curve of a PN junction diode showing forward and reverse bias regions.

2.8 CALCULATIONS

Cut-in Voltage
From the forward V–I characteristic graph, identify the point at which the current begins to increase sharply (the knee of the curve). The corresponding voltage on the X-axis is called the cut-in voltage, V_γ, of the diode.

Dynamic (AC) Resistance
Select two points (V_1, I_1) and (V_2, I_2) in the linear region of the forward characteristic (above the knee). The dynamic resistance of the forward characteristic curve.

$$r_d = \frac{V_2 - V_1}{I_2 - I_1} (\Omega)$$

where V is in volts and (*I*) is in amperes. If (*I*) is recorded in mA, multiply the result by 1000 to convert to ohms.

2.9 RESULT

- The cut-in (knee) voltage of the given PN junction diode = _____ V
- The dynamic (AC) resistance of the diode = _____ Ω

2.10 PRECAUTIONS

1. Verify the polarity of the diode, voltmeter, milliammeter, and microammeter before switching ON the supply.
2. Do not exceed the maximum forward current rating or the reverse breakdown voltage of the diode.
3. Use the appropriate ammeter (milliammeter for forward bias; microammeter for reverse bias) and select the correct measurement range before taking readings.
4. Take readings carefully and ensure the pointer (or digital display) has settled before recording a value.
5. Keep the supply voltage constant for a sufficient time at each step to allow the diode temperature to stabilize before recording the current.
6. Switch OFF the power supply immediately after completing the experiment.

2.11 SOURCES OF ERROR

- Loose or poor electrical connections causing fluctuating or incorrect readings.
- Instability or ripple in the DC supply voltage leading to scatter in the recorded data.
- Self-heating of the diode at higher forward currents, which shifts the V–I characteristic and reduces accuracy.

- Parallax error while reading analogue meters.
- Calibration errors in the measuring instruments (voltmeter, ammeter).
- Contact resistance at the breadboard terminals introducing an additional voltage drop not accounted for in the measurement.

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2.13 ANSWER THE FOLLOWING QUESTIONS

1. Why does a PN junction diode conduct current only in one direction?
2. What happens to the depletion region when the diode is forward biased and reverse biased?
3. Why is there negligible current in forward bias before reaching the cut-in voltage?
4. What is the physical significance of the cut-in (knee) voltage of a diode?
5. Why is the reverse current very small and almost constant in reverse bias?
6. What causes the sharp increase in current beyond the cut-in voltage in forward bias?
7. Why is a microammeter used in reverse bias and a milliammeter in forward bias?
8. What is the difference between static resistance and dynamic (AC) resistance of a diode?
9. Why should the reverse voltage not exceed the breakdown voltage during the experiment?
10. How does temperature affect the V–I characteristics of a PN junction diode?

****

EXPERIMENT NO. 3

Zener Diode Characteristics and Voltage Regulator Circuit Design

LEARNING OBJECTIVES OF THE EXPERIMENT

After performing the experiment, you will be able to

- study the forward and reverse bias I-V characteristics of a Zener diode.
- determine the threshold voltage and Zener breakdown voltage from the characteristic curve.
- design a Zener diode voltage regulator for a specified load and input voltage range.
- calculate the series resistor R_S and verify the power ratings of circuit components.

3.1 AIM

To design a voltage regulator circuit and study the characteristics of Zener diode.

3.2 APPARATUS REQUIRED

- Zener diode (e.g., 1N4740 or equivalent, $V_Z \approx 10$ V)
- Current-limiting resistor**:** 1 kΩ, ¼ W
- DC power supply**:** Variable, 0–30 V
- Digital multimeter**:** For voltage and current measurement
- Breadboard and connecting wires

Alternatively, a Zener diode characteristic trainer kit may be used (Figure 3.1).



Figure 3.1: Zener Diode Characteristic Trainer Kit
*(*Source: Reproduced from ASICO India.)

3.3 THEORY

Zener Diode

A Zener diode is a heavily doped p-n junction diode designed to operate reliably in the reverse breakdown region. The Zener voltage (V_Z) is the reverse voltage above which a controlled breakdown occurs without damaging the diode. Once the Zener voltage is reached, the voltage across the diode remains almost constant regardless of the reverse current, making it ideal for voltage regulation. The circuit symbol is shown in Figure 3.2.

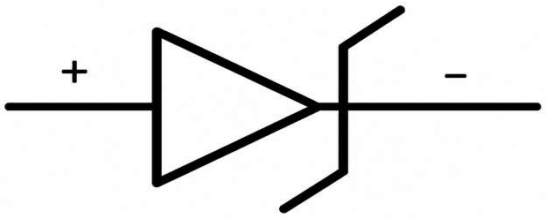


Figure 3.2: Circuit Symbol of the Zener Diode

I-V Characteristics

The I-V characteristic curve of the Zener diode (Figure 3.3) shows two distinct regions. In the forward bias region, the diode behaves like a conventional p-n junction diode with a threshold voltage of about 0.6–0.7 V. In the reverse bias region, a very small leakage current flows until the applied reverse voltage reaches V_Z, at which point the Zener breakdown occurs and the current increases sharply while the voltage remains nearly constant.

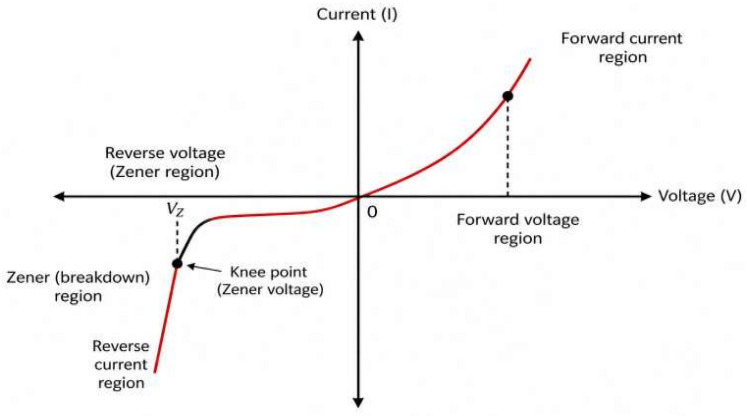


Figure 3.3: I-V Characteristics of the Zener Diode
(Source: standard electronics laboratory manuals.)

The voltage across the Zener diode in the breakdown region is expressed as:

$$V = V_z + I_z R_z \qquad (3.1)$$

where V_Z is the Zener voltage, I_Z is the Zener current, and R_Z is the Zener impedance (typically a few ohms).

Static and Dynamic Resistance

At any operating point on the I-V curve, two resistance values are defined. The static (DC) resistance is $R_{DC} = \frac{V_D}{I_D}$. The dynamic (AC) resistance is $r_d = \frac{\Delta V_D}{\Delta I_D}$, which is the inverse

of the slope of the curve at that point and is the quantity of practical significance for regulation.

3.4 PROCEDURE

Forward Bias Characteristics

1. Assembly: Assemble the circuit as shown in Figure 3.4. Connect to the (0–30) V DC power supply.
2. Switch on the supply and slowly increase the voltage in steps of 0.1 V. Record the diode voltage V_D and current I_D at each step.
3. When the current begins to increase rapidly (threshold crossed), switch to steps of 0.5 V and continue recording.
4. Switch off the supply after taking sufficient readings (at least 10–12 data points).
5. Plot the I-V characteristic and estimate the threshold voltage.
6. Select two operating points below and above the threshold voltage and calculate the static resistance $R_{DC}$and dynamic resistance r_d at each point.

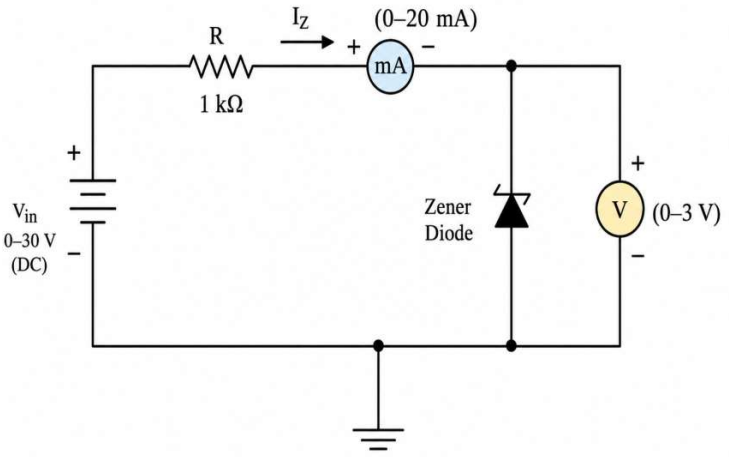


Figure 3.4*:* Circuit Connection for Forward Bias Characteristics *(*Source: standard laboratory manuals)

Reverse Bias Characteristics

1. Assembly**:** Reconnect the circuit with the Zener diode in reverse bias (Figure 3.5). Note that the initial current will be very small (μA range).
2. Increase the supply voltage in steps of 0.5 V and record V_D and I_D at each step.
3. Near the breakdown point (current increases sharply), switch to steps of 0.1 V for higher resolution.
4. Plot the I-V characteristic and estimate the Zener breakdown voltage V_Z.

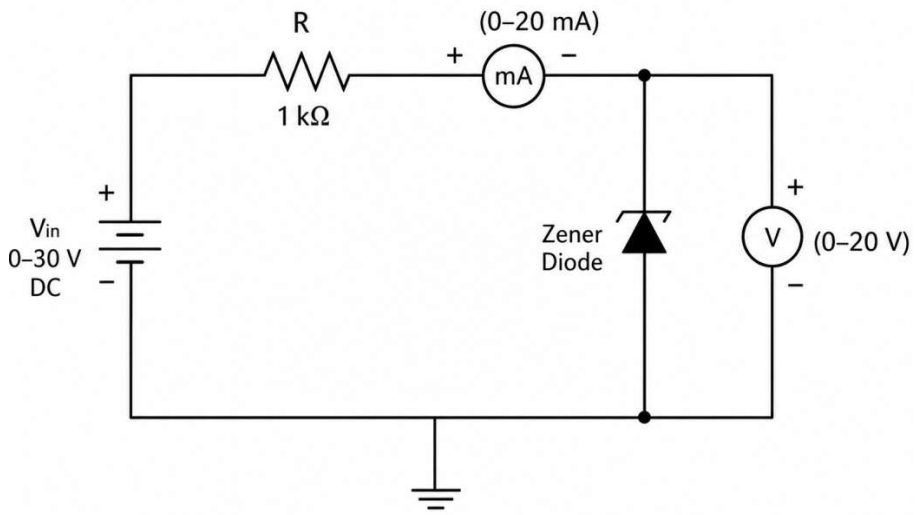


Figure 3.5: Circuit Connection for Reverse Bias Characteristics
*(*Adapted from standard laboratory manuals)

3.5 ZENER DIODE VOLTAGE REGULATOR DESIGN

A Zener diode voltage regulator maintains a constant output voltage despite variations in the input supply or load current. It consists of a Zener diode in reverse bias and a series current-limiting resistor R_S.

Design Specifications

Given Specifications

- Input voltage (V_{in})**:** Varies between 14 V (minimum) and 18 V (maximum)
- Output voltage (V_{out}): 10 V (regulated, constant)
- Load current (I_L):Varies from 0 mA (no load) to 35 mA (full load)

Series Resistor (R_S)

R_S is calculated at the worst case: minimum input voltage and maximum load current:

$$R_s = \frac{(V_{in,min} - V_z)}{I_{Lmax}} = \frac{(14-10)}{0.03} = 133.33\,\Omega. \qquad (5.1)$$

A standard value of 150 Ω is selected for practical implementation.

Power Rating of R_{RS}

$$P_{RS} = I_{Lmax} \times (V_{in,max} - V_z) = 0.03 \times 8 = 0.24\ W \qquad (5.2)$$

A 0.25 W resistor is selected, which provides adequate safety margin.

Power Dissipation of Zener Diode

The maximum Zener current occurs when $V_{in} = V_{in,max}$ and $I_L = 0$ (no load):

$$I_{zmax} = \frac{(V_{inmax} - V_Z)}{R_S} = \frac{(18-1\ )}{133.33} \approx 0.06\ A \qquad (5.3)$$

$$P_D = V_z \times I_{zmax} = 10 \times 0.06 = 0.6\ W \qquad (5.4)$$

A Zener diode with a power rating of at least 1 W is selected for reliability.

Practical Considerations

- The Zener diode maintains a nearly constant voltage under normal operating conditions.
- Minor variations in V_Z may occur due to the Zener impedance (Z_Z), which is specified in the manufacturer's datasheet.
- R_S too large**:** Insufficient Zener current → loss of regulation.
- R_S too small**:** Excessive current and overheating → damage to diode.

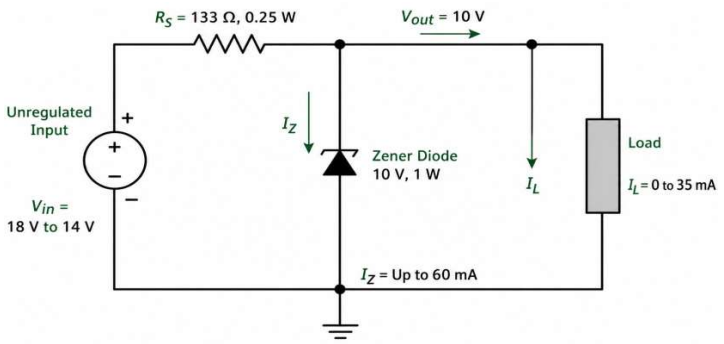


Figure 3.6: Zener Diode Voltage Regulator Circuit Design

3.6 OBSERVATIONS

Zener diode type: _____ (Si)

Obs. No.	Forward Bias			Reverse Bias		
	V_{appi} (V)	V_D(V)	I_D (mA)	V_{appi} (V)	V_D(V)	I_D(μA)
1						
2						
3						
4						
5						
6						
7						
8						

I-V Characteristic Graph

Plot I_D on the Y-axis and V_D on the X-axis for both forward and reverse bias on the same graph sheet. The expected shape of the I-V characteristic is shown in Figure 3.7 below:

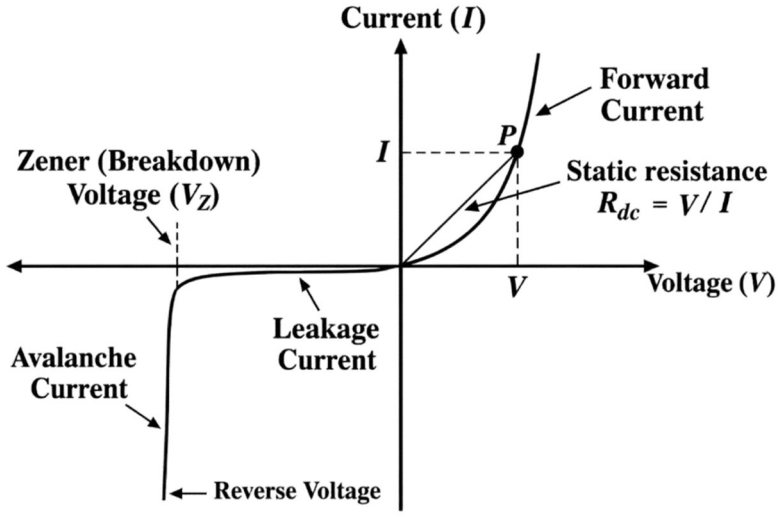


Figure 3.7: Expected I-V Characteristics of Zener Diode

3.7 RESULTS AND DISCUSSION

Results

1. Threshold voltage (forward bias): V_{th} = _____ V
2. Zener breakdown voltage: V_Z = _____ V
3. Static resistance at operating point P: $R_{DC} = \frac{V_D}{I_D}$= _____ Ω
4. Dynamic resistance at operating point P: $r_d = \frac{V_D}{I_D}$= _____ Ω

Discussion

a. The Knee Voltage

In the reverse I-V characteristic, the sharp transition from the low-current region to the high-current breakdown region is known as the knee. A sharp knee indicates low Zener impedance and good voltage regulation. A rounded knee increases the uncertainty in identifying V_Z and implies a higher dynamic resistance.

b. Line and Load Regulation

- **Line regulation:** Measures the ability of the circuit to maintain a constant V_{out} when V_{in} fluctuates. Mathematically: $\frac{\Delta V_{out}}{\Delta V_{in}} \times 100\%$.
- **Load regulation:** Measures how well the Zener maintains V_{out} as I_L varies. If I_L exceeds the available Zener current, the diode exits the breakdown region and regulation is lost.

c. Temperature Coefficient

Zener diodes with $V_Z < 5$ V exhibit a negative temperature coefficient (V_Z decreases with temperature), while those with $V_Z > 7$ V exhibit a positive temperature coefficient. Near 5–6 V, the two effects cancel, making these devices useful as precision voltage references.

3.8 PRECAUTIONS

1. Series resistor R_S: Always include R_S in series with the Zener diode. Omitting it causes the diode to draw excessive current and leads to thermal runaway.
2. Reverse bias for regulation: The Zener diode must be connected in reverse bias for voltage regulation. Forward biasing will not produce regulation.
3. Input voltage constraint: Always ensure $V_{in} > V_Z$. If $V_{in} \leq V_Z$, the Zener cannot enter breakdown and regulation fails.
4. Power rating compliance: Never exceed the rated power dissipation of the Zener diode. Use a component rated at least 50% above the calculated P_D for safety margin.
5. Meter connections: Connect the voltmeter in parallel with the diode and the ammeter in series. Incorrect connections give erroneous readings.

3.9 REFERENCES

- Boylestad, R. L., & Nashelsky, L. (2013). *Electronic devices and circuit theory* (11th ed.). Pearson Education.
- Horowitz, P., & Hill, W. (2015). *The art of electronics* (3rd ed.). Cambridge University Press.
- Mehta, V. K., & Mehta, R. (2014). *Principles of electronics* (11th ed.). S. Chand & Company.
- Neso Academy, *Zener diode—Video lecture* [Video]. YouTube. https://www.youtube.com/watch?v=6xGCOrPBL4s

3.10 ANSWER THE FOLLOWING QUESTIONS

1. Why is a Zener diode always operated in reverse bias for voltage regulation?
2. What is Zener breakdown, and how is it different from avalanche breakdown?
3. Why does the voltage across a Zener diode remain nearly constant in the breakdown region?
4. What is the role of the series resistor in a Zener voltage regulator circuit?
5. What will happen if the series resistor value is too small or too large?
6. Why does the Zener diode behave like a normal diode in forward bias?
7. What is the significance of the knee (breakdown) voltage in the *V–I* characteristics?
8. How does the load current affect the performance of a Zener voltage regulator?
9. Why must the input voltage always be greater than the Zener voltage for proper regulation?
10. How does temperature affect the Zener voltage and performance of the regulator?

****

EXPERIMENT NO. 4
BJT Common Emitter Characteristics and Current Gain

LEARNING OBJECTIVES OF THE EXPERIMENT

After performing this experiment, you will be able to:

- plot and interpret the input characteristics (I_B vs V_{BE}) of an NPN BJT in CE configuration.
- plot and interpret the output characteristics (I_C vs V_{CE}) for multiple base current values.
- identify the active, saturation, and cut-off regions from the output characteristic curves.
- calculate the DC current gain $\beta = \frac{I_C}{I_B}$ and the AC current gain $\beta' = \frac{\Delta I_C}{\Delta I_B}$.

4.1 AIM

To study the input and output characteristics of a Bipolar Junction Transistor (BJT) in the Common Emitter (CE) mode and determine the current gain.

4.2 APPARATUS REQUIRED

- NPN transistor**:** e.g., BC107 or BC547
- Resistors**:** As required for biasing circuits
- Two variable DC power supplies**:** 0–30 V
- Two digital multimeters**:** For voltage and current measurements
- Breadboard and connecting wires

Alternatively, a Transistor Characteristic Trainer Kit may be used (Figure 4.1).

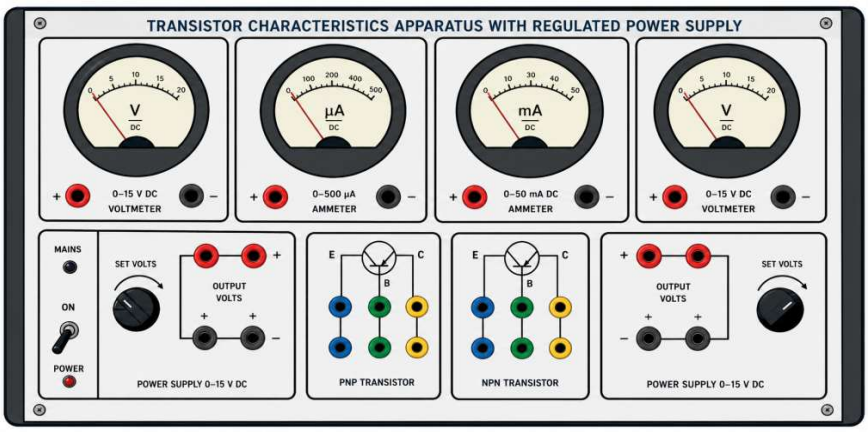


Figure 4.1*:* Transistor Characteristic Trainer Kit

4.3 THEORY

Transistors are semiconductor devices widely used for the amplification and switching of electronic signals. The behaviour of a BJT is analysed through its characteristic curves, broadly classified into static characteristics (measured under DC conditions) and dynamic characteristics (measured under AC signal conditions).

Static Characteristics

(a) Input Characteristics

The input characteristics show the variation of base current I_B with base-emitter voltage V_{BE}, while the collector-emitter voltage V_{CE} is held constant. These curves resemble the forward-bias characteristic of a p-n junction diode and provide insight into the input impedance of the transistor.

(b) Output Characteristics

The output characteristics show the variation of collector current I_C with collector-emitter voltage V_{CE}, for a fixed base current I_B. These curves define three operating regions: the active region (normal amplification), the saturation region (transistor fully ON), and the cut-off region (transistor fully OFF).

Current Gain

(a) DC Current Gain (β or h_{fe})

The DC current gain is defined as the ratio of the collector current to the base current at a fixed operating point:

$$\beta = \frac{I_C}{I_B} \text{ (at constant } V_{CE}) \qquad (4.1)$$

The value of β typically lies in the range 20 to 500, depending on the transistor type.

(b) Small-Signal (AC) Current Gain (β′or h_{fe})

The AC current gain is defined as the ratio of a small change in collector current to the corresponding small change in base current, at constant V_{CE}:

$$\beta' = \frac{\Delta I_C}{\Delta I_B} \text{ (at constant } V_{CE}) \qquad (4.2)$$

This parameter is determined graphically from the slope of the output characteristic curves and is important for small-signal amplifier analysis.

4.4 CIRCUIT DIAGRAMS

Before connecting the circuit, identify the Base (B), Emitter (E), and Collector (C) pins of the transistor from the datasheet.

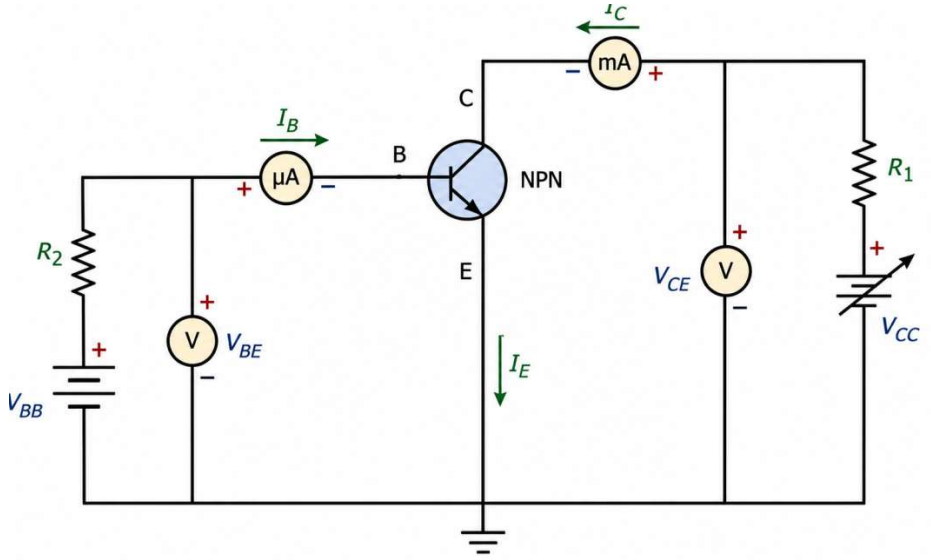


Figure 4.2: CE Circuit for NPN Transistor Characteristics

4.5 PROCEDURE

Input Characteristics ($\mathbf{I_B}$ vs. $\mathbf{V_{BE}}$)

1. Connect**:** Assemble the circuit as shown in Figure 4.2.
2. Set V_{CE}**:** Adjust V_{CC} until V_{CE} = 1 V as measured by the voltmeter.
3. Vary V_{BB}**:** Starting from 0 V, gradually increase V_{BB} in steps of 0.1 V.
4. Record**:** At each step, record V_{BE} and the corresponding I_B. Enter readings in Table 1.
5. Repeat**:** Set V_{CE} = 5 V and repeat steps 3–4 to obtain a second characteristic curve.

Output Characteristics ($\mathbf{I_C}$ vs. $\mathbf{V_{CE}}$)

1. Set I_B:Adjust V_{BB} until I_B = 10 μA.
2. Vary V_{CC}**:** Starting from 0 V, gradually increase V_{CC} in steps of 0.5 V.
3. Record**:** At each step, record V_{CE} and the corresponding I_C. Enter readings in Table 2.
4. Repeat**:** Repeat steps 1–3 of this sub-section for I_B = 20 μA and I_B = 30 μA.

4.6 OBSERVATIONS

Table 1: Input Characteristics

Transistor type: NPN (e.g., BC107) | V_{CE} = 1 V and V_{CE} = 5 V

Sl. No.	V_{CE} = 1 V (Constant)		V_{CE} = 5 V (Constant)	
	V_{BE} (V)	I_B (μA)	V_{BE} (V)	I_B (μA)
1				
2				

3				
4				
5				
6				
7				
8				

Table 2: Output Characteristics

Transistor type: NPN (e.g., BC107) | I_B = 10, 20, 30 µA

Sl. No.	I_B (µA) = 10 µA		I_B (µA) = 20 µA		I_B (µA) = 20 µA	
	V_{CE} (V)	I_C (mA)	V_{CE} (V)	I_C (mA)	V_{CE} (V)	I_C (mA)
1						
2						
3						
4						
5						
6						
7						
8						

4.7 PLOTTING OF GRAPHS

After recording observations, plot the following graphs on graph paper. The expected shapes are shown in Figures 4.3 and 4.4 for reference.

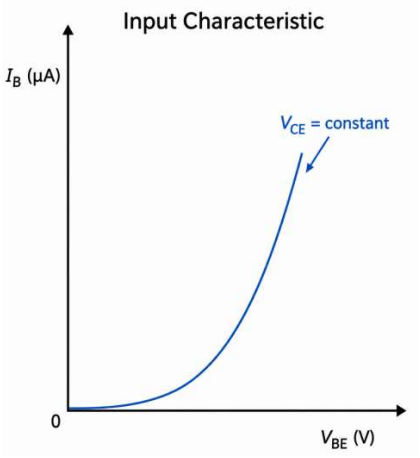


Figure 4.3a*:* Input Characteristics(I_B vs.V_{BE})

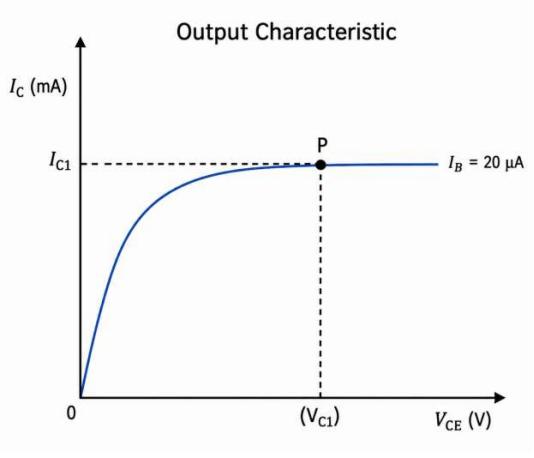


Figure 4.3b*:* Output Characteristics — Family of Curves (I_C vs.V_{CE})

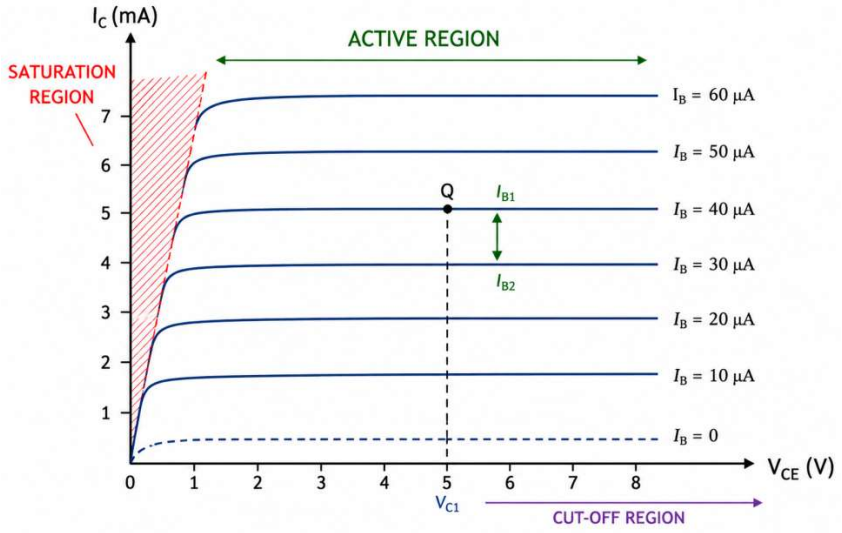


Figure 4.4: CE Output Characteristics Showing Active, Saturation, and Cut-off Regions

4.8 CALCULATION OF CURRENT GAIN

DC Current Gain (β)

1. From the output characteristics (Figure 4.5):select a point P in the active region.
2. Read the values of I_C and V_{CE} at point P and identify the corresponding I_B (the curve on which P lies).
3. Convert both currents to the same unit (amperes) and calculate:

$$\beta = \frac{I_C}{I_B} \text{(at the chosen } V_{CE}) \qquad (4.3)$$

AC Current Gain (β')

1. Select an operating point Qon the output characteristic graph (Figure 4.5) at a constant $V_{CE} = V_{CE0}$
2. Identify two adjacent output curves corresponding to base currents I_{B1} and I_{B2}. Read the corresponding collector currents $I_{C1}$and I_{C2} at the same V_{CE0}
3. Calculate the changes:

$$\Delta I_B = I_{B2} - I_{B1}$$

$$\Delta I_C = I_{C2} - I_{C1}$$

4. Calculate the AC current gain:

$$\beta' = \frac{\Delta I_C}{\Delta I_B} \text{(at constant } V_{CE}) \qquad (4.4)$$

4.9 RESULT

Experimental Results

DC current gain: $\beta = \frac{I_c}{I_B} =$ _____

AC current gain: $\beta' = \frac{\Delta I_c}{\Delta I_B} =$ _____

The transistor was confirmed to operate in three distinct regions: active, saturation, and cut-off.

4.10 PRECAUTIONS

1. Transistor pin identification**:** Always verify the Base (B), Emitter (E), and Collector (C) pin assignments from the transistor datasheet before making connections.
2. Do not exceed rated limits**:** Ensure the supply voltages and currents do not exceed the maximum ratings ($V_{CE,max}$, $I_{C,max}$) specified in the datasheet.
3. Gradual voltage increase**:** Always increase $V_{BE}$and V_{CE} slowly and in small steps to avoid damaging the transistor.
4. Consistent units**:** When computing β, convert I_B from μA to mA (or both to amperes) before dividing.
5. Stable I_B during output characteristic sweep:Monitor and maintain I_B at the target value throughout the V_{CE} sweep; I_B can drift as V_{CE} changes.

4.11 REFERENCES

- Boylestad, R. L., & Nashelsky, L. (2013). *Electronic devices and circuit theory* (11th ed.). Pearson Education.
- Mehta, V. K., & Mehta, R. (2014). *Principles of electronics* (11th ed.). S. Chand & Company.
- Zbar, P. B., Malvino, A. P., & Miller, M. A. (1994). *Basic electronics: A text-lab manual* (7th ed.). Glencoe/McGraw-Hill.
- IIT Kharagpur Virtual Lab. (n.d.). *Common emitter characteristics*. https://be-iitkgp.vlabs.ac.in/exp/common-emitter-characteristics/

4.12 ANSWER THE FOLLOWING QUESTIONS

1. Why is the common emitter (CE) configuration widely used for amplification?
2. Explain the difference between input characteristics and output characteristics of a BJT in CE mode.
3. Why do the input characteristics (I_B vs V_{BE}) resemble that of a PN junction diode?
4. What are the three operating regions of a transistor in CE configuration, and how are they identified from the graph?
5. Why is the collector current IC almost independent of VCE in the active region?
6. What is the physical significance of DC current gain (β)?
7. How is AC current gain (β') different from DC current gain?
8. Why must VCE be kept constant while plotting input characteristics?

9. Why is it necessary to maintain constant base current IB while plotting output characteristics?
10. What will happen if the transistor operates in saturation or cut-off region instead of active region?

****

EXPERIMENT NO. 5
Design and Study of a Class-A Transistor Amplifier

LEARNING OBJECTIVES OF THE EXPERIMENT

After performing the experiment, you will be able to:

- design a Class-A common-emitter transistor amplifier from given specifications (V_{CC}, I_C, β).
- calculate component values for R_C, R_E, R_1, R_2, C_1, C_2, C_E.
- measure the voltage gain $A_v = \frac{V_o}{V_i}$ using a CRO and function generator.
- observe the 180° phase inversion characteristic of the CE configuration.

5.1 AIM

To design a Class-A amplifier using a transistor.

5.2 APPARATUS REQUIRED

- NPN Transistor**:** e.g., BC547 or BC107
- Resistors**:** 1 kΩ, 10 kΩ, 100 kΩ (assorted, for biasing and load)
- Capacitors**:** C_1 = 10 µF (input coupling), C_2 = 10 µF (output coupling), C_E = 100 µF (emitter bypass)
- DC Power Supply**:** 12 V regulated
- Function Generator**:** Audio frequency, sinusoidal output
- Dual-trace Cathode Ray Oscilloscope (CRO**):** To observe input and output waveforms simultaneously
- Breadboard and Connecting Wires
- Digital Multimeter

5.3 THEORY

A Class-A amplifier is one in which the transistor conducts for the entire 360° of the input signal cycle. The transistor is biased at a quiescent operating point (Q-point**)** in the middle of its active region, ensuring that both positive and negative half-cycles of the input are amplified without clipping. This results in faithful (linear) amplification, but at the cost of relatively low efficiency (typically 25–50%), since the transistor dissipates power even with no input signal. When a small AC signal is applied at the base, the base current changes by a small amount, which causes a proportionally larger change in the collector current. This produces an amplified output voltage across the collector resistor R_C. In the CE configuration, the output signal is 180° out of phase with the input signal. The voltage gain is defined as:

$$A_v = \frac{V_{out}}{V_{in}} \qquad (5.1)$$

5.4 CIRCUIT DESCRIPTION

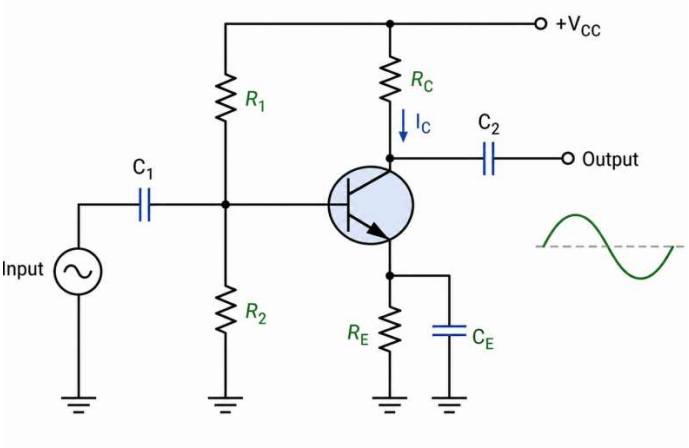


Figure 5.1*:* Single-Stage Class-A CE Transistor Amplifier

The input signal is applied to the base through coupling capacitor C_1, which blocks DC and passes only the AC signal. The amplified output is taken from the collector through coupling capacitor C_2. The voltage divider formed by R_1 and R_2 sets the DC base voltage and biases the transistor in the active region. The emitter resistor R_E provides thermal stability. The emitter bypass capacitor C_E short-circuits R_E for AC signals, thereby maximizing the AC voltage gain.

5.5 CIRCUIT DESIGN

Given: V_{CC} = 12 V, I_C = 2 mA, β ≈ 100 (BC547 NPN transistor)

Collector Resistor (R_c)

For maximum symmetrical output swing, the collector voltage V_C is chosen as half of V_{CC}:

$$V_C = \frac{V_{CC}}{2} = \frac{12}{2} = 6 \text{ V}$$

$$R_C = \frac{(V_{CC} - V_C)}{I_C} = \frac{(12-6)}{2}\text{mA} = 3\ \text{k}\Omega$$

Emitter Resistor (R_E)

The emitter voltage V_E is chosen as approximately 10% of V_{CC} for thermal stability:

$$V_E \approx 0.1 \times V_{CC} = 0.1 \times 12 = 1.2 \text{ V}$$

$$R_E = \frac{V_E}{I_E} \approx \frac{1.2}{2}\text{mA} = 600\ \Omega \rightarrow \text{use } 680\ \Omega \text{ (standard value)}$$

Base Voltage and Biasing Network (R_1, R_2)

For a silicon transistor, V_{BE} ≈ 0.7 V. The required base voltage is:

$$V_B = V_E + V_{BE} = 1.2 + 0.7 = 1.9 \text{ V}$$

The base current is $I_B = \frac{I_C}{\beta} = \frac{2}{100}\,\mathrm{mA}$ = 20 μA. For a stable bias, the divider current should be at least $10 \times I_B$ = 200 μA. Therefore:

$$R_2 = \frac{V_B}{I_2} = \frac{1.9\mathrm{V}}{200\mu\mathrm{A}} = 9.5\ \mathrm{k\Omega} \approx 10\ \mathrm{k\Omega}$$

$$R_1 = \frac{(V_{CC} - V_B)}{I_2} = \frac{(12-1.9)}{200}\mu\mathrm{A} = 50.5\ \mathrm{k\Omega} \rightarrow \text{use } 47\ \mathrm{k\Omega} \text{ or } 56\ \mathrm{k\Omega}$$

Coupling and Bypass Capacitors

Coupling capacitors C_1 and C_2 must have low reactance at the lowest operating frequency f_L . The capacitor value is selected using:

$$X_C = \frac{1}{(2\pi f\ )} \rightarrow \quad \text{for effective coupling, } X_C \leq \frac{R}{10}$$

$$C = \frac{1}{(2\pi f_L R)}$$

Example: For $f_L = 100\mathrm{Hz}$and $R = 10\mathrm{k\Omega}$: $C = \frac{1}{(2\pi\times100\times10000)} \approx 0.16\ \mu\mathrm{F} \rightarrow$ use 0.22 μF (standard)

Capacitor	Typical Range	Purpose
Input Coupling C_1	0.1 μF – 10 μF	Pass input signal; block input DC bias
Output Coupling C_2	1 μF – 100 μF	Pass amplified output; block collector DC
Emitter Bypass C_E	10 μF – 470 μF	Short-circuit R_E for AC; maximize AC gain

Recommended practical values
C_1 = 10 μF, C_2 = 10 μF, CE = 100 μF (suitable for audio range 20 Hz – 20 kHz)

5.6 PROCEDURE

1. Connect**:** Assemble the circuit on the breadboard according to Figure 5.1.
2. Power supply**:** Set the DC power supply to 12 V. Verify the quiescent operating point: V_{CE} should be approximately 6 V.
3. Input signal**:** Apply a small sinusoidal AC signal (20–50 mV peak-to-peak) from the function generator.
4. Observe on CRO**:** Display the input waveform on CRO Channel 1 and the output waveform on CRO Channel 2 simultaneously.
5. Measure**:** Measure the input voltage V_i and output voltage V_o from the CRO.
6. Vary**:** Repeat measurements for at least 5 different input signal amplitudes.
7. Calculate: Compute the voltage gain $A_v = V_o / V_i$ for each reading.
8. Phase: Observe and note the phase relationship between input and output waveforms.

5.7 OBSERVATIONS

Transistor**:** BC547 (NPN) | V_{CC} = 12 V | Quiescent V_{CE} = _____ V

Sl. No.	Input Voltage V_i(mV)	Output Voltage V_o(V)	Voltage Gain $A_v = \frac{V_o}{V_i}$	Phase Shift
1				
2				
3				
4				
5				
6				

5.8 CALCULATIONS

Voltage Gain

For each reading, calculate:

$$Av = \frac{V_o}{V_i}$$

Waveform Observations

Draw and observe the input and output waveforms on the CRO. Confirm that the output waveform is:

- **Amplified:** $V_o >> V_i$
- **Phase-inverted:** The output is shifted by 180° with respect to the input (characteristic of CE configuration)

5.9 RESULT

Experimental Results

The Class-A transistor amplifier was designed and tested successfully.

Measured voltage gain $A_V = \frac{V_o}{V_i} =$ _____

Phase shift observed: 180° (output is inverted relative to input).

5.10 PRECAUTIONS

1. Transistor pin orientation: Always verify Emitter (E), Base (B), and Collector (C) pin assignments from the datasheet before connecting.
2. Supply voltage limit**:** Do not exceed the rated V_{CC} for the transistor. For BC547, $V_{CE_{max}}$= 45V; keep V_{CC} at the designed 12 V.
3. Tight connections**:** Ensure all breadboard connections are firm. Loose connections introduce noise and spurious oscillations.

4. Coupling capacitors**:** Use correctly rated coupling capacitors. Insufficient capacitance causes attenuation at low frequencies.
5. Small input signal**:** Keep the input signal small (20–50 mV) to avoid driving the transistor into saturation or cut-off, which causes distortion.
6. Capacitor polarity**:** Electrolytic capacitors are polarized. Connect the positive terminal toward the higher DC potential side.

5.11 REFERENCES

- Boylestad, R. L., & Nashelsky, L. (2013). *Electronic devices and circuit theory* (11th ed.). Pearson Education.
- Sedra, A. S., & Smith, K. C. (2015). *Microelectronic circuits* (7th ed.). Oxford University Press.
- Amrita Virtual Labs. *CE amplifier simulation*. Amrita Vishwa Vidyapeetham. https://vlab.amrita.edu/?sub=1&brch=282&sim=1510&cnt=1
- Electronics-Lab.com. *Class-A amplifier analysis*. https://www.electronics-lab.com/article/class-a-amplifiers/

5.12 ANSWER THE FOLLOWING QUESTIONS

1. Why is a Class-A amplifier biased at the midpoint of the active region (Q-point)?
2. What is the significance of 360° conduction in a Class-A amplifier?
3. Why does the output signal in a common emitter amplifier show a 180° phase shift?
4. What is the role of the coupling capacitors $C_1$and C_2in the amplifier circuit?
5. Why is an emitter resistor $R_E$used in the circuit?
6. What is the function of the emitter bypass capacitor C_E?
7. How does the voltage divider network $R_1$and R_2stabilize the biasing of the transistor?
8. Why should the input signal amplitude be kept small during the experiment?
9. What happens to the output waveform if the transistor operates in saturation or cut-off region?
10. How is the voltage gain of the amplifier measured using a CRO?

****

EXPERIMENT NO. 6
FET/MOSFET Characteristics and Transconductance

LEARNING OBJECTIVES OF THE EXPERIMENT

After performing the experiment, you will be able to:

- understand the structure and operating principle of JFETs and MOSFETs.
- plot and interpret the drain characteristics (I_D vs V_{DS}) for different gate-to-source voltages.
- plot and interpret the transfer characteristics (I_D vs V_{GS}) at constant V_{DS}.
- determine the transconductance g_m from the slope of the transfer characteristics curve.
- identify the ohmic, saturation, and breakdown regions from the drain characteristics.

6.1 AIM

To study characteristics of a Field Effect Transistor (FET/MOSFET) and determine the transconductance.

6.2 APPARATUS REQUIRED

- FET / MOSFET: N-channel JFET (e.g., BFW10 or 2N3819) or MOSFET (e.g., IRF540)
- DC Power Supplies: Two variable supplies — one for V_{DD} (drain) and one for V_{GG} (gatebias)
- Digital Multimeters: Two units (for voltage and current measurement)
- Milliammeter / Microammeter: To measure drain current I_D
- Breadboard and Connecting Wires

6.3 INTRODUCTION

Field Effect Transistors (FETs), also known as unipolar transistors, are voltage-controlled devices that use an electric field to control current flow rather than carrier injection. Their three terminals are named Source (S), Gate (G), and Drain (D). Figures 6.1(a) and 6.1(b) show the physical appearance and circuit symbol of the JFET, respectively. FETs are classified into two main types: (i) Junction FET (JFET) and (ii) MOSFET/IGFET. JFETs are further sub-classified into n-channel and p-channel types. MOSFETs are sub-classified into Depletion-mode (DE-MOSFET) and Enhancement-mode (E-MOSFET). FETs are widely used in integrated circuits and amplifiers owing to their very high input impedance and compact size. Unlike the Bipolar Junction Transistor (BJT), which is a *current-controlled* device, the FET is a voltage-controlled device: the gate voltage controls the drain current.

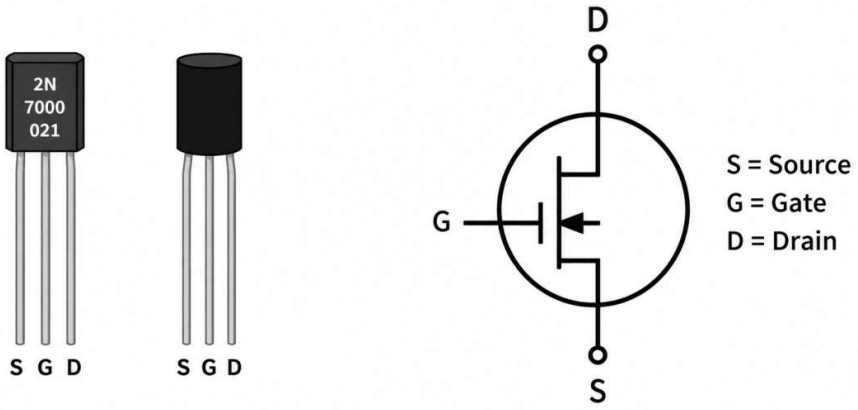


Figure 6.1(a): Physical Appearance of JFET

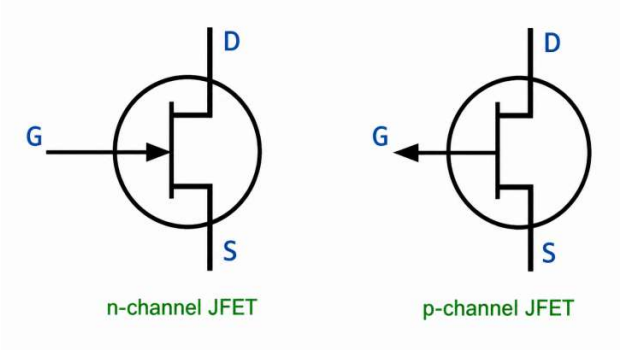


Figure 6.1(b): Circuit Symbol of JFET

In an n-channel JFET, the current carriers are electrons; in a p-channel JFET, they are holes. N-channel devices exhibit greater conductivity than p-channel devices. Depending on the gate voltage, the channel may be enhanced or depleted.

6.3.1 MOSFET

The Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET), also called the Insulated-Gate FET (IGFET), was developed to overcome limitations of the JFET such as moderate input impedance and higher drain resistance. It stands for Metal Oxide Semiconductor Field Effect Transistor. Like the JFET, MOSFETs are available in P-type and N-type variants. The gate is insulated from the channel by a thin oxide layer, allowing both positive and negative gate voltages. A negative gate bias gives depletion-mode operation; a positive gate bias gives enhancement-mode operation. Figures 6.2 and 6.3 show the circuit symbols of N-type and P-type MOSFETs.

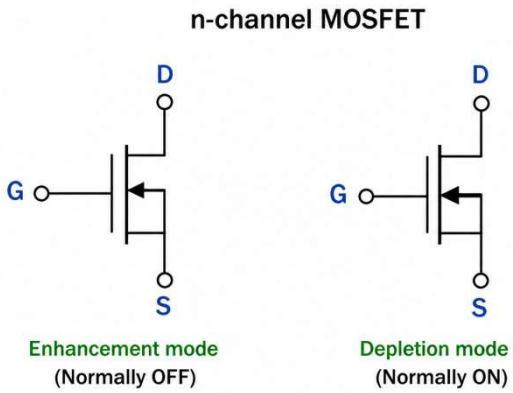


Figure 6.2: N-Channel MOSFET Circuit Symbols

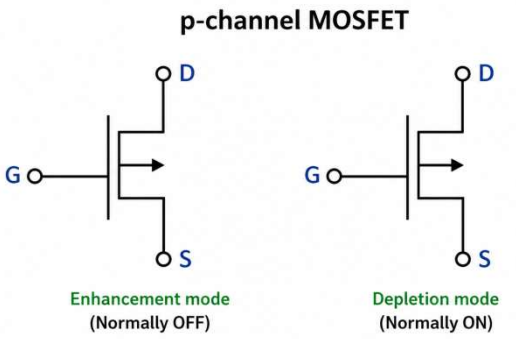


Figure 6.3: P-Channel MOSFET Circuit Symbols

6.4 FET CHARACTERISTICS

Drain Characteristics

- **Saturation (Active) Region:** I_D becomes nearly independent of V_{DS} beyond the pinch-off voltage. This is the normal amplification region.
- **Breakdown Region:** At very high V_{DS}, avalanche breakdown occurs and I_D rises sharply.

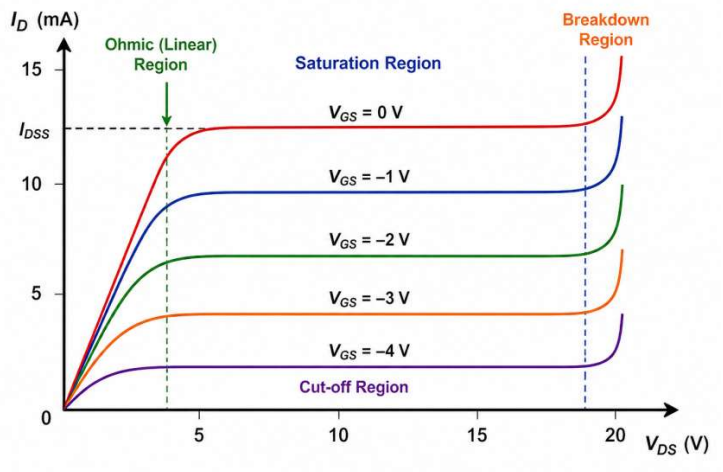


Figure 6.4: Drain Characteristics of N-Channel JFET

Transfer Characteristics

The transfer characteristics show the variation of drain current (I_D) with gate-to-source voltage (V_{GS}), while V_{DS} is kept constant. This curve is used to determine the transconductance.

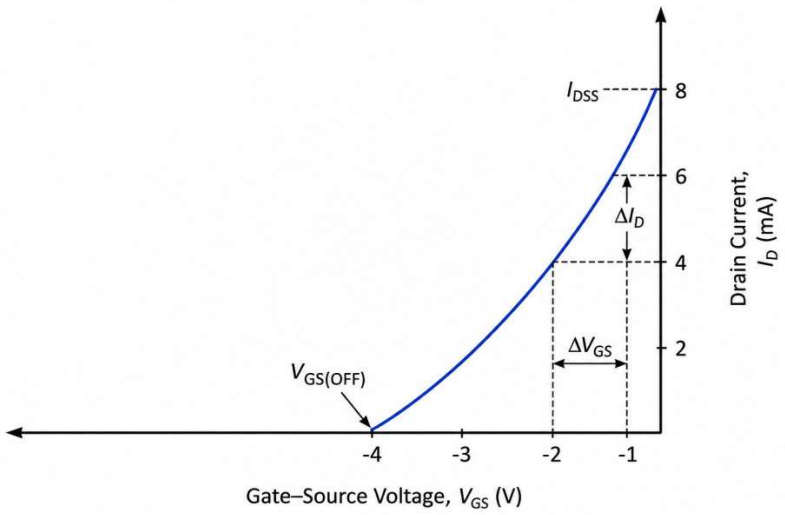


Figure 6.5: Transfer Characteristics of N-Channel JFET

Transconductance (G_m)

Transconductance (g_m) is defined as the ratio of the change in drain current (ΔI_D) to the change in gate-to-source voltage (ΔV_{GS}), at constant V_{DS}:

$$g_m = \frac{\Delta I_D}{\Delta V_{GS}} \text{ at constant } V_{DS}$$

Transconductance is measured in Siemens (S) or $\frac{A}{V}$. It represents the slope of the transfer characteristics curve at the operating point.

6.5 CIRCUIT DIAGRAMS

Circuit for Drain Characteristics

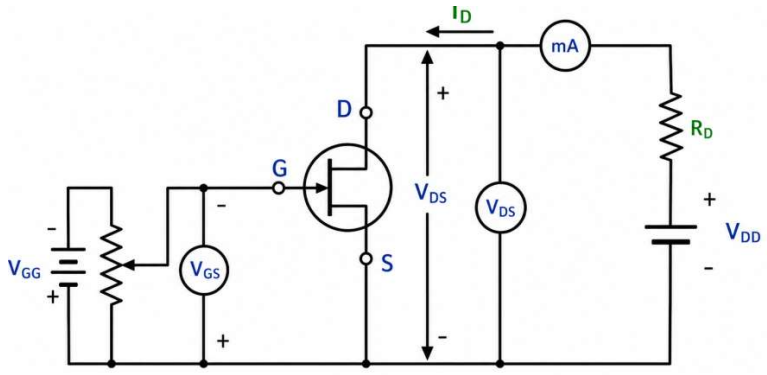


Figure 6.6: Circuit for Determining Drain Characteristics of N-Channel JFET

The gate-to-source voltage V_{GS} is set using the gate supply V_{GG}, while V_{DS} is controlled by the drain supply V_{DD}.

Circuit for Transfer Characteristics

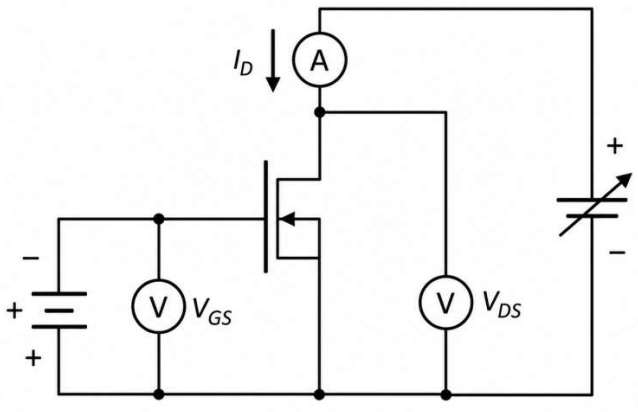


Figure 6.7: Circuit for Determining Transfer Characteristics of FET

Here V_{DS} is held constant and V_{GS} is varied from 0 V to the pinch-off voltage.

6.6 PROCEDURE

Drain Characteristics

1. Circuit assembly**:** Connect the circuit as shown in Figure 6.6.
2. Set V_{GS} = 0 V (verify using voltmeter V_2).
3. Gradually increase V_{DS} from 0 V to 10 V in steps of 1 V.
4. At each step, record the drain current I_D.
5. Repeat for V_{GS} = −1 V, −2 V, and −3 V.
6. Tabulate all readings in Table 1.
7. Plot I_D vs V_{DS} for each V_{GS} value on the same graph.

Transfer Characteristics

1. Keep V_{DS} constant at 5 V.
2. Vary V_{GS} from 0 V towards the pinch-off voltage in steps of 0.5 V.
3. At each step, record the corresponding I_D value.
4. Tabulate the readings in Table 2.
5. Plot I_D (mA) vs V_{GS} (V).

6.7 OBSERVATION TABLES

Table 1: Drain Characteristics

Device: N-Channel JFET | V_{GS} = 0 V, −1 V, −2 V

V_{DS}(V)	I_D (mA)	V_{DS} (V)	I_D (mA)	V_{DS} (V)	I_D (mA)
0		0		0	
1		1		1	
2		2		2	
3		3		3	
4		4		4	
5		5		5	
6		6		6	
7		7		7	
8		8		8	
10		10		10	

TABLE 2: TRANSFER CHARACTERISTICS

Device: N-Channel JFET | V_{DS} = 5 V (constant)

V_{DS} = 5 V (Constant)	V_{GS} (V)	I_D (mA)
5 V	0	
5 V	−0.5	
5 V	−1.0	
5 V	−1.5	
5 V	−2.0	
5 V	−2.5	
5 V	−3.0	

6.8 PLOTTING OF GRAPHS

Drain Characteristics

Plot I_D (mA) vs V_{DS} (V) for each V_{GS} value. The expected family of curves is shown in Figure 6.8.

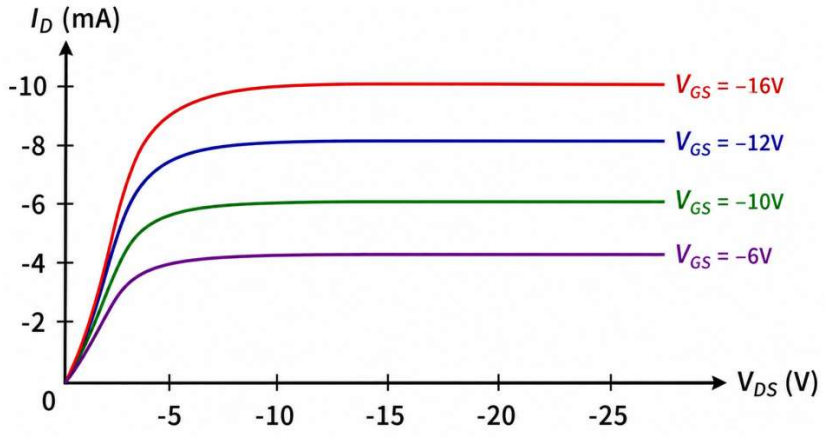


Figure 6.8: Expected Shape of Drain Characteristics (MOSFET)

Transfer Characteristics

Plot I_D (mA) vs V_{GS} (V) at constant V_{DS}. The expected curve is shown in Figure 6.9.

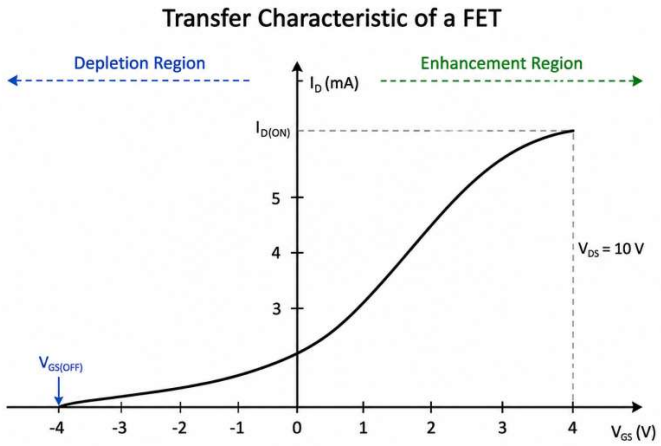


Figure 6.9: Expected Shape of Transfer Characteristics (MOSFET)

6.9 CALCULATION OF TRANSCONDUCTANCE

From the transfer characteristics graph (Figure 6.9), select two operating points in the linear region. For example:

- Point 1: I_{D1} = 6 mA at V_{GS1} = −1 V
- Point 2: I_{D2} = 4 mA at V_{GS2} = −2 V

Applying the definition of transconductance:

$$g_m = \frac{\Delta I_D}{\Delta V_{GS}} = \frac{(6-4)mA}{[(-1)-(-2)]V} = \frac{2mA}{1V} = 2\ \text{mS}$$

Note:
Students should determine g_m from their own experimental transfer characteristic curve. The transconductance may also be read as the slope of the tangent to the transfer curve at the Q-point.

6.10 RESULT

1. The drain and transfer characteristics of the FET/MOSFET were studied and plotted successfully.
2. The transconductance of the device is found to be g_m= _____ mS (to be filled from experimental data).
3. The three operating regions (ohmic, saturation, and breakdown) were identified from the drain characteristics.
4. The drain current decreased with increasing reverse gate-to-source voltage, consistent with n-channel JFET behaviour.

6.11 PRECAUTIONS

1. Connections: All connections must be firm and correct before switching on the power supply.
2. Power off during wiring: Always switch off the power supply while making or modifying connections.
3. Gradual voltage increase: Increase V_{DS} and V_{GS} slowly in small steps.
4. Maximum ratings: Do not exceed the maximum rated V_{DS}, V_{GS}, or I_D for the device.
5. Careful reading: Record all meter readings at each step carefully to minimize error.
6. Gate polarity (JFET): For n-channel JFET, V_{GS} must be zero or negative. A positive V_{GS} will forward-bias the gate junction and may damage the device.

6.12 REFERENCES

- Boylestad, R. L., & Nashelsky, L. (2013). *Electronic devices and circuit theory* (11th ed.). Pearson Education.
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6.13 ANSWER THE FOLLOWING QUESTIONS

1. Why is a FET called a voltage-controlled device, unlike a BJT?
2. What is the physical significance of gate-to-source voltage V_{GS} in controlling the drain current?
3. Explain the difference between JFET and MOSFET in terms of structure and operation.
4. What are the different regions (ohmic, saturation, breakdown) in the drain characteristics of a FET?
5. What is pinch-off voltage, and what happens to the drain current beyond this point?
6. Why does the drain current I_D become almost constant in the saturation region?
7. What is transconductance (g_m), and how is it determined graphically?
8. Why is V_{DS} kept constant while plotting transfer characteristics?
9. Why must the gate of an n-channel JFET be negatively biased?
10. How does increasing negative V_{GS} affect the channel and drain current?

*** *** ***

EXPERIMENT NO. 7
Single-Stage RC Coupled CE Amplifier

LEARNING OBJECTIVES OF THE EXPERIMENT

After performing this experiment, you will be able to:

- design a single-stage RC coupled Common Emitter (CE) amplifier from given specifications.
- measure the mid-band voltage gain A_v.
- plot the frequency response (gain in dB vs. log frequency) and determine the bandwidth BW = $f_H - f_L$
- observe and explain the 180° phase inversion characteristic of the CE configuration.
- understand the role of coupling and bypass capacitors on frequency response.

7.1 AIM

To design and study a single-stage RC coupled amplifier and determine voltage gain and bandwidth.

7.2 APPARATUS REQUIRED

Transistor	NPN Silicon Transistor (e.g., BC547 or 2N2222)
Resistors	R_1, R_2 (voltage-divider biasing), Rc (collector load), R_E (emitter stability)
Capacitors	C_{in}, C_{out}coupling, 10 µF each), C_E (emitter bypass, 100 µF)
DC Power Supply	12 V regulated
Function Generator	Audio-frequency sinusoidal, 20 Hz – 1 MHz
Oscilloscope	Dual trace, for simultaneous input/output observation
Breadboard	Solderless, with connecting wires
Multimeter	For DC bias-point verification

7.3 CIRCUIT DIAGRAM AND DESCRIPTION

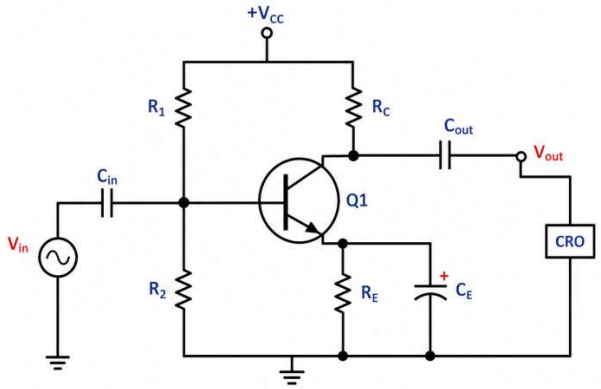


Figure 7.1: Single-Stage RC Coupled CE Amplifier

An RC coupled amplifier uses a resistor-capacitor network to connect stages. In this single-stage design, the transistor operates as a Common Emitter (CE) amplifier. The voltage-divider formed by R_1 and R_2 establishes a stable quiescent operating point (Q-point) for the transistor. The emitter resistor R_E provides thermal stability against variations in transistor parameters. The emitter bypass capacitor C_E short-circuits R_E for AC signals, thereby maximizing the AC voltage gain. The coupling capacitors C_{in} and C_{out} connect the signal source and load, respectively, passing AC while blocking DC so that the bias conditions of the stage are undisturbed. For optimum output swing, the quiescent collector-emitter voltage V_{CE} is typically set to approximately 50% of V_{CC}.

7.4 THEORY

Frequency Response

The frequency response of an RC coupled amplifier is a plot of voltage gain against frequency, as illustrated in Figure 7.2. The gain is stable over a broad mid-frequency range but falls at both the low and high ends.

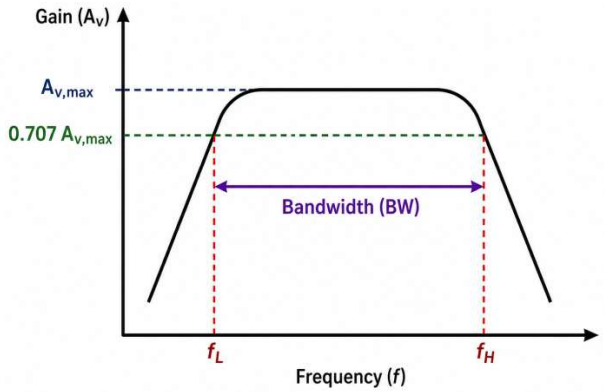


Figure 7.2: Frequency Response Curve of an RC Coupled Amplifier

- **Low-frequency roll-off:** At low frequencies, the coupling capacitors C_{in} and C_{out} present high reactance, attenuating the signal. Simultaneously, the bypass capacitor C_E also has high reactance and fails to shunt R_E

adequately, introducing negative feedback that further reduces the voltage gain.

- **High-frequency roll-off:** At high frequencies, the internal parasitic capacitances of the transistor (base-emitter junction capacitance and the Miller capacitance) present low reactance paths that divert signal current, reducing the current gain β and hence the voltage gain.
- **Mid-band (flat) region:** In this range, the coupling and bypass capacitors act as short circuits for AC signals. The gain reaches its maximum value and remains approximately constant.

Key Definitions

- **Lower cut-off frequency f_L:** The frequency below which the gain falls to $\frac{1}{\sqrt{2}(-3dB)}$of its mid-band maximum.
- **Upper cut-off frequency f_H:** The frequency above which the gain falls to $\frac{1}{\sqrt{2}(-3dB)}$ of its mid-band maximum.
- **Bandwidth (BW):** BW =$f_H - f_L$

7.5 CIRCUIT DESIGN

Given: V_{CC} = 12 V, I_C = 2 mA, β ≈ 200 (BC547 NPN transistor)

Collector Resistor (Rc)

For maximum symmetrical output swing, approximately 40% of V_{CC} is dropped across R_C:

V_{RC} = 0.4 × 12 = 4.8 V

$R_C = \frac{V_{RC}}{I_C} = \frac{4.8\ V}{2\ mA}$ = 2.4 kΩ → use 2.2 kΩ (standard)

Emitter Resistor (RE)

To improve thermal stability, about 10% of V_{CC} is dropped across R_E:

$$V_E = 0.1 \times 12 = 1.2\ V$$

$$R_E = \frac{V_E}{I_E} \approx \frac{1.2\ V}{2\ mA} = 600\ \Omega \rightarrow \text{use } 560\ \Omega \text{ or } 680\ \Omega \text{ (standard)}$$

Voltage Divider Bias Network (R_1, R_2)

For a silicon transistor, V_{BE} ≈ 0.7 V, so the required base voltage is:

$$V_B = V_E + V_{BE} = 1.2 + 0.7 = 1.9\ V$$

Base current: $I_B = \frac{I_C}{\beta} = \frac{2mA}{200} = 10\ \mu A$. For stable biasing, the divider current is set to at least $10 \times I_B$

$$I_2 \geq 10\, I_B = 100\ \mu A$$

$$R_2 = \frac{V_B}{I_2} = \frac{1.9V}{100\ \mu A} = 19\ k\Omega \rightarrow \text{use } 18\ k\Omega \text{ or } 22\ k\Omega$$

$$R_1 = \frac{(V_{CC} - V_B)}{(I_2 + I_B)} = \frac{10.1\ V}{110\ \mu A} \approx 91.8\ k\Omega \rightarrow \text{use } 100\ k\Omega$$

Coupling and Bypass Capacitors

The coupling capacitors C_{in} and C_{out} (typically 10 µF) block DC while passing AC. The emitter bypass capacitor C_E (typically 47–100 µF) short-circuits R_E for AC, maximising voltage gain. Values are chosen to ensure low reactance at the lowest operating frequency (~ 20 Hz).

Summary of Design Values

R_1	100 kΩ	Upper voltage-divider bias resistor
R_2	22 kΩ	Lower voltage-divider bias resistor
R_C	2.2 kΩ	Collector load resistor
R_E	560 Ω	Emitter resistor (thermal stability)
C_{in},C_{out}	10 µF each	Input / output coupling capacitors
C_E	100 µF	Emitter bypass capacitor

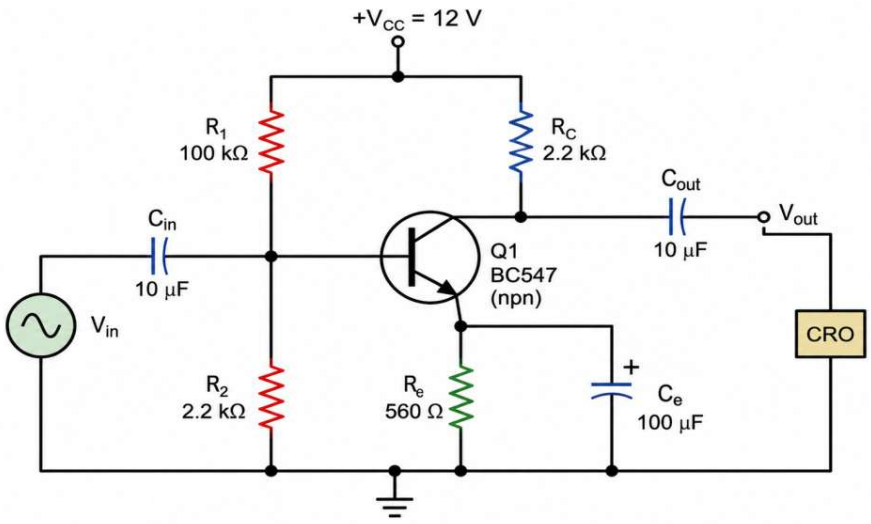


Figure 7.3: Single-Stage BC547 CE Amplifier with Specified Component Values

7.6 PROCEDURE

1. Circuit assembly: Construct the circuit on a breadboard as per the design (Figure 7.3).
2. DC bias verification: Apply V_{CC} = 12 V. Measure the DC voltages at the base, emitter, and collector with a multimeter to confirm the transistor is in the active region (V_{CE} ≈ 6 V, V_{BE} ≈ 0.7 V).
3. Input signal: Apply a sinusoidal signal (e.g., 20 mV peak-to-peak) from the function generator at a mid-band frequency (e.g., 1 kHz).

4. Waveform observation: Observe the input and output waveforms simultaneously on the dual-trace oscilloscope. Confirm that the output is 180° out of phase with the input.
5. Frequency sweep: Vary the input frequency from 20 Hz up to 1 MHz, keeping the input amplitude constant at 20 mV. Record V_{out} at each step.
6. Data recording: For each frequency, calculate $A_v = \frac{V_{out}}{V_{in}}$ and the gain in dB. Enter all values in Table 1.
7. Graph: Plot Gain (dB) on the Y-axis against Frequency on the X-axis (log scale). Identify f_L, f_H and the bandwidth BW = $f_H - f_L$.

7.7 CALCULATIONS

Voltage Gain

$$\mathrm{A_v} = \frac{\mathrm{V_{out}}}{\mathrm{V_{in}}}$$

Gain in Decibels

$$\mathrm{A_v(dB)} = 20.\log_{10}\left(\frac{\mathrm{V_{out}}}{\mathrm{V_{in}}}\right)$$

Bandwidth

$$\mathbf{BW = f_H - f_L}$$

where f_L and f_H are the lower and upper cut-off frequencies, defined as the points at which the gain falls by 3 dB from the mid-band maximum.

7.8 OBSERVATIONS

Table 1: Frequency Response Data

Device: BC547 NPN | $\mathrm{V_{CC}} = 12\mathrm{V}$ | $\mathrm{V_{in}} = 20\mathrm{mV}$(constant)

Frequency (Hz)	$\mathrm{V_{in}}$ (mV)	$\mathrm{V_{out}}$ (mV)	Voltage Gain $\mathrm{A_v} = \frac{\mathrm{V_{out}}}{\mathrm{V_{in}}}$	Gain (dB) = $20\log_{10}(\mathrm{A_v})$
20	20			
40	20			
100	20			
500	20			
1 k	20			
2 k	20			
5 k	20			
10 k	20			
20 k	20			
50 k	20			

100 k	20			
200 k	20			
500 k	20			
1 M	20			

Graph: Frequency Response Curve

Plot Gain (dB) vs. Frequency (log scale) using data from Table 1. The expected shape is shown in Figure 7.2: a flat mid-band region flanked by roll-offs at low and high frequencies. From the curve, read off f_L and $f_H$at the −3 dB points and calculate the bandwidth.

7.9 RESULT AND DISCUSSION

Observed Results

1. The mid-band voltage gain A_v was measured to be approximately _____ (to be filled from experimental data).
2. The lower cut-off frequency f_L= _____ Hz.
3. The upper cut-off frequency f_H= _____ Hz.
4. The bandwidth BW = $f_H - f_L$ = _____ Hz.
5. The output waveform was confirmed to be 180° out of phase with the input, consistent with the CE configuration.

Phase Reversal

A 180° phase shift between input and output is a fundamental property of the Common Emitter configuration. When the input voltage increases, the base current increases, causing a larger collector current and a greater voltage drop across R_C. This reduces the collector voltage, producing phase inversion at the output.

Effect of Coupling and Bypass Capacitors

The coupling capacitors C_{in} and C_{out}cause the low-frequency roll-off due to their increasing reactance at low frequencies. The bypass capacitor C_E is critical for maintaining high gain at mid and high frequencies. Without C_E, the AC signal experiences the full resistance R_E, which introduces negative feedback and significantly reduces the voltage gain.

Expected Performance

Summary of Expected Results

Mid-band Voltage Gain (A_v): Approximately 100 to 200 (depending on exact component values).
Phase: 180° phase inversion (inverting amplifier).
Flat bandwidth: Approximately 100 Hz to 100 kHz

7.10 PRECAUTIONS

1. Transistor and capacitor polarity: Electrolytic capacitors and the BJT are polarity-sensitive. Verify the emitter, base, and collector connections against the BC547 datasheet before powering on.
2. Supply voltage limits: Do not exceed the maximum collector-emitter voltage $V_{CE(max)}$for the transistor. V_{CC} = 12 V is within the safe operating range for BC547.
3. Input signal amplitude: Keep the input signal small (20–50 mV peak-to-peak). Excessive amplitude drives the transistor into saturation or cut-off, clipping the output waveform.
4. Common ground: Connect the grounds of the function generator, oscilloscope, and DC power supply to a single common point to prevent ground loops and noise.
5. Tight connections: On a breadboard, ensure all component leads are firmly inserted. Loose connections are the primary cause of spurious oscillations in CE amplifiers.

Conclusion

The experiment successfully demonstrates the design and characteristics of a single-stage RC coupled Common Emitter amplifier. The circuit provides significant voltage gain in the mid-band frequency range, where coupling and bypass capacitors act as short circuits for AC signals. The gain rolls off at low frequencies due to the increasing reactance of the coupling capacitors and at high frequencies due to the internal parasitic capacitances of the transistor. The 180° phase inversion between input and output, a fundamental property of the CE configuration, was confirmed experimentally. The bandwidth, defined by the 3 dB cut-off frequencies f_L and f_H, characterizes the effective frequency range of the amplifier.

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7.12 ANSWER THE FOLLOWING QUESTIONS

1. Why is RC coupling preferred in multistage amplifiers?
2. What is the significance of the mid-band region in the frequency response of an amplifier?
3. Why does the gain decrease at low frequencies in an RC coupled amplifier?
4. Why does the gain decrease at high frequencies?
5. What is the physical meaning of the −3 dB cut-off frequency?
6. How is bandwidth defined for an amplifier?
7. Why is the emitter bypass capacitor $C_E$important for voltage gain?
8. What is the role of coupling capacitors $C_{in}$and C_{out}?
9. Why does a CE amplifier produce a 180° phase shift between input and output?
10. What will happen to the output if the input signal amplitude is too large?

****

EXPERIMENT NO. 8
Determination of Wavelength of a Laser Source

LEARNING OBJECTIVES OF THE EXPERIMENT

After performing this experiment, the learner will be able to:

- determine the wavelength of a laser source by measuring interference fringe width (Young's Double Slit method).
- determine the wavelength of a laser source by measuring the central diffraction maximum width (Single Slit method).
- understand the physical principles of constructive/destructive interference and single-slit diffraction.
- compare the wavelength values obtained from both methods.

8.1 AIM

To determine the wavelength of a given laser source using (a) Young's Double Slit Experiment and (b) the Single Slit Diffraction method.

PART A — Young's double slit experiment (YDSE)
PART B — Single slit diffraction method

8.2 APPARATUS REQUIRED

PART A:

- Laser source (He-Ne or Diode Laser)
- Double slit slide (known slit separation d)
- Optical bench or steady flat surface
- Screen (white card or paper)
- Measuring tape and Vernier callipers (or a fine ruler)

PART B:

- Laser source (same as Part A)
- Single slit slide (known slit width a)
- Optical bench and screen
- Measuring scale / ruler

8.3 THEORY

PART A:

When coherent light from a laser passes through two closely spaced slits, the waves emerging from each slit overlap and interfere. This creates an interference pattern of

alternating bright (constructive) and dark (destructive) fringes on a distant screen. The wavelength λ of the light is calculated from the fringe width using:

$$\lambda = \frac{\beta\, d}{D}$$

Symbol	Definition
λ	The distance between two successive points in a wave that are in the same phase.
β	measures the phase change of a wave per unit distance.
d	The width of the single slit through which the laser light passes.
D	Distance between the single slit and the screen.

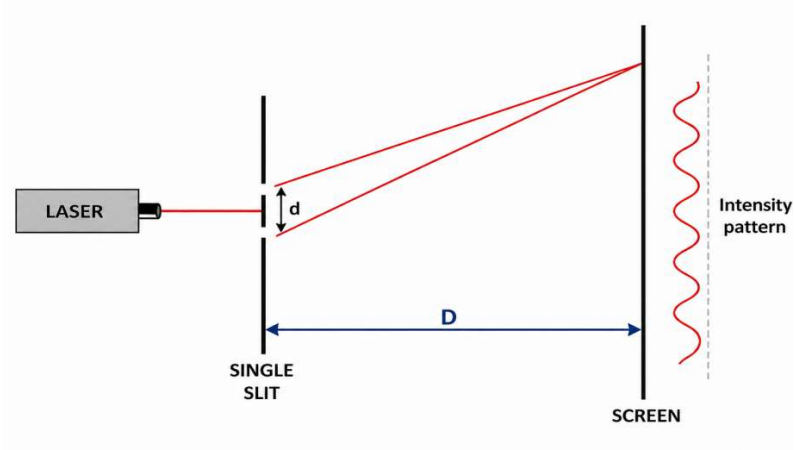


Figure 8.1: Intensity Pattern Produced by a Double slit (interference)

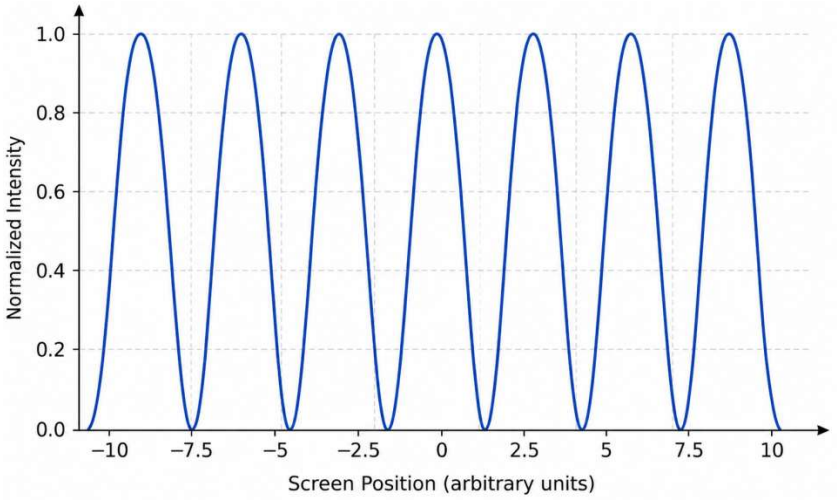


Figure 8.2: Interference Fringe Pattern — Young's Double Slit

PART B:

When laser light passes through a single narrow slit of width *a*, the wave diffracts and creates a diffraction pattern on a screen: a broad, bright central maximum flanked by

progressively narrower and dimmer secondary maxima, separated by dark minima. The condition for the m^{th}dark minimum is:

$$\mathrm{a}.\sin\theta \;=\; \mathrm{m}\lambda\;(\mathrm{m}\;=\pm1,\pm2,\pm3,\ldots,)$$

For small angles (sin θ ≈ tan θ = $\frac{y}{D}$), and taking the first minimum (m = 1):

$$\lambda \;=\frac{\mathrm{a}.\mathrm{y}}{\mathrm{D}}$$

Symbol	Definition
λ	The distance between two successive points in a wave that are in the same phase.
a	The width of the single slit through which the laser passes.
y	The perpendicular distance of the point from the central axis (central maximum) of the diffraction pattern.
D	The distance between the single slit and the screen on which the diffraction pattern is observed.

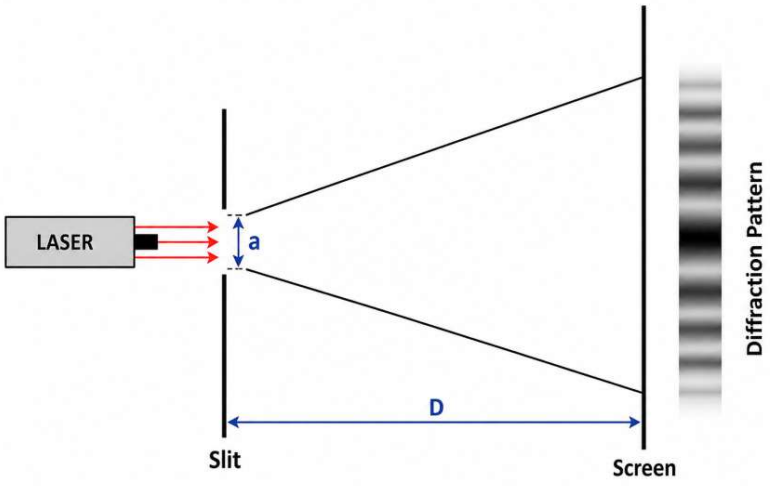


Figure 8.3: Diffraction pattern observed on a screen due to a single slit

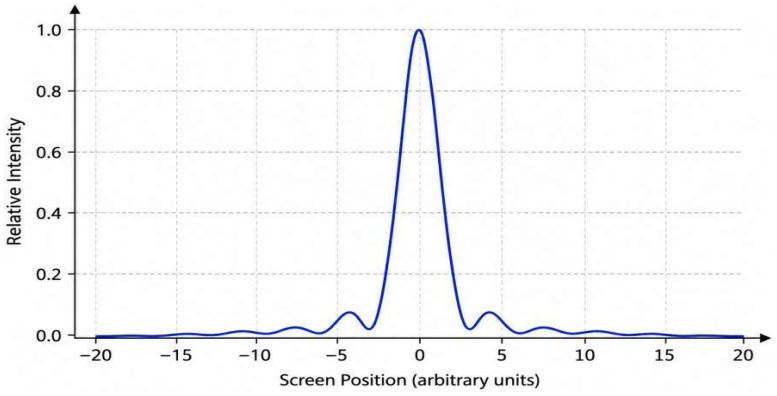


Figure 8.4: Single Slit Diffraction Pattern on Screen

8.4 PROCEDURE

PART A:

1. **Alignment:** Align the laser source so the beam strikes the double slit perpendicularly, with the slit plane vertical.
2. **Setup:** Place the screen at a distance D (typically 1–2 m) from the slits. Measure D accurately with a measuring tape.
3. **Observe pattern:** Switch on the laser and observe the interference fringe pattern on the screen. Adjust the setup until the fringes are sharp and well-separated.
4. **Mark fringes:** Mark the centers of n consecutive bright fringes (e.g., n = 5 or 10) on the screen to reduce measurement error.
5. **Measure:** Measure the total distance W across the n marked fringes.
6. **Calculate fringe width:** $\beta = \frac{W}{n}$
7. **Calculate wavelength:** $\lambda = \frac{\beta\, d}{D}$

PART B:

1. **Setup:** Replace the double slit with the single slit of known width a. Align the laser beam to pass through the slit.
2. **Distance:** Measure the distance D from the single slit to the screen accurately.
3. **Observe pattern:** Observe the single-slit diffraction pattern on the screen. Identify the central bright maximum and the first dark minima on either side.
4. **Measure width:** Measure the total width of the central maximum, i.e., the distance between the first dark fringe on the left and the first dark fringe on the right. Let this total width be 2y.
5. **Calculate half-width:** Compute $y = y = \frac{(2y)}{2}$.
6. **Calculate wavelength:** $\lambda = \frac{a.y}{D}$

8.5 OBSERVATIONS

Table 1: Young's Double Slit Experiment (YDSE)

Given: d = _____ mm, D = _____ mm

Sl. No.	No. of Fringes (n)	Total distance W across n fringes (mm)	Fringe width β = $\frac{W}{n}$(mm)	Wavelength λ (nm)
1				
2				
3				

4				
5				

Table 2: Single Slit Diffraction

Given: a = _____ mm, D = _____ mm

Sl. No.	Order n	Half-width y (mm)	Slit width a (mm)	Wavelength λ (nm)
1				
2				
3				
4				
5				

8.6 RESULT

(a) Young's Double Slit Method: Wavelength of the given laser source

$$\lambda = _____ \, nm$$

(b) Single Slit Diffraction Method: Wavelength of the given laser source

$$\lambda = _____ \, nm$$

Mean wavelength: $\lambda_{mean} = _____ \, nm$

8.7 PRECAUTIONS

1. Laser safety: Never look directly into the laser beam or at its specular reflection from any surface. Even low-power laser radiation can cause permanent eye injury.
2. Alignment: Ensure the laser, slit, and screen are co-axially aligned and the beam is perpendicular to the slit plane. Misalignment distorts the fringe pattern.
3. Use large D: Set the screen at the maximum practicable distance to increase fringe separation, thereby reducing the percentage error in measurement.
4. Multiple readings: Measure across several fringes $(n \geq 5)$ and divide by n to obtain the fringe width β. This significantly reduces random measurement error.
5. Stable setup: Secure all components on the optical bench. Vibrations cause the fringe pattern to shift and blur, making measurement unreliable.

8.8 REFERENCES

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8.9 ANSWER THE FOLLOWING QUESTIONS

1. Why is a laser source preferred in Young's Double Slit Experiment instead of ordinary light?
2. What is meant by coherent sources, and why are they necessary for interference?
3. What is fringe width (β), and how is it experimentally determined?
4. Why is it better to measure the distance across multiple fringes instead of a single fringe?
5. How does the fringe width change if the distance between slits (d) is increased?
6. How does the fringe width change if the screen distance (D) is increased?
7. What is the physical origin of the central bright maximum in single-slit diffraction?
8. Why is the central maximum wider than the secondary maxima in diffraction?
9. What is the condition for dark fringes (minima) in single-slit diffraction?
10. Why may the wavelength values obtain from YDSE, and single-slit methods differ slightly?

****

EXPERIMENT NO. 9
Input and Output Characteristics of a Transistor

LEARNING OBJECTIVES OF THE EXPERIMENT

After performing the experiment, you will be able to:

- study the static input and output characteristics of a BJT in all three configurations.
- determine the current gain (α for CB, β for CE) from the characteristic curves.
- identify the active, saturation, and cut-off regions from the output characteristic curves.
- compare the input impedance, output impedance, and gain properties of the three configurations.

9.1 AIM

To study the static input and output characteristics of a transistor in the Common Base (CB), Common Emitter (CE), and Common Collector (CC) configurations.

9.2 APPARATUS REQUIRED

- Regulated DC Power Supply**:** 0–30 V, two units
- Voltmeters**:** (0–2) V for input (CE/CC); (0–10) V for input (CB); (0–20) V for output (CB)
- Ammeters / Milliammeters**:** As required for I_B, I_C, I_E measurement
- Potentiometers (Rheostats**):** 1 kΩ or 10 Ω
- Resistors**:** 1 kΩ — 1 No.
- NPN Transistor**:** e.g., BC547 or 2N2222
- Connecting Wires and Breadboard.

Alternatively, a transistor characteristic trainer kit may be used (Figure 9.1).



Figure 9.1*:* Transistor Characteristic Trainer Kit

9.3 THEORY

The static characteristics of a BJT describe the steady-state (DC) relationships between voltages and currents at the transistor's terminals, in the absence of any AC signal. They are measured in two forms:

- **Input Characteristics:** Show the variation of input current with input voltage, with output voltage held constant.
- **Output Characteristics:** Show the variation of output current with output voltage, with input current held constant.

These characteristics are studied in three configurations depending on which terminal is common to both input and output circuits: Common Base (CB), Common Emitter (CE), and Common Collector (CC).

CONFIGURATION SUMMARY

Parameter	**CB**	**CE**	**CC**
Common terminal	Base	Emitter	Collector
Input terminal	Emitter	Base	Base
Output terminal	Collector	Collector	Emitter
Current gain $\left(\frac{\alpha}{\beta}\right)$	α < 1	β >> 1	β+1
Input impedance	Low	Medium	High
Output impedance	High	Medium	Low
Phase shift	0°	180°	0°

9.4 COMMON BASE CONFIGURATION

In the CB configuration (Figure 9.1), the base is the common terminal for both input and output circuits. The emitter is the input terminal, and the collector is the output terminal.

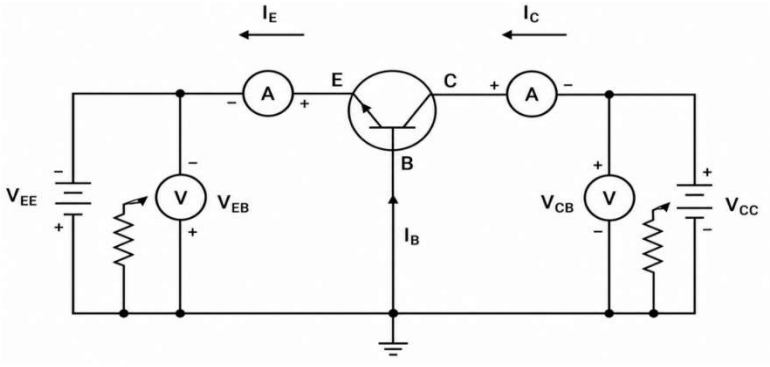


Figure 9.2: Common Base Configuration Circuit

CB Input Characteristics

The CB input characteristics show the variation of emitter current I_E with emitter-base voltage V_{EB}, at constant collector-base voltage V_{CB}.

Procedure

1. Connect the circuit as shown in Figure 9.1.
2. Set V_{CB} = 0 V. Starting from V_{EB} = 0 V, gradually increase V_{EB} and record I_E at each step.
3. Set V_{CB} to another constant value (e.g., 2 V). Repeat the sweep of V_{EB} and record I_E.
4. Repeat for further fixed values of V_{CB}. Tabulate readings in Table 1.

Observation Table 1: CB Input Characteristics

Fixed values: V_{CB} = 0 V and V_{CB} = 2 V

V_{CB} = 0 V		V_{CB} = 2 V	
V_{EB}(V)	I_E (mA)	V_{EB} (V)	I_E (mA)

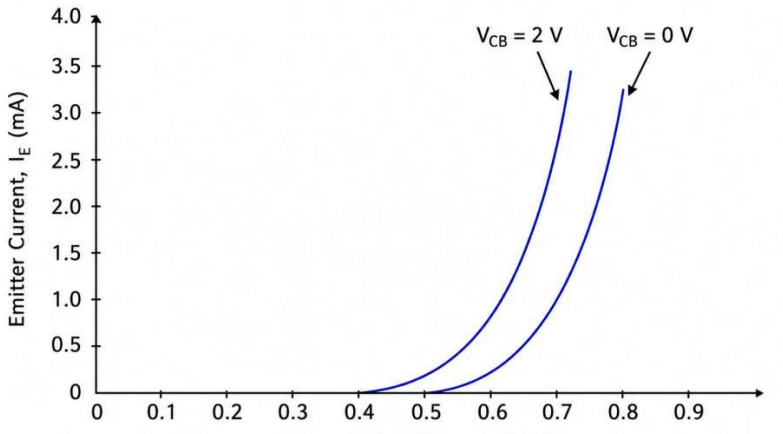


Figure 9.2*:* CB Input Characteristics

Source: Adapted from B.L. Theraja, A.K. Theraja, *A Textbook of Electronics: Devices and Circuits*, S. Chand Publishing.

When V_{CB} = 0 V, the emitter-base junction is forward-biased and the characteristic resembles that of a forward-biased diode, with I_E rising rapidly. As V_{CB} increases, the curve shifts slightly due to the early effect.

CB Output Characteristics

The CB output characteristics show the variation of collector current I_C with collector-base voltage V_{CB}, at constant emitter current I_E.

Procedure

1. Set I_E = 0 mA. Starting from V_{CB} = 0 V, increase V_{CB} and record I_C.
2. Set I_E to a fixed value (e.g., 10 mA) by adjusting V_{EB}. Again, sweep V_{CB} and record I_C.
3. Repeat for I_E = 20 mA, 30 mA, etc. Tabulate readings in Table 2.

Observation Table 2: CB Output Characteristics

I_E = 0 mA		I_E = 10 mA		I_E = 20 mA	
V_{CB}(V)	I_C (mA)	V_{CB} (V)	I_C (mA)	V_{CB}(V)	I_C (mA)

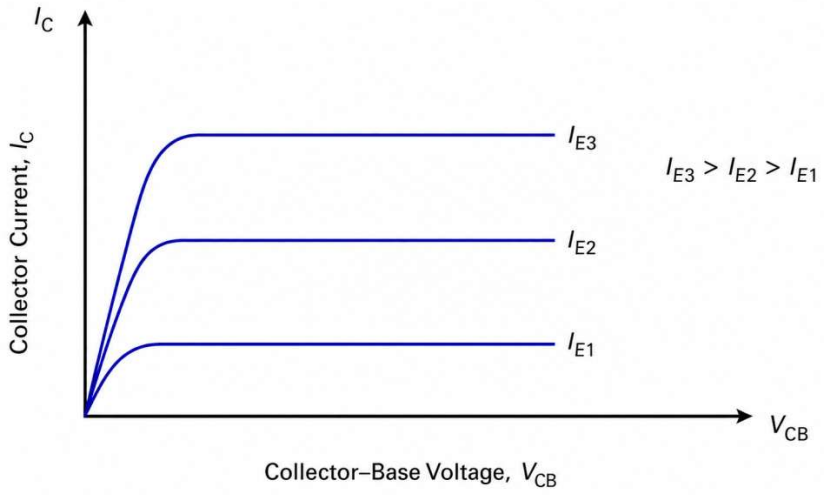


Figure 9.3: CB Output Characteristics

For a fixed I_E, the collector current I_C is nearly independent of V_{CB} in the active region, so the curves are approximately parallel to the V_{CB} axis. This reflects the high output impedance of the CB configuration.

9.5 COMMON EMITTER CONFIGURATION

In the CE configuration (Figure 9.4), the emitter is the common terminal. The base is the input terminal, and the collector is the output terminal. This is the most widely used BJT configuration owing to its high current and voltage gain.

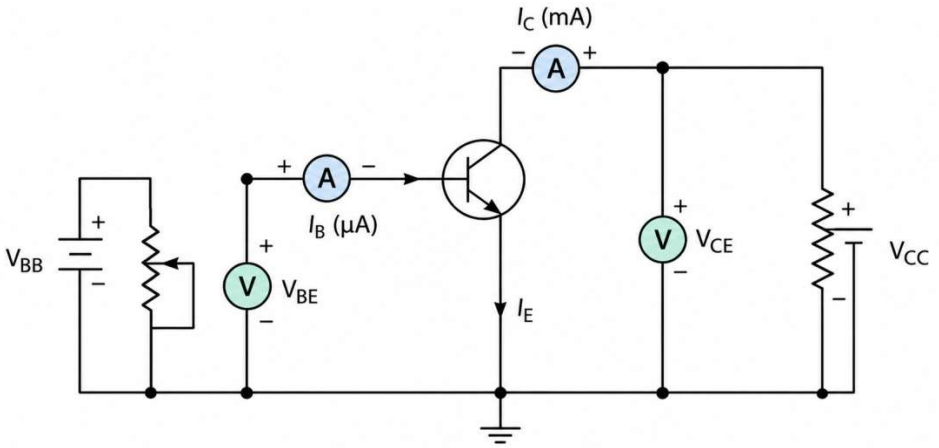


Figure 9.4*:* Circuit to Determine CE Static Characteristics

CE Input Characteristics

The CE input characteristics show the variation of base current I_B with base-emitter voltage V_{BE}, at constant collector-emitter voltage V_{CE}.

Procedure

1. Set V_{CE} = 0 V. Starting from V_{BE} = 0 V, gradually increase V_{BE} and record I_B at each step.
2. Set V_{CE} to another constant value (e.g., 5 V) and repeat the sweep. Tabulate readings in Table 3.

Observation Table 3: CE Input Characteristics

Fixed values**:** V_{CE} = 0 V and V_{CE} = 5 V

$V_{CE} = 0V$		$V_{CE} = 5V$	
$V_{BE}(V)$	$I_B((\mu A)$	$V_{BE}(V)$	$I_B((\mu A)$

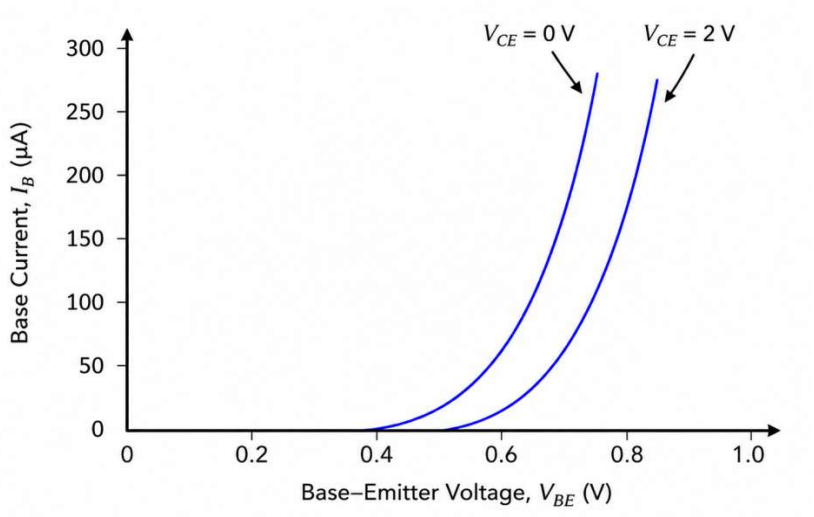


Figure 9.5: CE Input Characteristics *(*Source: Jacob Millman and Arvin Grabel, Microelectronics, 2nd Edition, McGraw-Hill Education.)

The curves resemble forward-biased diode characteristics. As V_{CE} increases, the effective base width decreases (Early effect), so the curve shifts to the right: a smaller V_{BE} is needed to sustain the same I_B.

CE Output Characteristics

The CE output characteristics show the variation of collector current I_C with collector-emitter voltage V_{CE}, at constant base current I_B.

Procedure

1. Set I_B = 0 μA. Starting from V_{CE} = 0 V, increase V_{CE} and record I_C.
2. Set I_B to a fixed value (e.g., 12 μA) by adjusting V_{BE}. Sweep V_{CE} and record I_C.
3. Repeat for I_B = 24, 36, 48 μA. Tabulate readings in Table 4.

Observation Table 4: CE Output Characteristics

I_B = 0 μA		I_B = 12 μA		I_B = 24 μA		I_B = 36 μA		I_B = 48 μA	
V_{CE}(V)	I_C(mA)	V_{CE}(V)	I_C(mA)	V_{CE}(V)	V_{CE}(V)	I_C(mA)	V_{CE}(V)	I_C(mA)	V_{CE}(V)

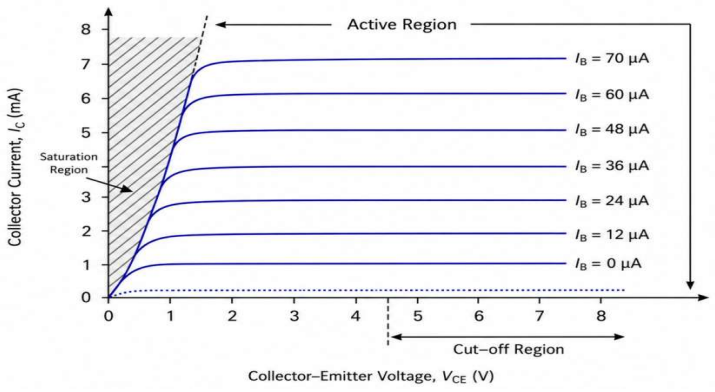


Figure 9.6*:* CE Output Characteristics *(*Source: Adapted from Donald A. Neaman, Electronic Circuits: Analysis and Design, 3rd Edition, McGraw-Hill Education.)

For a fixed $I_B, I_C$is nearly independent of V_{CE} in the active region. The output characteristics define three regions:

- Active region: Base-emitter junction forward-biased and base-collector junction reverse-biased. $I_C \approx \beta I_B$.
- Saturation region: Both junctions forward biased; $V_{CE} \approx 0.2$ V. Transistor acts as a closed switch.
- Cut-off region: Both junctions reverse-biased; $I_C \approx 0$. Transistor acts as an open switch.

9.6 COMMON COLLECTOR CONFIGURATION

In the CC configuration (Figure 9.7), the collector is the common terminal. The base is the input terminal, and the emitter is the output terminal. The CC configuration is also called the emitter follower. It is characterized by high input impedance, low output impedance, and a voltage gain slightly less than unity, making it useful as a buffer stage.

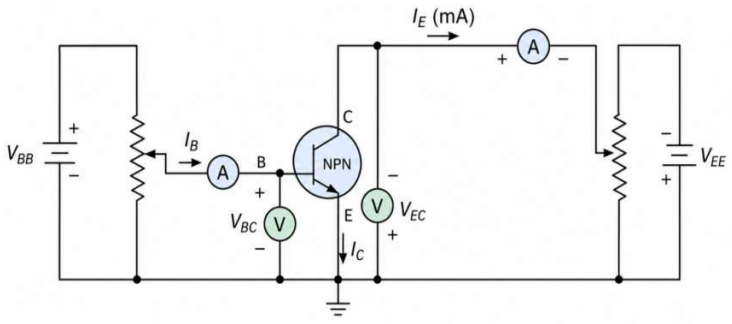


Figure 9.7: Common Collector (CC) Configuration Circuit

CC Input Characteristics

The CC input characteristics show the variation of base current $\mathbf{I_B}$ with base-collector voltage V_{BC}, at constant emitter-collector voltage V_{EC}.

Procedure

1. Set $V_{EC} = 0$ V. Starting from $V_{BC} = 0$ V, gradually increase V_{BC} and record I_B.

2. Set V_{EC} to another constant value (e.g., 5 V) and repeat the sweep. Tabulate readings in Table 5.

Observation Table 5: CC Input Characteristics

Fixed values: V_{EC} = 0 V and V_{EC} = 5 V

V_{EC} = 0 V		V_{EC} = 5 V	
V_{BC}(V)	I_B (μA)	V_{BC} (V)	I_B (μA)

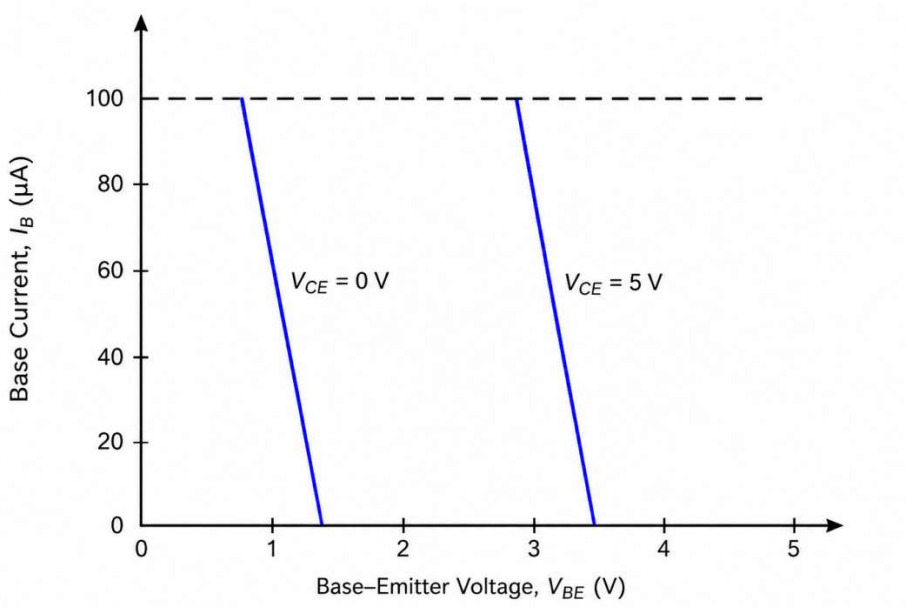


Figure 9.8: CC Input Characteristics *(*Source: Adapted from Sedra, A. S., & Smith, K. C., Microelectronic Circuits, 7th Edition, Oxford University Press.)

CC Output Characteristics

The CC output characteristics show the variation of emitter current I_E with emitter-collector voltage V_{EC}, while input current I_B is kept constant.

Procedure

1. Set I_B = 0 μA. Starting from V_{EC} = 0 V, increase V_{EC} and record I_E.
2. Set I_B to fixed values (e.g., 15, 30, 45, 70 μA) in turn. At each I_B, sweep V_{EC} and record I_E. Tabulate in Table 6.

Observation Table 6: CC Output Characteristics

I_B = 0 µA		I_B = 15 µA		I_B = 30 µA		I_B = 45 µA		I_B = 70 µA	
V_{EC} (V)	I_E (mA)	V_{EC} (V)	I_E (mA)	V_{EC} (V)	V_{EC} (V)	I_E (mA)	V_{EC} (V)	I_E (mA)	V_{EC} (V)

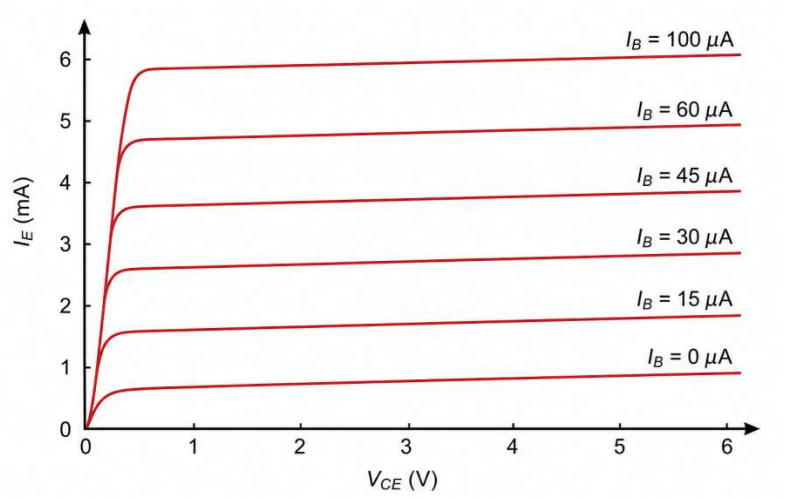


Figure 9.9*:* CC Output Characteristics

*(*Source: Boylestad, R. L., & Nashelsky, L., Electronic Devices and Circuit Theory, 11th Edition, Pearson.)

For a fixed I_B, I_E is nearly independent of V_{EC} in the active region, yielding curves parallel to the V_{EC} axis. The CC output impedance is low, which is its most useful property in impedance-matching applications.

9.7 RESULT

Record the following from your plotted curves**:**

CB configuration — Current gain**:** α = $\frac{\Delta I_C}{\Delta I_E}$= _____ (at V_{CB} = _____ V)

CE configuration — Current gain**:** β = $\frac{\Delta I_C}{\Delta I_B}$= _____ (at V_{CE} = _____ V)

CC configuration — Emitter follower gain**:** A_i =$\frac{\Delta I_E}{\Delta I_B}$ = _____ (at V_{EC} = _____V)

9.8 PRECAUTIONS

1. Correct biasing: For active-region operation, the base-emitter junction must be forward-biased (~ 0.7 V for Si) and the base-collector junction must be reverse-biased.
2. Do not exceed rated limits: Never exceed the maximum rated collector current $I_{C(max)}$or power dissipation $P_{D(max)}$specified in the transistor datasheet (e.g., BC547: $I_{C(max)}$= 100 mA, $P_{D(max)}$ = 500 mW).
3. Zero knobs before power-on: Before switching on the power supply, ensure all voltage adjustment knobs are at their minimum (zero) position.
4. Avoid prolonged heating: Do not leave the supply on at high bias levels while not taking readings. Sustained dissipation causes thermal drift and alters the transistor characteristics.
5. Verify connections: Double-check all connections against the circuit diagram before switching on, to avoid short circuits or reversed supply polarities.

9.9 REFERENCES

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9.10 ANSWER THE FOLLOWING QUESTIONS

1. What is meant by input and output characteristics of a transistor?
2. Why are three different configurations (CB, CE, CC) used for studying a BJT?
3. What is the physical meaning of current gain α, β, and γ in CB, CE, and CC configurations respectively?
4. Why is the input characteristic of CB configuration like a forward-biased diode?
5. Why is the output characteristic of CB configuration almost horizontal (parallel to voltage axis)?
6. What are the three operating regions of a transistor, and how are they identified from the output characteristics?
7. Why does the CE configuration provide high current gain compared to CB configuration?

8. What is the reason for 180° phase shift in CE configuration but not in CB and CC?
9. How does the Early effect influence the input characteristics of a transistor?
10. Why is the input impedance high in CC configuration and low in CB configuration?

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EXPERIMENT NO. 10

Determination of the Stefan–Boltzmann Constant by Ballistic Galvanometer Method/ Incandescent Lamp Method

LEARNING OBJECTIVES OF THE EXPERIMENT

After performing the experiment, you will be able to:

- understand the Stefan–Boltzmann law and its physical basis in blackbody radiation.
- part A**:** Calibrate a thermocouple, measure the heating rate of a blackened disc inside a hot enclosure, and calculate σ.
- part B**:** Determine σ from the power radiated by an incandescent lamp filament, using its measured resistance to infer temperature.
- compare the experimental value of σ with the standard value 5.67×10^{-8} W m^{-2} K^{-4}.

10.1 AIM

To determine the Stefan-Boltzman constant using a ballistic galvanometer/ incandescent lamp.

10.2 APPARATUS REQUIRED

Part A — Ballistic Galvanometer Method

- Metallic hemisphere: Black-body radiation enclosure with steam/hot-water heating jacket
- Test disc: Small blackened silver or copper disc of known mass, area, and specific heat
- Thermocouple: Copper–Constantan, one junction fixed to the disc; other at room temperature
- Ballistic galvanometer: Highly sensitive suspended-coil type
- Sand bath, oil-filled test tube, thermometer, stopwatch, steam generator

Part B — Incandescent Lamp Method

- Incandescent lamp: Tungsten filament lamp with known filament dimensions (length L and radius r), mounted in a glass envelope with known emissivity ε
- DC regulated power supply: Variable voltage
- Ammeter and Voltmeter: For accurate electrical power measurement

- Optical pyrometer or calibration table: To determine filament temperature from resistance
- **Meter rule and travelling microscope:** To measure filament dimensions

10.3 THEORY

Part A: Ballistic Galvanometer Method

According to the Stefan–Boltzmann Law, the total radiant power emitted per unit area by a perfect blackbody is proportional to the fourth power of its absolute temperature T:

$$E = \sigma T^4 \quad (10.1)$$

When a small, blackened disc at temperature T_2 is placed inside a uniform enclosure at a higher temperature T_1, the net rate of heat absorbed by the disc is:

$$\frac{dQ}{dt} = A\sigma(T_1^4 - T_2^4) \quad (10.2)$$

Equating this to $ms\frac{dT}{dt}$ gives the working formula:

$$\sigma = \frac{ms\frac{dT}{dt}}{[A(T_1^4 - T_2^4)]} \quad (10.3)$$

Symbol	Definition
σ	Stefan-Boltzman Constant
m	Mass of the blackened disc
s	Specific heat capacity of the disc
A	Surface area of the disc
T_1	Temperature of the surrounding enclosure
T_2	Temperature of the blackened disc
$\frac{dT}{dt}$	Rate of change of temperature of the disc

Part B: Incandescent Lamp Method

Incandescent Lamp Method

Physical Basis

In this method, an incandescent tungsten-filament lamp is used as the radiating body. When an electric current flows through the filament, electrical energy is converted to thermal energy. At steady state, the filament radiates all the input power to its surroundings. By measuring the electrical power input and the surface area of the filament, and by inferring the filament temperature from its electrical resistance, Stefan's constant can be determined.

Steady-State Energy Balance

At thermal equilibrium, the filament radiates energy at the same rate as it receives electrical energy. Ignoring convective and conductive losses (valid in a near-vacuum

environment or at high temperatures where radiation dominates), the power radiated by the filament is:

$$P_{\mathbf{rad}} = \varepsilon\, \sigma\, A_f\, (T_f^4 - T_0^4) \qquad (10.4)$$

where T_0 is the ambient temperature (surroundings) and T_f is the filament temperature. Since $T_f >> T_0$ at normal operating conditions, T_0^4 is negligible and the equation simplifies to:

$$P_{rad} \approx \varepsilon\, \sigma A_f T_f^4 \qquad (10.5)$$

Setting the electrical input power $P_{in} = V.I$ equal to P_{rad}:

$$\sigma = \frac{V.I}{(\varepsilon\, A_f T_f^4)} \qquad (10.6)$$

Symbol	Definition
σ	Stefan-Boltzmann Constant
V	Potential Difference (Voltage)
I	Electric Current
ε	Emissivity of the filament
A_f	Surface area of the filament
T_f	Absolute temperature of the filament
T_0	Absolute ambient (surrounding) temperature

Determining Filament Temperature from Resistance

The tungsten filament has a well-characterised resistance–temperature relationship. Since the resistance R of the filament can be measured directly $\left(R = \frac{V}{I}\right)$ and the resistance at room temperature R_0 is known, the filament temperature can be inferred using the resistance ratio method:

$$\frac{R_f}{R_0} = f(T_f) \qquad (10.7)$$

For tungsten, the ratio $\frac{R_f}{R_0}$ vs. temperature T_f is available in standardized tables (e.g., from the *American Institute of Physics Handbook*). Alternatively, if the temperature range is modest, the approximate linear relation may be used:

$$R_f = R_0\ [1 + \alpha\, (T_f - T_0)] \qquad (10.8)$$

where $\alpha \approx 4.5 \times 10^{-3}\ K^{-1}$ is the temperature coefficient of resistance of tungsten at room temperature. However, since α itself varies with temperature, use of the resistance ratio table is preferred for accuracy.

10.3.3 Surface Area of the Filament

The filament is approximated as a thin cylinder of length L and radius r (half the wire diameter d). Its lateral surface area is:

$$A_f = 2\pi rL = \pi dL \qquad (10.9)$$

The filament length L is measured using a travelling microscope or by direct measurement on the coiled filament. The filament diameter d is measured using a micrometer or inferred from the manufacturer's specifications.

Emissivity of Tungsten

A perfect blackbody has emissivity ε = 1. Tungsten is a gray body with total hemispherical emissivity approximately:

ε ≈ 0.30 at 1500 K, ≈ 0.35 at 2000 K, ≈ 0.40 at 2500 K, ≈ 0.46 at 3000 K

The value of ε must be interpolated from calibration tables at the measured filament temperature. An error in ε directly propagates to the calculated σ, so this is the dominant source of systematic uncertainty in this method.

Graphical Determination of σ

At different power settings, the filament reaches different steady temperatures. From Eq. (10.5), rearranging:

$$\boxed{P = \varepsilon\sigma A_f\left(T_f^4 - T_a^4\right)} \qquad (10.10)$$

where T_f is the filament temperature and T_a is the ambient temperature A graph of $\frac{P}{\varepsilon A_f}$ on the Y-axis against $\left(T_f^4 - T_a^4\right)$ on the X-axis should give a straight line through the origin. The slope of the line gives the Stefan–Boltzmann constant σ.

Summary of Key Equations:

Filament power:: $P = VI$

Filament resistance: $R_f = \frac{V}{I}$

Filament temperature: T_f is determined from the $\frac{R_f}{R_o}$ ratio table

Filament area: $A_f = \pi dL$

Stefan–Boltzmann constant: $\sigma = \frac{VI}{\varepsilon A_f\left(T_f^4 - T_a^4\right)}$

Graph method: Plot $\frac{P}{\varepsilon A_f}$ against $\left(T_f^4 - T_a^4\right)$

NOTE: If measurements are made in CGS units (mass in grams, area in cm², temperature in K), include the mechanical equivalent of heat J in the formula:

$$\sigma = \frac{Jms\left(\frac{dT}{dt}\right)}{A_f\left(T_f^4 - T_a^4\right)}$$

where J = 4.2 × 10^7 erg cal^{-1}.

10.4 PROCEDURE

Part A — Calibrating the Thermocouple

1. Connect: Fix one junction of the thermocouple to the disc (measuring junction) and submerge the other junction (cold junction) in a test tube of oil or mercury placed in a sand bath.

2. Heat: Heat the sand bath to approximately 120 °C.
3. Record while cooling: As the bath cools, record the galvanometer deflection (x, cm) for every 5°C drop in temperature T. Enter readings in Table 1.
4. Plot Graph 1: Plot deflection (x) on the Y-axis against temperature (T) on the X-axis. Draw the best-fit line.
5. Find slope: Determine $m_1=\frac{dx}{dT}$.The reciprocal $\frac{dx}{dT}$ gives the temperature sensitivity in °C per cm deflection.

Part A — Measuring the Heating Rate of the Disc

1. Heat enclosure: Pass steam through the jacket of the metallic hemisphere until it reaches a steady temperature T_1 Record T_1.
2. Set cold junction: Keep the cold junction at room temperature T_0
3. Insert disc: Quickly insert the cold disc. Start the stopwatch simultaneously.
4. Record: Record galvanometer deflection (x) every 15 seconds. Enter in Table 2.
5. Plot Graph 2: Plot deflection (x) vs. time (t). Draw a tangent at point P to find slope $m_2=\frac{dx}{dt}$.

Part B — Incandescent Lamp Method

1. Measure filament dimensions: Using a travelling microscope, measure the filament length L. Obtain the filament diameter d from the manufacturer's specifications or measure with a micrometer. Calculate $A_f = \pi dL$.
2. Measure R_0: With the lamp cold (at room temperature T_0), measure the cold filament resistance $R_0 = \frac{V}{I}$at a very small, applied voltage.
3. Increase power: Apply a series of increasing voltage settings V_1, V_2, … At each step, wait for steady state, then record V and I simultaneously.
4. Calculate R_f: For each reading, compute $R_f=\frac{V}{I}$
5. Find T_f: Look up T_f from the $\frac{R_f}{R_0}$ratio in the tungsten resistance-ratio table. Enter in Table 3.
6. Calculate $\frac{P}{\varepsilon A_f}$: For each setting, compute $P = VI$, look up ε at T_f and calculate $\frac{P}{\varepsilon A_f}$
7. Plot Graph 3: Plot $\frac{P}{\varepsilon A_f}$ on the Y-axis against T_f^4on the X-axis. The slope gives σ directly.

10.5 OBSERVATIONS

Table 1: Thermocouple Calibration (Part A)

Least count of thermometer: _____ °C | Cold junction temperature T_0: _____ K

Sl. No.	Temperature T (°C)	Temperature T (K)	Cold junction T_0 (K)	Deflection x (cm)
1				
2				
3				
4				

Slope from Graph 1: $m_1 = \frac{dx}{dT}$= _____ cm °C^{-1} $\Rightarrow \frac{dT}{dx}$= _____ °C cm^{-1}

Table 2: Rate of Temperature Rise of the Disc (Part A)

m = _____ g | Diameter: _____ cm | A: _____ cm² | s: _____ cal g^{-1} °C^{-1}| T_1**:** _____ K

Sl. No.	Time t (seconds)	Deflection x (cm)
1	0	0
2	15	
3	30	
4	45	
5	60	
6	75	
7	90	
8	...	

Slope from Graph 2 at point P: $m_2 = \frac{dx}{dT}$= _____ cm s^{-1}

Table 3: Lamp Method Observations (Part B)

Cold resistance R_0 **(at** T_0 **=** _____ K): _____ Ω | **Filament length L:** _____ m | **Diameter d:** _____ m | **Area** A_f**:** _____ m²

Sl. No.	Power Input $P = VI$ (W)	Filament Resistance $R_s = \frac{V}{I}(\Omega)$	Filament Temperature $T_s(K)$	$\frac{P}{A_s}$(W m^{-2})
1				
2				
3				
4				
5				
6				

10.6 CALCULATIONS

Part A

Compute $\frac{dT}{dt} = \left(\frac{dT}{dx}\right) \times \left(\frac{dx}{dt}\right) = m_1^{-1} \times m_2$

Here: $\frac{dT}{dx}$ = temperature calibration factor obtained from Graph 1,

$\frac{dx}{dt}$ = rate of change of thermocouple deflection at point P

The disc temperature at point P: $T_2 = T_0 + \theta$, where θ is read from Graph 1 at the deflection corresponding to point P.

$$\sigma = \frac{Jms\left(\frac{dT}{dt}\right)}{A_f\left(T_2^4 - T_1^4\right)}$$

with $J = 4.2 \times 10^7 \text{ erg cal}^{-1}$

Part B

From Graph 3, plotted as. $\frac{P}{\varepsilon A_f}$ vs. T_f^4,the slope is

$$\sigma = \frac{\Delta\left(\frac{P}{\varepsilon A_f}\right)}{\Delta T_f^4}$$

Therefore, σ is the slope of graph 3.

10.7 RESULT

Experimental Results

Part A (Galvanometer method): σ = _____ W m^{-2} K^{-4}

Part B (Incandescent lamp method): σ = _____ W m^{-2} K^{-4}

Standard value: σ = 5.67 × 10^{-8} W m^{-2} K^{-4}

Percentage error (Part A): _____ %

Percentage error (Part B): _____ %

10.8 PRECAUTIONS

1. Steam safety: The metallic enclosure reaches high temperatures when steam heated. Use insulated gloves. (Part A)
2. Blacken the disc: The disc must be uniformly blackened (lamp black) to behave as a true blackbody. Any shiny patch causes error. (Part A)
3. Insert disc quickly: Insert the disc rapidly and start the stopwatch simultaneously to capture the initial heating rate accurately. (Part A)
4. Stable enclosure temperature: Ensure T_1 is truly steady before inserting the disc. Fluctuations in T_1 directly affect the calculated σ. (Part A)

5. All temperatures in Kelvin: Always convert °C to K before substituting into the formula: T(K) = T(°C) + 273.15. (Both methods)

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10.10 ANSWER THE FOLLOWING QUESTIONS

1. What is the Stefan–Boltzmann law, and what physical quantity does it relate?
2. Define the Stefan–Boltzmann constant (σ) and state its SI unit and standard value.
3. Why is the disc blackened in the ballistic galvanometer method?
4. What is the role of a thermocouple in this experiment?
5. Why is a ballistic galvanometer used instead of an ordinary galvanometer?
6. In Part A, why must the disc be inserted quickly into the enclosure?
7. What assumptions are made while deriving the working formula for Part A?
8. In the incandescent lamp method, how is the temperature of the filament determined?
9. Why is the term T_0^4 neglected in comparison to T_f^4 in Part B?
10. What are the major sources of error in determining σ in this experiment?

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EXPERIMENT NO. 11
Determination of Modulus of Rigidity Using Maxwell's Needle

LEARNING OBJECTIVES OF THE EXPERIMENT

After performing the experiment, you will be able to:

- understand the principle of the torsional pendulum and Maxwell's needle method.
- measure the period of oscillation of Maxwell's needle in two configurations.
- calculate the modulus of rigidity (η) of the experimental wire material.
- practice use of a screw gauge to measure the diameter of a thin wire with zero-error correction.

11.1 AIM

To determine the modulus of rigidity of a wire using Maxwell's needle.

11.2 APPARATUS REQUIRED

- Maxwell's needle**:** A hollow brass tube with two solid and two hollow cylinders that can be interchanged.
- Experimental wire**:** A thin, uniform wire of known material (brass, steel, or copper), fixed at the top and supporting the needle.
- Stopwatch**:** For measuring the period of oscillation.
- Screw gauge**:** For measuring the diameter of the experimental wire.
- Meter scale**:** For measuring the length of the wire and the Maxwell needle.
- Physical balance**:** For measuring the masses of the solid and hollow cylinders.
- Vernier calipers and spirit level

11.3 THEORY

Maxwell's needle is a torsional pendulum. A cylindrical tube (the needle) is suspended horizontally by a thin wire whose rigidity modulus η is to be determined. The needle carries two solid and two hollow cylinders that can be placed in either of two arrangements, changing the moment of inertia of the system without altering its geometry.

When the needle is displaced angularly and released, it executes torsional simple harmonic motion. The time-period of oscillation is:

$$T = 2\pi\sqrt{\left(\frac{I}{C}\right)}$$

where I is the moment of inertia of the needle assembly and C is the torsional couple per unit angular twist of the wire, given by$C = \frac{\pi\eta r^4}{(2l)}$. By measuring the time-period T_1(solid cylinders inside, hollow outside) and T_2 (solid outside, hollow inside), and using the difference in moments of inertia, the modulus of rigidity η is obtained from the working formula below.

11.4 WORKING FORMULA

The modulus of rigidity of the wire material is:

$$\eta = \frac{8\pi\, l\, (M_s - M_H)\, L^2}{[r^4\, (T_2^2 - T_1^2)]} \qquad (11.1)$$

Symbol	Definition
η	Modulus of rigidity of the material of the wire.
l	Length of the suspension wire.
M_s	Mass of the solid cylinders
M_H	Mass of the hollow cylinders
L	Distance between the centers of the two cylinders
r	Radius of the suspension wire.
T_1	Time period of oscillation when the solid cylinders are inside
T_2	Time period of oscillation when the hollow cylinders are inside

11.5 EXPERIMENTAL SETUP

The two configurations of Maxwell's needle are illustrated in Figures 11.1 and 11.2. In the first configuration, the solid cylinders occupy the inner positions, and the hollow cylinders occupy the outer positions, giving a smaller moment of inertia and hence the shorter time-period T_1. In the second configuration, the positions are swapped, giving the larger time-period T_2.

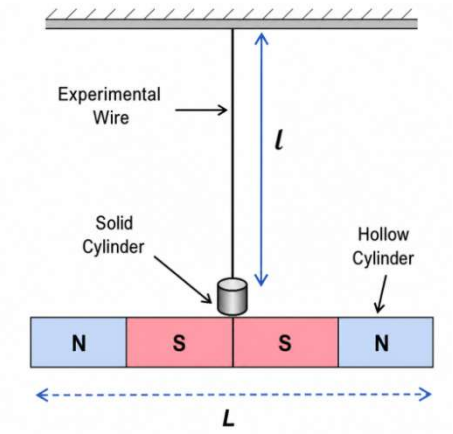


Figure 11.1: Maxwell Setup for T_1 (Solid inside, Hollow outside)

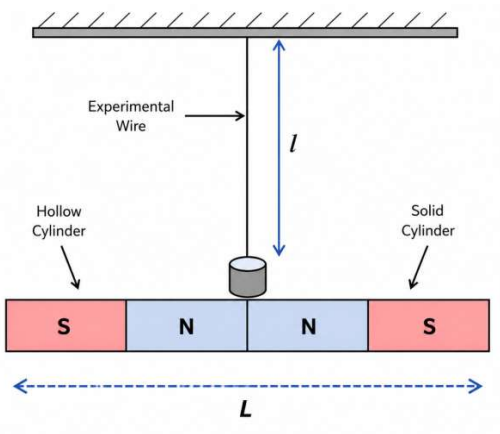


Figure 11.2: Maxwell Setup for T_2 (Solid outside, Hollow inside)

11.6 PROCEDURE

1. Wire length**:** Measure the length l of the experimental wire with a meter scale.
2. Needle length**:** Measure the length L of the Maxwell needle (distance between cylinder-center positions) using a meter scale.
3. Mass of solid cylinders**:** Weigh both solid cylinders individually on a physical balance. Let their masses be a and b. Calculate $M_S = \frac{(a + b)}{2.}$
4. Mass of hollow cylinders**:** Weigh both hollow cylinders individually. Let their masses be c and d. Calculate $M_H = \frac{(c + d)}{2.}$
5. Screw gauge calibration**:** Note the least count and zero error of the screw gauge.
6. Wire diameter**:** Using the screw gauge, measure the diameter of the experimental wire at five different positions. Take the mean corrected diameter D. Then $r = \frac{D}{2}$.
7. Stopwatch least count**:** Note the least count of the stopwatch.
8. Determine T_1**:** Place the hollow cylinders at the outer positions and the solid cylinders at the inner positions (Figure 11.1). Give the needle a small angular displacement and release it. Record the time for 10, 20, and 30 oscillations. Calculate $T_1 = \frac{t}{n}$ for each and take the mean.
9. Determine T_2**:** Swap the cylinders — place the solid cylinders at the outer positions and the hollow cylinders at the inner positions (Figure 11.2). Repeat the timing for 10, 20, and 30 oscillations and calculate the mean T_2.
10. Calculate η**:** Substitute all measured values into the working formula (Eq. 11.1) and compute η.

11.7 OBSERVATIONS

7.1 Physical Measurements

Length of experimental wire: l = _____ m

Length of Maxwell needle: L = _____ m

Mass of solid cylinder 1 (a): _____ g

Mass of solid cylinder 2 (b): _____ g

Mean mass of solid cylinder: $M_S = \frac{(a + b)}{2}$ = _____ kg

Mass of hollow cylinder 1 (c): _____ g

Mass of hollow cylinder 2 (d): _____ g

Mean mass of hollow cylinder: $M_H = \frac{(c + d)}{2.}$= _____ kg

Table 1: Diameter of the Experimental Wire

Least count of screw gauge: _____ cm | Zero error: _____ cm

Sl. No.	M. S. R (cm)	C. S. R (div)	d = M. S. R + (C. S. R × L. C) (cm)	Mean d (cm)	Corrected = d ± zero error (cm)
1					
2					
3					
4					
5					

Radius of wire: $r = \frac{D}{2}$= _____ m

Table 2: Time Period T_1 (Solid cylinders inside, Hollow cylinders outside)

Sl. No.	No. of Oscillations (n)	Total Time t (s)	$T_1 = t/n$ (s)	Mean T_1 (s)
1	10			
2	20			
3	30			

Table 3: Time Period T_2 (Solid cylinders outside, Hollow cylinders inside)

Sl. No.	No. of Oscillations (n)	Total Time t (s)	$T_2 = t/n$ (s)	Mean T_2 (s)
1	10			
2	20			
3	30			

11.8 CALCULATION

Substitute the measured values into the working formula given by equation (11.1),

$$\eta = \frac{8\pi\, l\, (M_s - M_H)\, \mathrm{L}^2}{[r^4\, (T_2^2 - T_1^2)]}$$

Substituting the values forl $= __\,\mathrm{m},\ \mathrm{M_s} = __\,\mathrm{kg}, \mathrm{M_H} = __\,\mathrm{kg}, \mathrm{L} = __\,\mathrm{m}, \mathrm{r} = __\,\mathrm{m}, \mathrm{T_1} = __\mathrm{s}, \mathrm{T_2} = __\mathrm{s}$, we get η

11.9 RESULT

The modulus of rigidity of the material of the experimental wire:

$$\eta = _____ N/m^2 \ (= _____ \times 10^{10} \ N/m^2)$$

11.10 PRECAUTIONS

1. Thin, uniform wire: Use a thin and uniform wire. Variations in diameter along the length will introduce error in the calculated value of r^4.
2. Small angular amplitude: The needle must be twisted through a very small angle so that Hooke's law is satisfied and the oscillation is truly simple harmonic.
3. Kink-free wire: Ensure the experimental wire is free from kinks or twists prior to the experiment, as these affect the torsional constant.
4. Horizontal alignment: Use a spirit level to confirm the Maxwell needle hangs horizontally. A tilted needle causes a gravitational restoring moment that corrupts the torsional period.
5. Count full oscillations: Count an oscillation as one complete back-and-forth swing. Start counting from the extreme position (0, 1, 2, …) and record time for at least 20–30 oscillations to reduce timing error.

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11.12 ANSWER THE FOLLOWING QUESTIONS

1. What is meant by the modulus of rigidity (η) of a material?
2. What is a torsional pendulum, and how does Maxwell's needle act as one?
3. What is the significance of using two different configurations in Maxwell's needle experiment?
4. Define time-period of torsional oscillation and write its dependence on moment of inertia.
5. What is meant by the torsional constant (C) of a wire?
6. Why should the oscillations be kept at a small angular amplitude?
7. Why is it necessary to use a thin and uniform wire in this experiment?
8. What is the role of a screw gauge, and why is zero error correction important?

9. Why do we measure time for multiple oscillations (10, 20, 30) instead of just one?
10. What are the main sources of error in determining the modulus of rigidity using this method?

****

EXPERIMENT NO. 12
Determination of Wavelength of Monochromatic Light Using Fresnel Biprism

LEARNING OBJECTIVES OF THE EXPERIMENT

After performing the experiment, you will be able to:

- understand wavefront division and interference using a Fresnel biprism.
- observe alternating bright and dark interference fringes from two virtual coherent sources.
- measure fringe width β, slit-to-screen distance D, and virtual source separation 2d.
- calculate $\lambda = \frac{\beta \times 2d}{D}$ and compare with the standard sodium D-line value (589.3 nm).

12.1 AIM

To determine the wavelength of monochromatic light using Fresnel's biprism.

12.2 APPARATUS REQUIRED

- Optical bench with uprights
- Monochromatic light source (sodium vapour lamp)
- Narrow adjustable slit
- Fresnel biprism with holder
- Convex lens with holder
- Micrometer eyepiece (travelling microscope)
- Meter scale and prism holder

12.3 THEORY

A Fresnel biprism consists of two identical thin prisms of very small refracting angle joined base to base. When quasi-monochromatic light from a narrow-slit falls on the biprism, the two halves refract light toward their bases, producing two virtual images of the slit. This creates two virtual coherent sources — S_1 and S_2 — that appear to originate from behind the biprism. Since both virtual sources are derived from the same original slit, they maintain a constant phase relationship and thus act as coherent sources capable of producing a stable interference pattern. At the point equidistant from the two virtual coherent sources, the path difference is zero; hence constructive interference occurs and the central bright fringe is formed.

The overlapping wavefronts from S_1 and S_2 produce alternating bright and dark interference fringes on the screen. The separation between any two consecutive bright (or dark) fringes is called the fringe width β.

Key Formula

The fringe width is given by:

$$\beta = \frac{\lambda D}{a}$$

where:

- λ = wavelength of the monochromatic light
- D = distance between the source slit and the eyepiece/screen
- a = separation between the two virtual coherent sources S_1 and S_2

Rearranging for wavelength:

$$\lambda = \frac{\beta\, a}{D}$$

Finding the Virtual Source Separation (a) — Displacement Method

A convex lens (whose focal length f must satisfy f $< \frac{D}{4}$) is placed between the biprism and the eyepiece. The lens is moved to find two positions where sharp, distinct images of the two virtual sources are formed in the eyepiece. If the separation of images in the two positions are d_1 and d_2, then for virtual source separation:

Principle

The experiment is based on the principle of superposition of waves. When two coherent light waves overlap:

- Constructive interference (bright fringe) occurs when the path difference $\Delta = n\lambda$, where n = 0, ±1, ±2, …
- Destructive interference (dark fringe) occurs when the path difference

$\Delta = \frac{(2n+1)\lambda}{2}$, where n = ±1, ±2, …

Because both virtual sources originate from the same slit, their phase difference remains constant, ensuring a stable and observable fringe pattern.

In the Fresnel biprism arrangement, the two virtual images (S_1) and $(S_2)$of the slit act as coherent sources. Their overlapping wavefronts produce equally spaced bright and dark fringes, with the fringe width depending on the wavelength (λ), the screen distance (D), and the source separation (a). Thus, the experiment demonstrates the wave nature of light and provides a method for determining the wavelength of monochromatic light.

12.4 EXPERIMENTAL SETUP

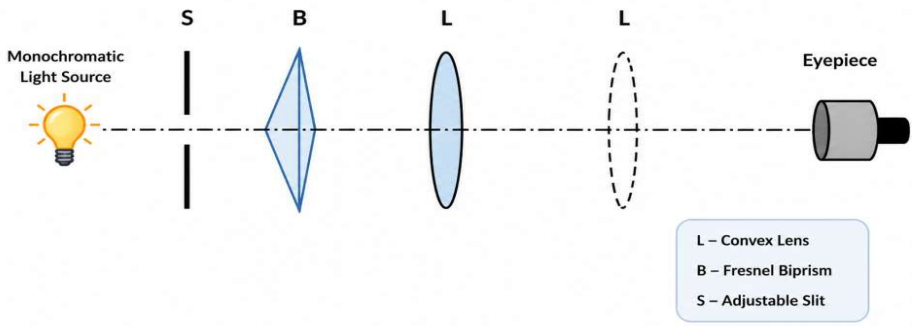


Figure 12.1*:* Optical Bench Layout for the Fresnel Biprism Experiment

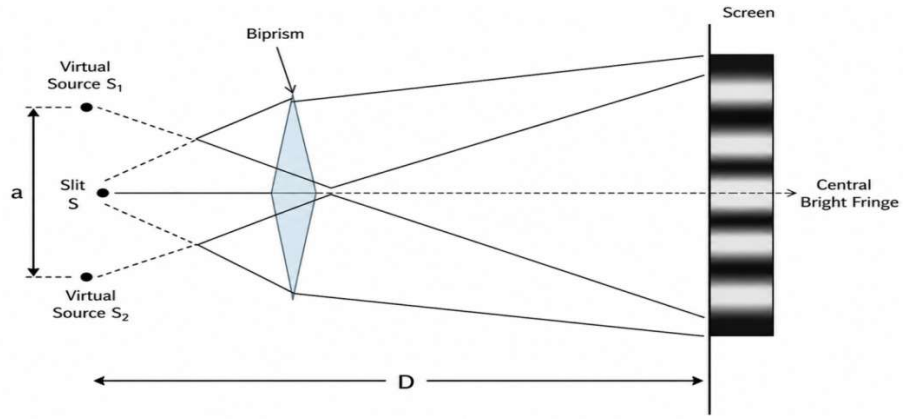


Figure 12.2*:* Ray Diagram Showing Formation of Virtual Sources S_1 and S_2

12.5 PROCEDURE

Initial Alignment

- Level the optical bench carefully using a spirit level and the levelling knobs.
- Mount the narrow slit at one end of the optical bench and adjust its width to produce a very narrow vertical slit.
- Place the Fresnel biprism on the bench with its refracting edge (apex) parallel to the slit.
- Place the micrometer eyepiece at the far end of the optical bench.
- Adjust the heights of the slit, biprism, and eyepiece so that all three lie on the same horizontal optical axis.

Observing Interference Fringes

- Switch on the sodium vapour lamp and allow it to warm up for 10–15 minutes so that it emits a stable **quasi-monochromatic** yellow light (Sodium D-line doublet).
-

- Look through the eyepiece. You should see two bright illuminated patches. If they are not overlapping, slowly rotate the biprism about the optical axis until they merge into a single central region.
- Once the patches overlap, vertical alternating bright and dark fringes should become visible.
- Move the eyepiece back and forth along the bench. If the fringes shift laterally, the biprism is slightly tilted; use the levelling screws on the biprism base to correct this until the fringes remain stationary when the eyepiece is moved.
- If the fringes appear blurred or fuzzy, narrow the slit width until the fringes become sharp and distinct.
- Adjust the lateral position of the biprism or slit to centre the fringe pattern in the eyepiece's field of view.

Measurement of Fringe Width (β)

- Use the micrometer eyepiece to align the crosswire with fringe No. 1 and note the reading.
- Move the crosswire from the 1st fringe to the 21st fringe and note the readings. The fringe width is obtained by dividing the total distance by 20.
- Repeat from the other side. The fringe width β = (total distance spanned) / (number of fringes).

Measurement of D

- Record the position of the upright carrying the slit and the upright carrying the eyepiece.
- D = |position of eyepiece − position of slit.

Measurement of Virtual Source Separation (a)

- Insert a convex lens between the biprism and the eyepiece. Ensure the focal length of the lens satisfies f <$\frac{D}{4}$(so that two real image positions can be found).
- Move the lens along the bench to find the first position where two sharp images of the virtual sources are seen; measure their separation as d_1.
- Move the lens further to find the second position; measure the separation as d_2.
- Calculate the virtual source separation:

$$a = \sqrt{d_1 d_2}$$

- Repeat for at least three sets of readings and take the mean.

12.6 OBSERVATIONS

Table 1: Measurement of Fringe Width (β)

Pitch of screw: _____ cm | Divisions on drum: _____ | Least count: _____ cm

Fringe No. (a)	**Micrometer Reading (a)**		**Total reading, a (cm)**	**Fringe No.(b)**	**Micrometer Reading (b)**		**Total reading b (cm)**	**Difference (a−b) for 20 fringes (cm)**	**Mean for 20 fringes (cm)**	**Fringe width β = $\frac{Mean}{20}$ (cm)**
	M.S.R. (cm)	**V.S.R. (cm)**			**M.S.R. (cm)**	**V.S.R. (cm)**				
1				21						
3				23						
5				25						
7				27						
9				29						
11				31						
13				33						
15				35						
17				37						
19				39						

Mean fringe width: $\beta = \frac{\beta_1+\beta_2+\beta_3+\beta_4+\beta_5}{5}, \beta =$ _____ cm

Table 2: Measurement of D (Slit-to-Screen Distance)

Measurement	**Value**
Position of slit upright	_____ cm
Position of eyepiece upright	_____ cm
Observed value of D	_____ cm
Bench error correction	± _____ cm
Corrected value of D	_____ cm

Table 3: Measurement of 2d (Virtual Source Separation)

Sl. No.	**1st Position of Lens**			**2nd Position of Lens**			**2d = $\sqrt{(d_1 \cdot d_2)}$ (cm)**	**Mean 2d (cm)**
	Image 1 (cm)	Image 2 (cm)	d_1 (cm)	Image 1 (cm)	Image 2 (cm)	d_2 (cm)		
1								
2								
3								

Mean virtual source separation: $a = \frac{a_1+a_2+a_3}{3} =$ _____ cm

12.7 CALCULATION

Substitute the measured values into the wavelength formula:

$$\lambda = \frac{\beta \times 2d}{D} \qquad (12.3)$$

β = _____ cm, $2d$ = _____ cm, D = _____ cm

12.8 RESULT

The wavelength of sodium light was determined experimentally using Fresnel biprism interference.

The experimentally determined wavelength of sodium light:

λ (experimental) = …… nm

1. Standard value of sodium D-line wavelength: λ (standard) = 589.3 nm(mean of Na , D_1 and D_2 lines)
2. Percentage error: $\frac{\lambda_{exp} - 58\ .3}{589.3}$ × 100% = _____ %

12.9 PRECAUTIONS AND SOURCES OF ERROR

- The slit must be kept very narrow to ensure adequate coherence length and sharp fringes.
- The slit must be perfectly parallel to the refracting edge of the biprism.
- All optical components — slit, biprism, lens, and eyepiece — must be co-axial (on the same optical axis).
- The experiment should be performed in a darkened room to improve fringe contrast.
- Avoid parallax error while taking micrometer readings; always approach from the same direction.
- Do not disturb the optical bench setup between successive measurements.
- Ensure the sodium lamp has fully warmed up before measurements are taken.

Sources of error:

- Improper alignment of the slit, biprism, and eyepiece along the optical axis.
- Inaccurate micrometer eyepiece readings due to backlash error.
- Incorrect positioning of the convex lens during the displacement method, leading to error in d_1 or d_2.
- Mechanical vibrations transmitted through the optical bench.
- Parallax error in reading the positions of uprights on the bench scale.

- The slit may not be perfectly parallel to the biprism edge, causing curved or blurred fringes.

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12.11 ANSWER THE FOLLOWING QUESTIONS

1. What is the aim of the Fresnel biprism experiment?
2. What type of light source is used in this experiment?
3. What is a Fresnel biprism made of?
4. How many virtual coherent sources are produced by the biprism?
5. What is meant by fringe width?
6. Write the expression for fringe width β.
7. Write the formula for wavelength determination in this experiment.
8. What is the purpose of using a convex lens in the displacement method?

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EXPERIMENT NO. 13
Calibration of a Temperature Sensor (Thermistor)

LEARNING OBJECTIVES OF THE EXPERIMENT

After performing the experiment, the you will be able to:

- understand the structure, operating principle, and NTC characteristic of a thermistor.
- derive the Steinhart–Hart equation relating thermistor resistance R to temperature T: plot lnR vs $\frac{1}{T}$ to extract the material constant β.
- construct the calibration circuit, measure the potential drop across the thermistor at known temperatures, and plot the calibration curve (V vs T).
- use the calibration curve to determine an unknown temperature from the thermistor voltage.
- construct and test the Op-Amp comparator temperature control circuit, verify its ability to maintain a set-point temperature, and understand the role of each component.

13.1 AIM

To calibrate a given temperature sensor (Thermistor)

13.2 APPARATUS REQUIRED

- Thermistor (NTC type): e.g., 10 kΩ at 25 °C; operating range −10 °C to +120 °C
- DC regulated power supply: 1.5 V or 3 V (for the calibration bridge circuit)
- Millivoltmeter or digital multimeter (mV range): To measure potential drop across the thermistor
- Thermometer: Mercury or digital, calibrated, range 0–150 °C
- Water bath (beaker + heating mantle or hot plate): With a 2000 W immersion heater
- Standard resistor R_S: Known value, selected to match thermistor resistance at mid-range temperature
- Op-Amp μA741 (or LM741): Configured as a voltage comparator
- Resistors: R_1 = 1 kΩ, R_2 = 22 kΩ, R_3 = 47 kΩpotentiometer, R_4 = 10 kΩ
- Capacitors: 0.1 μF (decoupling, optional)
- Relay: 12 V SPDT electromagnetic relay (or alternatively, an SCR/triac)
- Diode: 1N4007 (flyback protection across relay coil)
- ±12 V DC dual power supply: For the Op-Amp circuit
- Connecting wires, breadboard/PCB

13.3 THEORY

Thermistor

A thermistor (contraction of thermally sensitive resistor) is a type of resistor whose electrical resistance changes significantly and predictably with temperature. Unlike ordinary resistors, this change is intentional and exploited as a sensing mechanism. Thermistors are manufactured from sintered mixtures of metal oxides — typically manganese (Mn_2O_3), nickel (NiO), copper (CuO), cobalt (Co_2O_3), and iron (Fe_2O_3) — pressed into discs, rods, beads, or chips and fired at high temperatures. The resistance of a thermistor can vary from a few 0.5 Ω to 100 kΩ, and the operating temperature range is typically −100 °C to +350 °C, making thermistors suitable for precise temperature measurement and control in laboratory and industrial settings.

Types of Thermistors

Type	NTC (Negative Temperature Coefficient)	PTC (Positive Temperature Coefficient)
R vs T behaviour	Resistance decreases as temperature increases	Resistance increases sharply above Curie temperature
Typical material	Metal oxides (Mn, Ni, Co, Cu)	Barium titanate ceramics
Sensitivity	Very high (−3% to −6% per °C)	Moderate; sharp transition
Use in this experiment	Yes — temperature sensing and control	No

The NTC Resistance–Temperature Relationship

For an NTC thermistor, the resistance Rat absolute temperature T (in Kelvin) follows an approximately exponential law. The most used model is the simplified B-parameter (beta) equation:

$$R(T) = R_0 \exp\left[\beta\left(\frac{1}{T} - \frac{1}{T_0}\right)\right] \qquad (13.1)$$

where R_0 is the resistance at the reference temperature T_0 (usually T_0 = 298.15 K = 25 °C), and β (the material constant**)** is typically in the range 2000 K to 5000 K for NTC thermistors. A larger β implies greater sensitivity.

Taking the natural logarithm of Eq. (13.1):

$$\ln R = \ln R_0 + \beta\left(\frac{1}{T} - \frac{1}{T_0}\right) \qquad (13.2)$$

This shows that a plot of ln R vs $\frac{1}{T}$is a straight line with slope = β and intercept =

ln $R_0 - \frac{\beta}{T_0}$. his linear plot is used experimentally to determine β for the given thermistor.

More Accurate Model: Steinhart–Hart Equation

For higher accuracy over a wide temperature range, the Steinhart–Hart equation is used:

$$\frac{1}{T} = A + B\ln R + C.(\ln R)^3 \quad (13.3)$$

where A, B, and C are device-specific constants determined from three calibration points. This equation fits measured data to within ±0.02 °Cover the full operating range.

Voltage Divider Calibration Circuit

To measure the thermistor resistance indirectly as a voltage signal, the thermistor R_T is connected in series with a standard resistor R_S across a stable supply voltage V_{CC}. The voltage V_T across the thermistor is measured with a millivoltmeter:

$$V_T = V_{CC} \times \frac{R_T}{(R_T + R_S)} \quad (13.4)$$

As temperature increases, R_T decreases (NTC behaviour), causing V_T to decrease. The resulting V_T vs T calibration curve (Figure 13.1) is a smooth, monotonically decreasing curve which serves as the sensor's lookup table.

Symbol	Definition
V_T	Voltage across the thermistor R_T
V_{CC}	Stable supply voltage
R_T	Resistance of the thermistor
R_S	Series resistor (fixed)
β	Thermistor beta constant
T	Temperature of the thermistor

Temperature Control Using an Op-Amp Comparator

The Op-Amp in this circuit is wired as a voltage comparator. Its output switches between two saturated states (≈ +12 V and ≈ −12 V) depending on which input has the higher voltage:

- **Inverting terminal (−):** A reference voltage V_{ref} set by the 47 kΩ potentiometers. $V_{ref}$is chosen to equal $V_T(T_{set})$, i.e., the thermistor voltage corresponding to the desired temperature, as read from the calibration curve.
- **Non-inverting terminal (+):** The live thermistor voltage V_T, which reflects the actual bath temperature.

Comparator Logic

If $T_{bath} < T_{set}$: R_T is high → V_T is high → V (+) >V (−) → Output saturates to +12 V → Relay energises → Heater ON

If $T_{bath} > T_{set}$: R_T is low → V_T is low →V (+) <V (−) → Output saturates to −12 V → Relay de-energises → Heater OFF

The reference voltage at the non-inverting terminal is given by:

$$V_{ref} = V_T(T_{set}) = \frac{V_{CC} \times R_{T,set}}{(R_{T,set} + R_S)} \qquad (13.5)$$

where $R_{T,set}$ is the thermistor resistance at the set-point temperature T_{set}, read from the thermistor datasheet or from the resistance–temperature calibration table.

Role of Circuit Components

Component	Value	Function
R_1	1 kΩ	Current-limiting resistor; protects Op-Amp input from large thermistor voltage swings
R_2	22 kΩ	Part of the voltage divider at the non-inverting input; sets the reference voltage range
R_3 (pot.)	47 kΩ	Adjustable potentiometer; sets the exact reference voltage V_{ref} corresponding to T_{set}
Op − Amp	LM741	µA741 comparator; drives the relay through its output
Relay	12 V SPDT	Electrically isolates low-voltage Op-Amp circuit from 230 V AC heater circuit
Diode	1N4007	Flyback (freewheeling) diode across relay coil; suppresses inductive voltage spike when relay turns off
Thermistor	10 kΩ (at 25°C)	NTC sensor; resistance reflects bath temperature continuously
2000 W heater	AC mains	Immersion heater; controlled via relay to maintain bath temperature

13.4 CIRCUIT DIAGRAMS

Calibration Circuit

Shown by Fig 13.1, the thermistor R_T is connected in series with a standard resistor R_s (equal to the room-temperature resistance of the thermistor for maximum sensitivity) across the DC supply V_{cc}. A millivoltmeter is connected in parallel with the thermistor to measure V_T. The thermistor probe is immersed in the water bath.

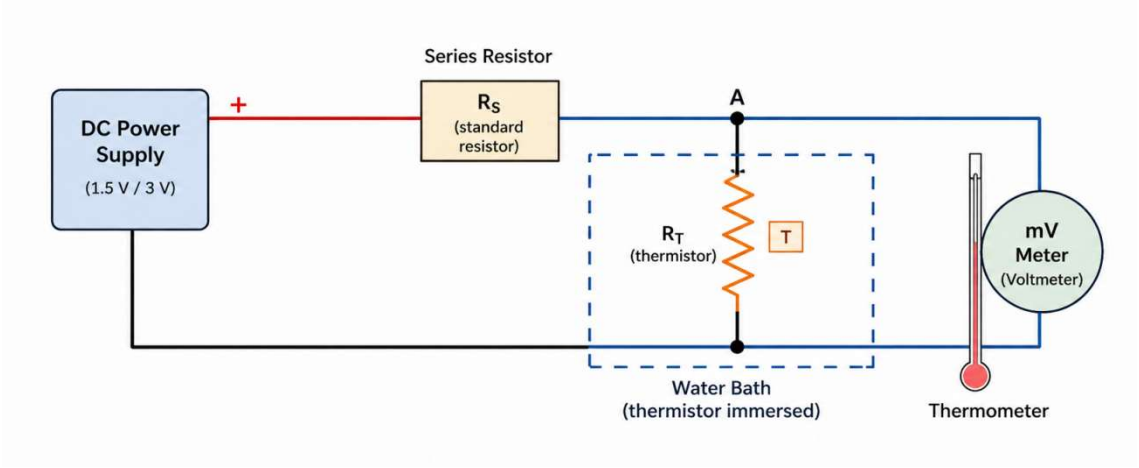


Figure 13.1: Thermistor Calibration Circuit

Calibration Curve

The expected calibration curve is shown below. V_T decreases monotonically as temperature increases, reflecting the NTC characteristic of the thermistor. To find an unknown temperature, locate the measured V_T on the Y-axis and read the corresponding temperature from the X-axis.

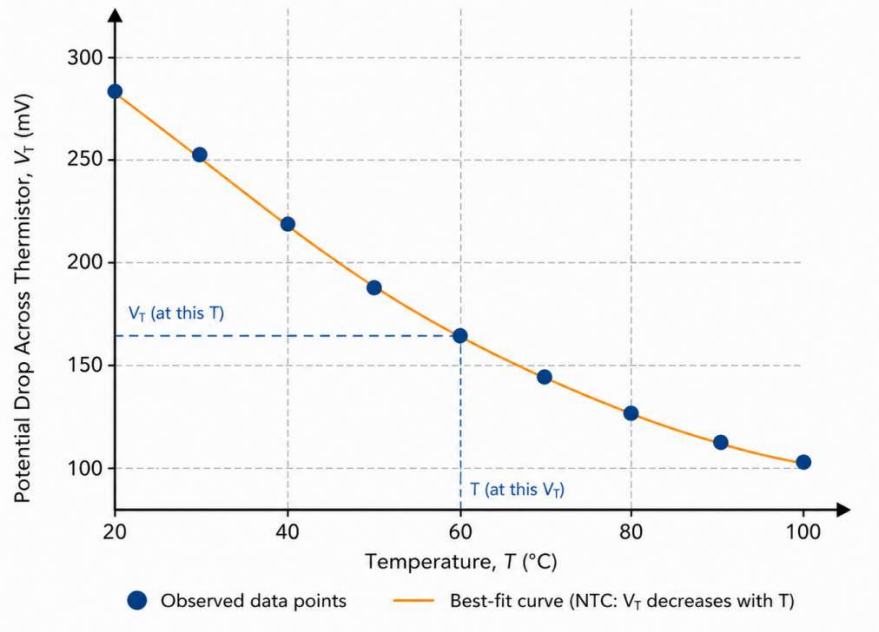


Figure 13.2: Calibration Curve: V_T (mV) vs Temperature T (°C)

Temperature Control Circuit

The Op-Amp (LM741) comparator circuit with thermistor, potentiometer, relay, and fly back diode. The relay contacts switch the 2000 W heater on the AC mains. All low-voltage signal circuitry is isolated from the 230 V AC side.

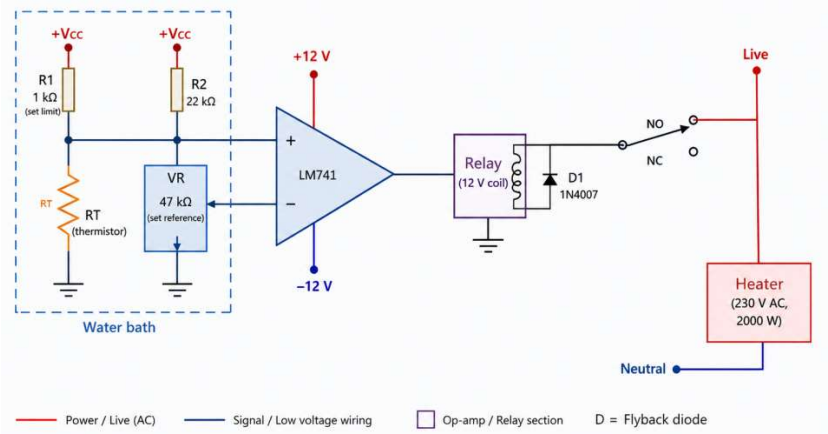


Figure 13.3: Op-Amp Comparator Temperature Control Circuit

13.5 PROCEDURE

Part A: Constructing the Calibration Curve

1. Circuit assembly**:** Make circuit connections as shown in Figure 13.1. Ensure the millivoltmeter has a high input impedance (>1 MΩ) to avoid loading the thermistor voltage divider.
2. Initial reading**:** Immerse the thermistor in the water bath at room temperature. Record the room temperature T (°C) and the potential drop V_T across the thermistor (mV). This is the first calibration point.
3. Heating**:** Switch on the heater. Increase the bath temperature in steps of approximately 5 °C. At each step, wait 2–3 minutes for the temperature to stabilise (confirmed when the thermometer reading is steady).
4. Record readings**:** At each stable temperature, simultaneously read T (°C) from the thermometer and V_T (mV) from the millivoltmeter. Enter both values in Observation Table 1.
5. Continue: Repeat until the bath reaches approximately 90–100 °C, collecting at least 10 data points.
6. Plot calibration curve**:** Plot V_T (mV) on the Y-axis against T (°C) on the X-axis. Draw a smooth best-fit curve through the data points. This is the thermistor's calibration curve (Figure 13.3).
7. Optional — R vs T characteristic**:** From each V_T reading, compute the thermistor resistance $R_T = R_S \times V_T / (V_{CC} - V_T)$. Plot ln R vs 1/T ($K^{-1}$) to obtain a straight line; determine β from the slope.

Part B: Temperature Control Circuit

1. Assemble circuit: Make connections as shown in Figure 13.2. Connect the Op-Amp with ±12 V supply. Ensure the relay is rated for 12 V coil, and the AC mains connections are made through a proper terminal block.
2. Set the reference voltage: Choose a desired set-point temperature T_{set}. From the calibration curve, read the corresponding voltage $V_T(T_{set})$. Adjust the 47 kΩ potentiometers until the voltage at the inverting (−) terminal of the Op-Amp equals this reference value.

3. Cold start: Begin with the bath at room temperature (well below T_{set}). The Op-Amp output should be at +12 V, the relay should be energised, and the heater should be ON.
4. Monitor temperature: Record the bath temperature every 3 minutes using the thermometer. Observe the relay clicking ON and OFF as the temperature approaches and oscillates around T_{set}.
5. Record steady state: Continue until the bath temperature stabilises around T_{set}. Record the temperature at each 3-minute interval in Observation Table 2.
6. Repeat for different set-points: Change T_{set} to a different value by adjusting the potentiometer. Confirm the circuit settles to the new set-point.

Determining Unknown Temperature

1. Place the thermistor in a medium of unknown temperature.
2. Measure V_T (mV) across the thermistor with the millivoltmeter.
3. Locate this voltage on the Y-axis of the calibration curve and read off the corresponding temperature T from the X-axis.
4. Verify by comparing with the thermometer reading.

13.6 OBSERVATIONS

Table 1: Thermistor Calibration — V vs T

Supply voltage V_{CC}: _____ V |Series resistor R_S: _____ kΩ |Room temperature T_{room}: _____ °C

Sl. No.	Room temp (°C)	Temperature of Heat Bath T (°C)	Potential Drop Across Thermistor V (mV)	Remarks
1				
2				
3				
4				
5				

Table 2: Resistance–Temperature Characteristic (for β determination)

Sl. No.	Temperature T (°C)	Thermistor Resistance R (Ω or kΩ)	lnR
1			
2			
3			
4			
5			
6			
7			
8			

Slope of ln R vs $1/T$ graph: β = _____K |R_0 at T_0 = 25 °C: _____ kΩ

Table 3: Temperature Control — Bath Temperature vs Time

Set-point temperature T_{set}: _____ °C | Reference voltage V_{ref}: _____ mV

Sl. No.	Set Temperature $\mathbf{T_{set}}$ (°C)	Time Elapsed (min)	Measured Bath Temperature T (°C)	Deviation ΔT (°C)
1				
2				
3				
4				
5				
6				
7				
8				

13.7 GRAPHS

Calibration Curve: V vs T

Plot the potential drop V_T (mV) on the Y-axis against temperature T (°C) on the X-axis. The expected shape is a smooth, monotonically decreasing curve — as temperature rises, the NTC thermistor's resistance decreases, reducing V_T. Draw the best-fit curve. From this curve, any unknown temperature can be determined given V_T.

ln R vs 1/T Plot (for β determination)

Plot ln R (Y-axis) against 1/T (K^{-1}) (X-axis). The expected result is a straight line. Determine the slope = β, the material constant of the thermistor.

13.8 CALCULATIONS

Thermistor Resistance from Voltage

At each temperature, the thermistor resistance is calculated from:

$$\boldsymbol{R_T} = \boldsymbol{R_S} \times \boldsymbol{V_T} \;/\; (\boldsymbol{V_{CC}} - \boldsymbol{V_T}) \qquad (13.6)$$

Material Constant β

From the slope of the ln R vs 1/T straight line:

$$\beta = slope = \Delta(ln\, R) \;/\; \Delta(1/T) \qquad (13.7)$$

Reference Voltage for Temperature Control

The potentiometer is set to the voltage corresponding to the set-point temperature T_{set}:

$$V_{ref} = V_T(\boldsymbol{T_{set}}) \text{ [read from calibration curve]} \qquad (13.8)$$

13.9. RESULT

Experimental Results

1. Calibration curve of the thermistor (V_T vs T) was plotted successfully.
2. Material constant of the thermistor: β = _____ K

3. Unknown temperature determined from calibration curve: T = _____ °C
4. Temperature maintained by the control circuit: T_{means} = _____ °C (Set: _____ °C)
5. Maximum steady-state deviation from set-point: ΔT = _____ °C

13.10 PRECAUTIONS

1. Stabilisation time: Allow the bath temperature to stabilise for at least 2–3 minutes at each step before recording readings. Rushing will give inaccurate calibration points.
2. High-impedance meter: Use a millivoltmeter or digital multimeter with input impedance > 1 MΩ to avoid loading the voltage divider and altering V_T.
3. Thermal contact: Ensure the thermistor bead is fully immersed in the water bath and the thermocouple/thermometer bulb is at the same depth for accurate temperature comparison.
4. Uniform stirring: Gently stir the water bath to ensure temperature uniformity. Temperature gradients within the bath cause systematic errors in calibration.
5. AC mains safety: The 2000 W heater operates on AC mains (230 V). All AC connections must be made through properly insulated terminals. Never touch live connections. Use a fuse in the mains circuit.
6. Flyback diode: Always include the 1N4007 flyback diode across the relay coil. Its absence will destroy the Op-Amp output stage with the inductive voltage spike when the relay turns off.
7. Op-Amp power supply: Connect the ±12 V supply correctly. Reverse polarity will damage the Op-Amp.
8. Potentiometer adjustment: Adjust the 47 kΩ potentiometer slowly and carefully to set V_{ref} precisely. Overshoot causes the heater to remain on or off for extended periods.
9. Temperature limit: Do not heat the water bath above 95 °C. Near-boiling water creates steam which can damage the thermistor leads and millivoltmeter probe

13.11 DISCUSSION

Sensitivity and Accuracy

The sensitivity of the thermistor (dV/dT, mV per °C) is highest near room temperature and decreases at elevated temperatures, because the resistance–temperature curve flattens at higher temperatures. This is visible as a changing slope in the calibration curve. For maximum measurement accuracy, the series resistor R_S should be chosen equal to the thermistor resistance at the mid-range temperature of interest.

On-Off vs Proportional Control

The Op-Amp comparator implements on-off (bang-bang) control: the heater is either fully ON or fully OFF. This leads to temperature oscillations (hunting) around the set-point, which is why a small steady-state deviation ΔT is observed. For smoother control

with lower overshoot, proportional-integral-derivative (PID) control would be used in practice. Positive feedback (hysteresis) can also be added to the comparator using a small resistor between the output and non-inverting input, creating a Schmitt trigger that prevents rapid relay chattering.

Alternative Switching Elements

Instead of an electromagnetic relay, a silicon-controlled rectifier (SCR) or a triac can be used as the switching element. These solid-state devices have no moving parts, switch faster, and do not produce audible clicks. The values of the circuit components (R_1, R_2) depend on the thermistor's resistance at room temperature and the gate trigger current and voltage of the SCR.

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13.13 ANSWER THE FOLLOWING QUESTIONS

1. What is a thermistor, and how does it differ from an ordinary resistor?
2. What is meant by Negative Temperature Coefficient (NTC) in thermistors?
3. Why does the resistance of an NTC thermistor decrease with increase in temperature?
4. What is the purpose of using a voltage divider circuit in this experiment?
5. Why is the V–T calibration curve non-linear for a thermistor?
6. What is the β (beta) constant, and how is it determined experimentally?
7. Why do we plot ln R versus 1/T, and what information does the slope provide?
8. What is the role of the Op-Amp comparator in the temperature control circuit?
9. Why is a relay used instead of directly connecting the heater to the Op-Amp?
10. Why does the temperature oscillate around the set-point instead of remaining exactly constant?

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