PREFACE

In a bid to standardize higher education in the country, the University Grants Commission (UGC) has introduced Choice Based Credit System (CBCS) based on five types of courses viz. *core, generic, discipline specific elective, ability and skill enhancement* for graduate students of all programmes at Honours level. This brings in the semester pattern which finds efficacy in sync with credit system, credit transfer, comprehensive continuous assessments and a graded pattern of evaluation. The objective is to offer learners ample flexibility to choose from a wide gamut of courses, as also to provide them lateral mobility between various educational institutions in the country where they can carry their acquired credits. I am happy to note that the university has been recently accredited by National Assessment and Accreditation Council of India (NAAC) with grade "A".

UGC (Open and Distance Learning Programmes and Online Programmes) Regulations, 2020 have mandated compliance with CBCS for U.G. programmes for all the HEIs in this mode. Welcoming this paradigm shift in higher education, Netaji Subhas Open University (NSOU) has resolved to adopt CBCS from the academic session 2021-22 at the Under Graduate Degree Programme level. The present syllabus, framed in the spirit of syllabi recommended by UGC, lays due stress on all aspects envisaged in the curricular framework of the apex body on higher education. It will be imparted to learners over the six semesters of the Programme.

Self Learning Material (SLMs) are the mainstay of Student Support Services (SSS) of an Open University. From a logistic point of view, NSOU has embarked upon CBCS presently with SLMs in English / Bengali. Eventually, the English version SLMs will be translated into Bengali too, for the benefit of learners. As always, all of our teaching faculties contributed in this process. In addition to this we have also requisioned the services of best academics in each domain in preparation of the new SLMs. I am sure they will be of commendable academic support. We look forward to proactive feedback from all stakeholders who will participate in the teaching-learning based on these study materials. It has been a very challenging task well executed, and I congratulate all concerned in the preparation of these SLMs.

I wish the venture a grand success.

Professor (Dr.) Subha Sankar Sarkar
Vice-Chancellor

NETAJI SUBHAS OPEN UNIVERSITY

Choice Based Credit System (CBCS)

Subject : Honours in Physics (HPH)

Course: Physics Laboratory-II

Course Code: CC-PH-02

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: Course Writer :

Unit 1-5, 8-9, 12-15: Dr. Pradip Kr. Datta
Retd. Reader of Physics,
Presidency College

Unit 6, 7, 11: Dr. Gautam Gangopadhyay
Professor of Physics,
University of Calcutta

Unit 10: Dr. Gahul Amin
Assistant Professor of Physics
Netaji Subhas Open University

: Course Editor :

Unit 1-5, 8-10, 12-15 : Dr. Gautam Gangopadhyay
Professor of Physics,
University of Calcutta

Unit 6, 7, 11: Dr. Pradip Kr. Datta
Retd. Reader of Physics,
Presidency College

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Under Graduate Degree Programme

Choice Based Credit System (CBCS)

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Unit 1 ❑ To draw the forward bias and reverse bias characteristics of a junction diode and to find the value of r_p in the active region

Structure

1.1 Objective

After reading this unit you will be able to

- find that a forward biased p-n junction diode carries current (of the order of mA)
- find that a reverse biased p-n junction diode carries a very small current (of the order of µA) upto a certain reverse voltage and then increases suddenly.
- draw the forward characteristic of a diode.
- draw the reverse characteristic of a diode.
- find the resistance r_p of a diode.

1.2 Introduction

A junction diode consists of two regions: p-region and n-region. If one side of a silicon or germanium crystal is doped with acceptor impurities (for example Boron, Indium) the portion becomes p-type and the if the other side is doped with donor impurities (for example Arsenic, Phosphorous) the portion becomes n-type. The junction between the p- and n- regions is called p-n junction and the crystal is called a p-n junction diode. If a battery is connected to the diode so that its p-region is connected to the positive terminal of the battery and the n-region to the negative terminal of the battery the p-n junction diode is said to be forward biased. Current flows through a forward biased p-n junction diode. Again, if the positive and negative terminals of the battery are connected to the n- and p-regions respectively the p-n junction diode is said to be reverse biased. In this case negligible current (of the order of microampere) flows through the diode. Fig.1.1 shows a p-n junction diode with its circuit symbol.

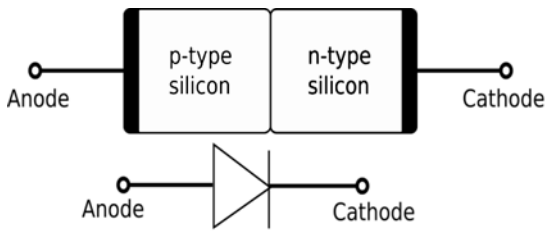


Fig.1.1 p-n junction diode with its circuit symbol

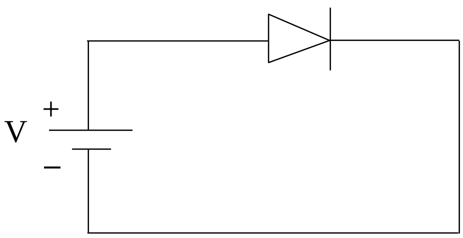


Fig. 1.2 Forward biased diode

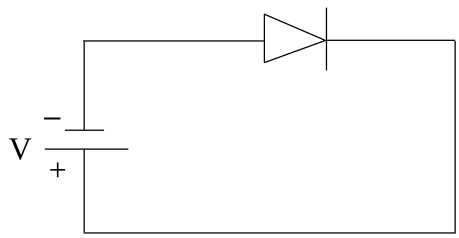


Fig.1.3 Reverse biased diode

1.3 Theory

(i) When the positive terminal of a voltage source is connected to the p-side of a diode and the negative terminal of the voltage source is connected to its n-side the diode is said to be forward biased (vide Fig. 1.2). The graph showing the variation of the diode current with the voltage across the diode is called the forward static characteristic of the diode.

If V is voltage across the diode, the diode current I is given by

$$I = I_s\left[\exp\left(\frac{eV}{\eta kT}\right) - 1\right], \text{ .... (1)}$$

where I_s = the reverse saturation current, e = electronic charge, k = Boltzmann constant, T = absolute temperature, η = a constant depending on the material of the diode (for Ge, η =1 and for Si, η = 2).

The dc resistance of the diode for a current I is $r_{dc} = \frac{V}{I}$, ...(2)

where V is the voltage across the diode.

The ac or the dynamic resistance of the diode for current I is

$$r_p = \frac{\Delta V}{\Delta I} \text{ .... (3)}$$

that is r_p is the reciprocal of the slope of the static characteristics at the given diode current I. When the diode is sufficiently forward biased eqn. (1) can be written approximately as

$$I = I_s \exp\left(\frac{eV}{\eta kT}\right) \quad \text{or,} \quad \frac{eV}{\eta kT} = \ln\left(\frac{I}{Is}\right)$$

So $r_p = \eta \frac{26}{I}$ .... (4), if I is in mA, r_p is in ohm.

(ii) When the positive terminal of a voltage source is connected to the n-side of a diode and the negative terminal of the voltage source is connected to its p-side the diode is said to be reverse biased (vide Fig.1.3). The graph showing the variation of the diode current with the reverse voltage across the diode is called the reverse characteristic of the diode. Upto a certain reverse bias the current through the diode is negligibly small and is called reverse saturation current. At a certain reverse bias the current suddenly increases. This is called breakdown and the voltage is called breakdown voltage. The ac resistance of the diode before breakdown is very high and after breakdown it is a few ohms.

1.4 Apparatus required

(i) a semiconductor diode, (ii) variable dc voltage source or a fixed voltage source with a variable resistance potentiometer, (iii) dc milli-ammeter, (iv) dc micro-ammeter, (v) dc voltmeter.

1.5 Experimental Procedure

1.5.1 To draw the static forward characteristic

1. Construct the circuit as shown in Fig.1.4 (if a variable voltage source is not available). If a variable voltage source is available connect the positive and negative terminals of the source to the p-side and n-side of the diode respectively. Switch on the voltage source.

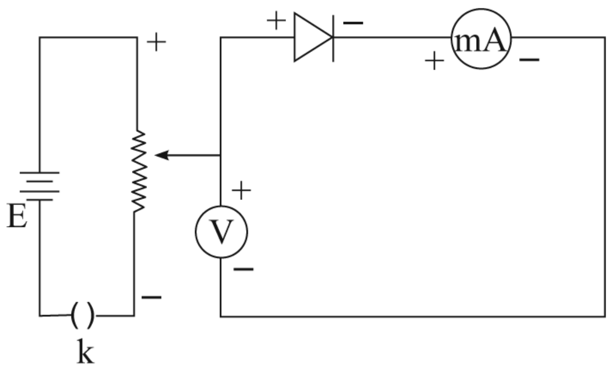


Fig.1.4 Circuit for forward characteristic

2. Slowly increase the input voltage from zero in suitable steps upto 2.0 V. In each step record the voltage across the diode by the voltmeter V and the diode current by the milliammeter mA. It can be noted that, initially the current increase very slowly. For a certain value of voltage, it shows a sharp increase. The corresponding voltage represents the knee voltage or threshold voltage of the diode.
3. Repeat the process by decreasing the input voltage in steps (as in step 2 above) and record the voltage across the diode and the diode current. Take the mean of diode currents for increasing and decreasing input voltages.

4. Draw the static forward characteristic by plotting the diode voltage along X-axis and the diode current along the Y-axis. The nature of the curve will be similar to that shown in Fig.1.5.
5. For a given value of the diode current, determine the dc and ac resistances, r_{dc} and r_p respctively, from the forward characteristics using equs.(2) and (3).
6. Compare the value of r_p determined in step 5 above and the theoretical value using eq. (4).

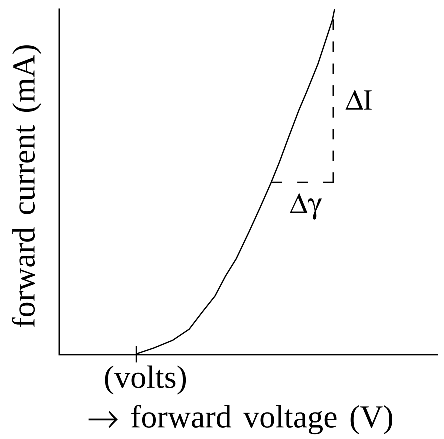


Fig.1.5 Nature of forward characteristic

Experimental Results

Table 1

Specification of the diode and the meters		
Diode type and Specifications	Milliammeter	Voltmeter
No.....	Range.....	Range ....
Max. diode current =	Smallest div. =	Smallest div =

Table 2

Data for static forward characteristic

Diode voltage (V_f) (in volt)	Diode current I_f (in mA)		Mean $I_f = (I_1 + I_2)/2$ (in mA)
	Increasing $V_f(I_1)$	Decreasing $V_f(I_2)$	
....	....	....	....
....	....	....	....
etc.	etc.	etc.	etc.

Table 3

Determination of diode dc and ac resistances

Given diode current I_f (in mA)	Corresponding diode voltage V_f from graph (in V)	Change ΔV in V_f from graph (in V)	Corresponding change ΔI in I_f from graph (in mA)	r_{dc} $=V/I$ (in ohm)	r_p $= \Delta V/\Delta I$ (in ohm)	Expected $r_p = \eta 26/I$ (in ohm)
...	...	...	...	...	...	...

1.5.2 To draw the reverse characteristic

1. Construct the circuit as shown in Fig.1.6. Switch on the voltage source.
2. Slowly increase the input voltage from zero in suitable steps. The current increases slowly in the beginning and then rapidly when the reverse voltage attains a certain value. This voltage is known as the reverse breakdown voltage V_B.
3. In each step record the voltage across the diode by the voltmeter V and the diode current by the micro-ammeter μA.
4. Draw the reverse characteristic by plotting the diode voltage along X-axis and the diode current along the Y-axis. The nature of the curve will be similar to that shown in Fig.1.7.
5. For given values of the diode current (one before breakdown and one in the breakdown region), determine the ac resistance, r_p, from the reverse characteristics using equ. (3).

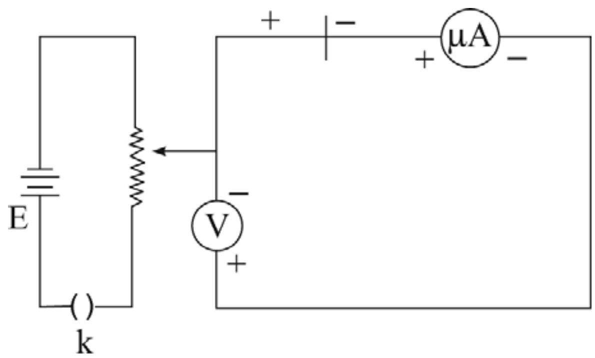


Fig.1.6 Circuit for reverse characteristic

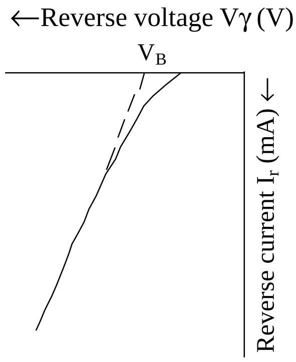


Fig.1.7 Nature of reverse characteristic

Experimental Results

Table 4

Specification of the diode and the meters

Diode type and Specifications	Microammeter	Voltmeter
No….. Max. reverse current =	Range….. Smallest div. =	Range…. Smallest div =

Table 5

Data for reverse characteristic

Reverse voltage V_r (in V)	Reverse current I_r (in μA)
…	…
…	…
…	…
…	…
etc.	etc.

Table 6

Determination of ac resistance r_p before and after breakdown

Diode current (in μA)	Change ΔV in V_r from graph (in V)	Corresponding change ΔI in I_r from graph (in μA)	$r_p = \Delta V/\Delta I$ (in ohm)
… (before breakdown)	…	…	…
… (after breakdown)	…	…	…

1.6 Discussions

1. The connections have to be checked properly before switching on the supply.
2. While increasing the voltage across the diode care must be taken that the maximum current through the diode is not exceeded.
3. The experimental value of r_p and its expected value are nearly equal.
4. In case of reverse bias the ac resistance of the diode is high before breakdown and small after breakdown.

1.7 Summary

You have learnt what are meant by the forward and reverse characteristics of a junction diode. The forward and reverse characteristics drawn on the same graph paper is shown in Fig.1.8.

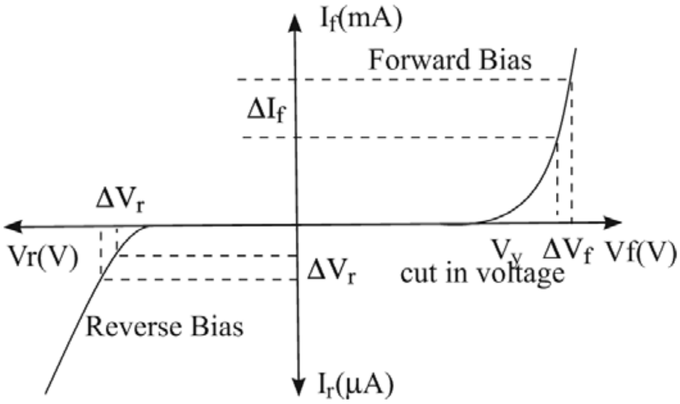


Fig. 1.8

The diode equation is given by:

$I = I_s$ [exp (eV/(ηkT) -1],where V is voltage across the diode, I is the diode current, I_s = the reverse saturation current, e = electronic charge, k = Boltzmann constant, T = absolute temperature, η = a constant depending on the material of the diode (for Ge η =1 and for Si η = 2).

The dc resistance of the diode for a current I is r_{dc}= V/I , where V is the voltage across the diode.

The ac or the dynamic resistance of the diode for current I is $r_p = \Delta V/\Delta I$.

You have also learnt how to determine experimentally the forward and reverse characteristics of a diode and to find the dc and ac resistances of a diode.

1.9 Exercise

1. What is a p-type semiconductor?
2. What is an n-type semiconductor?
3. Name two donor impurities and two acceptor impurities.
4. What is a p-n junction diode?
5. What is meant by forward bias?
6. What is meant by reverse bias?
7. What is meant by forward characteristic of a junction diode?
8. What is meant by reverse characteristics of a junction diode?
9. What are meant by dc and ac resistances of a junction diode?
10. What will happen if the reverse bias of a p-n junction diode is gradually increased?
11. What is reverse saturation current of a junction diode?
12. What is the use of a junction diode?
13. Is the ac resistance of a junction diode greater under reverse bias condition than that under forward bias condition?
14. Why does the ac resistance of a junction diode differ from the dc resistance?

1.9 Answers

1. If a semiconductor crystal is doped with acceptor impurities, it is called a p-type semiconductor.
2. If a semiconductor crystal is doped with donor impurities, it is called an n-type semiconductor.

3. Donor impurities: arsenic, phosphorous, acceptor impurities: boron, indium.

4. A junction diode consists of two regions: p-region and n-region. If one side of a silicon or germanium crystal is doped with acceptor impurities (for example boron, indium) the portion becomes p-type and the if the other side is doped with donor impurities (for example arsenic, phosphorous) the portion becomes n-type. The junction between the p- and n- regions is called p-n junction and the crystal is called a p-n junction diode.

5. If a battery is connected to the diode so that its p-region is connected to the positive terminal of the battery and the n-region to the negative terminal of the battery the p-n junction diode is said to be forward biased.

6. If a battery is connected to the diode so that its n-region is connected to the positive terminal of the battery and the p-region to the negative terminal of the battery the p-n junction diode is said to be reverse biased.

7. The graph of forward current vs. forward voltage is called the forward characteristic of the diode.

8. The graph of reverse current vs. reverse voltage is called the reverse characteristic of the diode.

9. The dc resistance of the diode for a current I is $r_{dc} = V/I$, where V is the voltage across the diode. The ac or the dynamic resistance of the diode for current I is $r_p = \Delta V/\Delta I$.

10. If the reverse bias of a p-n junction diode is gradually increased the reverse current remains initially and then increases abruptly a certain value of the reverse bias voltage. This occurs due to the breakdown in the junction diode.

11. When a p-n junction diode is reversed biased extremely small current flows through the diode due to the minority carriers. This current is called the reverse saturation current.

12. Since the diode conducts when it is forward biased and does not conduct when it is reverse biased it is used as a rectifier (which converts ac to dc).

13. Yes. the ac resistance of a junction diode under reverse bias condition is much greater than that under forward bias condition (when forward as voltage greater than the knee voltage).

14. The ac resistance of a junction diode differs from the dc resistance because the diode characteristic is non-linear.

1.10 References

1. An advanced Course in Practical Physics, D. Chattopadhyay and P.C. Rakshit, New Central Book Agency(P) Ltd., Kolkata

2. Advanced Practical Physics, Basudev Ghosh, Sreedhar Publishers, Kolkata

Unit 2 ❑ To draw the Zener Diode characteristics in forward bias and reverse bias conditions and find the breakdown voltage and the breakdown current

Structure

2.1 Objective

After reading this unit you will be able to

- find that a reverse biased Zener diode carries a very small current (of the order of μA) till a certain reverse bias, called the Zener breakdown voltage and then increases, but the voltage across the Zener diode remains practically unchanged.
- draw the forward characteristic of the Zener diode.
- draw the reverse characteristic of the Zener diode.
- find the breakdown voltage.

- find that the ac resistance of the Zener diode is very high before breakdown and very small after breakdown.

2.2 Introduction

A Zener diode is a particular type of diode that, unlike a p-n junction diode, allows current to flow not only from its anode to its cathode, but also in the reverse direction, when the Zener breakdown voltage is reached.

A Zener diode has a highly doped p-n junction. Ordinary p-n junction diodes will also break down with a reverse voltage but the voltage and sharpness of the knee are not as well-defined as for a Zener diode. Also p-n junction diodes are not designed to operate in the breakdown region, because the diode will be permanently damaged due to over-heating. But Zener diodes are specially designed to operate in this region. A diode with a Zener breakdown voltage of V_z exhibits a voltage drop of very nearly to V_z across a wide range of reverse currents.The Zener diode is therefore ideal for applications such as the generation of a reference voltage or as a voltage stabilizer for low-current applications. Though the Zener diode is not used in forward bias condition you may draw its forward characteristic only to show that the forward characteristic of a Zener diode and that of an ordinary p-n junction diode have the same nature. The circuit symbol of a Zener diode is shown in Fig. 2.1.

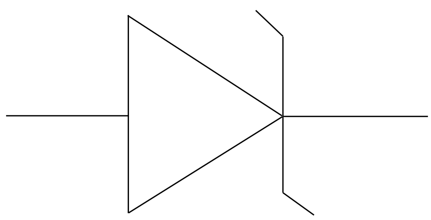


Fig. 2.1 Circuit symbol of a Zener diode

2.3 Theory

(iii) When the positive terminal of a voltage source is connected to the p-side of a diode and the negative terminal of the voltage source is connected to its n-side, the diode is said to be forward biased (Fig.2.2). The graph showing the variation of the diode current with the voltage across the diode is called the forward characteristic of the diode.

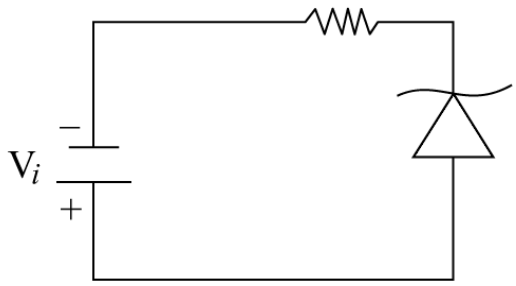


Fig. 2.2 Forward biased Zener diode

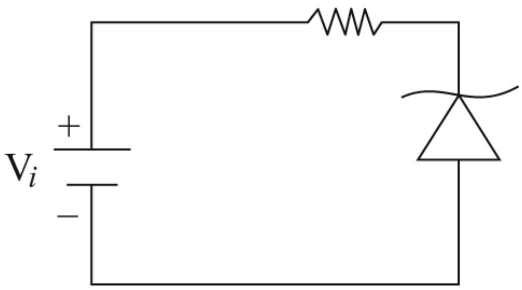


Fig.2.3 Reverse biased Zener diode

(iv) When the positive terminal of a voltage source is connected to the n-side of a diode and the negative terminal of the voltage source is connected to its p-side, the diode is said to be reverse biased (Fig.2.3). If the reverse voltage is increased from 0, the current through the diode is very small upto a certain reverse voltage after which the current sharply increases. This reverse voltage is called the breakdown voltage and the diode is said to be operating in the breakdown region. The diode current before breakdown is called reverse saturation current. The graph showing the variation of the diode current with the voltage across the Zener diode is called the reverse characteristic of the diode.

The ac or the dynamic resistance of the Zener diode for a current I_z is given by the slope of the reverse characteristic at I_Z. That is $r_{ac} = \frac{\Delta V_z}{\Delta I_z}$.

2.4 Apparatus

(i) A Zener diode (typically 3Z6.2 V, 3 Z 5.7 V), (ii) a variable dc voltage source (typically 0 – 10 V), (iii) a dc voltmeter (range 0–2V), (iv) two dc voltmeters (range 0–10 V), (v) a dc milliammeter (range 0–50 mA), (vi) resistors.

[Note: a Zener diode 3Z6.2 V means its breakdown voltage is typically 6.2 V, wattage is 3W]

2.5 Experimental Procedure

2.5.1 To draw forward characteristics

1. Construct the circuit as shown in Fig.2.4. Set R_s to a suitable value. Switch on the voltage source.

2. Slowly increase the input voltageV_i from zero in suitable steps upto 2.0 V. In each step record the voltage V_f across the diode by the voltmeter V and the diode current I_f by the milliammeter mA. It can be noted that, initially the current increase very slowly. For a certain value of voltage, it shows a sharp increase. The corresponding voltage represents the knee voltage or threshold voltage of the diode.

3. Repeat the process by decreasing the input voltage in steps (as in step 2 above) and record the voltage across the diode and the diode current. Take the mean of diode currents for increasing and decreasing input voltages.

10. Draw the static forward characteristic by plotting the diode voltage along X-axis and the diode current along the Y-axis. The nature of the curve will be similar to that shown in Fig.2.5

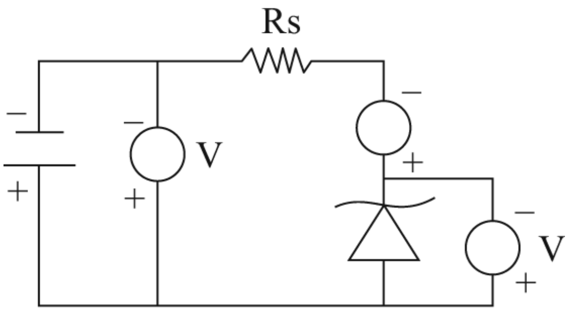


Fig. 2.4 Circuit for forward characteristic

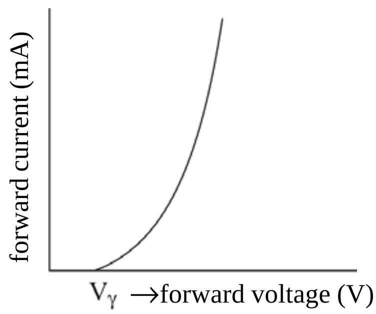


Fig.2.5 Nature of forward characteristic

Experimental Results

Table 1

Specification of the diode and the meters

Diode type and Specifications	Milliammeter	Voltmeter
No….. Max. diode current =	Range….. Smallest div. =	Range …. Smallest div. =

Table 2

Data for forward characteristic

$R_s = \ldots\ \Omega$

Diode voltage (V_f) (in volt)	Diode current I_f (in mA)		Mean $I_f = (I_1 + I_2)/2$ (in mA)
	Increasing V_f (I_1)	Decreasing V_f (I_2)	
….	….	….	….
….	….	….	….
….	….	….	….
….	….	….	….
etc.	etc.	etc.	etc..

2.5.2 To draw reverse characteristics

1. Construct the circuit as shown in Fig.2.6. (In the circuit R_s is the current limiting resistance.) Determine the value of R_s as follows:

   The maximum allowable Zener current (say I_{zm}) = wattage of the Zener diode / Zener breakdown voltage. If V_i is the maximum input voltage and V_z is the breakdown voltage, $R_s = (V_i - V_z)/ I_{zm}$.The wattage of R_s would be$(V_i - V_z) \times I_{zm}$[For example, for a 3Z 6.2 V Zener diode, I_{zm} = 3/6.2 = 484 mA. Use I_{zm} = 460 mA. If V_i = 10 V, R_s = (10 – 6.2)/0.460 Ω = 8.3 Ω. Use R_s = 10 Ω. The wattage of R_s would be (10 – 6.2) × 0.46 = 1.75 W]

   If, however, the wattage of the Zener diode (W) and the Zener test current (I_{zT}) is given, determine the approximate value of Zener breakdown voltage (V_z) as follows:

   $I_{zT} V_Z$ = (1/4) W, since I_{zT} is approximately one-fourth of I_{zm} . Then proceed as discussed above.

2. Switch on the voltage source.
3. Slowly increase the input voltage from zero in suitable steps. The current increases slowly in the beginning and then rapidly when the reverse voltage becomes a certain value. This voltage is known as the reverse breakdown voltage V_B.

4. In each step record the input voltage V_i by the voltmeter V_1, voltage drop V_s across resistance R_s by the voltmeter V_2 and the diode current I_z by the milliammeter mA. Calculate V_z in each case using the equation $V_z = V_i - V_s$. However, if digital voltmeter or multimeter is used (which have high resistance) V_z can be measured directly and there is no need to measure V_i and V_s.)
5. Draw the reverse characteristic by plotting the diode voltage along X-axis and the diode current along the Y-axis. The nature of the curve will be similar to that shown in Fig.2.7.
6. Specify the breakdown voltage and breakdown region.
7. Determine r_{ac} for one Zener current before breakdown and one Zener current after breakdown.

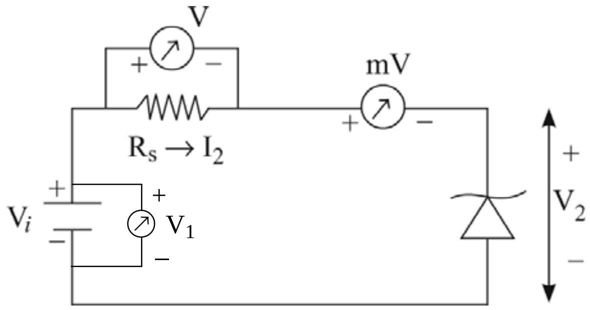


Fig. 2.6 Circuit for reverse characteristic

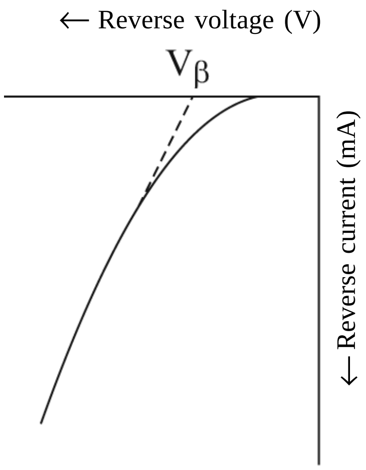


Fig. 2.7 Nature of reverse characteristic

Table 3

Specification of the diode and the meters

Diode type and Specifications	Milliammeter	Voltmeter V_1	Voltmeter V_2
No…..	Range…..	Range…..	Range…..
Max. diode current =	Smallest div. =	Smallest div. =	Smallest div. =

Table 4

Data for reverse characteristic

Calculate R_s as stated in step 1 above.

Input Voltage (V_i) (in Volt)	Voltage drop V_s across R_s (in Volt)	Zener Voltage $V_z = V_i - V_s$ (in Volt)	Zener current I_z (in mA)
….	….	….	….
….	….	….	….
….	….	….	….
etc.	etc.	etc.	etc.

(If digital voltmeter/multimeter is used the first two columns are not required.)

From graph, the Zener breakdown voltage is …. Volt and the breakdown region is shown in the graph.

Table 5

Determination of r_{ac}

I_z (in mA)	Corresponding V_z from graph (in Volt)	ΔV_z from graph (in Volt)	ΔI_z from graph (in mA)	$r_{ac} = \frac{\Delta V_2}{\Delta I_2}$ (in ohm)
(before breakdown)...	…	….	…	…
(after breakdown)...	…	….	…..	…

2.6 Discussions

1. The connections have to be checked properly before switching on the perior supply.
2. While increasing the voltage across the diode care must be taken that the maximum current through the diode is not exceeded.
3. A limiting resistance R_s of proper value and wattage must always remain connected in the circuit to avoid burn-out of the Zener diode.

4. Since the reverse saturation current is of the order of μA, and a milliammeter is used for measuring Zener current, the Zener current observed before breakdown is zero.
5. It is found that the ac resistance of the Zener diode is very high near breakdown and very small after breakdown.
6. It is preferable not to measure Zener voltage directly using an ordinary voltmeter, because after breakdown the change in Zener voltage is very small and would not be detected with a voltmeter of range 0 – 10 V. But since voltage across R_S is less than 4 V, voltmeter with finer scale division can be used to detect the small change in Zener voltage.

2.7 Summary

In this unit you have learnt how a Zener diode differs from a p-n junction diode and how to draw the forward characteristic and reverse characteristic of the Zener diode. Also it has been discussed how to find the ac resistance of the Zener diode in reverse biased condition, the Zener breakdown voltage from the reverse characteristic.

2.8 Exercises

1. How does a Zener diode differ from a p-n junction diode?
2. What is the use of a Zener diode?
3. What is Zener breakdown voltage?
4. Why is a current limiting resistance required to be used for drawing reverse characteristic ?
5. How is a Zener diode used to construct a regulated voltage source?
6. What is reverse saturation current?
7. How is limiting resistance determined?
8. Why is the Zener voltage measured indirectly using two voltmeters?
9. Why can the Zener voltage be measured directly using a digital voltmeter or multimeter?
10. Mention one application of a Zener diode.

11. What is a voltage regulator?
12. Is a full-wave rectifier with filter can be considered a voltage regulator?

2.9 ANSWERS

1. Zener diodes have a highly doped p-n junction.Other p-n junction diodes will also break down with a reverse voltage but the voltage and sharpness of the knee are not as well defined as for a Zener diode. Also p-n junction diodes are not designed to operate in the breakdown region, because the diode will be permanently damaged due to over-heating. But Zener diodes are specially designed to operate in this region. A diode with a Zener breakdown voltage of Vz exhibits a voltage drop of very nearly to Vz across a wide range of reverse currents.
2. The Zener diode is used for the generation of a reference voltage or as a voltage stabilizer for low-current applications.
3. If the reverse voltage across the Zener diode is increased initially the current through the diode is very small. But at a certain reverse biasV_z the current increases sharply, though the voltage across the diode changes very slightly. This value of the reverse bias is called Zener breakdown voltage.
4. The input voltage is greater than the Zener breakdown voltage. The limiting resistance is used so that the extra voltage is dropped in it. If the resistance is not used excessive current will flow through the diode and it will be permanently damaged due to overheating.
5. If a load resistance R_L is connected across the Zener diode in reverse bias condition (as shown in Fig. 2.8 below) the voltage across the resistance R_L becomes practically independent of the load current because the voltage across the Zener diode remains practically constant.
6. The current through a reverse biased Zener diode before breakdown is independent of the reverse voltage and is called reverse saturation current.
7. See serial number 1 of Sec. 2.5.2.
8. The resistance of ordinary voltmeters is not very high. So if such a voltmeter isused to measure the Zener voltage it will draw some current. So the current through the milliammeter will be sum of the currents through the

Zener diode and the voltmeter and there will be error in the measurement of Zener current. So the input voltage V_i and the voltage drop across R_s are measured by two separate voltmeters and this difference gives the zener voltage.

9. The resistance of digital voltmeters and multimeter is very high (of the order of MΩ) and the meters draw negligible current. So there is no error in the measurement of Zener current and the voltage across the Zener diode can be measured directly. .

10. Reverse biased Zener diode can be used as a voltage regulator. Since after breakdown the Zener voltage is practically constant irrespective of the current through it, the voltage across the load resistance R_L in the circuit of Fig. 2.8 remains practically constant whatever be the value of the load current.

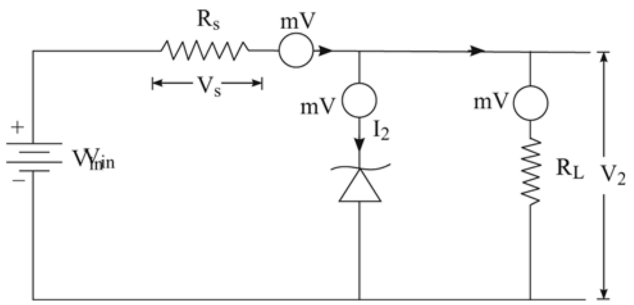


Fig. 2.8. Zener voltage regulator

11. A voltage regulator is a voltage source, the voltage of which remains unchanged irrespective of the current drawn from it.

12. Since in a unregulated voltage source has an internal resistance, the voltage across the load connected to the source decreases when the load current is increased by decreasing the load resistance due to internal drop of potential. But in a regulated voltage source the load voltage remains unchanged when the load current is increased.

2.10 References

1. An advanced Course in Practical Physics, D. Chattopadhyay and P.C. Rakshit, New Central Book Agency(P) Ltd., Kolkata

2. Advanced Practical Physics, Basudev Ghosh , Sreedhar Publishers, Kolkata

Unit 3 ❑ To verify Thevenin, Norton and the Maximum power transfer theorems

Structure

3.1 Objective

In this unit we will be acquainted with Thevenin's theorem, Norton's theorem and Maximum power transfer theorem and will learn to verify the theorems experimentally. We will use an unbalanced Wheatstone bridge to verify the theorems.

3.2 Introduction

An interconnection of current-carrying devices, such as resistor, capacitor, inductor etc., with voltage and/or current sources providing closed paths for the flow of electric current is called an electric circuit or network. A network consisting of linear circuit elements is called a linear network. (A circuit element in which the current- voltage relationship is linear, such as a resistor, inductor, capacitor, is termed as a linear circuit element.) Simple networks can be analysed by Kirchhoff's laws. But in case of complex networks the analysis using Kirchhoff's laws is difficult. To facilitate the analysis of such networks electric circuit theorems are used. These theorems use fundamental rules or formulas and basic equations of mathematics to analyze voltages, currents, resistance, and so on. These fundamental theorems include the basic theorems like Thevenin's theorem, Norton's theorem, Maximum power transfer theorem, Superposition theorem etc..

3.3 Thevenin's theorem

In a linear circuit the current passing through a load impedance is the same as that supplied by a single voltage source V_{TH} having internal impedance R_{TH}, where V_{TH} is the open-circuit voltage across the load terminals and R_{TH} is the impedance of the circuit looking back from the load terminals when all the energy sources are replaced by their internal impedances.

3.3.1 Verification of Thevenin's theorem

3.3.2 Theory

Let us consider the circuit given in Fig, 3.1.The resistances of the four arms of the Wheatstone bridge are R_1, R_2, R_3 and R_4. R_L is the load resistance connected across the terminals 1 and 2. To calculate V_{TH} we have to disconnect the load resistance R_L. Then the potential difference between the points 1 and 2 is the Thevenin voltage. Hence, $V_{TH} = V_i\left(\frac{R_3}{R_1+R_3} - \frac{R_4}{R_2+R_4}\right)$......... (1).

To calculate R_{TH} we have to disconnect the load resistance R_L and disconnect the voltage source V_i and short the terminals 3 and 4 (assuming that the voltage source has negligible resistance). Then the resistance between the terminals 1 and 2 is the Thevenin resistance. Hence,

$$R_{TH} = \frac{R_1R_3}{R_1+R_3} + \frac{R_2R_4}{R_2+R_4} \quad \ldots\ldots (2)$$

The Thevenin equivalent of the network left to the points 1 and 2 is as shown in Fig. 3.2. By Thevenin theorem the load current I_L in Fig.3.1 is the same as that flowing in Fig. 3.2. In Fig. 3.2 the load voltage V_L is given by $V_L = V_{TH} - I_L R_{TH}$ …… (3)

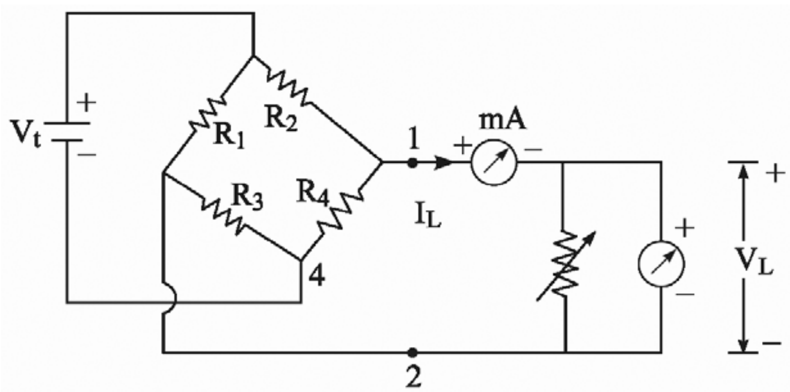


Fig. 3.1 Circuit for verification of Thevenin and Norton theorems

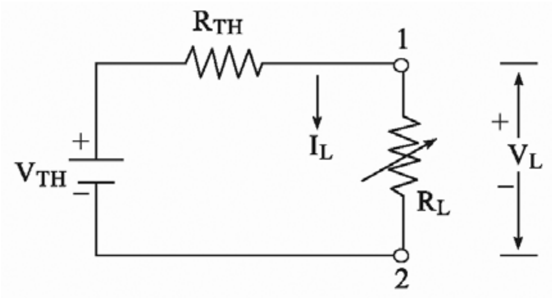


Fig. 3.2 Thevenin equivalent of the network of Fig.3.1

Thus the plot of V_L vs. I_L is a straight line of intercept V_{L0} on the V_L axis and slope $-R_{TH}$.(Fig. 3.3)

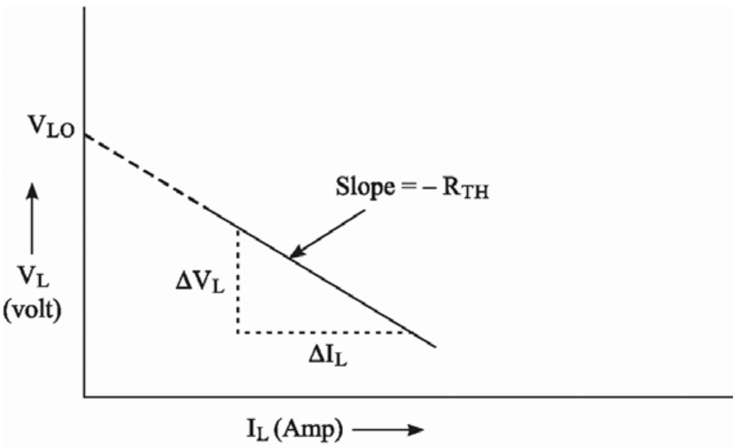


Fig. 3.3 $V_L - I_L$ graph

In the experiment, different values of R_L are taken in Fig. 3.1 and for each R_L the load voltage V_L and the load current I_L are measured. A graph is plotted with I_L as abscissa and V_L as ordinate. The graph is a straight line. By extrapolation of the line to the ordinate V_{L0} and slope of the line are determined. The voltage (V_0) across the terminals 1 and 2 are measured after removing R_L from the circuit in Fig.3.1. The calculated value of V_{TH}, V_0 and V_{L0} obtained from Fig.3.3 are found to be equal. Again, the resistance (R) between the terminals 1 and 2 is measured by a multimeter with the voltage source V_i removed from the circuit of Fig. 3.1, and its terminals 3 and 4 shorted. It will be found that R, calculated value of R_{TH} and the magnitude of the slope of the line in Fig. 3.3 are equal. This proves the Thevenin theorem.

3.3.3 Apparatus

(1) A regulated power supply (2) colour-code resistances or a P.O. Box (3) bread board (4) a dc voltmeter or a multimeter (5) a milliammeter (6) carbon potentiometer.

3.3.4 Experimental Procedure

1. Set up the circuit as shown in Fig. 3.1. Set R_L to a high value.
2. Switch on the power supply and set its output voltage V_i to a convenient value (say, 10 V).Keep the voltage constant throughout the experiment.
3. By a dc voltmeter or a multimeter measure the voltage V_L across R_L and measure the load current I_L by a milliammeter. If milliammeter is not available calculate I_L by the equation $I_L = \frac{V_L}{R_L}$.
4. Keeping V_i constant decrease R_L several times in suitable steps and repeat Step 3.
5. Plot V_L- I_L graph and find the intercept V_{L0} and the slope R_{TH} of the graph.
6. Keeping V_i unchanged, disconnect R_L and measure the open circuit voltage V_0 across the terminals 1 and 2 using a multimeter or digital voltmeter.
7. Disconnect the power supply, short the terminal 3 and 4, disconnect the load resistance R_L and measure the resistance R between the terminals 1 and 2.
8. Calculate the values of V_{TH} and R_{TH} using equations (1) and (2)
9. It will be found that the calculated value of V_{TH}, V_{L0} and V_0 are equal. Also calculated value of R_{TH}, R and the slope of $V_L - I_L$ graph are equal. This verifies Thevenin theorem.

3.3.5 Experimental Data

Table 1

Data for $V_L - I_L$ graph

Supply voltage V_i = …….Volt

Load resistance R_L (in Ω)	Load voltage V_L (in Volt)	Load Current I_L (in mA)
∞	….	….
….	….	….
etc.	etc.	etc.

Table 2

Determination of the slope and the intercept of the $V_L - I_L$ graph

Intercept on the V_L axis V_{L0} (in Volt)	ΔV (in Volt)	ΔI (in mA)	Slope $R_0 = \frac{\Delta V}{\Delta I}$ (in Ω)
…	…	…	…

Table 3

Direct measurement of V_{TH} and R_{TH}

Supply voltage V_i = …….Volt

V_{TH} (in Volt)	R_{TH} (in Ω)
…	…

Table 4

Verification of Thevenin theorem

Calculated value of V_{TH} (in Volt)	V_{L0} (from Table 2) (in Volt)	Measured value of V_{TH} (from Table 3) (in Volt)	Calculated value of R_{TH} (in Ω)	Slope R_{TH} (from Table 2) (in Ω)	Measured value of R_{TH} (from Table 3) (in Ω)	Remarks
…	…	…	…	…	…	Calculated value of $V_{TH} = V_{L0}$ = measured value of V_{TH} and Calculated value of $R_{TH} = R_{TH}$ = measured value of R_{TH}. Hence Thevenin theorem is verified.

3.3.6 Discussions

1. The values of the resistances in the four arms of the Wheatstone bridge must be such that V_{TH} is of appreciable value and R_{TH} is low so that I_L is high and the accuracy of the measurements of V_L and I_L is increased.
2. The internal resistance of the voltmeter should be high. For this purpose it is preferable to use a digital voltmeter or a multimeter.
3. The voltage source must have very low internal resistance as we have assumed its resistance to be zero.
4. The voltage of the voltage source should be checked every time before taking readings so that it can be kept constant.
5. The wattage of the resistances used should be such that they do not get heated during the experiment so that the value of the resistances do not change significantly.

3.4 Norton's theorem

3.4.1 Theory

In a linear circuit the current passing through a load impedance is the same as that supplied by a single current source I_N in parallel with an impedance R_N, where I_N is the short-circuit current at the load terminals and R_N is the impedance of the circuit looking back from the load terminals when all the energy sources are replaced by their internal impedances.

Refer to the circuit of Fig. 3.1. By Norton's theorem the load current I_L in Fig. 3.1 is the same as that flowing in Fig. 3.4, where I_N is the short-circuited current through the load terminals 1 and 2 in Fig. 3.1 and R_N is the input resistance looking back at the terminals 1 and 2 of Fig. 3.1 with the voltage source removed and the terminals 3 and 4 short-circuited. In Fig. 3.4 the load current I_L is $I_L = I_N - \frac{V}{R_N}$ … (4) where V_L is the load voltage. The plot of I_L against V_L is a straight line of slope $-1/R_N$ and of intercept I_0 on the ordinate.

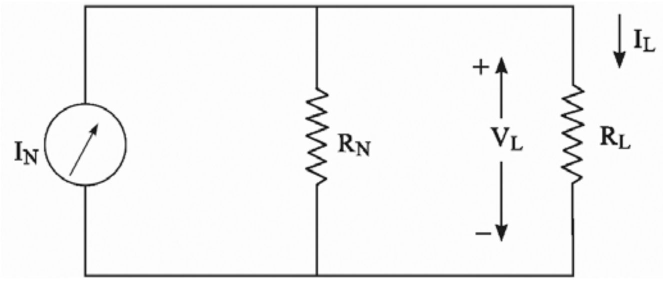


Fig. 3.4 Norton equivalent of the circuit of Fig.3.1

Different values of R_L are used in Fig. 3.1 and for each R_L the load voltage V_L is measured by a dc voltmeter or a multimeter and the load current I_L by a milliammeter. Eqn. (4) shows that the plot of $I_L$vs V_L is a straight line (Fig. 3.5).

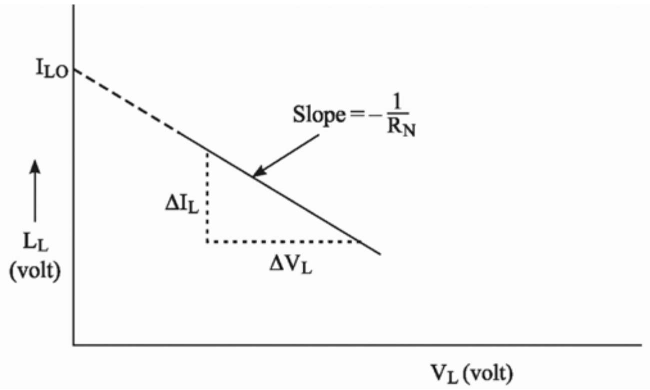


Fig. 3.5 I_L – V_L graph

The load terminals 1 and 2 of Fig. 3.1 are short-circuited and the short-circuit current I_0 are measured. Again, the resistance (R) between the terminals 1 and 2 is measured by a multimeter with the voltage source V_i removed from the circuit of Fig. 3.1, and its terminals 3 and 4 shorted. Now, $R_N = R_{TH}$ and can be calculated using Eqn. (2). Again, I_N can be calculated by calculating V_{TH} using Eqn. (1) and using the Eqn. $I_N = V_{TH}/R_N$. It will be found that the intercept I_{L0} of the I_L –V_L graph on the ordinate is equal to I_N and the slope of the graph is – $1/R_N$. This verifies Norton's theorem.

3.4.2 Apparatus

(1) A regulated power supply (2) colour-code resistances or a P.O. Box (3) bread board (4) a dc voltmeter or a multimeter (5) a milliammeter (6) carbon potentiometer.

3.4.3 Experimental Procedure

1. Set up the circuit as shown in Fig. 3.1. Set R_L to a high value.
2. Switch on the power supply and set its output voltage V_i to a convenient value (say, 10 V).Keep the voltage constant throughout the experiment.
3. By a dc voltmeter or a multimeter measure the voltage V_L across R_L and measure the load current I_L by a milliammeter.
4. Keeping V_i constant decrease R_L several times in suitable steps and repeat Step 3.
5. Plot $I_L - V_L$ graph and find the intercept I_0 and the slope R_0 of the graph.
6. Keeping V_i unchanged, disconnect R_L and measure the short circuit current I_s across the terminals 1 and 2 using a milliammeter.
7. Disconnect the power supply, short the terminal 3 and 4, disconnect the load resistance R_L and measure the resistance R between the terminals 1 and 2.
8. Calculate R_N using Eqn. (2) It will be found that the calculated value of I_N, I_0 and I_s are equal. Also calculated value of R_N, R and the slope of I_L-V_L graph are equal. This verifies Norton's theorem.

3.4.4 Experimental Data

Table 1

Load current- Load voltage data

Supply voltage V_i= …. Volt

Load resistance R_L (in Ω)	Load current I_L (in mA)	Load voltage V_L (in Volt)
0	…	…
…	…	…
etc.	etc.	etc.

Table 2

Determination of the slope and intercept of the I_L-V_L graph

Intercept on the I_L-axis I_{L0} (in mA)	ΔI_L (in mA)	ΔV_L (in Volt)	Slope $m = \frac{\Delta I_L}{\Delta V_L}$ (in Ω^{-1})
…	…	….	….

Table 3

Direct measurement of I_N and R_N

Supply voltage Vi = …….Volt

I_N (in mA)	R_N (in Ω)
…	…

Table 4

Verification of Norton's theorem

I_{L0} (in mA) (from Table 2)	m (in Ω^{-1}) (from Table 2)	I_N(in mA) (from Table 3)	R_N (in Ω) (from Table 3)	Calculated value of I_N and R_N	Remarks
…	….	…	…	$I_N \ \frac{V_{TH}}{R_N} \ \cdots mA$ R_N = ... Ω	$I_N = I_{L0}$ = calculated value of I_N and $m = -1/R_N$ = calculated value of R_N Hence Norton's theorem is verified.

3.4.6 Discussions

Same as Sec. 3.3.6

3.5 Maximum power transfer theorem

3.5.1 Theory

A load will receive maximum power from a linear bilinear dc network. When its total resistive value is exactly equal to the Thevenin's resistance of the network as "seen" by the load.

For the network shown in figure 3.6 maximum power will be delivered to this load when $R_L = R_{TH}$.

3.5.2 Proceedure

In the circuit of Fig. 3.6, R_{TH} is a known resistance and R_L is a variable load resistance. If V_L be the voltage drop across R_L, the power dissipated in R_L is

$$P_L = \frac{V_L^2}{R_L} \quad \ldots\ldots \quad (5)$$

Different known values of R_L are used and P_L is calculated each time using equation (5). A graph is plotted with R_L as abscissa and P_L as ordinate (Fig. 3.7). From the graph it is found that P_L is maximum when $R_L = R_{TH}$. This verifies the maximum power transfer theorem.

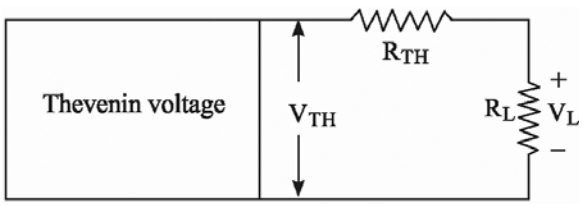


Fig. 3.6

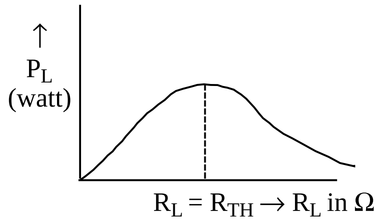


Fig. 3.7 $P_L - R_L$ graph

3.5.3 Apparatus

(1) Thevenin's supple voltage (2) a resistance box (3) a dc voltmeter/multimeter.

3.5.4 Experimental Procedure

1. Set up the circuit as shown in Fig. 3.6., R_{TH} (Thevenin's resistance), R_L is applied by a resistance box.
2. Switch on the power supply, preferably $V_{TH} \simeq 2$. Keep V_{TH} constant throughout the experiment.
3. Measure the voltage drop V_L across raviable load resistance R_L by a dc voltmeter/multimeter.

4. Increase R_L by suitable steps from 25Ω to 250Ω. For each value of R_L measure the voltage drop V_L across R_L.

5. Now decrease R_L to the values used in steps 3 and 4. For each value decreasing R_L measure the voltage drop V_L across R_L. Take the mean values V_L for each R_L and calculate P_L in each case.

6. Plot P_L vs. R_L curve. From the graph find the value R_L of R_L for which P_L is maximum. It will be seen that this value of R_L is equal to R_{TH}. This verifies the maximum power transfer theorem.

3.5.5 Experimental Data

Table 1

$P_L - R_L$ data

$V_i = V_{TH}$ Volt, R_{TH} = ….Ω

Load resistance R_L (in Ω)	Load Voltage V_L (in Volt)		Mean V_L (in Volt)	$P_L = V_L^2 / R_L$ (in Watt)
	increasing	R_L decreasing	R_L	
…	…	…	…	…
…	…	…	…	…
etc.	etc.	etc.	etc.	etc.

Table 2

Verification of maximum power transfer theorem.

R_{TH} (in Ω)	R_L from $P_L - R_L$ graph (in Ω)	Remarks
…	…	$R_L = R_{TH}$. This verifies the maximum power transfer theorem

3.5.6 Discussions

1. The internal resistance of the voltmeter should be high. For this purpose it is preferable to use a digital voltmeter or a multimeter.

2. The voltage source must have very low internal resistance as we have assumed its resistance to be zero.
3. The voltage of the voltage source should be checked every time before taking readings so that it can be kept constant.
4. The wattage of the resistances used should be such that they do not get heated during the experiment so that the value of the resistances do not change significantly.
5. The plugs of the resistance box must be tight.

3.6 Summary

In this unit we have discussed how to verify the Thevenin theorem, Norton theorem and the maximum power transfer theorem.

3.7 Exercise

1. State Thevenin theorem.
2. State Norton theorem.
3. State maximum power transfer theorem.
4. What is a linear circuit ?
5. Is a resistor a linear circuit element ?
6. Will Thevenin and Norton theorems remain valid in case of a non-linear circuit?
7. Are Kirchhoff's laws valid in any circuit ?
8. Is maximum power transfer theorem applicable in ac circuits?
9. What is power delivered from the source when maximum power is dissipated in the load resistance?
10. What is a network?
11. What is the importance of Thevenin and Norton's theorems?
12. What precaution would you take to verify Thevenin and Norton's theorem?

13. Find the Thevenin voltage,Thevenin resistance and Norton current of the circuit of Fig. 3.8.
14. Find the load resistance for which the power delivered to the load in the circuit of Fig. 3.9 maximum.

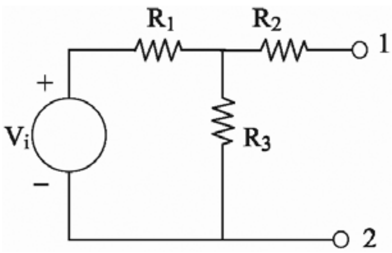


Fig. 3.8

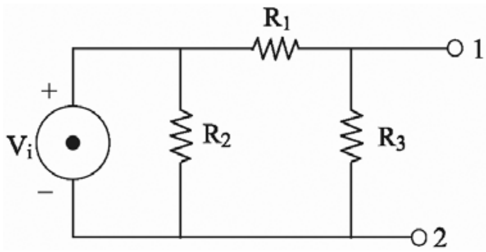


Fig. 3.9

3.8 Answers

1. See Sec. 3.3
2. See Sec. 3.4
3. See Sec. 3.5
4. In a circuit where the current-voltage characteristics of thr circuit elements is a straight line is referred to as a linear circuit.
5. For low values of voltages and currents, a resistor is a linear circuit element. But for high voltages and currents due to Joule heating the resistance changes significantly and it ceases to be a linear circuit element.
6. No.
7. Yes. The KCL and KVL represents principle of conservation of electric charge and principle of conservation of energy, respectively.
8. Yes. In ac circuits the theorem is modified. Maximum power will be delivered from the source to the load impedance when the load impedance is a complex conjugate of the source impedance.
9. Since $R_L = R_0$, and same current flows through both power dissipated in both is the same. So the power delivered from the source is double the load power.

10. See Sec. 3.1
11. See Sec. 3.1
12. See Sec. 3.3.6
13. V_{TH} = voltage drop across $R_3 = V_i\, R_3/(R_1 + R_3)$, R_{TH} =the parallel combination of R_1 and R_3 in series with $R_2 = R_2 + R_1R_3/(R_1 + R_3)$, $I_N = V_{TH}/R_{TH}$
14. $R_{TH} = R_1 \parallel R_3 = R_1R_3/(R_1 + R_3)$. Thus the required load resistance is R_{TH} according to maximum power transfer theorem.

3.9 References

1. An advanced Course in Practical Physics, D. Chattopadhyay and P.C. Rakshit, New Central Book Agency(P) Ltd., Kolkata.
2. Advanced Practical Physics, Basudev Ghosh, Sreedhar Publishers, Kolkata.

Unit 4 ❑ To determine the Y of a material by flexure method

Structure

4.1 Objectives

In this unit you will be able to learn:

- how to level a bar by rotating leveling screws,
- to use a travelling microscope to measure the depression of a bar,
- to measure the dimensions of a bar using a screw gauge and a slide calipers,
- using the measurements to determine the Y of the material of the bar,
- to compute the percentage error in the determination of Y.

4.2 Introduction

You have learnt at the level +2 course what is meant by elasticity of a material. It is the ability of a material to recover its original dimensions, and to return to its original shape, after being subjected to a stress and subsequent removal of the stress. According to Hooke's law, within the elastic limit of a solid material, the deformation (strain) produced by a force (stress) of any kind is proportional to the force. If the elastic limit is not exceeded, the material returns to its original shape and size after the force is removed. When a body is deformed an internal resistive force is developed within the body which opposes the deformation and helps the body to regain its original shape and size after the external force is removed. The internal resistive force per unit cross-section of the body is the measure of the stress. Since under equilibrium the internal resistive force equals the external applied force (P), stress is P/A, where A is the cross-section of the body. Its unit is N/m^2.The fractional change in some dimension is a measure of strain. Within elastic limit, the ratio of the stress and strain is called the modulus of elasticity. If it is the ratio of longitudinal stress to longitudinal strain, it is called Young's modulus Y and its unit is N/m^2 since strain is dimensionless. In this unit the determination of Y of a material by flexure method has been discussed.

4.3 Theory

If a light bar of breadth 'b' and depth 'd' is placed horizontally on two knife-edges separated by a distance 'L', and a load of mass 'm' is applied at the mid-point of the bar, the mid-point of the bar is depressed by 'l'. Then the Young's modulus Y of the material of the bar is given by:

$$Y = [gL^3/(4bd^3)].\ m/l,$$

where g is the acceleration due to gravity. This is the working formula of the experiment and is valid so long as the depression of the bar is such that the elastic limit is not exceeded.

4.4 Apparatus

(1) A bar of rectangular cross-section of about 1 m long (AB in Fig. 4.1), (2) Two stands with labeling screws and knife- edges N_1 and N_2, (3) A light frame F and a

scale pan or hanger S, (4) Weights, (4) A travelling microscope, (5) A spirit level, (6) A screw gauge, (7) A slide calipers, (8) A meter scale.

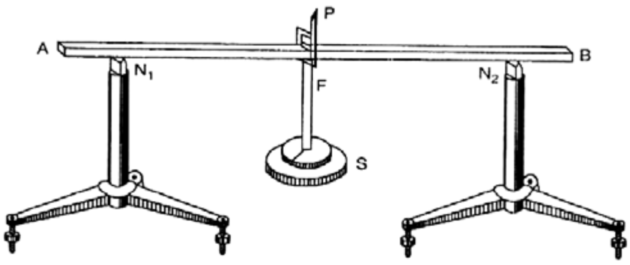


Fig. 4.1 Experimental set-up for determination of Y

4.5 Experimental Procedure

1. Measure the length of the given bar with a metre scale and mark the mid-point of the bar by a transverse line on the bar. Draw three pairs of marks L_1L_2, L_3L_4 and L_5L_6 , which are equidistant from the mid-point of the bar and lie on both sides of the mid-point. Choose L_1L_2 = 70 cm, L_3L_4= 80 cm and L_5 L_6 = 90 cm. Mount on the bar the frame F carrying the knife edge.
2. Place the bar, with its least dimension vertical, on the knife-edges N_1 and N_2 such that L_1L_2 marks coincide with the knife-edges. Place a spirit level on the bar along its length. Adjust the labeling screws of the stands until the bar becomes horizontal at the mid-point.
3. Bring the knife-edge of the frame F on the central transverse line on the bar**.** Place the microscope in front of the knife-edge of the frame F. Adjust the leveling screws of the microscope until its vertical scale is perfectly vertical and the axis of microscope is horizontal. Rotate the eyepiece of the microscope so that one of its cross-wires is horizontal. Focus it on the pointer P so that the image of its tip touches the horizontal cross-wire. Avoid parallax.
4. Determine the vernier constant of the vertical scale of the microscope. With no load on the hanger S, take readings of the main scale and vernier scale.
5. Place a load of 0.5 kg or 1 kg on the hanger. The bar will be depressed. Adjust the vertical position of the microscope so that the image of the tip

of pointer P again touches the horizontal cross-wire. Take reading of the main scale and the vernier scale.

6. Increase the load on the hanger S in steps of 0.5 kg or 1 kg six to eight times. Each time repeat step5.
7. Now decrease the load on the hanger S in the same steps of 0.5 kg or 1 kg till the load is zero. Each time repeat step5. Thus for a particular load there will be two readings, one for load increasing and the other for load decreasing. Take the mean of the readings.
8. Calculate the depression of the bar for each load by subtracting the reading for a particular load and the reading for zero load.
9. Remove the bar from the knife-edges without disturbing the positions of the stands. Measure the distance between the knife-edges by a metre scale. This gives the length L.
10. Repeat step 2 to step 9 for L = 80 cm and 90 cm.
11. Determine the vernier constant of the slide calipers and measure with it the breadth 'b' of the bar at three/four different places. Calculate mean 'b'. Record the zero-error of the slide calipers, if any and find the correct value of 'b'.
12. Determine the least count of the screw gauge and measure with it the depth 'd' of the bar at five/six different places. Calculate mean 'd'. Record the zero-error of the screw gauge, if any and find the correct value of 'd'.
13. Draw a graph with load 'm'along the x-axis and the corresponding depression 'l'along the y-axis for each value of 'L' taken. The load-depression graph is a straight line passing through the origin. Take a suitable point on the line and find the values of 'm' and 'l' corresponding to that point. Calculate mL^3/l for the three graphs and find the mean value of mL^3/l.
14. Determine Y using the mean value of mL^3/l, mean values of 'b' and 'd'.

4.6 Experimental Results

Determination of the vernier constant (V.C.) of the microscope

Value of 1 smallest division of the main scale = …. cm

…… divisions (say, v) of the vernier scale = …… divisions (say, m) of the main scale.

Value of 1 vernier division = (v/m) x value of 1 msd.

V.C. = $\left(1-\frac{v}{m}\right)$ × value of 1 msd. = …. cm

Table 1

Load–depression data for length L = …. cm

No. of Obs.	Load m (kg)	Microscope reading for increasing load (cm)			Microscope reading for decreasing load (cm)			Mean Reading (cm)	Depression 1 (cm)
		Main scale	Vernier Scale	Total	Main Scale	Vernier Scale	Total		
1	0	…	…	…	…	…	…	… (a)	0
2	0.5	…	…	…	…	…	…	… (b)	(b) – (a)
3	1.0	…	…	…	…	…	…	… (c)	(c) – (a)
…	…	…	…	…	…	…	….	….	….
...	…	…	…	…	…	…	…	….	…
…	….	….	….	….	…	…	…	…	…

Make similar Tables 2 and 3 for two other lengths L.

Table 4

Measurement of the breadth (b) of the bar by a slide calipers

Determination of the vernier constant (V.C.) of the slide calipers - Same as determination of the vernier constant (V.C.) of the microscope given before Table 1.

No. of obs.	Main scale reading (cm)	Vernier scale reading	Total reading b (cm)	Mean b (cm)	Instrumental error (cm)	Corrected b (cm)
1	…	…	…			
2	…	…	…	…	…	…
3	…	…	…			
4	…	…	…			

Table 5

Measurement of the depth (d) of the bar by a screw gauge

Determination of the Least Count (L.C.) of the screw gauge

Pitch of the screw (p) = … cm

No. of divisions of the circular scale (n) = …

L. C. = p/n = … cm

No. of obs.	Linear scale reading (x) (cm)	Circular scale Reading (y)	Total reading d = x + y × L.C. (cm)	Mean d (cm)	Instrumental error (cm)	Corrected d (cm)
1	…	…	…			
2	…	…	…			
3	…	…	…		…	…
etc.	…	…	…			

Table 6

Determination of mL^3/l from the load- depression graph

Value of m on the graph (kg)	Length L (cm)	Depression l from the graph (cm)	mL^3/l (kg.m^2)	Mean mL^3/l (kg.m^2)
…	…	…	…	
…	…	…	…	…
…	…	…	…	

Table 7

Determination of Y

Mean mL^3/l (from Table 6) (kg.m^2)	b (cm) (from Table 4)	d (cm) (from Table 5)	Given g cm/s^2	Y N/m^2
…	…	…	…	…

4.7 Computation of Percentage Error

Y = (gL^3/4bd^3). (m/l). The quantities L, b, d and l are measured. The maximum proportional error in Y due to the errors in the measurement of these quantities is given by

$$\frac{\delta Y}{Y} = 3\frac{\delta L}{L} + \frac{\delta b}{b} + 3\frac{\delta d}{d} + \frac{\delta l}{l}$$

Here L is measured by a metre scale. So the maximum error in the measurement of L is δL = 0.1 cm, since the value of the smallest division of the scale is 0.1 cm. The breadth is measured by a slide calipers of V.C = 0.01 cm. Hence the maximum error in the measurement of b is δb = 0.01 cm. The depth d is measured by a screw gauge of L.C. = 0.001 cm. So the maximum error in the measurement of d is δd = 0.001 cm. l is measured by a travelling microscope of V.C. = 0.001 cm (say). So the maximum error in the measurement of l is twice this value, i.e., δl = .002 cm. So δY/Y=3 × 0.1/L+ 0.01/b+3 × 0.001/d+0.002/l

So the maximum percentage error in the determination of Y = (δY/Y)x 100 %

For example, if L = 90 cm, b = 1.5 cm, d = 0.5 cm and l = 0.5 cm, we get, δY/Y= 0.0199. So the maximum percentage error in the determination of Y = 1.99 %.

4.8 Discussions

1. Care must be taken to make the beam horizontal and to load it at its mid-point.
2. In the expression for Y, L and d have power 3. But since d is much smaller than L, it should be measured accurately so that the percentage error in the determination of Y is small.
3. Parallax and back-lash error of the screw gauge must be avoided.
4. ‘b’ and ‘d’ are measured at different places since ‘b’ and ‘d’ may slightly vary at different places.

4.9 Summary

In this unit we have discussed the theory of determination of the Young's modulus of the material of a bar by the method of flexure and the experimental method. We have discussed , with an example, how to compute the percentage error in the determination of Y.

4.10 Answers

1. See Sec. 4.1
2. Due to depression of the bar its upper surface becomes concave and the bottom surface becomes convex. So the length of the upper part of the beam decreases and that of the lower part increases. So longitudinal strain is produced in the bar. The change is length is due the force acting along the length of the bar. These forces give rise to longitudinal stress.

   Currature of the beam in due to differential longitudinal strain of the beam which chnges sign at an intermediate horizontal surface called mentral surface.
3. The consistency of the depressions both for increasing and decreasing the load ensures that the elastic limit is not exceeded. Further, the load-depression graph is a straight line. This also indicates that the elastic limit is not exceeded.
4. In deducing the working formula it is assumed that the maximum slope of the bar w.r.t. its unstrained horizontal position is much less than 1. The maximum slope of the bar occurs at the knife- edges near the ends. The slope is approximately l/ (L/2). Putting its upper limit to 0.1 gives l = L/20. The maximum load giving this amount of depression can be reasonably applied.
5. In the expression for Y, L and d have power 3. But since d is much smaller than L, it should be measured very carefully so that the percentage error in the determination of Y is small.

6. Since the depression of the bar is measured by subtracting the zero-load reading the weight of the bar does not affect the result.
7. Steel is more elastic than rubber since the stress is much higher in steel than in rubber for the same strain produced.
8. See Discussion No. 4.

4.11 Exercise

1. What are meant by elasticity, stress, strain and elastic limit? State Hooke's law.
2. You are not applying any force along the length of the bar. Then how are longitudinal stress and strain produced in your experiment?
3. How do you ensure that you have not exceeded the elastic limit?
4. What maximum load can be applied without exceeding the elastic limit?
5. Which dimension – L, b, d- should be measured very carefully? Why?
6. Is the result affected by the weight of the bar?
7. Which one is more elastic- rubber or steel?
8. Why do you measure 'b' and 'd' at different places?

Unit 5 ❑ To draw the input-output characteristics of a common emitter transistor

Structure

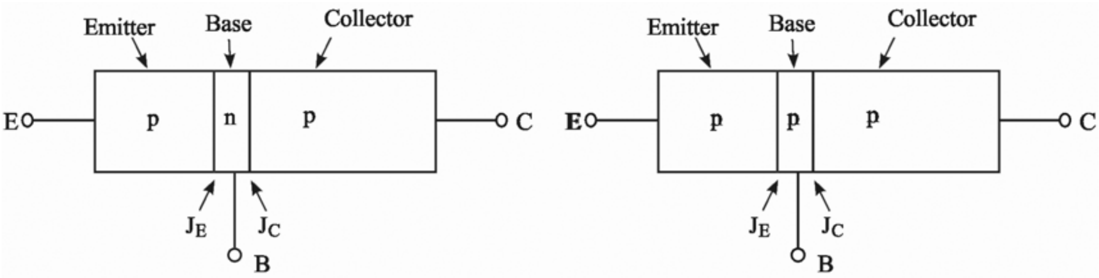
5.1 Objectives

After studying this unit you will learn

- what are meant by input and output characteristics of a transistor
- draw input and output characteristics of a transistor
- to find the hybrid parameters of the transistor from its input and output characteristics.

5.2 Introduction

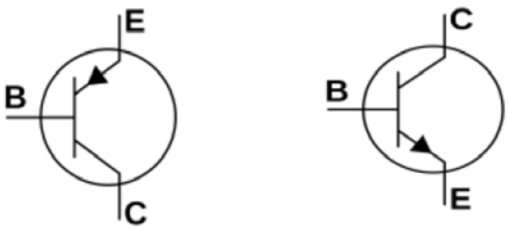
A bipolar junction transistor is a semiconductor device used to amplify or switch electronic signals and electrical power. It is composed of semiconductor material usually with three terminals for connection to an external circuit. A voltage or current applied to one pair of the transistor's terminals controls the current through another pair of terminals. Because the controlled (output) power can be higher than the controlling (input) power, a transistor can amplify a signal.The transistor is the fundamental building block of practically most modern electronic devices, and is ubiquitous in modern electronic systems. It is also used in different integrated circuits. Transistors are of two types : p-n-p and n-p-n. A transistor has three doped regions—emitter, base and collector. A bipolar junction transistor is made up of a semiconductor, such as Ge or Si, in which a p- type thin layer is sandwiched between two n- type layers. The transistor so formed is called an n-p-n transistor. Alternatively, a transistor can also have an n-type layer between two p-type layers. The transistor is then called p-n-p transistor. n-p-n and p-n-p transistors are schematically shown in Fig. 5.1.



(a) p-n-p (b) n-p-n

Fig. 5.1 Bipolar junction transistors (a) p-n-p (b) n-p-n

The base of the transistor is very thin and lightly doped. The emitter is highly doped. The doping of the collector is in between the two.The emitter –base junction is called the emitter junction J_E and the collector- base junction is called the collector junction $J_{C.}$ For normal operation J_E is forward biased and J_C is reverse biased. The circuit symbols are shown in Fig. 5.2. The arrow on the emitter specifies the direction



(a) p-n-p (b) n-p-n

Fig. 5.2 Circuit symbols of p-n-p and n-p-n transistors of the current when J_E is forward biased. Since both types of carriers, electrons and holes, conduct current through the transistor it is called bipolar junction transistor (BJT).

A transistor can be used in three configurations—Common Emitter (CE), Common Base (CB) and Common Collector (CC). The circuits for CE configuration for p-n-p and n-p-n transistors are shown in Fig. 5.3. (Since the emitter is common to both the input and output sections in the circuit, it is called the CE configuration.)

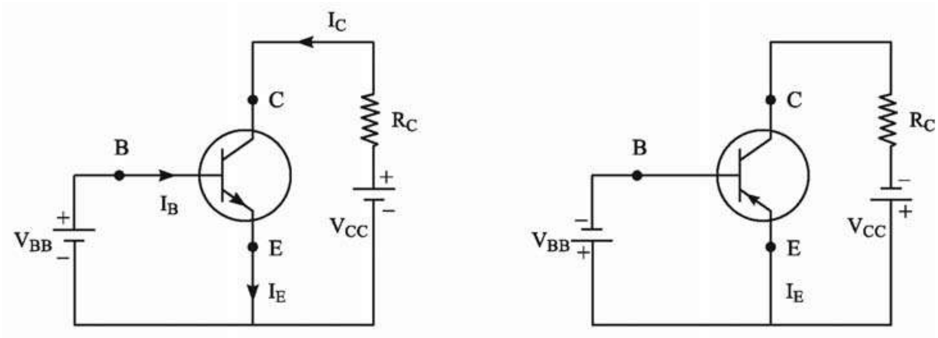
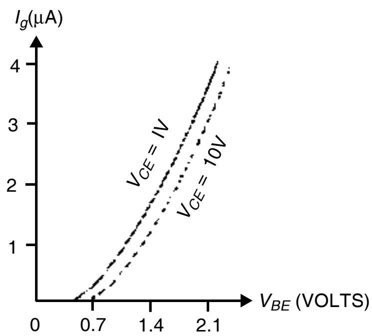
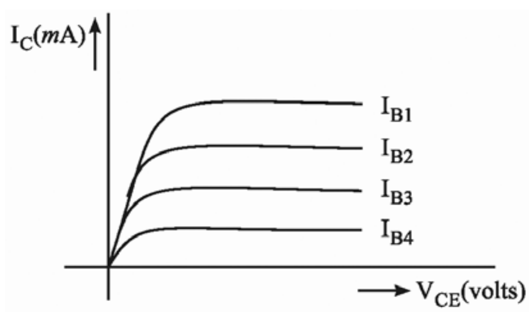


Fig. 5.3 CE configurations for p-n-p and n-p-n transistors

Here the base-emitter junction is forward biased and the collector- base junction is reversed biased. The voltages of the base and the collector w.r.t. the emitter are denoted by $V_{BE,}$ and V_{CE} respectively, the base current and collector current are denoted by I_B and I_C respectively.The graph of I_B versus V_{BE} for a particular value of V_{CE} is called the input characteristics. Similarly, the graph of I_C versus V_{CE} for a particular value of I_B is called the output characteristic.The nature of the input and output characteristics of a transistor in CE configuration is shown in Fig. 5.4.



(a) Input characteristics



(b) output characteristics

Fig. 5.4 Nature of input and output characteristics in CE configuration

The input characteristics represent essentially the forward characteristic of the base-to-emitter diode for various collector- emitter voltages. The family of output characteristic may be divided in three regions – the active region, the cut-off region and the saturation region. In the active region, the base-emitter junction is forward biased and the collector-base junction is reverse biased. In Fig. 5.4 (b) the active region is the area to the right of the ordinate V_{CE} = a few tenths of a volt and above $I_B = 0$. In this region the transistor output current responds most sensitively to an input signal. In the saturation region both the base- emitter junction and the base-collector junction is forward biased. The cut-off region is the region below the characteristic for $I_B = 0$.The saturation region is very close to the zero- voltage axis where all the curves merge and fall rapidly toward the origin. In this region the collector current is approximately independent of the base current for given values of V_{CC} and R_C.

In this configuration, the input current I_B and the collector- emitter voltage V_{CE} are considered as the independent variables, whereas the input voltage V_{BE} and the collector current I_C are considered as the dependent variables. We may write

$V_{BE} = f_1(V_{CE}, I_B)$ and $I_C = f_2(V_{CE}, I_B)$ ………(1)

The different parameters of the transistor in CE configuration are:

(i) dc current gain $\beta_{dc} = (I_C/I_B)$

(ii) ac or forward current gain $\beta_{ac} = h_{fe} = \dfrac{\partial I_C}{\partial I_B}$ for a given $V_{CE} = \dfrac{\Delta I_C}{\Delta I_B}$

(iii) Output admittance $h_{oe} = \dfrac{\partial I_C}{\partial V_{CE}}$ for a given I_B = the slope of the output characteristic for a given $I_B = \dfrac{\Delta I_C}{\Delta V_{CE}}$.

(iv) Input impedance $h_{ie} = \dfrac{\partial V_{BE}}{\partial I_B}$ for a given $V_{CE} = \dfrac{\Delta V_{BE}}{\Delta I_B}$

5.3 Theory

When the emitter terminal of a transistor is common to both the input and output sections in the circuit, it is called the CE configuration. If the base-emitter junction is forward biased and the collector- base junction is reversed biased the graph of I_B

versus V_{BE} for a particular value of V_{CE} is called the input characteristics. Similarly, the graph of I_C versus V_{CE} for a particular value of I_B is called the output characteristic.

(i) dc current gain $\beta_{dc} = (I_C/I_B)$for a given V_{CE}. For the operating point Q (a point on the output characteristic) β_{dc} can be determined by calculating the ratio of the value of I_C corresponding to the point and the value of I_B for that characteristic.

(ii) ac or forward current gain $\beta_{ac} = h_{fe} = (\delta I_C/\delta I_B)$ for a given $V_{CE} = (\Delta I_C/\Delta I_B)$. For the operating point Q, if the base current is changed between I_{B1} and I_{B3} keeping V_{CE} constant, the corresponding collector current changes between I_{C1} and I_{C3} respectively. (Fig. 5.5) Then $\beta_{ac} = h_{fe} = [(I_{C3} - I_{C1})/(I_{B3} - I_{B1})] \times 10^3$, where the collector and base currents are in mA and μA respectively.

(iii) Output admittance $h_{oe} = (\delta I_C/\delta V_{CE})$ for a given I_B = the slope of the output characteristic for a given $I_B = (\Delta I_C/\Delta V_{CE})$. Thus h_{oe} can be determined by drawing a tangent to the output characteristic at the point Q and measuring its slope. Let AB be the tangent at Q (Fig. 5.5 (a)). Then h_{oe} = BC/AC.

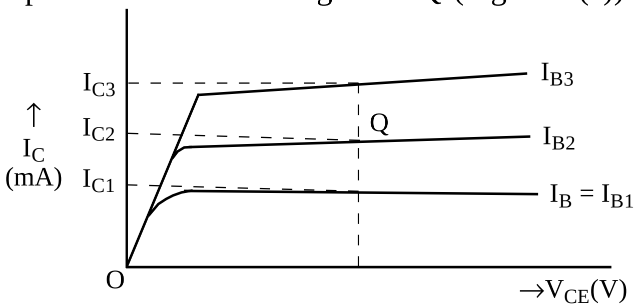


Fig. 5.5 Output characteristics in CE configuration

(iv) Input impedance $h_{ie} = (\delta V_{BE}/\delta I_B)$ for a given $V_{CE} = (\Delta V_{BE}/\Delta I_B)$. It can be determined from the input characteristic. If for a particular value of V_{CE} the base currents are I_{B1} and I_{B2} for base-emitter voltages V_{BE1} and V_{BE2} respectively, $h_{ie} = (V_{BE2} - V_{BE1})/(I_{B2} - I_{B1})$.

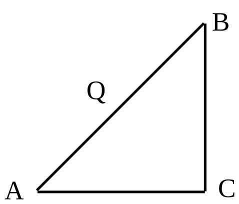


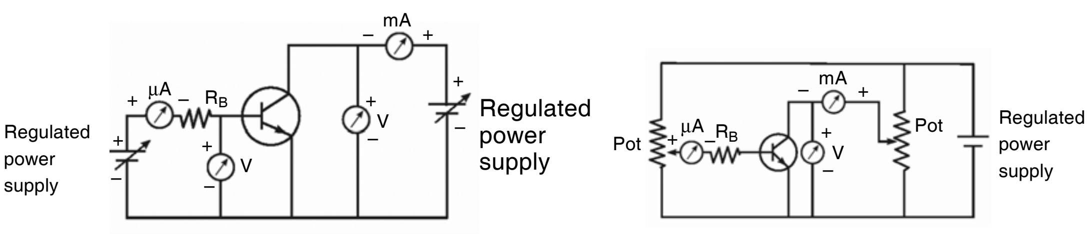
Fig. 5.5 (a) Tangent at the operating point Q of the output characteristics

5.4 Apparatus

(1) A transistor, typically SL 100, CL 100, BC 107, AC 127 (these are n-p-n), CK 100(p-n-p), etc. (2) a regulated power supply (0-2 V), (3) a regulated power supply (typically 0-12 V, 100 mA), (4) a dc microammeter (typically 0 – 100 μA), (5) a dc milliammeter (typically 0 – 10 mA), (6) a dc voltmeter (0 – 10 V), (7) a dc voltmeter (0 – 2 V), (8) a digital multimeter. (9) A resistor (say, 100 KΩ). (10) If a 0 – 2 V regulated power supply is not available a 5 kΩ potentiometer for supplying voltage to the base.

5.5 Experimental Procedure

1. Identify the base, emitter and collector of the given transistor. [This can be found in the transistor manual or can be ascertained by observing the notch (a projected part on the body) or dot on the transistor. For example, in SL 100, CL 100, BC 107 transistors the terminal closed to the notch is the emitter and the terminal furthest to the notch is the collector. The remaining terminal is the base. In AC 127 there is a coloured dot near the collector and the terminal furthest to the dot is the emitter.] The terminals may be identified by using a multimeter.
2. Measure the β_{dc} of the transistor using a multimeter. Calculate the maximum allowable value of I_B using $(I_C)_{max}/\beta_{dc}$. For an n-p-n transistor, set up the circuit as shown in Fig. 5.6(a) if two power supplies are available or Fig. 5.6 (b) otherwise. If the transistor is p-n-p reverse the polarities of the power supply and the meters. Fix R_B to a suitable value (say 100 kΩ)
3. Disconnect the power supply from the collector and short the collector to the emitter.



(a) (b)

Fig. 5.6 Experimental set-up

4. Fix the base-emitter voltage V_{BE} to a minimum using the potentiometer knob of the power supply and measure V_{BE} by a voltmeter and the base current using the microammeter.
5. Increase V_{BE} in suitable steps and measure V_{BE} by a voltmeter and the base current using the microammeter.
6. Repeat step 5 for six different values of V_{BE}.
7. Repeat step 4 to step 6 for some suitable value of V_{CE} (say 10V).
8. Draw the input characteristics and find h_{ie}.
9. Set I_B to say 10 μA.
10. Increase V_{CE} in very small steps from 0 V and record V_{CE} and I_C in each step. Since I_C increases slightly in the active region, increase V_{CE} in steps of 1V in this region. Always keep I_B unchanged.
11. Increase I_B by steps of 10 μA and in each case repeat step 10. Take at least five different values of I_B.
12. Draw the output characteristics.
13. Determine the parameters β_{dc}, β_{ac} and h_{oe}.

5.6 Experimental Results

Type of the transistor ……

Maximum permissible collector current $(I_C)_{max}$ = …..

Approximate β of the transistor = ….

Maximum allowable base current $(I_B)_{max} = (I_C)_{max}/\beta$ = ….…..

Table 1

Specification of the meters used

Meter	Range	Value of Smallest division	Zero error
Voltmeter for measuring V_{BE} Voltmeter for measuring V_{CE} Milliammeter Microammeter			

Table 2

Data for Input Characteristics

V_{CE} = …Volt		V_{CE} = …Volt	
V_{BE} (Volt)	I_B (μA)	V_{BE} (Volt)	I_B (μA)
…	…	…	…
…	…	…	…
…	…	…	…
etc.	etc.	etc.	etc.

Table 3

Determination of h_{ie}

V_{CE} (Volt)	ΔV_{BE} (Volt) (from graph)	ΔI_B (μA) (from graph)	$h_{ie} = \Delta V_{BE}/\Delta I_B$ (Ω)
…	…	…	…
…	…	…	…

Table 4

Data for Output Characteristics

I_B = 10μA		I_B = 20 μA		I_B = … μA		I_B = …. μA		I_B = … μA	
V_{CE} (Volt)	I_C (mA)	V_{CE} (Volt)	I_C (mA)	V_{CE} (Volt)	I_C (mA)	V_{CE} (Volt)	I_C (mA)	V_{CE} (Volt)	I_C (mA)
…	…	…	…	…	…	…	…	…	…
…	…	…	…	…	…	…	…	…	…
…	…	…	…	…	…	…	…	…	…
etc.	etc.	etc.	etc.	etc.	etc.	etc.	etc.	etc.	etc.

Table 5

Determination of β_{dc}, β_{ac} and h_{oe}

Operating point (mA)	I_{C3} (mA)	I_{C1} (μA)	I_{B3} (μA)	I_{B1}	β_{dc}	β_{ac}	BC (mA)	AC (V)	h_{oe} = BC/AC (Ω^{-1})
Q_1(I_C =…mA, V_{CE} =… V, and I_B = …μA) Q_2(I_C =…mA, V_{CE} =… V, and I_B = …μA)									

5.7 Discussions

1. Since the leads (emitter, base and collector terminals) of the transistor are very close to each other care should be taken so that one does not touch another.
2. R_B in the base circuit is used to limit the base current so that proper forward bias appears at J_E.
3. While taking readings for the output characteristics, care should be taken to keep the base current unchanged each time V_{CE} is changed. Slight changes in I_B may occur due to Early effect.
4. Care should be taken so that the rating of the transistor is not exceeded.
5. The transistor should not be inserted or removed from the circuit when the power is on.

5.8 Summary

In this unit we have discussed the basics of a transistor (such as transistor types, input and output characteristics of a transistor, active and saturation regions, transistor parameters, etc.), how to find experimentally the input and output characteristics of a transistor, determine the transistor parameters from the characteristics.

5.9 Answers

1. See Sec. 5.1
2. See Sec. 5.1
3. See Sec. 5.1
4. Common- emitter, common- base and common-collector.
5. 1^{st} part: See Sec. 5.1. 2^{nd} part: A Field Effect Transistor (FET) is unipolar.
6. See Sec. 5.1
7. The emitter junction of a transistor is forward biased. So its resistance is small. Again the collector junction is reverse biased. So its resistance is very high. So the current in a transistor is transferred from a low resistance input circuit to a high resistance collector with nearly unchanged magnitude. So the name 'transfer resistor' or transistor.
8. See Sec. 5.1
9. The curves give the current-voltage relationship of a transistor. From these curves we can identify the active, cut-off and saturation regions required for applications of the transistor in circuits. Also we can find the transistor parameters needed for circuit analysis, from the curves.

5.10 Exercise

1. What is a transistor ?
2. Name the regions of a transistor. Which portion has highest doping and which portion has the lowest doping?
3. What is meant by CE configuration? Why?
4. In what configurations is a transistor used?
5. Why is the transistor called bipolar? Is there any unipolar transistor?
6. What are meant by dc current gain, ac current gain, input impedance and output admittance?
7. What is the significance of the name 'transistor'?
8. What are meant by input and output characteristics?
9. Why do you determine the characteristic curves of a transistor?

Unit 6 ❑ To determine the band gap energy of a semiconductor by four probe method

Structure

6.1 Objective

In this unit you will learn how to measure the resistance of semiconductor samples and find out the band gap of a semiconductor sample.

6.1 Introduction

We know that bound states in isolated atoms are discrete. However, due to the interaction between the atoms in a crystal, these levels split up. Because of the huge number of atoms in a crystal, the level density is extremely high and these levels can be treated as continuous. Thus bands of allowed energies are formed in crystalline solids and electrons are located in these bands. The band which contains the valence electrons is called the valence band. The unoccupied energy levels also split up and form another band called the conduction band. The energy spacing between the top of the topmost valence band and the bottom of the conduction band is called bandgap, E_g (or forbidden region).

At absolute zero temperature, the bands below the energy gap E_g are completely filled and the conduction band is empty. Current conduction is not possible in empty and filled bands. Empty bands cannot contribute to current conduction as there are no carriers. On the other hand, the valence electrons move about the crystal, but they cannot be accelerated by an external electric potential/field because the acceleration means gain of energy and there are no higher energy levels available within the valence band to which they could rise.

At temperature T>0K, some valence electrons will have energy more than the band gap and consequently can go to the conduction band. The actual fraction of elecrons having energy more than E_g can be calculated using the Fermi-Dirac distribution function (discussed elsewhere). The electrons in the conduction band are called free electrons and they can gain energy when an electric field is applied, because there are many higher energy states available. The valence band now has equal number of empty energy levels, these are called holes. Electrons in the valence band can now gain energy in the valence band also, and we observe a motion of holes in the direction of the field. Thus, free electrons and holes are considered as carriers of electricity in a crystal.

An insulator has a large bandgap (~ 6 eV), so that at room temperature the conduction band is practically empty and the valence band is practically filled. In metals, the valence and conduction bands overlap and a large number of electrons can take part in the conduction of current. An electric field can accelerate these electrons leading to very high conductivity. A semiconductor has a band gap between the metal and the insulator (~1 eV). As a result its conductivity lies in between the two.

Measurement of resistivity of semiconductors faces some special problems. High resistance or rectification appears fairly often in electrical contacts to semiconductors and in fact is one of the major problem. Soldered probe contacts may disturb the current flow shorting out part of the sample. Since the resistivity is large, this leads to error in measurement. Soldering directly to the body of the sample can also affect the sample properties by heating effect and by contamination. These problems can be avoided by using pressure contacts. The principal draw backs of this kind of contacts are that they may be noisy.

The current through the sample should not be large enough to cause heating. A further precaution is necessary to prevent minority carrier injection from affecting the measured value of resistivity. An excess concentration of minority carriers will affect the potential of other contacts and modulate the resistance of the material.

The four probe method overcomes these difficulties and also offers several other advantages. It permits measurements of resistivity in samples having a wide variety of shapes, including the resistivity of small volumes within bigger pieces of semiconductor. In this manner the resistivity of both sides of p-n junction can be determined with good accuracy before the material is cut into bars for making devices. This method of measurement is also applicable to silicon and other semiconductor materials.

The basic model for all these measurements is indicated in Fig. 6.1. Four sharp probes are placed on a flat surface of the material whose band gap energy is to be

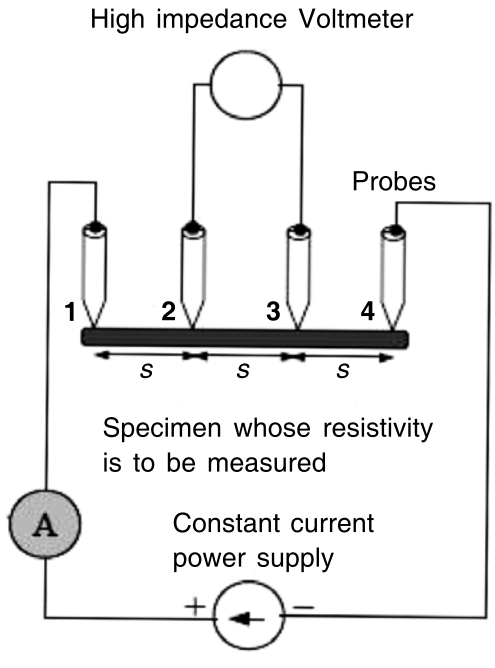


Fig. 6.1: Schematic diagram of four probe showing the electrical contacts

For this method in semiconductor crystals it is necessary to assume that:

1. The resistivity of the material is uniform in the area of measurement.
2. The surface on which the probes rest is flat with no surface leakage.

measured, current is passed through the two outer electrodes, and the floating potential is measured across the inner pair. If the flat surface on which the probes rest is adequately large and the crystal is big the semiconductor may be considered to be a semi-infinite volume.

3. The diameter of the contact between the metallic probes and the semiconductor should be small compared to the distance between probes. The boundary between the current-carrying electrodes and the bulk material is hemispherical and small in diameter.

4. Mechanically lapped surfaces ensure good contact between the probe and the sample over a wide area so as the minority carriers are injected over a wider region. Measurements should be made on surface which has a high recombination rate, such as mechanical lapped surfaces so that most of the minority carrier injected into the semiconductor by the current – carrying electrodes recombine near these electrodes. The injection effect is further reduced by keeping the voltage drop at the contacts low. Since voltaage is measured between the two inner probes, the injected carriers will recombine before reaching the measuring probes.

5. The surfaces of the semiconductor crystal may be either conducting or non-conducting. In the first case a material of much lower resistivity than semiconductor is plated on the crystal. In the case of a non-conducting boundary, the surface of the crystal is in contact with an insulator. There are corrections for these two cases. However, in our experiment we will neglect them.

6.3 Theory

The concentration of intrinsic carriers i.e. the number of electrons in conduction band per unit volume is given by the expression:

$$n = 2\left(\frac{m_e kT}{2p\hbar^2}\right)^{\frac{3}{2}} e^{\frac{m-E_g}{kT}} \quad \text{.....} \; (1)$$

and the concentration of holes in valence band is given by the expressions

$$p = 2\left(\frac{m_h kT}{2p\hbar^2}\right)^{\frac{3}{2}} e^{\left(-\frac{m}{kT}\right)} \quad \text{.....} \; (2)$$

where,

m_e = Effective mass of an electron

m_h= Effective mass of a hole

k= Boltzmann's constant,

E_g = Band gap,

μ = Fermi level

T = Temperature in K

Multiplying the above expressionswe obtain the equilibrium relation

$$np = 4\left(\frac{kT}{2p\hbar^2}\right)^3 (m_e m_h)^{\frac{1}{2}} e^{\left(\frac{-E_g}{kT}\right)} \quad ..... (3)$$

This does not depend on the Fermi level μ and is known as the expression of law of mass action.

In intrinsic (pure) semiconductors the number of electrons is equal to the number of holes, because the thermal excitation of an electron leave behind a hole in the valence band. Thus, we have, letting the subscript i denote intrinsic,

$$n_i = p_i = 2\left(\frac{kT}{2p\hbar^2}\right)^{\frac{3}{2}} (m_e m_h)^{\frac{1}{4}} e^{\left(\frac{-E_g}{2kT}\right)} \quad ..... (4)$$

It is clear from the above expression that the dominating temperature dependence arises from the exponential term.

The electrical conductivity σ of an intrinsic semiconductor will be the sum of the contributions of both electrons and holes:

$$s = \left(n_i e m_e + p_i e m_h\right) \quad ..... (5)$$

where e is the electronic charge, μ_e and μ_h are respectively the average velocities acquired by the electrons and holes in a unit electric field and are known as mobilities. We may write

$$s = n_i e(m_e + m_h) \quad ..... (6)$$

since n_i = p_i. We thus have

$$s = \frac{1}{r} = KT^{3/2}\left(m_e + m_h\right) e^{\left(\frac{-E_g}{2kT}\right)} \quad ..... (7)$$

where K is a constant and ρ is the resistivity.

The factor $T^{3/2}$ and the mobilities change relatively slow with temperature compared with the exponential term, and hence the logarithm of resistivity varies linearly with 1/T. The width of the energy gap may be determined from the slope of the curve.

Thus, we have,

$$\log_e r = \frac{E_g}{2kT} - C, \quad ..... (8)$$

Where C is a constant.

The graph for $\log_{10} \rho$ vs. T^{-1} will be a straight line. The slope of the graph will provide the band gap energy E_g.

The assumption that the semiconductor is intrinsic is applicable only at higher temperatures because then the intrinsic carrier density may be considered to be higher than the carrier density due to impurities. Thus use the high temperature part of the curve to calculate the slope.

We assume that the probes are far from any of the other surfaces of the sample and the sample can thus be considered a semi-infinite volume of uniform resistivity material. Fig. 6.2 shows the geometry of this case. Four probes are spaced S_1, S_2 and S_3 apart. Current I is passed through the outer probes and the floating potential V is measured across the inner pair of probes.

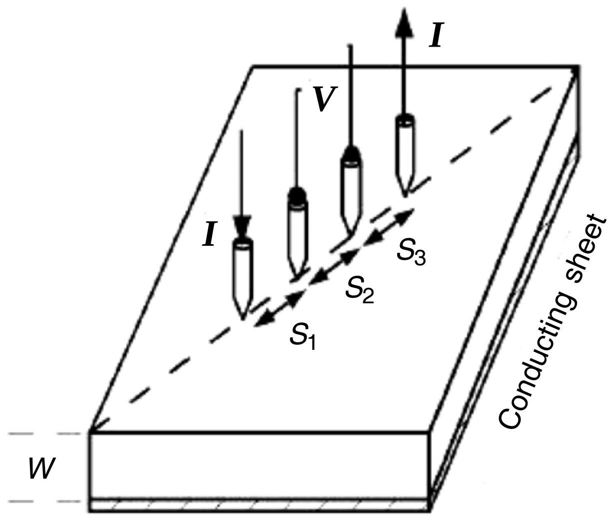


Fig. 6.2: The four probe in pressure contact with the surface of the crystal.

The floating potential V_f at distance r from an electrode carrying a current in a material of resistivity ρ is given by

$$V_f = \frac{\rho I}{2\pi r}$$

There are two current-carrying electrodes, numbered 1 and 4, and the floating potential V_f, at any point in the semiconductor is the difference between the potential induced by each of the electrodes, since they carry currents of equal magnitude but in opposite directions.

$$V_f = \frac{\rho I}{2\pi}\left(\frac{1}{r_1} - \frac{1}{r_4}\right),$$

where r_1 and r_4 are distances of the point from probe number 1 and 4, respectively.

The floating potentials at probe 2, V_{f2}, and at probe 3, V_{f3} can be calculated.

$$V_{f2} = \frac{\rho I}{2\pi}\left(\frac{1}{S_1} - \frac{1}{S_2 + S_3}\right)$$

$$V_{f3} = \frac{\rho I}{2\pi}\left(\frac{1}{S_1 + S_2} - \frac{1}{S_3}\right)$$

The potential difference V between probes 2 and 3 is then

$$V = V_{f2} - V_{f3} = \frac{\rho I}{2\pi}\left(\frac{1}{S_1} + \frac{1}{S_3} - \frac{1}{S_1 + S_2} - \frac{1}{S_2 + S_3}\right)$$

In our experiment, $S_1 = S_2 = S_3 = S$. Thus

$$V = V_{f2} - V_{f3} = \frac{\rho I}{2\pi S}$$

and we have a simple expression for resistivity,

$$\rho = 2\pi S \frac{V}{I} \quad \text{.....} \quad (9)$$

6.4 Apparatus

(1) the probe arrangement, (2) sample (The sample is millimetre in size and have a thickness w), (3) an oven provided with a heater to heat the sample, (4) constant

current generator, (5) oven power supply, (7) a thermometer, (8) a multimeter, (9) an ammeter, (10) a voltmeter

The sample is millimetre in size and have a thickness w. The four probes are arranged linearly in a straight line at equal distance S from each other. A constant current is passed through the two probes and the potential drop V across the middle two probes is measured. An oven is provided with a heater to heat the sample so that behaviour of the sample is studied with increase in temperature

6.5 Experimental Procedure

1. The sample is usually already mounted and the probes are placed on it. A constant current is passed through the outer two probes and the potential drop V across the middle two probes is measured.
2. The four probe arrangement is placed in the oven. Check the continuity between the probes for proper electrical contacts using a multimeter.
3. Connect the outer pair of probes leads to the constant current power supply and the inner pair to the probe voltage terminals. Fix the thermometer in the oven through the hole provided.
4. Switch on the AC mains of Four Probe Set-up. Adjust the current to a desired value by checking the ammeter.
5. Connect the oven power supply and start heating the sample. Wait till the temperature shown by the thermometer reaches a steady value. Note down the temperature in the thermometer and the voltage across the inner probes using a voltmeter.
6. Allow the temperature to rise from the room temperature to a maximum of approximately 200^{o}C in steps of 20^{o}C. Wait till the temperature shown by the thermometer reaches a steady value. Note down the temperature in the thermometer and the voltage across the inner probes using a voltmeter. Now allow the sample to cool by decreasing the oven current to the previous values of temperatures. Note the temperature when the temperature becomes steady and the voltage during the cooling also. This will reduce the effect of any lag in temperature between the sample and the thermometer.

7. Calculate the resistivity ρ using the expression, $r=2pS\frac{V}{1}$ for each temperature.

8. Plot a graph for $\log_{10}\rho$ vs. T^{-1}. We know that

$$\log_e r=\frac{E_g}{2kT}-\log_e K$$

The slope of the curve will provide the band gap energy E_g. Remember that the assumption that the semiconductor is intrinsic is applicable only at higher temperatures because then the intrinsic carrier density may be considered to be higher than the carrier density due to impurities. So use the high temperature part of the curve to calculate the slope.

9. Repeat steps 5 to 9 for at least two more currents through the sample and calculate the band gap in each case. Determine the mean band gap.

6.6 Experimental results

Data supplied:

S = …..

Table 1

Data for calculating the resistivity of the sample

Current through the sample =….amp

Sl No.	Temp. (^{o}C)	Voltage (V)		Temp. T (K)	Resistivity ρ (ohm-cm)	$T^{-1}(K^{-1})$	$\log_{10}\rho$
		Temp. increasing	Temp. decreasing				
1.	**...**	**...**	**...**	**...**	**...**	**...**	**...**
2.	**...**	**...**	**...**	**...**	**...**	**...**	**...**
3.	**...**	**...**	**...**	**...**	**...**	**...**	**...**
4.	**...**	**...**	**...**	**...**	**...**	**...**	**...**
							etc.

The band gap as determined from the slope of the curve E_g =….eV

Repeat the experiment for two other current values.

Mean value of E_g= …eV

6.7 Discussions

1. The thickness of the sample *w* is impoprtant for correction on the nature of the bottom surface on which the sample is placed. The correction depends of the values of *w/S*. We assume that the thickness is large so that the current flow through the sample does not depend on the bottom surface on which the sample is placed.

2.The assumption that the semiconductor is intrinsic is applicable only at higher temperatures because then the intrinsic carrier density may be considered to be higher than the carrier density due to impurities. So the high temperature part of the graph of $\log_{10} \rho$ vs. T^{-1} is used to calculate its slope.

3. To reduce the effect of any lag in temperature between the sample and the thermometer, the temperature and the voltage are recorded when the temperature becomes steady both during heating and cooling.

6.8 Summary

In this experiment, the resistivity of an intrinsic semiconductor is measured. Studying its variation with temperature, the band gap of the semiconductor has been determined.

6.9 Answers

1. See Section 6.1 for the advantages of the four-probe method.
2. Ordinary millivoltmeters have a low input resistance compared to electronic meters. Ideally potentiometer does not draw any current at balanced condition, that is it has an infinite resistance. Thus ordinary millivoltmeters requires more current to operate. As the semiconductor resistivity is high, we require a meter with very high input resistance compared to the resistance of the sample. Thus, we cannot use ordinary millivoltmeters to measure the probe voltage.
3. Refer to Section 6.3.
4. See Discussion 2 in Sec.6.7

5. At 0 K, there are no free electrons or holes in a semiconductor. This is the reason that it acts as an insulator.
6. See Section 6.1
7. See Section 6.1
8. See Section 6.1
9. See Section 6.1
10. See Section 6.1
11. See Section 6.1

6.10 Exercise

1. What is the advantage of Four Probe method over the other conventional methods?
2. Can we use an ordinary millivoltmeter instead of electronic millivoltmeter or potentiometer to measure the inner probe voltage? Why?
3. Explain the behaviour of the $\log_{10} \rho$ vs. 1/T curve.
4. Why do we calculate the band gap only from the high temperature region of the graph?
5. Why does a semiconductor behave as an insulator at 0K?
6. Why bands are formed in a solid?
7. Classify semiconductor, insulator and metal on the basis of band theory.
8. What is band gap in a solid?
9. What are free electrons and holes?
10. Is conduction of current is possible when a band is completely filled or completely empty?
11. What is an intrinsic semiconductor?

Unit 7 ❑ To determine H by using vibrational magnetometer

Structure

7.1 Objectives

Studying this unit you will be able to learn about the Earth's magnetic field and how to measure its horizontal component.

7.2 Introduction

The Earth behaves like a big magnet. The magnetic poles do not coincide with the geographical poles. Three elements are used to specify the Earth's magnetic field at any point on the globe. Magnetic declination is the angle on the horizontal plane between magnetic north, the direction the north end of a magnetized compass needle points, corresponding to the direction of the Earth's magnetic field lines, and true north. Magnetic dip or the angle of dip is the angle made with the horizontal by the Earth's magnetic field lines. These two angles vary at different points on the Earth's surface. The horizontal component of the Earth's magnetic field is termed H. This is related to the Earth's magnetic field B by the relation, H = B cos δ, where δ is the magnetic dip.

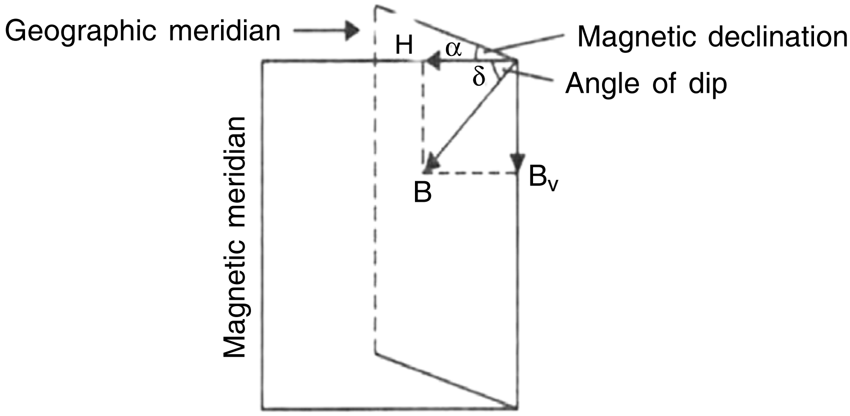


Fig. 7.1: Magnetic elements of Earth

7.3 Theory

The intensity of the magnetic field due to a magnet of length 2*l* calculated at a point P at a distance *d* from the centre of the magnet (O) (Fig. 7.2) lying on the axial line of the magnet (end-on position) is given by

$$F = \frac{\mu_0}{4\pi}\frac{4m_p ld}{(d^2 - l^2)^2} = \frac{\mu_0}{4\pi}\frac{2Md}{(d^2 - l^2)^2} \qquad (1)$$

Here, m_p is the strength of the magnetic pole and $M=2m_pl$ is its magnetic moment. Here, $4\pi \times 10^{-7}$ H/m.

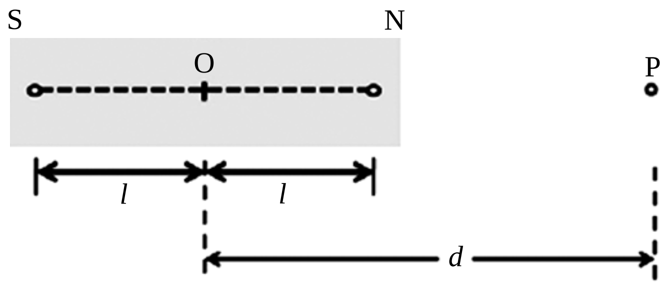


Fig. 7.2: End-on position of a bar magnet

A bar magnet is placed in the east-west direction near the magnetic needle of the deflection magnetometer. This arrangement is called the tanA position. The needle is then under the influence of the horizontal component of the earth's magnetic field as well as the field of the bar magnet acting perpendicularly to each other. The magnet produces a deflection θ in the magnetic needle. At equilibrium the couples acting on the needle must be equal.

If M′ is the magnetic moment of the couple, then

$$M'F\cos\theta = M'H\sin\theta$$

$$\text{or, } F = H\tan\theta \text{ or, } \frac{\mu_0}{4\pi}\frac{2Md}{(d^2 - l^2)^2} = H\tan\theta$$

$$\frac{M}{H} = \frac{4\pi}{\mu_0}\frac{(d^2 - l^2)^2}{2d}\tan\theta \quad (2)$$

When a magnet freely suspended in a uniform magnetic field is deflected through a small angle θ, the restoring couple acting on it is $M H \sin\theta$, which, as the angle of deflection is small, may be written as MHθ. When the magnet is released from its deflected position, the restoring couple tends to set it parallel to the magnetic field. The magnet thus acquires angular acceleration and the couple due to inertial reaction is $I\frac{d^2\theta}{dt^2}$, where I is the moment of inertia of the magnet about the axis of rotation. Thus we have an equation for θ,

$$I\frac{d^2\theta}{dt^2} = MH\theta \quad (3)$$

The above equation represents a simple harmonic motion, whose time-period is given by

$$T = \frac{1}{2\pi}\sqrt{\frac{1}{MH}}$$

$$\text{or, } MH = \frac{4\pi^2 I}{T^2}$$

Thus, if we wish to determine the value of H in the laboratory, we can do so by performing the deflection and oscillation.

From the above results we obtain an expression for the horizontal component of earth's magnetic field, *H*

$$H = \frac{2\pi}{T(d^2 - l^2)}\sqrt{\frac{2\mu_0 I d}{4\pi \tan\theta}} \quad (5)$$

The moment of inertia of a uniform bar of length *a*, width *b* and mass *m* is given by

$$I = \frac{m}{12}\left(a^2 + b^2\right) \quad (6)$$

7.4 Apparatus

Deflection and vibration magnetometers, a magnet, a brass bar with identical size of the magnet, a compass needle, a vernier callipers, a meter scale, a balance with weight box, and a stop-watch/stop clock.

Description of the apparatus:

Deflection magnetometer: A deflection magnetometer consists of a small magnetic needle pivoted on a sharp support such that it is free to rotate in a horizontal plane (Fig. 7.4). A light, thin, long aluminium pointer is fixed perpendicular to the magnetic needle. The pointer also rotates along with the needle.There is a circular scale divided into four quadrants and each quadrant is graduated from 0^o to 90^o. A plane mirror fixed below the scale ensures reading without parallax error, by ensuring that image of the pointer is coincident exactly with pointer itself. The needle, aluminium pointer and the scale are enclosed in a box with a glass top. There are two arms graduated in centimetre and their zeroes coincide at the centre of the magnetic needle.

Vibration magnetometer: In this instrument, a light brass stirrup suitable for mounting a bar magnet is suspended from a torsion head by means of an unspun silk fibre. It hangs within a wooden box with glass walls (Fig. 7.3). A plane mirror having a central line marked LL is placed on the floor of the box. Two slits on the top of the box, parallel to LL, are used to determine the time of transit of the magnet during its oscillation.

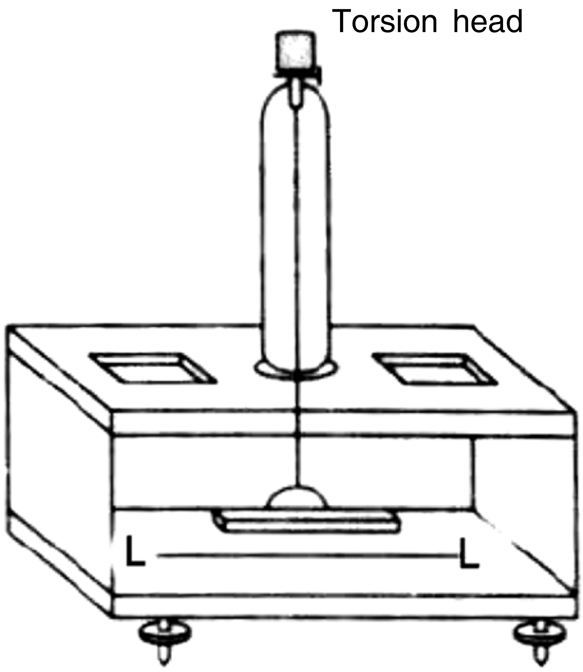


Fig. 7.3: Vibrational magnetometer

7.5 Experimental Procedure

(A) Deflection Experiment

(i) Remove all magnets and magnetic substances from the neighbourhood of the table on which the deflection magnetometer is placed. Set the magnetometer in tan A position. For this purpose, turn the arms of the magnetometer on the table till they are parallel to the aluminium pointer. Rotate the compass box without disturbing the arms till the pointer reads zero-zero on the graduated circular scale.

(ii) Now place the magnet on one arm in such a way that its axis is parallel to the arms of the magnetometer and when produced it passes through the centre of the magnetic needle. Since, the sensitivity of the magnetometer is more at 45^o, try to get a deflection between 30^o and 60^o.Obtain the distance d from the centre of the magnet to the centre of the needle by noting down the distance of the two edges of the magnet from the centre, d_1 and d_2, and hence, $d = (d_1 + d_2)/2$.

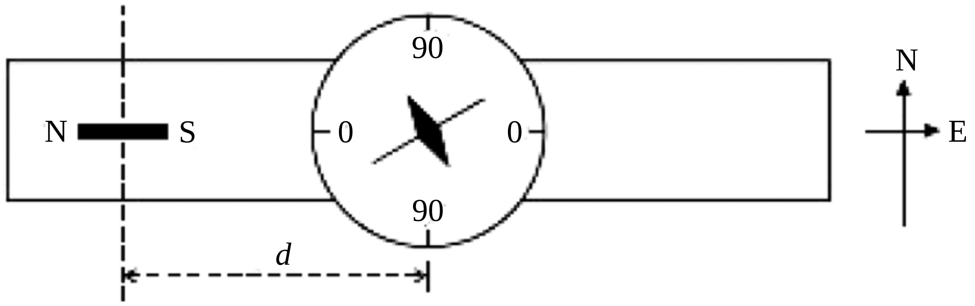


Fig.7.4: Bar magnet and deflection magnetometer in tan A position

(iii) The deflection is subjected to a number of errors:

(a) The pivot of the needle may not pass exactly through the centre of the graduated circular scale. To correct for this error, both the ends of the pointer should be read and the mean of the angles should be taken.

(b) The magnetic centre of the bar magnet may not be exactly coincident with its geometrical centre. This may be so due to the unsymmetrical magnetisation of the magnet. To correct for this error, readings should be taken by reversing the polarity of the magnet at the same position. In this operation, the two poles simply interchange their positions.

(c) The poles may not be exactly in symmetrical positions. Turn the magnet upside down and repeat the measurements.

(d) The centre of the linear scale on which the distance is read may not coincide with the pivot of the magnetic needle. To correct for this error, transfer the bar magnet on the other arm so that the centre of the magnet lies at the same scale reading.

Take readings of the deflection for all the above. Take the mean of all the deflections to eliminate these errors.

(B) **Oscillation Experiment**

(i) Remove all magnets and magnetic substances from the neighbourhood of the table on which the oscillation magnetometer is placed. Determine the direction of the magnetic meridian on the table using a long needle and draw a line. Place the vibration box with its longer edge parallel to this line. Now put the compass needle inside the box along the line marked on the plane mirror fixed to the base, and adjust the magnetometer, it necessary, to bring this scratch line exactly in the magnetic meridian.

(ii) For conducting this experiment it is essential that when the magnet hangs in the magnetic meridian, the suspension fibre should have no twist, since in deriving the formula for the time-period it has been assumed that the only restoring couple is due to the earth's magnetic field alone, and that the torsional couple is negligible. Thus, a brass bar of identical size with the magnet is used to untwist the fibre. Place the brass bar in the stirrup and wait for the fibre to untwist. When the bar becomes motionless when hanging freely from the fibre, it is set parallel to the scratch line by turning the torsion head. During the process of removal of twist, the motion of the brass rod should be checked after every few revolutions, otherwise, when the fibre is untwisted, the inertia of the rotating bar may cause it to twist in the opposite direction.

(iii) Hold the stirrup tightly in position and withdraw the brass rod. Replace it with the bar magnet used in the deflection experiment. The magnet should lie perfectly horizontal in the stirrup and its north pole should point northwards. Now with the help of a second magnet deflect the suspended magnet through a small angle and take away the second magnet to a safe distance from this oscillating magnet. Count twenty-five oscillations by looking through the slit at the top of the box and note the time with an accurate stopwatch/stop clock. Repeat the process four times and calculate the time-period of the magnet.

C) **Determination of the Constants of the Magnet**

(i) Measure the vernier constant of the slide calliper.

(ii) Measure the effective length ($2l$) of the magnet. Measure its total length (a) with a metre scale/ slide calliper. Since the poles are not exactly at the ends of the bar magnet, take

$$2l = 0.85a$$

as the effective length, half of which gives l.

(ii) Measure the breadth (b) of the magnet with a vernier calliper. Weigh the magnet, and then with the help of a, b, and m, calculate the moment of inertia (I) of the magnet using eqn. (6).

Finally, calculate H with the help of the formula (5) given above.

7.6 Experimental results

Table 1

Measurement of the distance *d* of the magnet from the needle

d_1 (m)	d_1 (m)	$d = \frac{d_1 + d_2}{2} (m)$
...	...	...

Table 2

Measurement of the deflection of the needle of the deflection magnetometer

	Magnet on the east arm				Magnet on the west arm				Mean deflection θ
	Pole facing needle				Pole facing needle				
	North		South		North		South		
Pointer end	One end	Other end	One end	Other end	One end	Other end	One end	Other end	
Face up	...	...	...	...	...	...	...	...	
Face down	...	...	...	...	...	...	...	...	...

Repeat the measurement for different values of *d*.

Table 3

Determination of the time period of the oscillation

No. of observations	Time t for 25 oscillations (s)	Mean time for 25 oscillations (s)	T=t/25 (s)
1.	...	...	...
2.	...		
3.	...		

Table 4

Measurement of the mass of the magnet

No. of obs	Mass of the magnet m (kg)	Mean mass of the magnet m (kg)
1.	...	
2.	...	...
3.	...	

Table 5

Determination of the vernier constant of the slide calliper.

..... divisions of the vernier scale (p) = ... divisions of the main scale (q)

Value of 1 smallest scale division (L_1) (cm)	Value of 1 vernier division (cm) $L_2 = \frac{q}{p} L_1$	Vernier constant (cm) ($L_1 - L_2$)

Table 6

Determination of length (a), breadth (b) and moment of inertia of the magnet

No. of obs.	Length			Mean Length a (cm)	Breadth			Mean breadth b(cm)	$I = \frac{m}{12}\left(a^2 + b^2\right)$ (kg m^2)
	Main scale reading (cm)	Vernier scale reading (cm)	Total (cm)		Main scale reading (cm)	Vernier scale reading (cm)	Total (cm)		
1.	...	...	...		...	...	...		
2.	...	...	...	...	...	...	...	...	....
3.	...	...	...		...	...	...		

We assume that the length can be measured with slide callipers. If it is not possible, measure it carefully with a metre scale.

Table 7

Determination of *H*

No. of Obs.	d (m)	θ	I (kg m^2) (From Table 6)	T (s)	$l = 0.85\frac{a}{2}$ (m)	$H = \frac{2\pi}{T(d^2-l^2)}\sqrt{\frac{2\mu_0 Id}{4\pi\tan\theta}}$ (tesla)	Mean H (tesla)
1.	...	...				...	
2.	...	...	...	...	...	...	...
3.	...	...				...	

7.7 Calculation of percentage error

We have from equation (5)

$$H^2 = \frac{4\pi^2}{T^2(d^2-l^2)^2}\frac{2\mu_0 Id}{4\pi\tan\theta} = \frac{2\pi\mu_0 Id}{T^2(d^2-l^2)^2\tan\theta}$$

Taking logarithmic derivative,we have the maximum proportional error as

$$\frac{2\delta H}{H} = \frac{\delta I}{I} + \frac{\delta d}{d} + 2\frac{\delta T}{T} + \frac{2(d^2-l^2)}{(d^2-l^2)} + \frac{\sec^2\theta\,\delta\theta}{\tan\theta}$$

Here we write,

$$\frac{2(d^2-l^2)}{(d^2-l^2)} = \frac{4d\delta d + 4l\delta l}{(d^2-l^2)}$$

From equatin (6), we see that

$$\frac{\delta I}{I} = \frac{\delta m}{m} + \frac{2a\delta a + 2b\delta b}{a^2+b^2}$$

Since $T=t/2$, we see that $\delta T/T = \delta t/t$.

Noting the smallest scale reading in each instrument, the relative error in H, i.e. $\delta H/H$ can be estimated. Remember that $\delta\theta$ must be expressed in radian.

7.8 Discussions

1. All pieces of magnetic materials and current-carrying conductors should be removed to a considerable distance from the magnetometers. Examine your pockets for the presence of magnetic materials.
2. The deflection magnetometer should be carefully set in the tanA position and the magnet should be so placed on the arms that its axis, when produced, passes through the centre of the magnetometer needle.
3. The deflection of the needle should be as nearly equal to 45° as possible, since under the condition the deflection shall be susceptible of yielding maximum accuracy. Further the value of *d* should be large, so that the field due to the magnet in the region occupied by the needle is sufficiently uniform. However, if it is not feasible to procure the above two conditions at the same time, a compromise should be affected by making d large so that the deflection falls in the neighbourhood of 30°-60°.
4. The pivot of the needle may not pass exactly through the centre of the graduated circular scale.

   If the magnet is unsymmetrically magnetised, the magnetic centre shall not be coincident with its geometrical centre, hence the distance between the magnetic centre of the bar magnet and the centre of the magnetic needle in the compass box, shall not be correctly measured. The poles may not be exactly symmetrical. The centre of the linear scale on which the distance *d* is read may not be coincident with the pivot of the needle. Care must be taken to eliminate these errors by taking maesurements as discussed above.
5. While reading the deflection of the aluminium pointer on the graduated scale, the error due to parallax should be avoided. For this purpose, use should be made of the plane mirror attached to the base of the compass-box.
6. Before oscillating the magnet in the vibration box, initial twist in the suspension fibre should be completely removed with the help of a metallic bar of some non-magnetic material. The bar should preferably be of the same size and shape as the magnet itself.

7. As the moment of inertia of the stirrup is not taken into account in the derivation of the above formula for T, it should be very light.
8. In the derivation of the formula for the time-period of the magnet it has been assumed that θ is small so that the restoring couple $M\ H \sin\theta = M\ H\theta$. In order to satisfy this condition, the deflection of the oscillating magnet should not be more than 4^o.
9. The oscillations should not be counted by looking at the magnet from the glass side of the box but the eye should be held vertically over the slit made on the top of the box, and the counting should be done with reference to the scratch line made on the glass plate at the bottom of the box.
10. The main sources of error in this experiment are: —
    - (i) The magnetometer needle is not sufficiently short, hence it cannot be justified that it moves in a uniform field produced by the bar magnet — a condition which is absolutely necessary for the validity of the Tangent Law.
    - (ii) The friction at the pivot is not totally absent; hence the measurement of the deflection is not very accurate. Moreover, the pointer and scale method is not very accurate. Generally the two conditions that the deflection of the pointer be around 45^o, and the distance of the magnetic needle from the magnet be fairly large, cannot be satisfied simultaneously.
    - (iii) The effective length of the magnet is not accurately determined.
    - (iv) In the derivation of the formula for the time-period, the moment of inertia of the stirrup is neglected.
    - (v) The suspension fibre may not be completely free from torsional reaction.

7.9 Summary

In this unit we discuss what is the horizontal component of Earth's magnetic intensity and how to measure it accurately. Proportional error has been calculated.

7.10 Answers

1. Refer to Section 6.1
2. The moment of a magnet M is related to the pole strength m_p and true length $2l$ by the relation $M = 2m_p l$.

   The poles are not at the exact end of the bar but near the end because of the repulsion between the similar poles of the molecular magnets.
3. We can measure the quantities M/H and MH, respectively form equations (2) and (4). We can estimate M using the above results as

$$M = \frac{2p}{T(d^2 - l^2)}\sqrt{\frac{2pl \tan q}{m_0 d}}$$

4. In the tan B position, the magnetic field at a distance d from the centre of the magnet is given by

$$F = \frac{m_0}{4p}\frac{Md}{(d^2 - l^2)^2}$$

   Since the field is weaker by a factor of two the corresponding deflection will be smaller and the accuracy will be less.
5. Since, the sensitivity of the magnetometer is maximum at 45^0, try to get a deflection between 30^0 and 60^0
6. In the derivation of the formula for the time-period of the magnet it has been assumed that θ¸ is small so that the restoring couple M H sin θ¸ = M H θ. In order to satisfy this condition, the deflection of the oscillating magnet should not be more than 4^0..
7. Refer to serial No. 10 of Sec. 7.8 and Sl. No. A(iii) of Sec. 7.5.
8. Refer to Sec.7.3.
9. Magnetic moment of a magnet is the product of the distance between its poles and the strength of either pole.
10. The moment of inertia of a rigid body is a quantity that determines the torque needed for a desired angular acceleration about a rotational axis; similar to how mass determines the force needed for a desired acceleration.

7.11 EXERCISES

1. What are meant by declination, dip and horizontal component of earth's magnetic intensity?
2. How is the moment of a bar magnet related to its pole strength and length? Why do we take the length of the actual magnet smaller than its actual length?
3. Can the magnetic moment of the bar magnet be measured from the above measurements?
4. What would be the difference if in the deflection measurement the magnet be placed in the tan B position, that is in the north-south orientation with the centre coinciding with the centre of the needle in the east west direction?
5. Why should the deflection of the magnet be kept between 30^0 and 60^0?
6. Why should the deflection of the oscillating magnet be within 4^0 ?.
7. What are the main sources of error in the experiment ?
8. What is meant by tan A position?
9. What is magnetic moment of a magnet?
10. What is meant by moment of inertia of a rigid body?

Unit 8 ❑ To determine the self-inductance of a coil by Anderson's bridge

Structure

8.1 Objectives

In this unit you will learn how to determine the self- inductance of a coil by Anderson's bridge.

8.2 Introduction

You have learnt in your +2 course what is meant by self- inductance. An insulated wire wound into a coil around a core is called an inductor. The coil has a self- inductance. When the current flowing through the coil changes, the time-varying magnetic field induces an electromotive force (e.m.f.) (voltage) in the coil described by Faraday's law of induction. According to Lenz's law, the induced voltage has a polarity (direction) which opposes the change in current that created it. As a result, inductors oppose any changes in current through them. The ratio of the induced voltage to the rate of change of current through the coil is called the self- inductance of the coil. Its unit is henry (H). Along with capacitors and resistors, inductors are one of the three passive linear circuit elements that make up electronic circuits. Inductors are widely used in alternating current electronic equipment, particularly in radio equipment.They are also used in electronic filters to separate signals of different frequencies, and in combination with capacitors to make tuned circuits, used to tune radio and TV receivers.

8.3 Theory

When the current flowing through coil a changes, a voltage is induced in the coil. The ratio of the induced voltage to the rate of change of current through the coil is called the self- inductance of the coil. For low frequencies, a practical coil can be represented by a self- inductance in series with a resistance which accounts for the losses in the coil. The circuit for the measurement of the self- inductance of a coil by Anderson's bridge is given in Fig. 8.1.

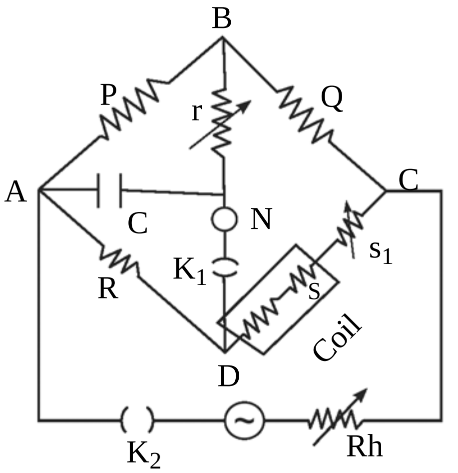


Fig. 8.1 Anderson's bridge

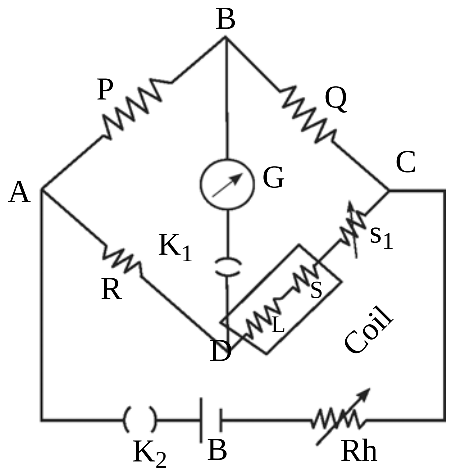


Fig.8.2 Circuit for dc balance

Let L be the self- inductance of the given coil and s be its resistance. A variable resistance s_1 is connected in series of the coil. Let $S = s + s_1$ be the total resistance in the arm CD of the bridge. P, Q, R and s_1 are non-inductive resistances. C is a capacitor, N is a null detector, usually a headphone, and r is a variable non-inductive resistance. At balance, that is when the current through the detector is zero, we have

$S = RQ/P$ ….. (1) and $L = CR[Q + r(1 + Q/P)]$ …….. (2)

Equations (1) and (2) are referred to the dc and ac balance conditions of the bridge.

If $P = Q$, Eqn. (2) reduces to $L = CR(Q + 2r)$ ………………….(3)

The ac balance represented by Eqn.(3) can be achieved only when $L > CRQ$, otherwise the resistance r will be negative. If C is expressed in farad, R, Q and r are expressed in ohm, then L will be obtained in henry from Eqn. (3).

A graph with 1/C along the abscissa and r along the ordinate will be a straight line of slope L/(2R)(Fig. 8.3). L can be calculated by determining the slope of the graph.

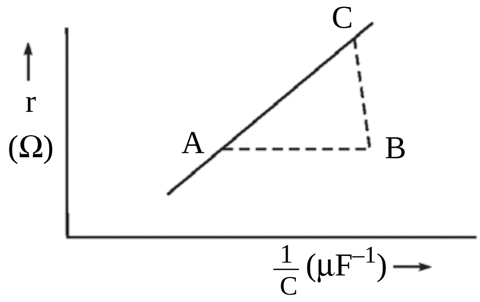


Fig.8.3 (1/C)-r graph

8.4 Apparatus

(1) A P. O. Box to provide the resistances P, Q and R, (2) a resistance box containing fractional ohm and resistances from 1 to 200 ohm which will provide the variable resistance s_1, (3) a resistance box containing resistances of 1 to 10000 ohm to provide the variable resistance r, (4) a few capacitors having capacitance 0.1μF and higher, (5) a headphone/ ac null detector, (6) an audio oscillator, (7) a dc galvanometer, (8) a rheostat, (9) a dc power supply, (10) two plug keys.

8.5 Experimental Procedure

(a) Attainment of dc balance:

1. Set up the circuit as shown in Fig. 8.2. Here G is a dc galvanometer; K_1 and K_2 are plug keys.

2. Take P = Q = R = 100 Ω in the P.O. Box.
3. Close key K_2.
4. Close key K_1. Take the resistance $s_1 = 0$ and note whether the deflection of the galvanometer is towards left or right (say, for example, it is left). Then take resistance $s_1 = 200\ \Omega$ and it will be observed that the galvanometer deflection is in the opposite direction (i.e., right).
5. Decrease s_1 and observe the galvanometer deflection. If it is right decrease s_1 further. Continue decreasing s_1 till the deflection is towards left.
6. Increase s_1 and observe the galvanometer deflection till the galvanometer deflection is in the opposite direction for 1Ω change of s_1.
7. Now insert a fractional resistance and observe the galvanometer deflection. Change the value of the fractional resistance and each time observe the galvanometer deflection till the galvanometer deflection is zero. The total resistance in the arm CD of the bridge will then be $S = 100\ \Omega = s + s_1$.

   Hence the resistance of the coil $s = 100 - s_1$.

(b) Attainment of ac balance:

1. Set up the circuit as shown in Fig.8.1.Close the key K_2. Adjust the output voltage of the audio oscillator to a suitable value and set its frequency near 1 kHz.
2. Choose the lowest value of C. Close key K_1. Vary the resistance r until the sound in the headphone (or the deflection of null detector) is zero or a minimum.
3. Repeat step 2 for at least 4 different values of C.
4. Calculate L using Eqn.(3) for different values of C taken and find their mean.
5. Draw a graph with 1/C along the abscissa and r along the ordinate. The graph will be a straight line of slope L/(2R). Find the slope of the graph and calculate L.

8.6 Experimental Results

Table 1

Data for dc balance

(Numerical figures are for illustration only)

P (in Ω)	Q (in Ω)	R (in Ω)	s_1 (in Ω)	Galvanometer deflection	Value of s_1 at Null point s_{1n} (in Ω)	Coil resistance $s = 100 - s_{1n}$ (in Ω)
100	100	100	0	Left		
100	100	100	200	Right		
100	100	100	50	Left		
100	100	100	80	Right		
100	100	100	79	Left		
100	100	100	79.5	Left		
100	100	100	79.6	0	79.6	20.4
100	100	100	79.7	Right		

Table 2

Data for ac balance

$P = 100\ \Omega$, $Q = 100\ \Omega$, $R = 100\ \Omega$, $S = s + s_1 == 100\ \Omega$,
Frequency of the oscillator = …. Hz.

Capacitance C (in μF)	Value of r (in Ω)	Sound intensity in the headphone/ deflection of the null detector	Value of r at null point (in Ω)	L (in mH)	Mean L (in mH)
	…	…			
	…	…			
…	…	…	…	…	
	…	…			

	…	…			
	…	…			
	…	…			
…	…	…	….		…
	…	…			
	…	…			
etc.	etc.	etc.	etc.	etc.	

Table 3

Data for (1/C) –r graph

C (in μF)	1/C (in μF^{-1})	BC (Ω)	AB (μF^{-1})	Slope m = L/(2R) = BC/AB	L = 2Rm (in mH)
….	….	….	….		
….	….	….	….	…	…
etc.	etc.	etc.	etc.		

8.7 Discussions

1. The value of C must be such that L > CRQ. So either an approximate value of L has to be known or the lowest value of C has to be used.
2. To make the bridge sensitive, so that the ac balance can be determined accurately, same values of resistances have been used in the four arms of the bridge.
3. Since our ear is most sensitive at about 1 kHz the frequency of the ac source was fixed at 1 kHz. If, however, an ac null detector is used we can use other frequency.
4. All resistances used were non-inductive.
5. All the connecting wires should be straight and short.

8.8 Summary

In this unit we have discussed what is meant by self- inductance, mentioned some use of self- inductance and measure the self- inductance of a coil by Anderson Bridge.

8.9 Answers

1. See Sec. 8.1
2. When the rate of change of current in a coil is 1Amp/sec induces a voltage of 1 Volt in the coil the self- inductance is 1 Henry.
3. To reduce the self- inductance of the connecting wires.
4. If a headphone is used to find ac balance the frequency of the ac source should be about 1 kHz since our ear is most sensitive at this frequency. If, however, an ac null detector is used we can use other frequency.
5. The self- inductance of a coil depends on the number of turns/unit length, the diameter and length of the coil, permeability of the material of the core on which the coil is wound.
6. The self- inductance of the coil will increase as the permeability of iron is about 1000.
7. If the resistances used have inductance the ac balance condition will be affected and the determination of self- inductance of the coil will not be correct.
8. If a piece of insulated wire is doubled on itself and then wound on a wooden/porcelain/ebonite rod, the resulting winding will have negligibly small self-inductance. Due to doubling, the current through the two halves of the wire flows in opposite directions so that the effective magnetic flux linked with the wire is practically zero.
9. See Sec. 8.1.
10. Maxwell's bridge.
11. See Sec. 8.1.

12. Each 10 mH.
13. See Sec. 8.3.

8.10 Exercise

1. Define self- inductance. What is its unit?
2. Define Henry.
3. Why should all the connecting wires be straight and short?
4. What frequency of the ac source should be used? Why?
5. On what factors does the self- inductance of a coil depend?
6. A piece of iron is placed inside a coil. Will the self-inductance of the coil change?
7. Why should resistances used be non-inductive?
8. How is a resistance made non-inductive?
9. Mention some uses of an inductor.
10. Name another bridge for the measurement of self- inductance.
11. State Lenz's law.
12. Self- inductance of a coil is 20 mH. If it is broken in two equal parts what will be the self- inductance of the parts?
13. How is a practical coil represented?

Unit 9 ❑ To draw e-t curve of a thermocouple

Structure

9.1 Objectives

By studying this unit you will learn

- to measure the resistance of the wire of a potentiometer by a P.O. Box.
- to use a potentiometer to measure a potential difference
- to draw the e-t curve of a thermocouple.

9.2 Introduction

If two metallic conductors made of two different metals are joined at their two ends it is called a thermocouple. If the junctions are kept at different temperatures a current flows in the thermocouple, that is an electromotive force is generated in it. This e. m. f. is called thermo-e.m.f.. This effect is called thermoelectric effect and is known as the Seebeck effect. The thermo-e.m.f. first increases with the increase in temperature difference between the junctions and after a certain temperature difference, decreases and becomes zero. If the temperature difference is increased further the thermo-e.m.f. increases again but in the opposite direction. If one junction is kept at 0°C, the temperature at which the thermo-e.m.f. is maximum is called the *neutral temperature* (t_n) and the temperature at which the thermo-e.m.f. is zero is called the *temperature of inversion* (t_i). The amount of thermo-e.m.f. generated for a given temperature difference between the junctions depends on the metals of the thermocouple. By measuring the thermo-e.m.f. generated in a thermocouple temperature can be measured. That is, a thermocouple can be used as a thermometer. To measure the temperature a curve is drawn with the thermo-e.m.f. generated (e) versus the temperature of the hot junction (t) when the other junction is kept at 0^0 C. This curve is called the e-t curve. If the temperature of hot junction is much less than the neutral temperature the e-t curve is a straight line. To measure the temperature of a body, one junction of the thermocouple is kept at 0^0 C and the other junction is kept in contact with the body whose temperature is to be measured. The thermo- e.m.f. generated is measured. The temperature is obtained from the e-t curve corresponding to the measured thermo- e.m.f.

9.3 Theory

An e.m.f. is generated in a thermocouple when its two junctions are at different temperatures. If this thermo-e.m.f. e is balanced against a potential drop produced across a length l of a potentiometer wire, then $e = \rho l$, …….. (1)

where ρ = potential drop/unit length of the potentiometer wire.

In the circuit of Fig. 9.1 if E = the e.m.f. of the storage battery B connected with the potentiometer, R_p is the resistance of the potentiometer wire, L = length of the potentiometer wire, R = resistance connected in series with the potentiometer, then

$\rho = ER_p/[(R_p + R)L]$ ……. (2)

Hence, $e = ER_p l/[(R_p + R)L]$ ……. (3)

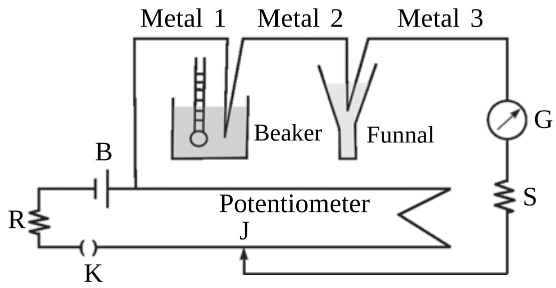


Fig. 9.1 Experimental arrangement

By maintaining the temperature of one junction constant (usually 0^0 C) and increasing the temperature of the other junction, a curve relating the variation of thermo- e.m.f. (e) against the temperature (t) of the hot junction can be drawn. This curve is called the e-t curve of the thermocouple.

9.4 Apparatus

(1) a potentiometer, (2) a P. O. Box, (3) a storage battery, (4) a resistance box R, (5) a dc galvanometer, (6) a resistance box to be connected in series with the galvanometer, (7) a voltmeter/ multimeter, (8) a thermocouple, (9) a thermometer reading upto 0.1^0 C, (10) a glass beaker containing water, (11) a funnel containing powdered ice, (12) a burner, (13) a plug key, (14) a stirrer, (15) connecting wires, (16) a glass rod, (17) a beaker to collect the water of melted ice in the funnel.

9.5 Experimental Procedure

1. Measure the resistance R_p of the potentiometer wire by connecting it to the fourth arm of a P. O. Box. First use P = Q = 10 Ω. Then use P = 100 Ω and Q =10 Ω. (The circuit is similar to that in Fig. 8.2 expect that the potentiometer is in the fourth arm instead of the coil and the fractional resistance box.)
2. Measure the e.m.f. of the storage battery by a voltmeter/ multimeter before and after the experiment. Rectify the zero error of the voltmeter, if any.
3. Connect the circuit as shown in Fig. 9.1. One junction of the thermocouple is immersed in the powdered ice in the funnel and the other junction is

immersed in the water, at room temperature, in the beaker. The bulb of the thermometer is immersed in the water close to the thermocouple junction. Note the reading of the thermometer.

4. Calculate the value of the resistance R from Equ. (2) taking ρ = 5 mV/cm. Use this value of R. To ensure that the polarities of the battery B and the terminals of the thermocouple are properly connected close the plug key K and make a momentary contact of the jockey J first at one end of the potentiometer wire and then at the other end. If the polarities of the battery B and the terminals of the thermocouple are properly connected, the deflections of the galvanometer G will be in the opposite directions in the two cases. If not, reverse the polarity connections of the battery.

5. Put some resistance in the resistance box S. Increase the value of resistance in the resistance box R so that the null point is obtained (that is, the deflection of the galvanometer is zero) on the 9^{th} or 10^{th} wire of the potentiometer. Now make the resistance in the resistance box S zero to increase the sensitivity and find the null point. Changing the position of the jockey note the null point three times and take the mean. [If the galvanometer is not sensitive enough, the null point may be obtained over a small range of length of the potentiometer wire. In such a case note the range and take the middle of the range as the null point.]

6. Heat the water in the beaker using the burner to increase its temperature by about 10^0 C, stir the water and adjust the burner so that the temperature remains constant for 2/3 minutes. Decrease the resistance R such that the null point is obtained on the 10^{th} or 9^{th} wire. Record the null point three times during the time the temperature of the water remains constant and take the mean. Record the temperature of water.

7. Repeat step 6 several times till the temperature of the water increases to about 95^0 C. Throughout the experiment the temperature of the cold junction should be kept at 0^0 C. To achieve this powdered ice in the funnel has to be pressed by a glass rod and adding more powdered ice in the funnel time to time.

8. Calculate the thermo- e.m.f. for each temperature recorded using Eqn. (3) and draw the e-t curve by plotting the temperature of the hot junction along the abscissa and the corresponding thermo-e.m.f. along the ordinate.

9.6 Experimental Results

Table 1

Measurement of the resistance R_p of the potentiometer wire

(Numerical figures are for illustration only)

P (in Ω)	Q (in Ω)	R (in Ω)	Direction of the deflection of the galvanometer	Resistance Rp of the potentiometer wire (in Ω)
10	10	0	Right	
		∞	Left	
		10	Right	
		30	Left	
		20	Right	
		22	Left	
		20	Slight right	$20 < R_p < 21$
		21	Slight left	
100	10	200	Slight right	
		210	Slight left	
		….	….	
		….	….	
		205	Zero	$R_p = 20.5$

Table 2

Measurement of the e.m.f. of the battery

Zero error of the voltmeter = …. Volt

Time of observation	E.M.F. (E) of the battery (in Volt)	Corrected E (in Volt)	Mean E (in Volt)
Before experiment	….	….	….
After experiment	….	….	

Table 3

Data for thermo-e.m.f. vs. temperature graph

Length of the potentiometer wire (L) = …. cm

Resistance of the potentiometer wire R_p = …. Ω (from Table 1)

E.m.f. of the battery E = V (from Table 2)

Temperature of the cold junction = °C

No. of obs.	Temperature (t) of the hot junction (in °C)	Resistance R (in Ω)	Null point			Length for Balance (in cm)	Thermo-e.m.f. e (in mV) (using Equ. (3))
			Wire No.	Scale Reading (in cm)	Mean Scale Reading (in cm)		
1.	Room temp. =	….	….	…. …. ….		….	….
2.	….	….	….	…. …. ….	….	….	….
3.	….	….	….	…. …. ….	….	….	….
etc.	etc.	etc.	etc.	etc.	etc.	etc.	etc.

9.7 Discussions

1. Ensure that the temperature of the cold junction is maintained at 0^0 C throughout the experiment. The powdered ice in the funnel has to be pressed from time to time and fresh powdered ice to be added.
2. The water in the beaker should be heated slowly and stirred so that the temperature of water remains constant for about 2/3 minutes and the null point can be determined three times for each temperature.
3. The e.m.f. of the battery should remain constant throughout the experiment. It is to be checked from time to time.
4. To reduce the error in the measurement of thermo-e.m.f. the length of the potentiometer wire to balance the thermo-e.m.f. should be more than 800 cm. So the resistance R should be such that the null point is obtained on the 9^{th} or 10^{th} wire.
5. The plug keys of the P. O. Box and the resistance box are to be kept tight.
6. The wires of the thermocouple must be kept in an insulated cover so that the wires do not touch each other.

9.8 Summary

In this unit we have discussed what is a thermocouple, its use as a thermometer, how to draw the e-t curve of the thermocouple.

9.9 ANSWERS

1. See sec. 9.1
2. See sec. 9.1
3. See sec. 9.1
4. See sec. 9.1
5. To ensure that the polarities of the battery B and the terminals of the thermocouple are properly connected close the plug key K and make a momentary contact of the jockey J first at one end of the potentiometer wire

and then at the other end. If the polarities of the battery B and the terminals of the thermocouple are properly connected, the deflections of the galvanometer G will be in the opposite directions in the two cases.

6. No. Because the thermo-e.m.f. is few millivolts. Also a voltmeter actually measures potential difference and not e.m.f.
7. The e-t curve is parabolic. But since the temperature of the hot junction is much less than the neutral temperature we obtain a small portion of the curve and is a straight line.
8. See sec.9.1.
9. The temperature of inversion is as far above the neutral temperature as the cold junction is below it.
10. To reduce the error in the measurement of thermo-e.m.f. the length of the potentiometer wire to balance the thermo-e.m.f. should be more than 800 cm. So the resistance R should be such that the null point is obtained on the 9th or 10th wire.

9.10 Exercise

1. What is a thermocouple? How is it used to measure the temperature of a body?
2. What is thermoelectric effect?
3. What is Seebeck effect?
4. What are meant by neutral temperature and temperature of inversion?
5. How would you identify whether the polarities of the battery and the thermocouple are properly connected to the potentiometer?
6. Can you use an ordinary voltmeter to measure thermo-e.m.f.?
7. What is the nature of the e-t curve?
8. How will the thermo-e.m.f. change if we go on increasing the temperature of the hot junction?
9. How is the temperature of inversion related to the neutral temperature?
10. Why have you choose to have the null point on the 10th or 9th wire?

Unit 10 ❑ To determine the elastic constants of the material of a wire by Searle's method

Structure

10.1 Objective

In this unit you will be able to learn:

- to measure the diameter of a wire using a screw gauge
- to measure the elongation of a wire using micrometer screw
- use the measurements to determine Y of the material of the wire

10.2 Introduction

In Unit 4 you have learnt what is meant by elasticity of a material. The elastic constants are Young's modulus Y, bulk modulus K, rigidity modulus nand Poissons ratio σ. You have also learnt to determine the Young's modulus Y of the material ofa wire by flexure method. In this unit you will learn to determine Y by Searles method.

10.3 Theory

Young's modulus is a measure of the stiffness of a solid material. It is calculated for elongation or compression which are within elastic limit when the external applied force is removed. Young's modulus is a characteristic property of the material and is independent of its dimensions i.e., its length, diameter etc. Consider a wire of length L and area of cross-section A and radius r. Let its length L increases by an amount l when the wire is pulled by a longitudinal external force F. Young's modulus of the material of the wire is given by,

$$Y = \frac{Longitudinal\ Stress}{Longitudinal\ Strain} = \frac{F/A}{l/L} = \frac{FL}{Al} = \frac{mgL}{pr^2 l} = \frac{gL}{pr^2}\left(\frac{m}{l}\right) \qquad \text{... (1)}$$

10.4 Apparatus

(1) Searle's apparatus (which consists of a dummy wire and an experimental wire, a micrometer screw with linear and circular scale), (2) a spirit level, (3) a meter scale, (4) hanger for placing weights, (5) weights.

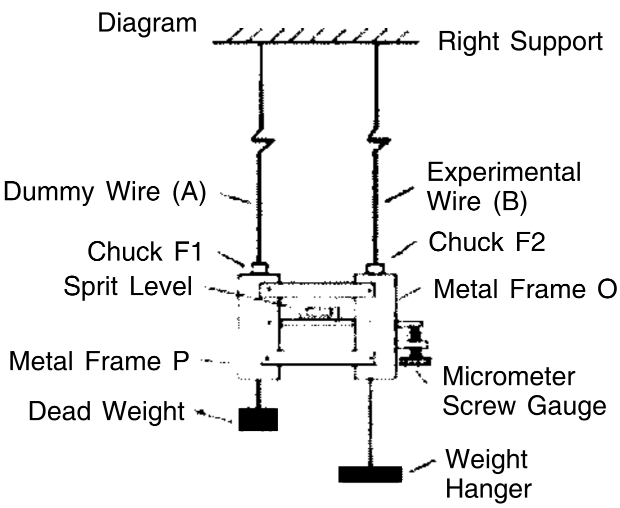


Fig. 10.1 Searle's apparatus

10.5 Experimental Procedure

1. Apply suitable weights on the hangers of both the dummy wire and the experimental wire to keep them taut. Call this load 'dead load' or zero load. Measure the length L of the experimental wire by a meter scale.
2. Find the least count of the screw gauge. Record its instrumental error, if any. Measure the diameter d of the experimental wire at five/six different places. At each place take readings at two mutually perpendicular directions [(a) and (b)] to correct for the ellipticity of the cross-section, if any.
3. Find the least count of the micrometer screw.
4. Turn the micrometer screw to adjust the spirit level in horizontal position. Record the readings of the linear scale and circular scale of the micrometer screw.
5. Increase the load on the hanger of the experimental wire in steps of 0.5 kg six to eight times. The spirit level is tilted due to the elongation of the experimental wire. Each time repeat step 4.
6. Now decrease the load on the hanger in the same steps of 0.5 kg till the load is zero. Each time repeat step 4. Thus for a particular load there will be two readings, one for load increasing and the other for load decreasing. Take the mean of the readings.
7. Calculate the elongation 'I' of the experimental wire for each load "m" by subtracting the reading for a particular load and the reading for zero load.
8. Draw a graph with load 'm' along the x-axis and the corresponding depression 'I' along the y-axis. This load-elongation graph is a straight line passing through the origin.
9. Take a suitable point on the load-elongation graph and find the values of'm' and 'I' corresponding to that point.
10. Calculate Y using equation (1).

10.6 Experimental Results

Measurement of the length L of the experimental wire: (1) ...... cm (2) ...... cm (3) ...... cm Mean L = ... cm.

Table 1

Measurement of the radius r of the experimental wire

Determination of the Least Count (L.C.) of the screw gauge

Pitch of the screw (p) = ... cm

No. of divisions of the circular scale (n) = ...

L.C. = p/n = ... cm

No. of obs.	Linear scale reading (x) (cm)	Circular scale Reading (y)	Total reading d = x + y × L.C. (cm)	Mean d (cm)	Instrumental error (cm)	Corrected d (cm)	Radius r (cm)
1 (a)	...	...	...				
(b)	...	...	...				
2 (a)	...	...	...	...	...	...	
(b)	...	...	...				
3(a)	...	...	...				
(b)	...	...	...				
etc.							

Table 2

Data for load-elongation graph

Deterrni nation of the Least Count (L.C.) of the m icrorneter screw

Pitch of the screw (p) = ... cm

No. of divisions of the circular scale (n) = ...

L.C. = p/n = ... cm

Load m (kg)	Micrometer reading							Elongation (cm)
	Load increasing			Load decreasing			Mean reading (cm)	
	Linear scale reading (x) (mm)	Circular scale reading (y)	Total reading d=x+yx L.C. (cm)	Linear Scale reading (x) (mm)	Circular Scale reading (y)	Total reading d=x+yx L.C. (cm)		
0	...	...	...	...	...	...	... (a)	0
0.5	...	...	...	...	...	....	... (b)	(a) – (b)
1	...	...	...	...	. ..	...	... (c)	(a) – (c)
....	...	...	....	...	...	...	...	...
etc.								

Table 3

Determination of Y

g = ...

L (cm)	r(cm) from Table 1	m (kg) from graph	1 (cm) from graph	$Y = \frac{gLm}{\pi r2l}$ (Eqn. (I)) N/m^2
...	...	...	...	...

10.7 Calculation of Percentage Error

Y = gLm/$\pi r^2 l$. The quantities L, *l* and r are measured. The maximum proportional error in Y due to the errors in the measurement of these quantities is given by

$$\frac{\delta Y}{Y} = \frac{\delta L}{L} + 2\frac{\delta r}{r} + \ldots + \frac{\delta l}{l}$$

Here L is measured by a metre scale. So the maximum error in the measurement of L is δL = 0.1 cm. The diameter of the wire is measured by a screw gauge ofL. C. = 0.001 cm. So the maximum error in the measurement of diameter is 0.001 cm. So δr = 0.001/2 cm = 0.0005. 1 is measured by a micrometer screw
L.C. = 0.001 cm (say). So the maximum error in the measurement of 1 is twice this value, i.e., δ1 = .002 cm. So δY/Y= 0.1/L + 2 × 0.0005/r +0.002/1

So the maximum percentage error in the determination ofY = (oY/Y)x 100 %

10.8 Discussions

1. The loads should be such that the elastic limit is not exceeded. Since the load-elongation graph is a straight line the elastic limit has not exceeded
2. In the expression for Y since the radius of the wire r has a power of 2 it should be measured accurately so that the percentage error in the determination of Y is small. The cross-section of the wire may not be uniform at all places. For this reason the diameter of the wire is measured at five/six places of the wire.

3. The cross-section of the wire may not be exactly circular. So at each place readings are taken at two mutually perpendicular directions to correct for the ellipticity of the cross-section, if any.
4. The micrometer screw must be rotated in the same direction to avoid back-lash error.
5. The dummy wire and the experimental wire should be made of the same material. If are wires are of different materials then their thermal expansion (due to temperature change during experiment) will be different. This will introduce an error in the measured elongation *l*.
6. The wires used in the experiment should be identical. long and thin. The long and thin wires give larger elongation and hence better measurement accuracy.
7. The wires should be taut otherwise length L cannot be measured correctly. The-control weight or dead weight is used to make the wires taut.
8. After adding a load or removing a load, wait for some time before taking the next reading; this will help the wire to elongate or contract fully.
9. The load must be placed on the hanger or removed from it gently.

10.9 Summary

In this unit we have discussed the theory of determination of the Young's modulus of the material of a wire by Searle's method and the experimental method. We have discussed how to compute the percentage error in the determination of Y.

10.10 Answers

1. See Sec. 4.1
2. Steel is more elastic than rubber since the stress is much higher in steel than in rubber for the same strain produced.
3. Since the load-elongation graph is a straight line the elastic limit has not exceeded
4. The cross-section of the wire may not be uniform at all places. For this reason the diameter of the wire is measured at five/ six places of the wire.

5. See discussion no. 3 at Sec. 10. 8.
6. See discussion no. 5 at Sec. 10. 8.
7. Thin wire, since thin wires give larger elongation and hence better measurement accuracy.
8. ln the expression for Y since the radius of the wire r has a power of 2 it should be measured accurately so that the percentage error in the determination of Y is small.

10.11 Exercise

1. What are meant by elasticity, stress,strain and elastic limit? State Hooke's law.
2. Which one is more elastic- rubber or steel?
3. How do you ensure that you have not exceeded the elastic limit?
4. Why do you measure the radius of the wire at different places?
5. Why do you measure the radius of the wire in mutually perpendicular directions?
6. Is there any harm if the wires are not made of the same material?
7. Would you prefer the experimental wire to be thin or thick?
8. Why should the radius of the wire be measured accurately?

Unit 11 ❑ To study the V-I curve of a solar cell and find the maximum power point and efficiency

Structure

11.1 Objective

In this experiment you will learn about the solar cell, study its characteristics and performance.

11.2 Introduction

Solar cell is the basic unit of solar energy generation system where electrical energy is extracted directly from light energy without any intermediate process. The working of a solar cell solely depends upon its photovoltaic effect, hence a solar cell also known as photovoltaic cell. There are a variety of different measurements we can make to determine the solar cell's performance, such as its power output and its conversion efficiency.

11.3 Theory

You have learned about n-type and p-type semiconductors earlier in unit 6. A solar cell is basically a semiconductor p-n junction device. It is formed by joining p-type and n-type semiconductor material. At the junction excess electrons from n-type try to diffuse to p-side and excess holes try to diffuse to the n-side. This results in an electric field from the n-side to the p-side at the junction, called barrier field. The electrons and holes combine in the region near the barrier thus forming an area with no free carrier. This is called the *depletion region*.

When sunlight falls on the solar cell, photons with energy greater than band gap of the semiconductor are absorbed by the cell and generates electron-hole (e-h) pair. These electrons and holes migrate respectively to n- and p- side of the pn junction due to barrier field. Thus, the p-side has an excess of holes while the n-side has an excess of electrons. In this way a potential difference is established between two sides of the cell. This is called the *photo emf*.

This photo emf is proportional to the illumination and on the size of the illuminated area. When an external load is connected across the terminals of the cell, it acts as a battery as the holes return to the n-side and the electrons to the p-side thus driving a current from the p-side to the n-side. Solar cells are often formed from silicon single crystals. For silicon, the band gap at room temperature is E_g= 1.1 eV.

Solar cells produce direct current (DC) electricity and current times voltage equals power, so we can create solar cell I-V curves representing the current versus the voltage for a photovoltaic device.The main electrical characteristics of a solar cell are summarized in the relationship between the current and voltage produced on a typical solar cell I-V characteristics curve. The intensity of the solar radiation that hits the cell controls the current (I), while the increase in the temperature of the solar cell reduces its voltage (V). *Solar Cell I-V Characteristics Curves* are basically a graphical representation of the operation of a solar cell or module summarising the relationship between the current and voltage at the existing conditions of irradiance and temperature. I-V curves provide the information required to configure a solar system so that it can operate as close to its optimal peak power point (MPP) as possible. The voltage generated by the solar cell depends on the current drawn. Thus an appropriate load has to be connected across the cell to derive maximum power from it.

From the I-V characteristics various parameters of the solar cell can be determined, such as: short-circuit current (I_{SC}), open-circuit voltage (V_{OC}) and efficiency. The rating of a solar panel depends on these parameters. .

The short-circuit current is the current through the solar cell when the voltage across the solar cell is zero (i.e., when the solar cell is short circuited). This current is due to the generation and collection of light-generated carriers. For an ideal solar cell at most moderate resistive loss mechanisms, the short-circuit circuit current and the light-generated current are identical. Therefore, the short-circuit current is the largest current which may be drawn from the solar cell.

The open-circuit voltage, V_{OC}, is the maximum voltage available from a solar cell, and this occurs at zero current. The open-circuit open circuit voltage corresponds to the amount of forward bias on the solar cell due to the bias of the solar cell junction with the light-generated current.

The efficiency is the most commonly used parameter to compare the performance of one solar cell to another. Efficiency is defined as the ratio of energy output from the solar cell to input energy falling on the cell. In addition to reflecting the performance of the solar cell itself, the efficiency depends on the frequency of the incident sunlight and the temperature of the solar cell.

11.4 Apparatus

The experimental set up consists of solar cell, light source (LED or bulb) with known power, resistance box, voltmeter and milliammeter, a scale.

11.5 Experimental Procedure

1. Set up the circuit as shown in Fig. 11.1.

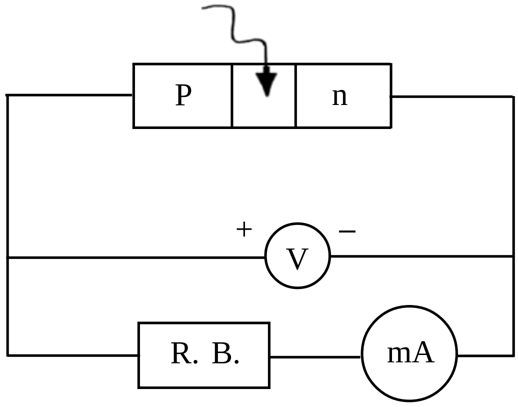


Fig 11.1 Circuit for solar cell characteristics

2. Find out the power P of the light source. Set up the voltage to the bulb to its maximum rating so that it delivers that power.
3. Set up the solar cell so that light from the source falls normally on it. Measure the distance of the solar cell, *d*, from the light source.
3. Obtain the surface area, *A*, of the solar cell. If it is recatngular, the area is given by multiplying length and breadth. If it is circular, the area is given by $\pi D^2/4$ where D is the diameter.
4. Calculate the intensity of the light falling on the solar cell as $I = {}^{PA}/_{4\pi d^2}$.
5. Disconnect the load resistance (R_L) in the resistance box and note the open-circuit voltage (V_{OC}).
6. Change the load resistance to 0 ohms. Note the short-circuit current (I_{SC}).
7. Now increase the load resistance in steps of 100 ohms upto a maximum of 1100 ohms. In each case, note the current.
8. Plot a graph for current vs voltage.
9. Plot a graph for power versus load. Find out the maximum power e to the load from the graph.
10. Calculate the efficiency by dividing the maximum power delivered to the load by the intensity *I* falling on the solar cell.
11. Repeat steps 3 ro 10 by changing the distance between the source and the solar cell.

11.6 Experimental Results

Data for calculation of intensity of light falling on the solar cell

Area of the solar cell = ...m^2

Power of the light source = ...W

Distance of the solar cell from the light source = ...m (d_1)

Intensity of light falling on the cell = ...W (I_1)

Distance of the solar cell from the light source = ...m (d_2)

Intensity of light falling on the cell = ...W (I_2)

Table 1

Data for V-I characteristics and power vs. load resistance for a solar cell

R_L (Ohm)	Intensity = (I_1)			Intensity = (I_2)		
	Voltage (V)	Current (mA)	Power (mW)	Voltage (V)	Current (mA)	Power (mW)
0	...	...	...	...	...	...
100	...	...	...	...	...	...
200	...	...	...	...	...	...
...	...	...	...	...	...	...

For I_1:

The power delivered to the load is maximum at $R_L$is ..... .

The efficiency of the solar cell at this point is .....

For I_2:

The power delivered to the load is maximum at $R_L$is ..... .

The efficiency of the solar cell at this point is .....

11.7 Discussions

1. The light should fall normally on the solar cell.

2. Intensity of light is calculated as the power falling on the solar cell. We have made a few assumptions:

   (i) The complete power delivered to the bulb is available as radiation.

   (ii) The bulb is treated as a point rather than an extended source.

   (iii) The radiation of the bulb is isotropic, that is same in all directions.

   (iv) There is no absorption of light between the bulb and the solar cell.

   (v) The distance of the cell from the light is large.

3. Efficiency depends on the frequency of light as well as the temperature of the solar cell.

11.8 Summary

In this experiment you learned about the solar cell, calculate its power and efficiency.

11.9 Answers

1. A photodiode, like a solar cell, is a photovoltaic semiconductor device. Photodiodes, however, are optimized for light detection while solar cells are optimized for energy conversion efficiency. A photo diode has to be fast, which means low capacitance, which means small area. Solar cells are much bigger than photodiodes to catch sunlight. Photodiodes can be used in forward as well as reverse bias while solar cells need not be biased from outside. It essentially works in the fourth quadrant of the V-I graph.
2. Silicon single crystals are generally used to make solar cell. Polycrystalline silicon has been used for lower costs though its efficiency is smaller. Other materials include cadmium telluride, silicon thin film, etc. This is a very active field of research.
3. Dark current is the current in a photodiode in absence of illumination.
4. The response time of a photodiode is the time that it takes to change the current when it is suddenly exposed to light or the light source is suddenly

cut off. Since it depends on the capacitance of the cell, photodiodes are small devices.

5. Refer to Sec. 11.3.
6. Refer to Sec. 11.3.
7. Refer to Sec. 11.3.
8. Refer to Sl. No. 3 of Sec. 11.7.

11.10 Exercise

1. What is the difference between solar cell and a photodiode?
2. What are the types of semiconductor materials used for solar cell?
3. What is dark current in a photodiode?
4. What is the response time of photodiode?
5. How is depletion layer formed?
6. How is photo- emf generated?
7. What are meant by short-circuit current, open-circuit voltage and the efficiency of a solar cell?
8. On what factors does the efficiency of the cell depend?

Unit 12 ❑ To study the variation of mutual inductance of a given pair of coaxial coils by using a ballistic galvanometer

Structure

12.1 Objectives

After studying this unit you will learn

- to use a ballistic galvanometer to measure charge
- to determine the mutual inductance between two given coils

12.2 Introduction

If two coils are placed close to each other and the current through one of them is changed, the flux linked with the other coil changes as a result of which an an e.m.f. is induced in the other coil according to Faraday's laws of induction. This phenomenon is known as Mutual Inductance. The first coil is called the primary and the other coil is called the secondary. The induced e.m.f. (e) is proportional to the rate of change of current in the primary coil, i.e., e = – M. dI/dt, where ‘I’ is the current in the primary coil. ‘M’ is called the *co-efficient of mutual inductance* between the coils or simply mutual inductance. Then,

$M = \left|\frac{e}{dI/dt}\right|$. Mutual inductance is defined as the e.m.f. induced in a coil when the rate of change of current in the other coil is unity. If e = 1 volt and dI/dt = 1 A/sec, then M = 1 henry. But 1henry is very large and usually mutual inductance is of the order of mH.

Mutual inductance is also defined as flux linked with one coil when the current through the other coil is unity. It can be shown that the mutual inductance of coil 1w.r.t. coil 2 = that the mutual inductance of coil 2 w.r.t. coil 1.

The value of mutual Inductance depends upon the number of turns of the coils, their cross-sectional area, closeness of the two coils and the orientation of one coil w.r.t. the other.

12.3 Theory

Mutual inductance is defined as the e.m.f. induced in a coil when the rate of change of current in the other coil is unity. Let M be the mutual inductance between the primary coil P and the secondary coil S in the circuit of Fig. 12.1. If a current of magnitude I is broken in the primary coil P then a charge of magnitude MI/R will flow in the secondary coil S, where R is the total resistance of the secondary circuit. This charge will produce a deflection, of the ballistic galvanometer, so that

$$MI/R = \frac{T}{2p}\cdot\frac{C}{nAB}\cdot q\left(1+\frac{1}{2}\right), \quad ..... (1)$$

where T = the time period of the moving parts of the ballistic galvanometer under open circuit condition,

C = couple/unit twist of the suspension fibre of the ballistic galvanometer,

n = the number of turns of the galvanometer coil,

A = the mean area of each turn of the galvanometer coil,

B = the magnetic field in which the galvanometer coil is placed, and

λ = the log decrement of the galvanometer under the condition of the throw.

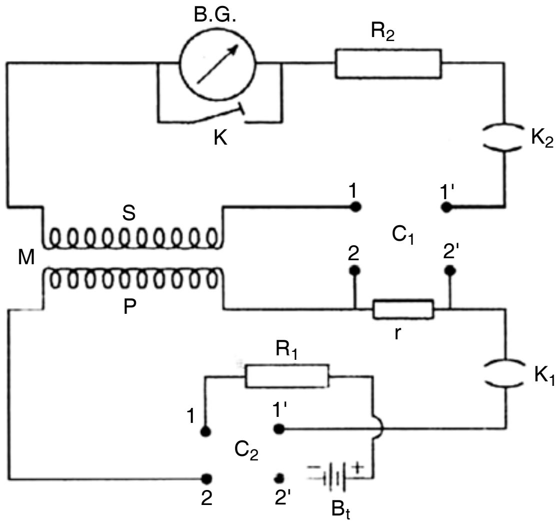


Fig. 12.1 Experimental arrangement

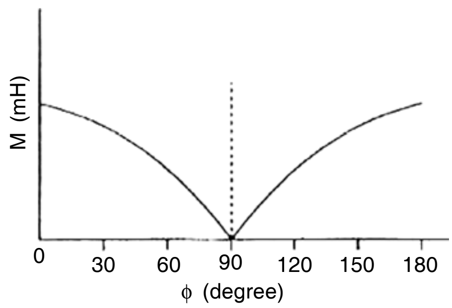


Fig. 12.2 M-ϕ graph

To eliminate $\frac{C}{nAB}$, a dc potential drop rI is applied in the secondary circuit. This will produce a steady deflection θ' of the ballistic galvanometer. Then $\frac{rI}{R} = \frac{C}{nAB}.q'$ ..... (2)

From Equ. (1) and (2) we have, M = $\frac{Tr}{2p}.\frac{q}{q'}.\left(1+\frac{l}{2}\right)$ ….. (3)

When the angles θ and θ' are small, $\frac{q}{q'}$ may be replaced by $\frac{d}{'d'}$ where d is the first throw of the ballistic galvanometer and d' is the steady deflection of the spot of light on the scale (of the lamp and scale arrangement) corresponding to θ and θ', respectively. Therefore,

M = $\frac{Tr}{2p}\frac{d}{d'}\left(1+\frac{l}{2}\right)$ ..... (4)

If r and T are expressed in ohm and second respectively, M will be in henry.

12.4 Apparatus

(1) A ballistic galvanometer (B.G), (2) a tapping key, (3) two plug keys, (4) two plug –type commutators, (5) two resistance boxes, (6) a low resistance (typically 0.01 to 0.1 Ω), (7) a storage battery/ regulated power supply, (8) two mutually coupled coils (P and S), one (P) fixed and the other (S) can rotate about a common axis, (9) a voltmeter/ multimeter, (10) a lamp and scale arrangement to measure the throw/ deflection of the ballistic galvanometer, (11) a stop watch/clock.

12.5 Experimental Procedure

1. Connect the circuit as shown in Fig. 12.1. Make the angle between the coils zero.
2. Measure the e.m.f. of the battery, both before and after the experiment by a voltmeter/multimeter.
3. Insert a resistance R_2 in the galvanometer circuit which is larger than the critical damping resistance (CDR) of the ballistic galvanometer. This resistance should not be changed throughout the experiment.
4. Put a suitable resistance R_1 in the battery circuit. Insert the plugs in the commutator C_2 and close the key K_1.Insert a plug between 1,1′ of the commutator C_1 and close the key K_2.Bring the spot of light on the zero of the scale of the lamp and scale arrangement with the help of the tapping key K.
5. Open the key K_1 in the primary circuit and observe the first throw (d) of the spot of light on the scale. Adjust R_1 such that this throw is about 16-18 cm. This resistance is kept fixed throughout the experiment.
6. Close the key K_1 and then open it. The ballistic galvanometer will be found to oscillate. Open the key K_2 so that the galvanometer circuit is open. Measure the time t for 20- 30 oscillations of the spot of light. Repeat this observation several times, say n, (at least three) and find the mean t. Calculate the time period T. (T = t/n).

7. Close the key K_1. Remove the plugs between 1,1′ and insert plugs between 1,2 and 1′, 2′ of the commutator C_1. Close key K_2 and observe the steady deflection (d′) of the spot of light on the scale due to the steady voltage drop across r. d′ should preferably be between 10- 16 cm. If necessary, adjust r to bring d' within this range. Do not change this value throughout the experiment. Note the steady deflection d′ several times for both direct and reverse currents, Find mean d′.

8. Remove the plugs between 1,2 and 1′, 2′ of the commutator C_1 and put a plug between 1, 1′ in C_1. Bring the spot of light on the zero of the scale by the tapping key K. Break the current in the primary suddenly by removing the key K_1 and record the first throw d of the spot of light on the scale. Repeat this thrice. Now reverse current in the primary by the commutator C_2 and repeat this step and find the first throw d of the spot of light on the scale thrice. Find the mean of six d's.

9. Increase the angle ϕ between the coils in steps of about 10° till ϕ = 110°. Repeat step 8 for each ϕ.

10. Set the angle ϕ between the coils zero. Bring the spot of light on the zero of the scale. Break the primary circuit and note the positions of the light spot on the scale first towards left and then towards right during the first half of the first oscillation. Let these readings be α_1 and α_2 respectively.

    Let $\beta_1 = \alpha_1 + \alpha_2$. After n complete oscillations measure α_{2n+1} and α_{2n+2}, where α_{2n+1} and α_{2n+2} are the first reading of the spot of light towards left and right respectively during the first half of the (n+1)th.oscillation. Let $\beta_{2n+1} = \alpha_{2n+1} + \alpha_{2n+2}$.

    Find λ from the equation: $\lambda = \frac{2.303}{2n}(\log_{10}\beta_1 - \log_{10}\beta_{2n+1})$ ..... (5)

    Find λ at least three times and take the mean.

11. Calculate M for each ϕ using equ.(4) and plot a graph with ϕ along the X-axis and M along the Y-axis. The nature of the graph will be as in Fig. 12.2.

12.6 Experimental Results

Table 1

Measurement of the e.m.f. of the battery

(Make a table similar to Table 2 of Unit 9)

Table 2

To determine the time period (T) of the galvanometer coil

(under open circuit condition)

R_2 = …. Ω, R_1 = … Ω

No. of obs.	Time for n complete oscillations (Sec)	Mean time (t) for n complete oscillations (Sec)	Time period T =t/n (sec)
1.	…		
2.	…	…	…
3.	…		

Table 3

Steady deflection

r = …. Ω (fixed)

Direction of current	Steady deflection d′ (cm)	Mean d′ (cm)
Direct	…	
	…	
	…	…
Reverse	…	
	…	
	…	

Table 4

Ballistic throws

CDR of the galvanometer = …Ω

R_2 = ….Ω

d′ = …. cm (from Table 3)

Dial reading ϕ (in degree)	Direction of current	Ballistic throw (d) (cm)	Mean d (cm)	Ratio d/d'
0	Direct	… … …	…	…
	Reverse	… … …		
etc.	etc.	etc.	etc.	etc.

Table 5

Determination of λ

No. of obs.	α_1 (cm)	α_2 (cm)	$\beta_1 = \alpha_1+\alpha_2$ (cm)	α_{2n+1} (cm)	α_{2n+2} (cm)	β_{2n+1} $\alpha_{2n+1}+\alpha_{2n+2}$ (cm)	n	λ (using Equ. (5))	Mean λ
1.	…	…	…	…	…	…	…	…	
2.	…	…	…	…	…	…	…	…	…
3.	…	…	…	…	…	…	…	…	

Table 6

Calculation of M and data for M – ϕ graph

Time period T (from Table 2) (sec)	λ from Table 5	Dial reading ϕ (degree)	Corresponding d/d' from Table 4	$M = \frac{Tr}{2p}\cdot\frac{d}{d'}(1+\lambda/2)$ (henry)
…	…	0	…	…
		10	…	…
		20	…	…
		etc.	etc.	etc.

12.7 Calculation of percentage error

The maximum proportional error in the measurement of M is given by

$$\frac{dM}{M} = \frac{dT}{T} + \frac{dd}{d} + \frac{dd'}{d'} + \frac{d\left(1+\frac{l}{2}\right)}{1+l/2}$$

Since T = t/n, $\frac{dT}{T} = \frac{dt}{t}.dt$ is the error in the measurement of time t for n oscillations = the minimum scale division of the stop watch used. $\delta d = \delta d' = 0.1$ cm, the smallest division of the scale of lamp and scale arrangement. Since λ is very small the last term in the right can be neglected. Substituting the values of δt, δd and $\delta d'$ we can find the percentage error $\frac{dM}{M}\times 100$.

12.8 Discussions

1. Be sure that the resistance in series with the B.G. is greater than its CDR. This resistance should not be changed during the experiment.
2. The battery voltage should remain constant during the experiment. The resistance R_1 in the battery circuit should not be changed during the experiment.

3. The throw d of the spot of light should be recorded during the break of the primary current only, because at break the resistance becomes infinite and the time constant for the decay of current is very small. Consequently, the change in flux within the secondary occurs in a very short time. The charge MI/R will thus flow through the galvanometer in a very short time so that ballistic condition of the galvanometer is achieved.
4. It is preferable to have d and d′ of nearly the same value.
5. The plugs of the resistance boxes should be light.

12.9 Summary

In this unit we have discussed what is meant by mutual inductance, the factors on which it depends and its measurement using a ballistic galvanometer.

12.10 Answers

1. See sec. 12.1
2. The mutual inductance is minimum when the coils are mutually perpendicular and maximum when the coils are mutually parallel.
3. Yes.
4. To bring the galvanometer to rest quickly, because the electromagnetic damping is large. When the key is tapped the galvanometer coil is short-circuited. So the induced current in the coil due to its motion in the permanent magnetic field of the galvanometer increases and the electromagnetic damping is large.
5. The mutual inductance will increase as the flux linked with the secondary increases.
6. Yes because $M = k\sqrt{(L_1 L_2)}$, where L_1 and L_2 are the self-inductance of the coils. k = the coefficient of coupling.
7. See Discussion 3 in sec.12.8

8. An ordinary galvanometer detects and measures current. A ballistic galvanometer measures charge. The time period of its moving parts is large and the damping of its moving parts is very small.
9. The minimum external resistance to be connected in series with the galvanometer so that it becomes oscillatory is called the critical damping resistance.
10. Due to damping the deflection (d′) of the galvanometer observed is less than the actual deflection (d). d and d′ are related by $d = d'(1 + \lambda/2)$. λ is called the logarithmic decrement.

12.11 Exercise

1. What is meant by mutual inductance? On what factors does it depend?
2. For which orientations of the coils will the mutual inductance be minimum and maximum?
3. Is the mutual inductance same if the primary and the secondary coils are interchanged?
4. Why is a tapping key connected to the galvanometer?
5. What will happen if an iron core is introduced in the primary?
6. Does the mutual inductance depend on the self-inductance of the coils?
7. Why don't you find the throw during establishing current in the primary?
8. How does a ballistic galvanometer differ from an ordinary galvanometer?
9. What is CDR of a ballistic galvanometer?
10. What is logarithmic decrement?

Unit 13 ❑ To find out temperature coefficient of the material of a wire by Carey-Foster bridge

Structure

13.1 Objectives

After studying this unit you will learn

- to use a Carey-Foster bridge to measure unknown resistance
- to find the temperature coefficient of the material of a wire

13.2 Introduction

The resistance of a substance changes with the change of temperature. In case of conductors, resistance increases with the rise of temperature, but in case of semiconductors and other non-metals resistance decreases with the rise of temperature. The electrical resistance of conductors such as silver, copper, gold, aluminum, etc., depends upon collision process of electrons within the material. As the temperature increases, this electron collision process becomes faster, which results in increased resistance with the rise in temperature of the conductor.But in case of semiconductors or other non-metals, the number of free electrons increases with increase in temperature. Because at a higher temperature, due to sufficient heat energy supplied to the crystal, a significant number of covalent bonds get broken, and hence more free electrons get created. That means if temperature increases, a significant number of electrons come to the conduction bands from valence bands by crossing the forbidden energy gap. As the number of free electrons increases, the resistance of this type of non-metallic substance decreases with an increase in temperature.

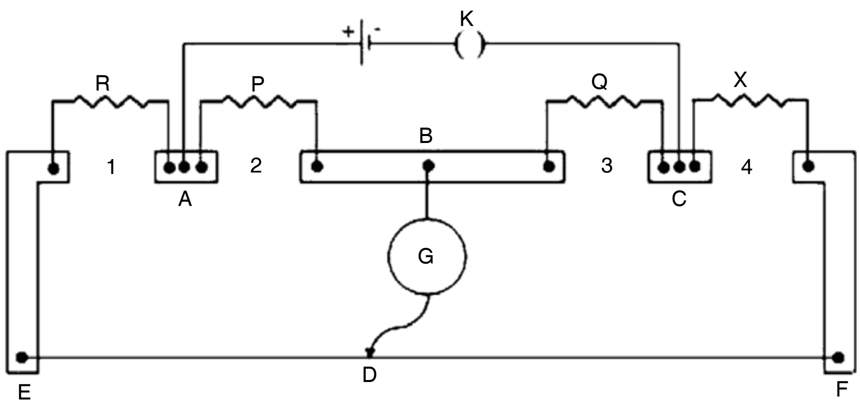
The change of resistance with the change of temperature of a material is expressed by the temperature coefficient of resistance. It is the measure of change in electrical resistance of any substance per degree of temperature change.Its unit is per °C. The temperature coefficient of resistance is positive for metals and negative for semiconductors and other non-metals. The increase in resistance of platinum with the increase of temperature is used to measure temperature.

13.3 Theory

Let R_0 and R_t be the resistances of a conductor at 0°C and t°C respectively, then $R_t = R_0 (1 + \alpha t)$, where α is a constant known as the temperature coefficient of the material. That is, $\alpha = (R_t - R_0)/(R_0 t)$. …… (1)

The resistances R_t and R_0 are measured by a Carey- Foster bridge. The circuit for measurement of an unknown resistance X by a Carey-Foster bridge is given in Fig. 13.1.

Fig. 13.1



Let P and Q be the equal resistances connected in the inner gaps 2 and 3, the standard resistance R is connected in gap 1 and the unknown resistance X is connected in the gap 4. Let l_1 be the balancing length ED measured from the end E. By Whetstone's bridge principle,

$$\frac{P}{Q}=\frac{R+a+l_2 r}{X+b+(100-l_2)r} \quad ......(2)$$

Here, a and b are the end corrections at the ends E and F respectively, and ρ is the resistance per unit length of the bridge wire.

If the experiment is repeated with X and R interchanged and if l_2 is the balancing length measured from the end E,

$$\frac{P}{Q}=\frac{R+a+l_2 r}{R+b+(100-l_2)r} \quad ......(3)$$

From equations (2) & (3) we get X = R + ρ (l_1 – l_2) .... (4)

Let l_1' and l_2' be the balancing lengths when the above experiment is done with a standard resistance r (say 0.1Ω) in the place of R and a thick copper strip of zero resistance in place of X.

From equation (4), we get

$$r=\frac{r}{l_2{'}-l_2{'}} \quad ...... (5)$$

If X_1 and X_2 be the resistances of the given wire at temperatures t_1°C and t_2°C respectively, the temperature coefficient of resistance is given by the equation,

$$a=\frac{X_2-X_1}{X_1 t_2-X_2 t_1} \quad .... (6)$$

Also, if X_0 and X_{100} be the resistances of the wire at 0°C and 100°C,

$$a=\frac{X_{100}-X_0}{X_0\times 100} \quad .... \quad (7)$$

The resistances are measured at 0°C and 100°C and from equation (7) the temperature coefficient of resistance is calculated.

13.4 Apparatus

(1) A carey foster bridge, (2) a standard low resistance (0.1 Ω), (3) three 10Ω resistances, (4) a storage battery/regulated power supply, (5) a plug key, (6) a galvanometer, (7) a thermometer, (8) a beaker containing water, (9) a stirrer, (10) a burner, (11) connecting wires.

13.5 Experimental Procedure

1. Connect the circuit as shown in Fig. 13.1. Use P = Q = 10 Ω in the gaps 2 and 3 respectively.
2. Connect the standard low resistance in gap 1 and a copper strip in gap 4. Close the key K. Move the jockey to find the balancing length l_1'. Find l_1' thrice and take their mean. Open the key K.
3. Interchange the standard low resistance and the copper strip in the gaps. Close the key K. Move the jockey to find the balancing length l_2'. Find l_2' thrice and take their mean. Open the key K.
4. Repeat steps 2 and 3 with three different low resistances.
5. Calculate ρ using the Equ.(5) in the three cases and compute mean ρ.
6. Remove the copper strip and connect the given wire temperature coefficient of resistance of whose material is to be determined in gap 4 and the low resistance in gap 1. Close the key K. Move the jockey to find the balancing length l_1. Find l_1 thrice and take their mean. Open the key K.
7. Interchange the standard low resistance and the experimental wire in the gaps. Close the key K. Move the jockey to find the balancing length l_2. Find l_2 thrice and take their mean. Open the key K.
8. Measure the room temperature, before and after the measurement, assuming that the experimental wire is at room temperature (t_1).
9. Calculate the resistance X_1 at temperature t_1 using the equ. (4).
10. Place the experimental wire immersed in the water in the beaker. Gently heat the water by a burner and stir the water with the stirrer so that the

temperature of water remains constant for 2/3 minutes. Keep the bulb of the thermometer close to the wire. Measure the temperature of water (t_2). Repeat steps 6 and 7 to find the balancing length l_2.

11. Calculate the resistance X_2 at temperature t_2 using the equ. (4).
12. Calculate the temperature coefficient of resistance using Equ. (6).

13.6 Experimental Results

Table 1

To find ρ

P = Q = 10 Ω, R = …Ω

Gap1	Gap 4	Balancing length (cm)	Mean (cm)	ρ Using Equ. (5) (Ω/cm)	Mean ρ
Low resistance (R)	0Ω	…. (l_1') …. (l_1') ….(l_1')	….(l_1')	...	... Ω/cm
0 Ω	Low resistance (R)	…(l_2') …. (l_2') ….(l_2')	…. (l_2')	...	

Table 2

To measure the room temperature (t_1)

Before experiment	…°C	Mean t_1
After experiment	…°C	…°C

Table 3

To measure the resistance (X_1) of the given wire at temperature t_1

$P = Q = 10\ \Omega$, ρ = …. Ω/cm (from Table 1)

Room temperature = ….°C (from Table 2)

Gap1	Gap4	Balancing length (cm)	Mean (cm)	$X_1 = R + \rho(l_1 - l_2)$ (Ω)	Mean X_1
Low (R) resistance (R)	X_1	…. (l_1) …. (l_1) ….(l_1)	…. (l_1)	...	…. Ω
X_1	Low resistance (R)	…. (l_2) …. (l_2) ….(l_2)	…. (l_2)	...	

Table 4

To measure the resistance (X_2) of the given wire at temperature t_2

Make Table similar to Table 3 and calculate the temperature coefficient of resistance using Equ. (6)

13.7 Discussions

1. The temperature of water in the beaker should be kept constant during the measurement of X_2.
2. The low resistance R should be of such a value that the null points are obtained near the ends of the bridge wire.
3. The Carey-Foster bridge is basically a Wheatstone bridge.

13.8 Summary

In this unit we have discussed what is meant by temperature coefficient of resistance, how does it change with the change of temperature and how to determine the temperature coefficient of resistance by a Carey- Foster bridge.

13.9 Answers

1. See sec.13.1
2. See sec.13.1
3. Yes. Then ρ will not be uniform and the measurement of resistance will not be correct.
4. The wire of the Carey-Foster bridge is soldered at the ends. So there is some resistance at the junctions. These resistances are end errors. The end errors are eliminated by determining the null point with the resistances interchanged between the gaps 1 and 4 of the bridge.
5. Usually it is used to measure low resistance. However, it can be used to find small differences between large resistances.
6. Because the bridge is most sensitive when the resistances of the four arms are equal and we are measuring low resistance.

13.10 Exercise

1. What is meant by temperature coefficient of resistance? What is its unit? How does it change with the change of temperature?
2. Why is the temperature coefficient of resistance positive in case of metals and negative in case of semiconductors?
3. Is there any harm if the wire of the Carey-Foster bridge is not of uniform cross-section?
4. What are end errors of the Carey- Foster bridge? How is it eliminated?
5. Can you measure high resistance by Carey-Foster bridge?
6. Why have you used $P = Q = 10\ \Omega$?

Unit 14 ❑ To find leakage resistance by discharging a capacitor

Structure

14.1 Objectives

After studying this unit you will learn to determine experimentally the leakage resistance of a capacitor.

14.2 Introduction

A capacitor has two plates with a dielectric in between the plates. A capacitor can store charge. But when a charged capacitor is left alone, its charge slowly leaks away due to the imperfection of the insulation between the plates. For this reason, a practical capacitor is represented by a capacitor with perfect insulation, in parallel with a resistance R, called the natural leakage resistance of the capacitor. In this unit we will discuss how the leakage resistance of a capacitor is determined using a ballistic galvanometer.

14.3 Theory

If a capacitor containing a charge Q is discharged through a ballistic galvanometer, then the ballistic throw θ is given by $Q = K\theta\ (1 + \lambda/2)$, ………… (1)

where K is the galvanometer constant and λ is the logarithmic decrement of the galvanometer coil.

When a charged capacitor is left alone, its charge slowly leaks away due to the imperfection of the insulation between the plates. For this reason, a practical capacitor is represented by a capacitor with perfect insulation, in parallel with a resistance R, called the natural leakage resistance of the capacitor. If Q' be the charge on the capacitor, of capacitance C, after it has been left alone for a time t, we can write

$$Q' = Q\exp\left(-\frac{t}{CR}\right) \ldots\ldots.(2)$$

When the charge Q' is discharged through the same galvanometer then a throw θ' is produced. Then

$$Q' = K\theta'\ (1 + \lambda/2) \quad \ldots\ldots.(3)$$

Using Eqs. (1), (2) and (3) we get,

$$\theta/\theta' = \exp\left(\frac{t}{CR}\right) \quad \text{or } R = t/\ [2.303\ C\ \log 10\ (\theta/\theta')] \ldots..\ (4)$$

If the movement of spot of light on the scale of the lamp and scale arrangement moves through d and d' corresponding to the throws θ and θ' respectively, then equ. (4) reduces to

$$R = t/\ [2.303\ C\ \log_{10}\ (d/d')] \quad \ldots..\ (5)$$

If d' is observed for several values of t and $\log_{10}\ (d/d')$ is plotted against t, a straight line passing through the origin is obtained. A point on the line gives t and corresponding $\log_{10}\ (d/d')$. Hence R can be calculated using equ. (5)

14.4 Apparatus

(1) A ballistic galvanometer (B.G), (2) a tapping key (K_1), (3) a capacitor (C) of known capacitance (typically, 1 μF), (4) two resistance boxes (R_1, R_2), (5) a commutator (M), (6) a special type of charging and discharging key (FK), (7) a stop watch/ clock, (8) a lamp and scale arrangement (9) a storage battery/ regulated power supply, (10) a voltmeter/ multimeter.

14.5 Experimental Procedure

1. Construct the circuit as shown in Fig. 14.1. Measure the e.m.f. of the battery before and after the experiment
2. Choose suitable values of resistances in the resistance boxes R_1 and R_2 in the following way.

   Charge the capacitor C by closing the battery circuit and depressing the rocker arm FK to the point b for a few seconds. Discharge the capacitor through the ballistic galvanometer quickly by putting the rocker arm FK to the point a and observe the first throw of the spot of light on the scale of the lamp and scale arrangement.The throw should be nearly equal to the maximum permissible value (about 18 cm) on the scale. If it is much smaller, then either increase resistance R_1 or decrease resistance R_2. If it is greater than the maximum permissible value, then either increase resistance R_2 or decrease resistance R_1. These resistances should be kept unchanged throughout the experiment.
3. Connect the points C_2, C_3 and C_1, C_4 of the commutator M.
4. Charge the capacitor with a charge Q by putting the rocker arm FK in contact with the point b for a few seconds. Tap the tapping key K to stop the spot of light on the lamp and scale arrangement and set the spot on the zero of the scale. Then press the charge-discharge key K to put the rocker arm FK in contact with the point a suddenly and the capacitor will be discharged through the galvanometer. Note the first throw (d) of the spot of light.

5. Connect the points C_2, C_4 and C_1, C_3 of the commutator M. This will reverse the current.
6. Repeat step 4.
7. Repeat steps 3 to 6 two more times and find the mean value of d.
8. Charge the capacitor with a charge Q by putting the rocker arm FK in contact with the point b for a few seconds. Put the rocker arm FK in the middle (that is, not in contact with the points a and b) for a convenient period of time (t) such that the capacitor undergoes natural leakage. Measure the time with a stop watch/clock. Now suddenly put the rocker arm in contact with the point a and the remaining charge of the capacitor discharges through the galvanometer. Note the first throw (d') of the spot of light. If it is not less than d by 1 – 2 cm decrease the time of natural leakage (t) to achieve this. Record the time and d'.
9. Repeat step 8 with reverse current.
10. Repeat steps 8 and 9 three times and find the mean d'. Find $\log_{10}$ (d/d').
11. Repeat steps 8 to 10 for at least five different values of natural leakage time t.
12. Draw a graph plotting natural leakage time t along the abscissa and $\log_{10}$ (d/d′) along the ordinate. The graph is a straight line passing through the origin. Choose a suitable point on the line and find t and $\log_{10}$ (d/d′) corresponding to the point. Calculate the leakage resistance R using equ. (5).

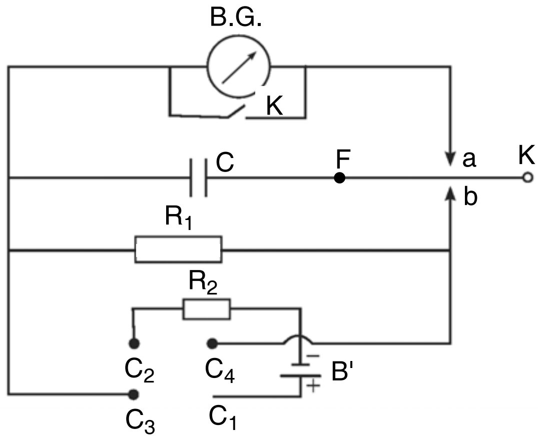


Fig. 14.1

14.6 Experimental Results

Table 1

Measurement of the e.m.f. of the battery

(Make a table similar to Table 2 of Unit 9)

Table 2

Determination of ballistic throw (d) for full charge Q

Capacitance of the capacitor = ….μF

R_1 = …. Ω, R_2 = ….Ω

No. of obs.	Ballistic throw d (in cm)			Grand mean throw d (in cm)
	Direct current	Reverse current	Mean	
1.	…	…	…	
2.	…	…	…	…
3.	…	…	…	

Table 3

Data for natural leakage resistance R

d = ….. cm (from Table 2)

No. of obs.	Time of leakage (sec)	Throw d' in cm for			Grand mean d' (in cm)	$\log_{10}$ (d/d')
		Direct Current	Reverse Current	Mean		
1.	…	… … …	… … …	… … …	… .	…
2.	…	… … …	… … …	… … …	...	…
etc.	etc.	etc.	etc.	etc.	etc.	etc.

Table 4

Determination of natural leakage resistance R

Capacitance C	t (from graph)	$\log_{10}$ (d/d′) (from graph)	R = t/ [2.303 C $\log_{10}$ (d/d′)]
….μF(Given)	…. Sec	....	….Ω

14.7 Calculation of percentage error

R = t/[2.303 C $\log_{10}$ (d/d′)] = t/[C ln (d/d′)]   or, ln (d/d′) = t/CR

So, $\dfrac{\partial(d/d')}{(d/d')} = \partial(t/CR) = (1/C).\partial(t/R)$

Now, $\partial(d/d') = \dfrac{\partial d}{d'} - \dfrac{d\,\partial d'}{d'^2}$ and $\partial(t/R) = \dfrac{\partial t}{R} - \dfrac{t}{R}.\dfrac{\partial R}{R}.$

Hence $\dfrac{\partial\left(\dfrac{d}{d'}\right)}{d/d'} = \dfrac{\partial d}{d} - \dfrac{\partial d'}{d'}.$

Again, δd = δd' = the minimum division of the scale of the lamp and scale arrangement.

Therefore, replacing the negative sign before δd'/d' by a positive sign for maximum error, we have,

$$\frac{\partial\left(\dfrac{d}{d'}\right)}{d/d'} = \partial d\left(\frac{1}{d} + \frac{1}{d'}\right) = \frac{1}{C}.\frac{\partial t}{R} - \frac{1}{C}.\frac{t}{R}.\frac{\partial R}{R}$$

Or, $\dfrac{\partial R}{R} = \left[\dfrac{1}{C}.\dfrac{\partial t}{R} + \partial d\left(\dfrac{1}{d} + \dfrac{1}{d'}\right)\right]\dfrac{CR}{t}$

For determining the maximum error the negative sign is made positive.

δt = the minimum division of the stop watch/ clock. Substituting the values of δt, δd, δd', C, etc. we get $\dfrac{\partial R}{R}$ Multiplying it by 100 we get the percentage error.

14.8 Discussions

1. During the experiment the capacitor is charged several times. It should be ensured that each time it is charged to the same potential. So it is to be checked that the e.m.f. of the battery remains constant during the experiment.
2. After charging the capacitor it should not be touched.
3. The plugs of the resistance boxes and the commutator should be tight.
4. Before recording the throw the galvanometer must be stopped using the tapping key and the spot of light should be brought at zero of the scale.

14.9 Summary

In this unit we have discussed what is meant by the leakage resistance of a capacitor and how to determine it experimentally. Percentage error has been calculated.

14.10 Answers

1. See sec. 14.1
2. Capacitance is the amount of charge stored in a capacitor for unit potential difference between the plates of the capacitor. Its SI unit is farad. As farad is a large unit it is expressed in μF.
3. $ER_1/(R_1 + R_2)$, where E is the e.m.f. of the battery.
4. The time of leakage is determined by the time constant CR. R is of the order of MΩ. If C is of the order of farad, CR is of the order of 10^6 sec. the leakage time will be very large. If C is very small leakage time will be very small to be measured by a stop watch.
5. Because we have determined the ratio of two throws and hence $(1 + \lambda/2)$ is eliminated.
6. To bring the galvanometer to rest quickly, because then the electromagnetic damping is large. When the key is tapped the galvanometer coil is short-

circuited. So the induced current in the coil due to its motion in the permanent magnetic field of the galvanometer increases and the electromagnetic damping is large.

7. Due to damping the deflection (d′) of the galvanometer observed is less than the actual deflection (d). d and d′ are related by $d = d' (1+ \lambda/2)$. λ is called the logarithmic decrement.
8. An ordinary galvanometer detects and measures current. A ballistic galvanometer measures charge. The time period of its moving parts is large and the damping of its moving parts is very small.
9. See sec. 14.8 (Discussion No. 1)
10. The resistance of the capacitor is very high. So during discharge of the capacitor through the galvanometer the resistance in the galvanometer circuit is very large.

14.11 Exercise

1. What is a capacitor? What is meant by its natural leakage resistance?
2. What is capacitance of a capacitor? What is its unit?
3. What is the voltage to which the capacitor is charged in your experiment?
4. What will happen if the capacitance is very large or very small?
5. Why have you not measured the log decrement ?
6. Why is a tapping key connected to the galvanometer?
7. What is logarithmic decrement?
8. How does a ballistic galvanometer differ from an ordinary galvanometer?
9. Why is it necessary to measure the e.m.f. of the battery before and after experiment?
10. Why have not connected any resistance in series with the ballistic galvanometer?

Unit 15 ❑ To study Lissajous figures

Structure

15.1 Objectives

After studying the unit you will learn

- what is Lissajuos figure and how it is produced on a CRO screen
- how the frequency of a sinusoidal wave and the phase difference between two sinusoidal waves can be determined using Lissajuos figures.
- experimental method to determine the frequency of a sinusoidal wave and the phase difference between two sinusoidal waves.

15.2 Introduction

When two mutually perpendicular simple harmonic motions superimpose the resulting motion is not simple harmonic and the resulting pattern is called a Lissajous figure. Let, $x = A \sin (at + \theta)$ …. (1) and $y = B \sin (bt)$ …. (2) be two SHMs acting along the x-axis and y-axis respectively and they are acting on the same particle. The resulting motion will be a Lissajous figure. The figure will depend on the ratio a/b and the phase difference θ. If $\frac{a}{b} = 1$, the figure is a straight line, an ellipse or a circle depending upon the amplitude and the phase of the two waves. A straight line results when the phase difference is zero or 180°. A circle is produced when the amplitudes are equal and the phase difference is 90°. If the amplitudes are unequal and/or the phase difference is arbitrary an ellipse is formed. (Fig. 15.1).

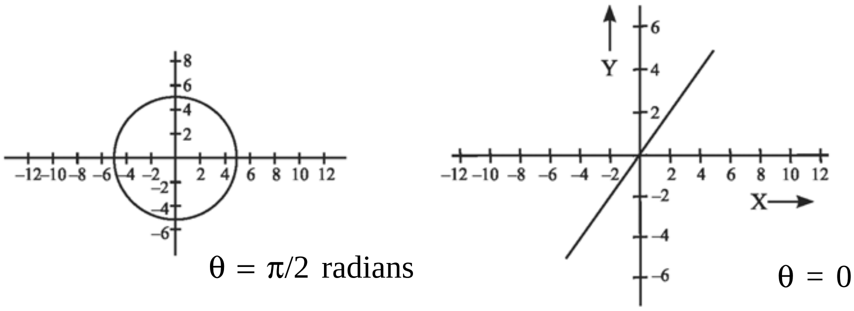
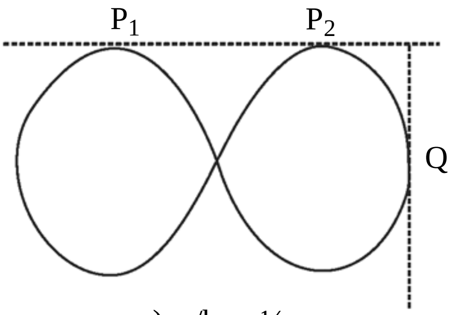
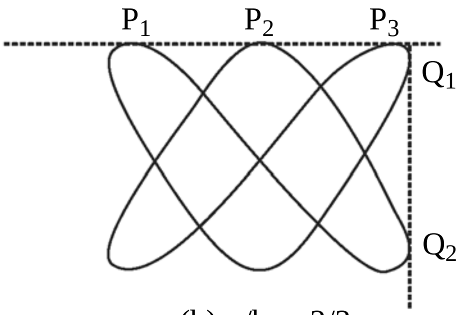


Fig. 15.1 Lissajous figures

The Lissajous figures are closed only if a/b is rational. The ratio a/b determines the number of "lobes" of the figure. For example, if a/b = ½, i.e., the ratio of the frequencies of the horizontal wave to the vertical wave is 1:2, the resulting Lissajous figure is a figure of eight (Fig. 15.2 (a)). If a/b = 2/3,the resulting Lissajous figure is as shown in Fig. 15.2 (b). From the Lissajous figures we can determine the ratio of the frequencies of the horizontal and vertical waves. In Fig. 15.2 (a), a tangent at the top edge of the pattern has two points of contact P_1 and P_2, whereas a tangent at a vertical side has one point of contact Q. Similarly, in Fig. 15.2 (b), a tangent at the top edge of the pattern has three points of contact P_1, P_2 and P_3, whereas a tangent at a vertical side has two points of contact Q_1 and Q_2. In general, the number of horizontal tangencies refers to the frequency of the vertical wave and the number of vertical tangencies refers to the frequency of the horizontal wave, i.e., $a/b = n_v/n_h$, where n_v and n_h are the number of vertical tangencies and horizontal tangencies respectively.



a) a/b = ½



(b) a/b = 2/3

Fig. 15.2

Lissajous figures can be used to determine the frequency of a sinusoidal wave and the phase difference between two sinusoidal waves. The figures can be displayed on a CRO (Cathode Ray Oscilloscope) screen. To determine the frequency of a sinusoidal wave, the wave and another sinusoidal wave of known frequency are applied to the vertical and horizontal deflecting plates respectively of a CRO and a the frequency of the wave using equation $a/b = n_v/n_h$.

Let us now briefly discuss about a CRO. A sketch of a CRO is shown in Fig.15.3. It consists of a cathode from which electrons are emitted when it is heated by passing current through a filament, an electron gun and focusing anodes to provide a focused electron beam which is accelerated towards the phosphor screen, horizontal and vertical deflection plates. If a sinusoidal voltage is applied to the horizontal deflection plates the spot of light on the screen moves to and fro along the horizontal direction. Similarly, if a sinusoidal voltage is applied to the vertical deflection plates the spot of light on the screen moves to and fro along the vertical direction. If sinusoidal voltages are applied both to the horizontal and vertical deflection plates a Lissajuos figure is obtained on the screen.

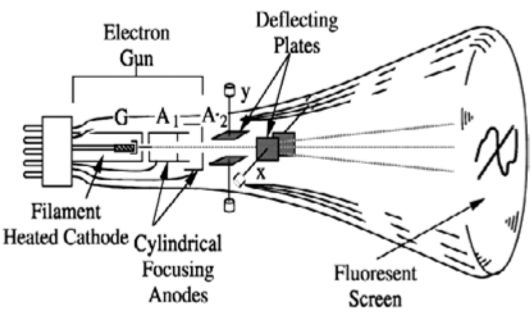


Fig. 15.3 Cathode Ray Oscilloscope

15.3 Theory

If sinusoidal voltages are applied both to the horizontal and vertical deflection plates of a CRO a Lissajuos figure is obtained on the screen. If a and b be the frequencies of voltages and n_v and n_h be the number of vertical tangencies and horizontal tangencies respectively, then $a/b = n_v/n_h$ ……. (3)

If one of the frequencies is known the other can be determined from the equation.

The phase difference θ can be determined by applying the voltages (Equations (1) and (2)) at the horizontal and vertical deflection plates of a CRO. Then if θ = 0, a straight line of positive slope is obtained. If θ ≠ 0 a Lissajous figure as shown in Fig. 15.4 is obtained on the screen. If in the figure the point of intersection of the ellipse with the y-axis is (0, A) and the maximum vertical displacement is B, then $\theta = \sin^{-1}(\pm A/B)$ ….. (4)

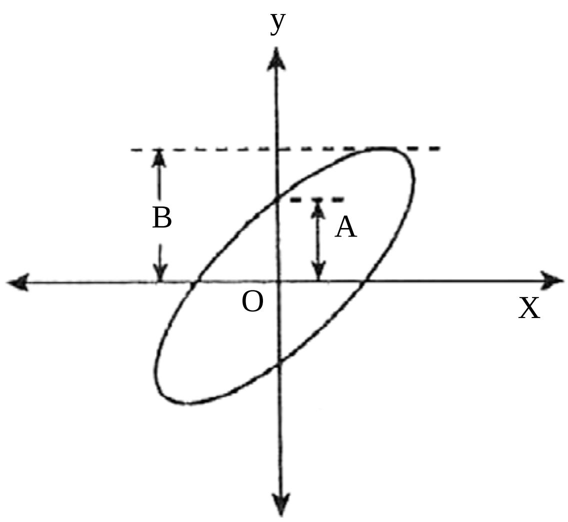


Fig. 15.4

15.4 Apparatus

(1) A dual trace CRO, (2) two audio frequency oscillators, (3) two capacitors, (4) two resistors, (5) probes of CRO.

15.5 Experimental Procedure

At the start of the experiment the spot on the CRO screen has to be properly focused, the intensity of the spot should be adjusted so that it is not very low or very high, the probes of the CRO should be grounded and the spot be brought at the centre of the screen. It is to be checked from time to time that the spot is at the centre.

15.5.1 Measurement of frequency

1. Connect the output of one audio oscillator (say, 1) to the horizontal deflection plates of the CRO and that of the other oscillator (say, 2) to the vertical deflection plates. Adjust the frequency 'a' of the first oscillator to a suitable value (say, 1 kHz) (take it to be unknown) and the frequency 'b' of the second oscillator to 2 kHz, and their amplitudes to 1 V.
2. Observe the Lissajous figure on the CRO screen and find the number of horizontal and vertical tangencies. Calculate the frequency a.
3. Repeat steps 2 by changing frequency b of oscillator 2 to 3 kHz and 4 kHz.
4. Repeat steps 2 and 3 by changing the amplitude of oscillator 2 twice.

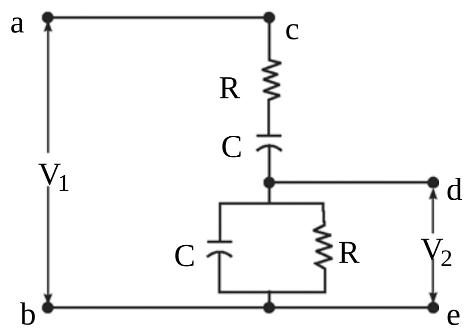


Fig. 15.5

15.5.2 Measurement of phase difference

1. Construct the circuit as shown in Fig.15.5. The oscillator is connected to the terminals a and b. Select suitable values of R and C so that the frequency f is about 1 kHz. ($f = 1/2\,\pi RC$). The voltage V_1 is applied to the horizontal deflecting plates and the voltage V_2 to the vertical deflecting plates.

2. Select a suitable frequency of the oscillator. Observe the Lissajous figure on the CRO screen. Find the point of intersection of the ellipse with the y-axis is (0,A) and the maximum vertical displacement is B. Calculate the phase difference θ.

3. Repeat step 2 with two other frequencies of the oscillator.

15.6 Experimental Results

Table 1

Measurement of frequency

Amplitude of the oscillator 1 = …. V

Frequency of the oscillator 1 = …. kHz (Take it to be unknown, a)

No. of obs.	Frequency of the oscillator2 (in kHz)	Amplitude of the oscillator2 (in V)	No. of horizontal tangencies	No. of vertical tangencies	Frequency a (in kHz)	Mean frequency a (in kHz)
1.	…	… … …	… … …	… … …	… … …	….
2.	…	… … …	… … …	… … …	… … …	....
3.	etc.	etc.	etc.	etc.	etc.	

Table 2

Measurement of phase difference

Frequency of the oscillator (in kHz)	Shape of the Lissajous figure	A (No. of divisions)	B (No. of divisions)	$\theta = \sin^{-1}(\pm A/B)$ (degree)
… … etc.	… … etc.	… … etc.	… … etc.	… … etc.

15.7 Discussions

1. Though the frequency of oscillator 1 has been fixed at 1 kHz it is considered to be the unknown frequency. It is observed that the measured frequency is close to this value.
2. It has been checked that the spot is at the centre of the screen.
3. The intensity of the spot should not be very bright so that the florescent screen is not damaged.
4. The Lissajous figure should be stable.

15.8 Summary

In this unit we have given an elementary ideas about Lissajous figure and the CRO. We have discussed how to measure frequency and phase difference.

15.9 Answers

1. See sec.15.1
2. See sec.15.1
3. See sec.15.1
4. See sec.15.1
5. See Discussion 3 (sec.15.7)
6. See sec.15.1

15.10 Exercise

1. What is Lissajous figure? When will the figure will be an ellipse?
2. When will the Lissajous figure be a closed curve?
3. When is the Lissajous figure a figure of eight?
4. What are the different parts of a CRO?
5. Why the intensity of the spot on the screen be moderate?
6. What are horizontal and vertical deflection plates of a CRO?